1. *FY04 Progress for PEP II by John Seeman and Michael Sullivan*

PEP-II is a particle beam accelerator which collides 1588 bunches of electrons with 1588 bunches of positrons in two counter-circulating storage rings to produce continuous luminosity to make B mesons in the BaBar physics detector. It is called a B-Factory. Each bunch contains about 100 billion particles. The beams collide on every turn of the accelerator or about 130,000 times per second.

Construction and installation of PEP-II was completed within budget in early July 1998. First collisions were observed in late July 1998 that was two months ahead of the final PEP-II DOE construction milestone. The BaBar detector was installed in May 1999. PEP-II has been delivering luminosity to BaBar nearly continuously over the past five years. PEP-II exceeded its design luminosity in October 2000 by achieving 3.30 x 10^{33} $cm^{-2}s^{-1}$. Through steady progress, PEP-II exceeded twice it design luminosity in May 2003 and over three times it design luminosity in May 2004. The peak integrated luminosity per day has reached 710 pb^{-1} which is 5.5 times the design of 130 pb^{-1} per day. The total integrated luminosity in July 2004 was over 17 fb^{-1}.

Progress in FY2004:

Looking back at the details of the past year, a ten-month PEP-II BaBar colliding beam run was planned for FY2004, during which a large quantity of data was to be collected. PEP-II and BaBar turned on very rapidly and started producing excellent physics results from the recorded data samples. The luminosity increases over the past twelve months have come from several factors. Reducing β_y^*s from 12 to about 11 mm increased the luminosity by about 10%. The bunch spacing has been changed from the By-3 to the By-2 which has a bunch every second RF bucket. This By-2 spacing has some (anticipated) parasitic crossing effects but the adverse affects were measured to be below 5 to 7 percent in the luminosity, consistent with our beam-beam computer simulations. The new bunch spacing has allowed more bunches to be collided which also allowed the beam currents to be increased with constant bunch current. The higher beam currents with the new RF stations are now about 2450 mA in the LER and 1550 mA in the HER. The betatron tunes were optimized near the half integer reducing the effects of the beam-beam interaction. The optical magnet lattice have been improved by reducing "beta" errors around the rings which down the road should allow higher beam-beam tune shifts.

Trickle injection was a great improvement for PEP-II in FY2004. In a beam-beam collision, the vast majority of the particles in each bunch pass through the opposing bunch without anything happening. Occasional, two particles annihilate each other in a collision and are lost. In addition, as the beams travel around the rings, the particles occasionally interact with the residual gas in the vacuum system and are lost by hitting the beam vacuum pipe scattering all around the ring. In this way, the beam particles are used up slowly with lifetimes of about 2 to 4 hours. If unreplenished, the beam currents would slowly fade away and the luminosity would rapidly fall. The data each detector collects is proportional to the luminosity.

The traditional approach for colliders, until last November, has been to inject with the detector turned off until the rings are full, stop injection, and then turn on the detector to take data. The beams slowly “coast down” for about 40 minutes, after which the detector is turned off and a refill is started. As is obvious, this is inefficient. The injection time is lost for data taking and the coast down has an average luminosity which is significantly less than the peak. The inefficiency can be as large as 30 to 40%. T he detector and accelerator physicists wanted to get that back.

It has been a dream of accelerator physicists for a long time to injection while the detector is taking data. An accelerator can only do this if the injection energy is the same as the colliding energy. The B-Factories are ideal candidates. PEP-II was designed to inject continuously (i.e. trickle charge). The answer was to make injection very “clean” with few lost particles hitting the detector!

A collaboration between the PEP-II accelerator operators and the BaBar detector operators have worked for several years to make the injection losses small. After ten or so machine studies shifts spaced over a year and hard work in between, PEP-II and BaBar have reduced the backgrounds to an acceptable level to allow BaBar to take data continuously. Trickle injection for the positron ring of PEP-II was good enough for production data running at BaBar in November of 2003. PEP-II and BaBar have never gone back. The improved efficiency for data taking was about 30% within a few days. Trickle injection for positrons uses about three injection pulses per second from the linac, resulting in the positron current being stable to about 0.1% and BaBar getting better than 99% of the data.

The injection for the electron ring HER at PEP-II was more difficult and studies continued until March 2004 before trickle injection was successful. About two linac pulses per second is all that is needed to keep the electron current stable to 0.1%. Since March 2004, both PEP-II rings are trickle injected with BaBar taking data. The SLAC linac was designed to allow up to 40 injected positron pulses and also 40 electron pulses each second in any order, although fewer pulses are actually needed. So PEP-II has true trickle injection with very steady currents and steady luminosity. The overall improvement in efficiency jumped 10% with the second ring and to just over 40% with both. The PEP-II and BaBar groups are all very pleased with this improvement.

In summary, in the FY2004 beam run several milestones for the PEP-II program were achieved. PEP-II exceeded three its design luminosity this year (May 2004) by achieving 9.21 x 10^{33} $cm^{-2}s^{-1}$. These luminosity levels correspond to giving BaBar over 1 million new particle physics events every day! This very high luminosity was reached using 1588 bunches with 2450 mA of positrons and 1550 mA of electrons. The vertical and horizontal beam sizes at the interaction region were about 4.0 by 125 microns, respectively. Furthermore, PEP-II delivered 710 pb^{-1} in one day to BaBar in May 2004. This rate is 5.5 times the design delivered luminosity per day of 130 pb^{-1}/day. Thus, the luminosity delivery efficiency is excellent. From September 2003 to September 2004

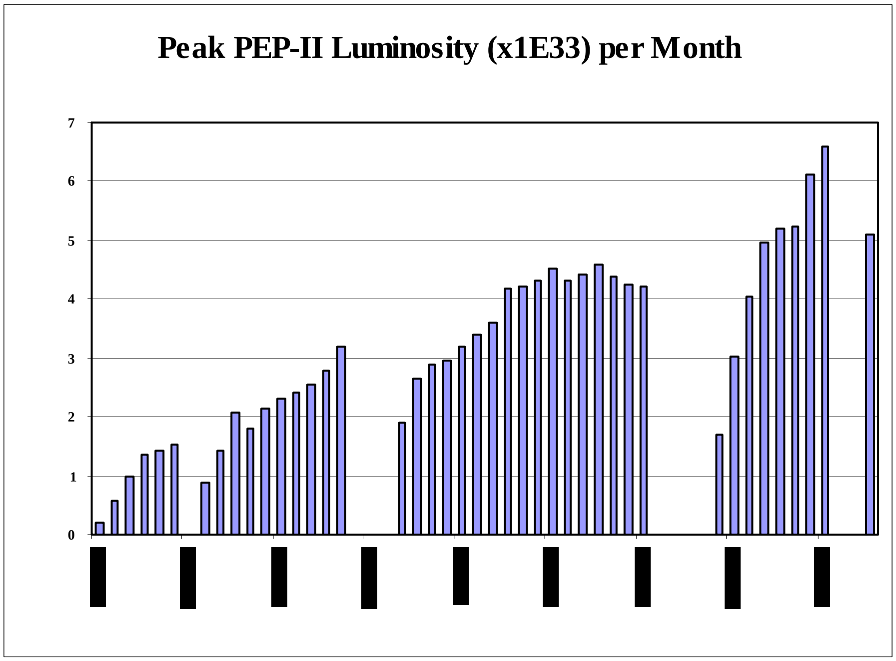
PEP-II has delivered about 114 fb^{-1}, which is a very sizable data sample by itself. Overall, from May 1999 to October 2004, PEP-II has delivered over 256 fb^{-1} to BaBar.

These achievements can be seen in the figures below which show the peak luminosity in each month, the delivered luminosity in each month, the running total of the delivered luminosity over Run 4 and since PEP-II started. The luminosity delivered per month has shown a large increase due to trickle injection of both the LER and HER and the increase in the peak luminosity.

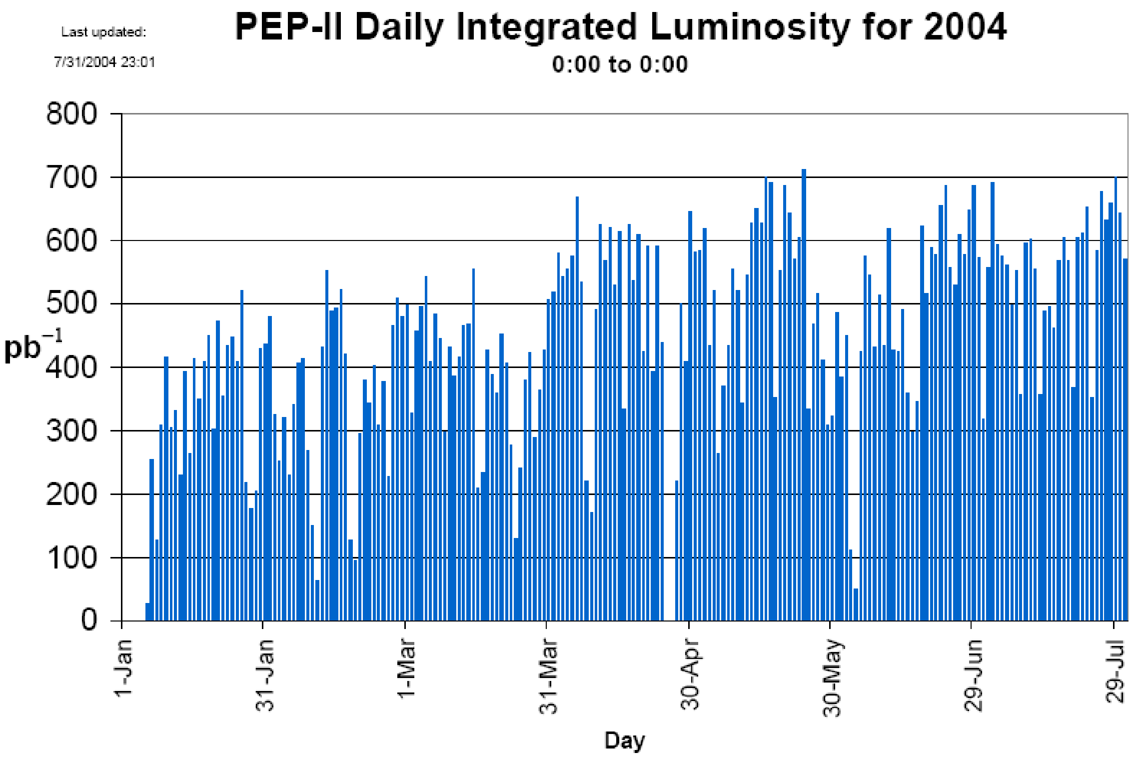
The FY2004 Summer maintenance period started August 1, 2004, and is planned to end about October 18, 2004. The original PEP-II design had considerable flexibility built in to allow upgrades to increase the luminosity with time as funding became available. For example, the original vacuum chambers (arcs and straights) were designed to handle twice the LER current and four times the HER current. However, to reach these higher currents the interaction region vacuum system needs upgrading. Similarly, space was left to add many RF stations, as needed, to increase the current and hence the luminosity of the ring. Several specific hardware upgrades were done in the summer of 2004 to allow increased luminosity. The bunch-by-bunch feedback systems were strengthened to accommodate the higher beam currents. New longitudinal feedback amplifiers and two new “Frascati style” longitudinal feedback kickers were installed in the LER to improve feedback reliability at higher beam currents. A new large steel shielding wall was installed at the forward end of the BaBar detector, shielding the forward muon chambers from lost particles in PEP-II. A fourth LER RF station was installed to increase the LER current capability from 2.7 to 3.6 A. A ninth HER RF station was installed to increase its current capability to 1.8 A. With the expected higher RF voltages and magnetic lattice changes, the bunch lengths will be shortened by a factor of about 10% reducing the beam-beam hourglass effect. A new synchrotron-light beam size monitor for the LER was installed to improve the resolution of the vertical beam size measurement aiding in luminosity optimization as very small vertical emittances are needed to get more luminosity out of the accelerator. We are looking forward to a new high luminosity run starting this fall.

Figures:

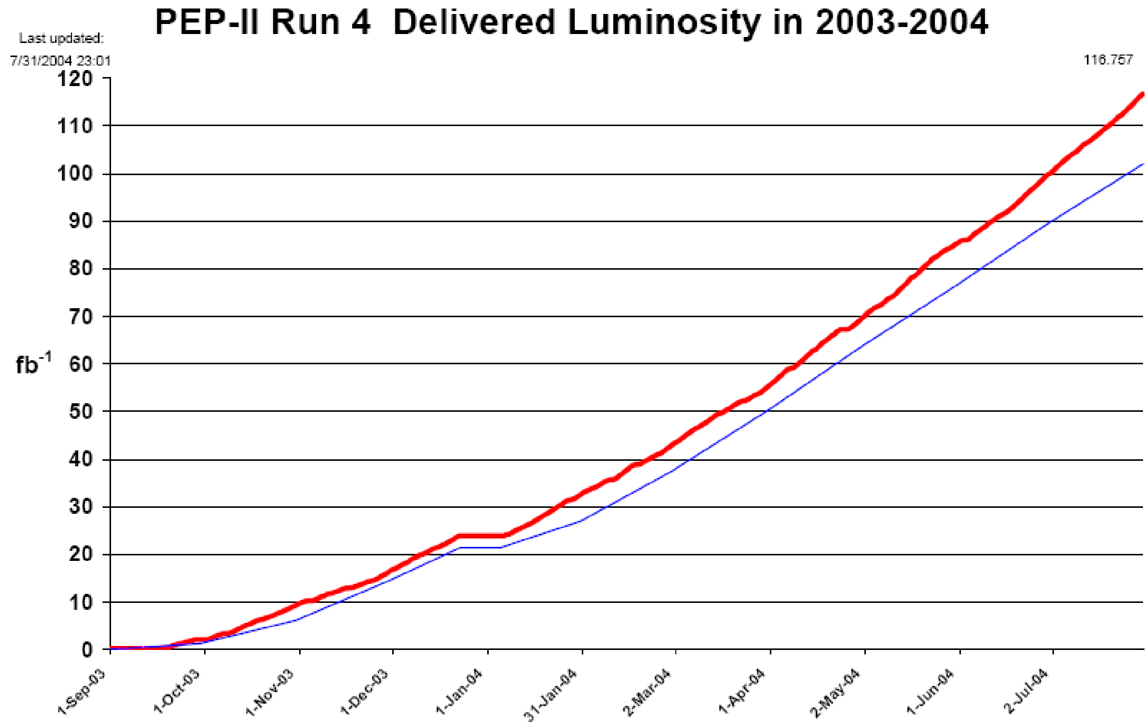
PEP-II peak luminosity in each month since May 1999.



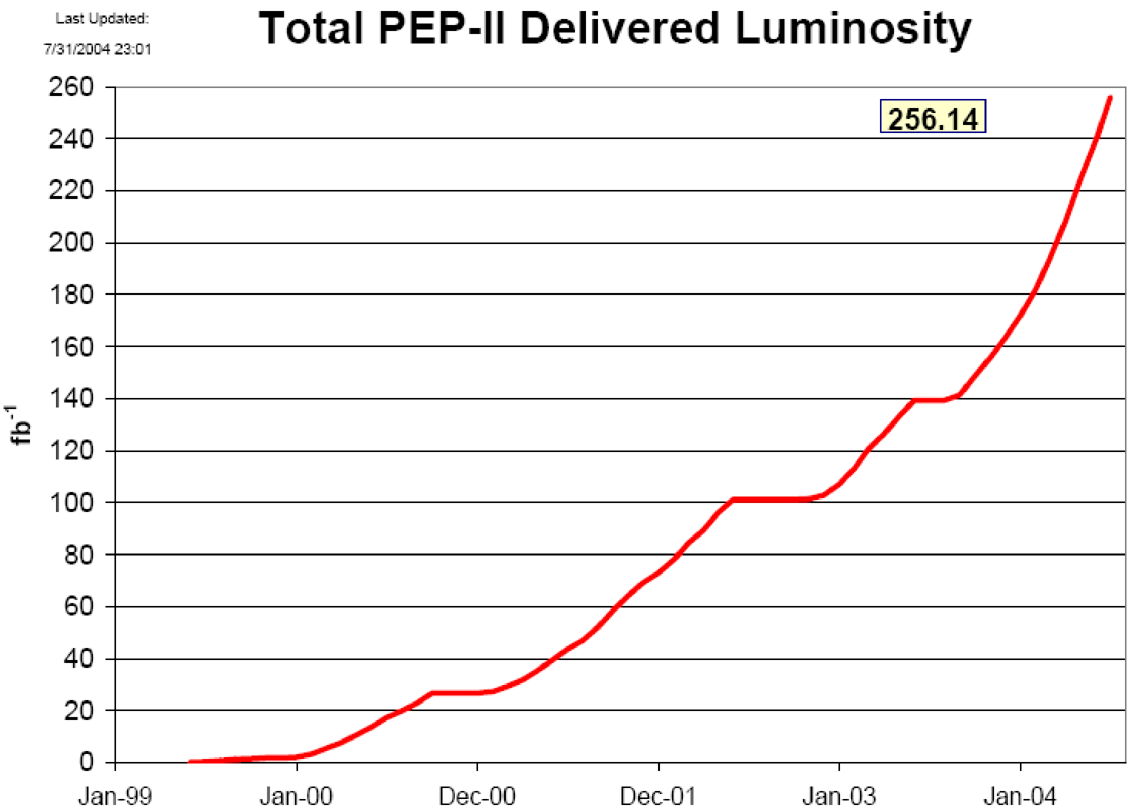
PEP-II integrated luminosity per day



PEP-II accumulated integrated luminosity during FY 2004. The blue line is the prediction from August 2003.



PEP-II accumulated integrated luminosity since May 1999.



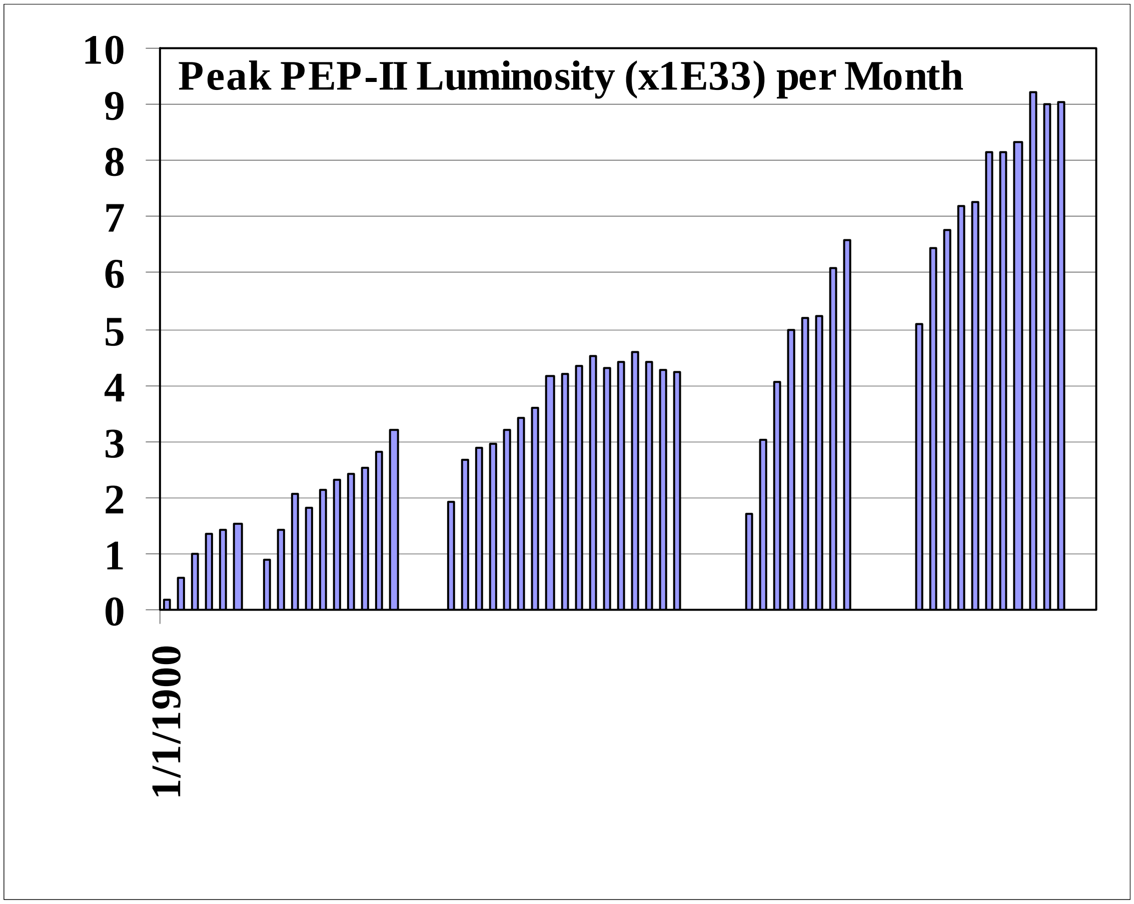
PEP-II integrated luminosity per month since May 1999.

Peak Luminosity in a Given Month for PEP-II

Luminosity Start	Correction factor	Date	Maximum PEP-II Luminosity (x1E33)
0.180	1.06	Jun-99	0.1908
0.543	1.06	Jul-99	0.57558
0.929	1.06	Aug-99	0.98474
1.270	1.06	Sep-99	1.3462
1.350	1.06	Oct-99	1.431
1.434	1.06	Nov-99	1.52004
0.000	1.06	Dec-99	0
0.837	1.06	Jan-00	0.88722
1.336	1.06	Feb-00	1.41616
1.945	1.06	Mar-00	2.0617
1.711	1.06	Apr-00	1.81366
2.015	1.06	May-00	2.1359
2.167	1.06	Jun-00	2.29702
2.280	1.06	Jul-00	2.4168
2.398	1.06	Aug-00	2.54188
2.638	1.06	Sep-00	2.79628
3.020	1.06	Oct-00	3.2012
0.000	1.06	Nov-00	0
0.000	1.06	Dec-00	0
0.000	1.06	Jan-01	0
1.800	1.06	Feb-01	1.908
2.661	1	Mar-01	2.661
2.900	1	Apr-01	2.9
2.950	1	May-01	2.95
3.189	1	Jun-01	3.189
3.399	1	Jul-01	3.399
3.592	1	Aug-01	3.592
4.166	1	Sep-01	4.166
4.214	1	Oct-01	4.214
4.327	1	Nov-01	4.327
4.513	1	Dec-01	4.513
4.305	1	Jan-02	4.305
4.412	1	Feb-02	4.412
4.602	1	Mar-02	4.602
4.400	1	Apr-02	4.4
4.256	1	May-02	4.256
4.229	1	Jun-02	4.229
0.000	1	Jul-02	0

0.000	1	Aug-02	0

Luminosity Start	Correction factor	Date	Maximum PEP-II Luminosity (x1E33)
0.000	1	Sep-02	0
0.000	1	Oct-02	0
1.708	1	Nov-02	1.708
3.017	1	Dec-02	3.017
4.050	1	Jan-03	4.05
4.971	1	Feb-03	4.971
5.213	1	Mar-03	5.213
5.221	1	Apr-03	5.2214
6.103	1	May-03	6.103
6.582	1	Jun-03	6.582
0.000	1	Jul-03	0
0.000	1	Aug-03	0
5.100	1	Sep-03	5.1
6.430	1	Oct-03	6.43
6.777	1	Nov-03	6.777
7.179	1	Dec-03	7.179
7.266	1	Jan-04	7.266
8.158	1	Feb-04	8.158
8.158	1	Mar-04	8.158
8.339	1	Apr-04	8.339
9.213	1	May-04	9.213
8.998	1	Jun-04	8.998
		Jul-04	9.042
		Aug-04	0
9.042	1	Sep-04	0


Peak PEP-II Luminosity (x1E33) per Month
10
9
8
7
6
5
4
3
2
1
0
1/1/1900

2. FY04 Progress in BaBar: CP Violation Studies at the PEPII B Factory by David MacFarlane and William Wisniewski

Overview

Over this past year, *BABAR* experiment has been spectacularly productive, with many new results on time-dependent and direct *CP* asymmetries, rare and semileptonic *B* decays, and charm and tau physics. The detector continues to perform extremely well, with an operational efficiency of 97%. Since the start of running in October 1999, *BABAR* has accumulated an integrated luminosity of 210 fb^{-1} on the $\Upsilon(4S)$ resonance, corresponding to 230 M *B*-meson pairs, and an additional 23 fb^{-1} taken 40 MeV below the resonance. The analysis of the data has led to a broad range of results and over 100 submitted publications. Of particular note was the large outpouring of new results from the *B* Factories for this summer's major conference, the International Conference on High Energy Physics in Beijing (ICHEP04). In total, *BABAR* contributed 72 conference papers, with *BABAR* speakers giving 22 parallel session talks on the full spectrum of new results, as well as a major plenary talk by Marcello Giorgi, *BABAR* Spokesperson. Clearly, PEP-II and *BABAR* have been highly productive in recording, reconstructing, analyzing and simulating data, more than fulfilling expectations for the promise for exciting physics from the project.

BaBar Physics Highlights

The *BABAR* physics program, based on this enormous data sample, encompasses three main goals: (1) comprehensive measurement of a compete set *CP*-violating asymmetries in *B* meson decays; (2) systematic exploration of rare decay processes; and (3) detailed studies to elucidate the dynamics of processes involving heavy quarks. The first two goals focus on testing the Standard Model, measuring its parameters, and searching for the effects of new physics, while the third goal is designed to build a solid foundation by elucidating the interplay between electroweak and strong interactions in heavy-quark processes.

During the past year, we have made substantial progress in all three areas. The original discovery of time-dependent *CP* violation in the modes $B^0 \to J/\psi K_S^0, B^0 \to J/\psi K_L^0$ and related charmonium channels has now become a precision measurement, with an updated value for the *CP* violation parameter $\sin 2\beta = 0.722 \pm 0.040 \pm 0.023$ shown at ICHEP04 (Fig. 1). This result provides a precise benchmark for *CP* violating effects within the Standard Model due to interference between amplitudes for *B* decay and *B* mixing. The angle . remains the most precisely measured angle of the Cabibbo-Kobayashi-Masakawa (CKM) unitarity triangle, whose three internal angles .. , and characterize *CP* asymmetries in a wide variety of processes. The remarkable predictive power of the Standard Model arises from the fact that both the angles and sides of the unitarity triangle govern the full range of quark transitions in a highly interrelated manner.

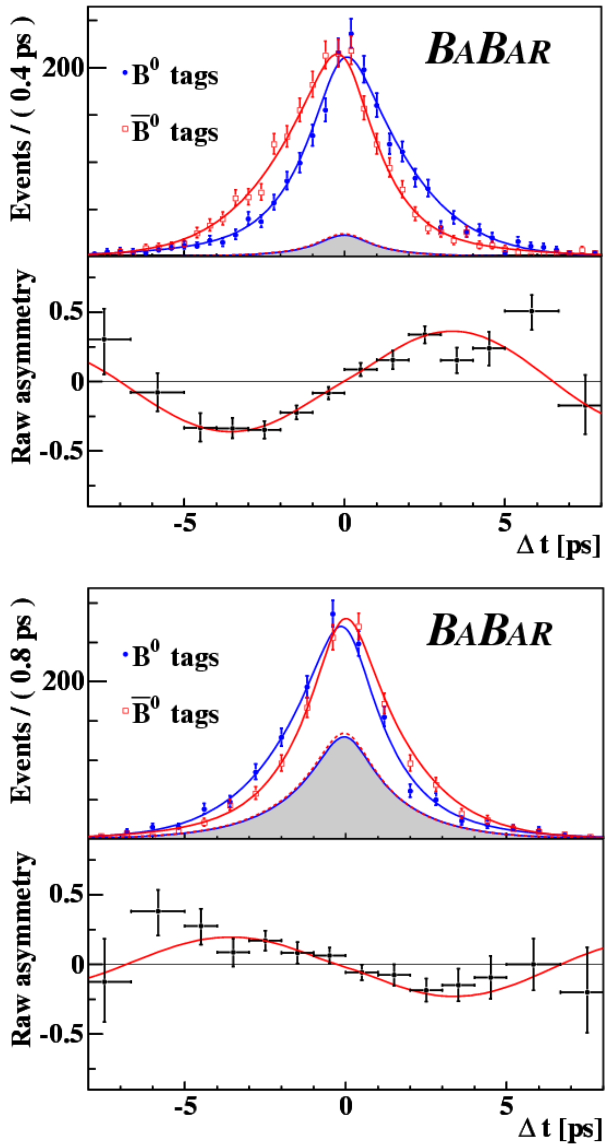


Fig.1. Δt distributions and raw asymmetries for flavor-tagged samples of $B^0 \to J/\psi K_S^0$ and other $CP = -1$ channels (left) and $B^0 \to J/\psi K_L^0$ (right). The shaded portion is the background contribution in the samples.

Measurements of time-dependent *CP* asymmetries are now being extended to rare decay modes involving so-called $b \to s\bar{s}s$ penguin diagrams containing virtual quarks and vector bosons. While such modes, include $B^0 \to \varphi K^0$, $B^0 \to \eta' K^0$ and a number of related channels, should show the same *CP* asymmetry as the benchmark charmonium result for $\sin 2\beta$, they are also sensitive to new physics at high mass scales beyond those directly produced by present day experiments. Figure 2 shows an example of the candidate sample for the $B^0 \to \varphi K_S^0$ and the observed asymmetry in the time evolution for these events.

A full compilation of measurements of *CP* asymmetries in $b \to s\bar{s}s$ is shown in Fig. 3. All results were updated at CHEP04 this summer, based on the complete data set. The average value 0.42 ± 0.10 for the product of the amplitude of the sine $(S_{\pi\pi})$ term in the time-dependent asymmetry and the *CP* eigenvalue for the final state (η_{CP}) should be equal to the well-measured value of $\sin 2\beta = 0.726 \pm 0.037$. Intriguingly, this is not the case at present, with a discrepancy at the level of 2.7 standard deviations for the *BABAR* results alone. When combined with a similar suite of measurements from Belle, the discrepancy increases to about 3.6□. Clearly this is a result to watch in the future as more data is accumulated, since such a discrepancy is exactly the kind of signature one would expect from new physics.

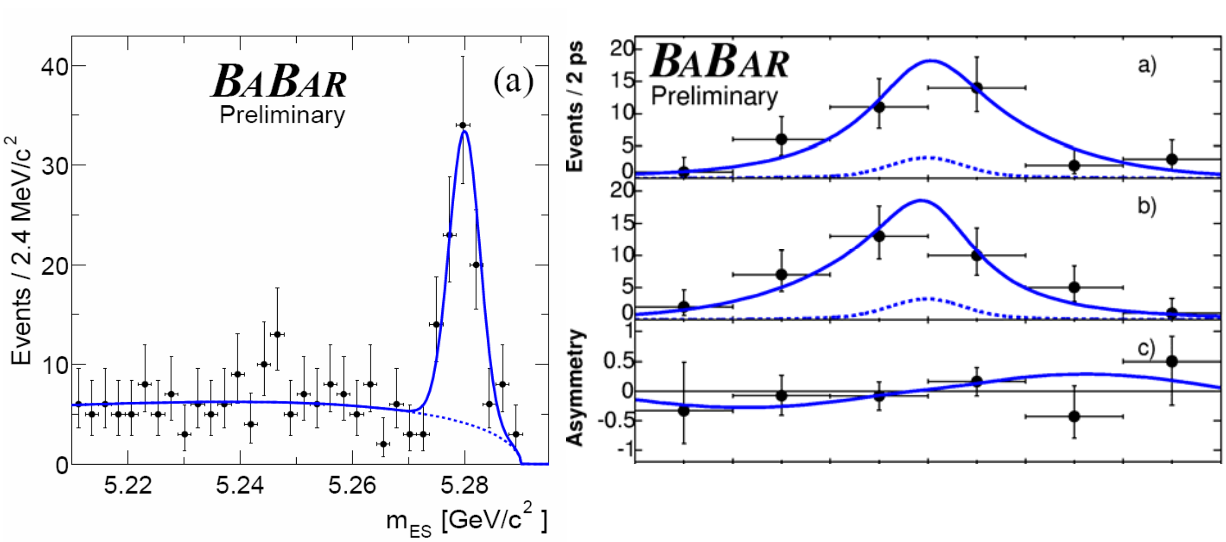


Fig.2. Mass distribution for a sample of $B^0 \to \varphi K_S^0$ (left), Δt distributions for B^0-tagged (right-upper) and $\bar{B}^0$-tagged (right-middle) events, and visible asymmetry (right-bottom) with overlayed fit results.

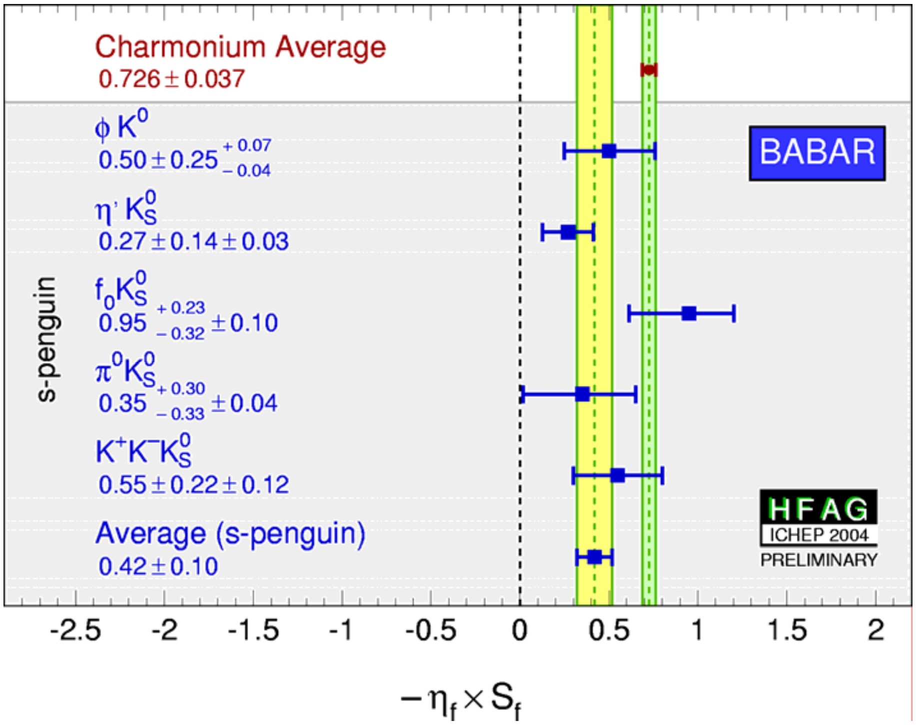


Fig.3. Compilation of fit results for the amplitude of the sine $(S_{\pi\pi})$ term in the time-dependent asymmetry multiplied by the *CP* eigenvalue for the final state (η_{CP}) as obtained for various $b \to s\bar{s}s$ channels. The average over the five channels is about 2.7 standard deviations below the precision measurement of $\sin 2\beta$ obtained in the charmonium modes.

With our increasing data samples, the focus of the *CP* violation program has also turned to measurements related to the remaining angles of the unitarity angles triangle. The angle is related to time-dependent asymmetries in two-body modes involving $b \to u$ transitions such as $B^0 \to \pi^+\pi^-$, $B^0 \to \rho\pi$, and $B^0 \to \rho^+\rho^-$. However, the additional complication for many of these channels is the significant contribution of an additional decay mechanism, involving a so-called penguin diagram. Figure 4 summarizes the observed amplitudes for the sine and cosine dependent terms of the asymmetry for the two-body mode $B^0 \to \pi^+\pi^-$. While Belle has claimed to observe significant *CP* violation in this channel, along with evidence for direct *CP* violation through interference of two competing decay amplitudes, these claims are not supported by the *BABAR* results. Clearly more data will be needed to resolve this important puzzle. A direct measurement of the unitarity angle requires a complete isospin analysis of the full set of tagged two-body decays. Following the initial observation of the rarest of these modes $B^0 \to \pi^0\pi^0$ reported at LP03 by *BABAR*, a first measurement of the flavor-tagged time-integrated asymmetry has now been performed allowing us to constrain the correction due to the additional penguin decay mechanism.

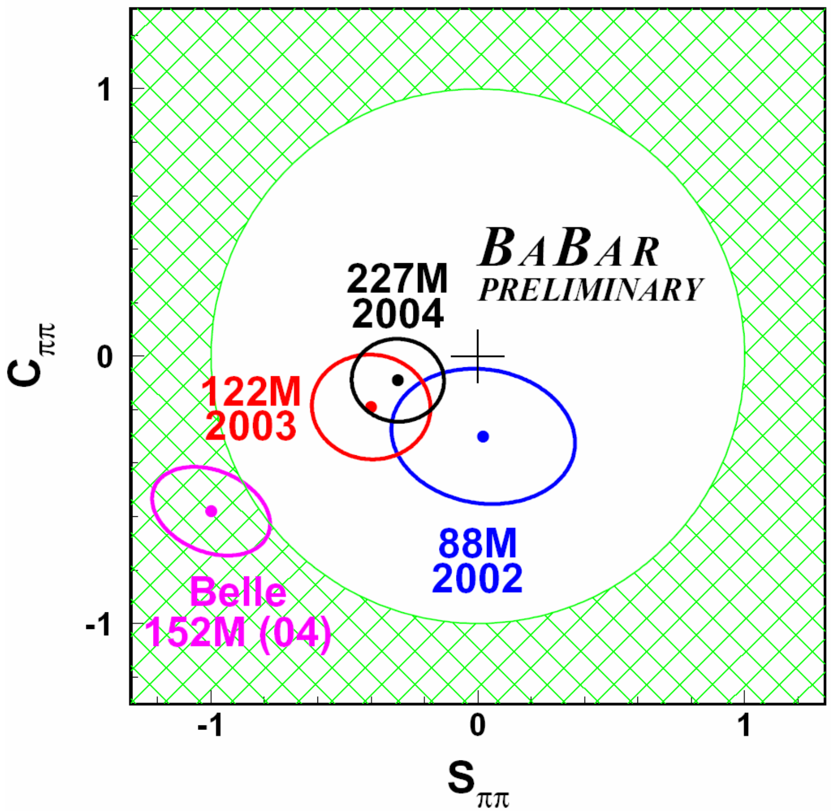


Fig.4. Compilation of fit results for the amplitude of the sine ($S_{\pi\pi}$) and cosine ($C_{\pi\pi}$) terms in the time-dependent asymmetry observed for samples of $B^0 \to \pi^+\pi^-$ signal events observed at *BABAR* and Belle. The most recent *BABAR* measurement, reported at ICHEP04 and based on a sample of 227 million $B\overline{B}$ pairs, is indicated by the smallest error ellipse.

An important development this year in our study of has been the discovery that $B^0 \to \rho^+\rho^-$ has a comparatively small contamination from the penguin amplitude while also being an essentially pure *CP* eigenstate. The Δt distributions for tagged samples of $B^0 \to \rho^+\rho^-$ candidates, and the corresponding visible asymmetry, is shown in Fig. 5. On the basis of the observed asymmetry we have obtained a first measurement of the unitarity angle, which we find to be $\alpha = \left[96 \pm 10_{stat} \pm 4_{sys} \pm 11_{penguin}\right]^{\circ}$. The compilation of available measurements of shown in Fig. 6 demonstrates significant progress over the past year, dominated by this exciting result from $B^0 \to \rho^+\rho^-$.

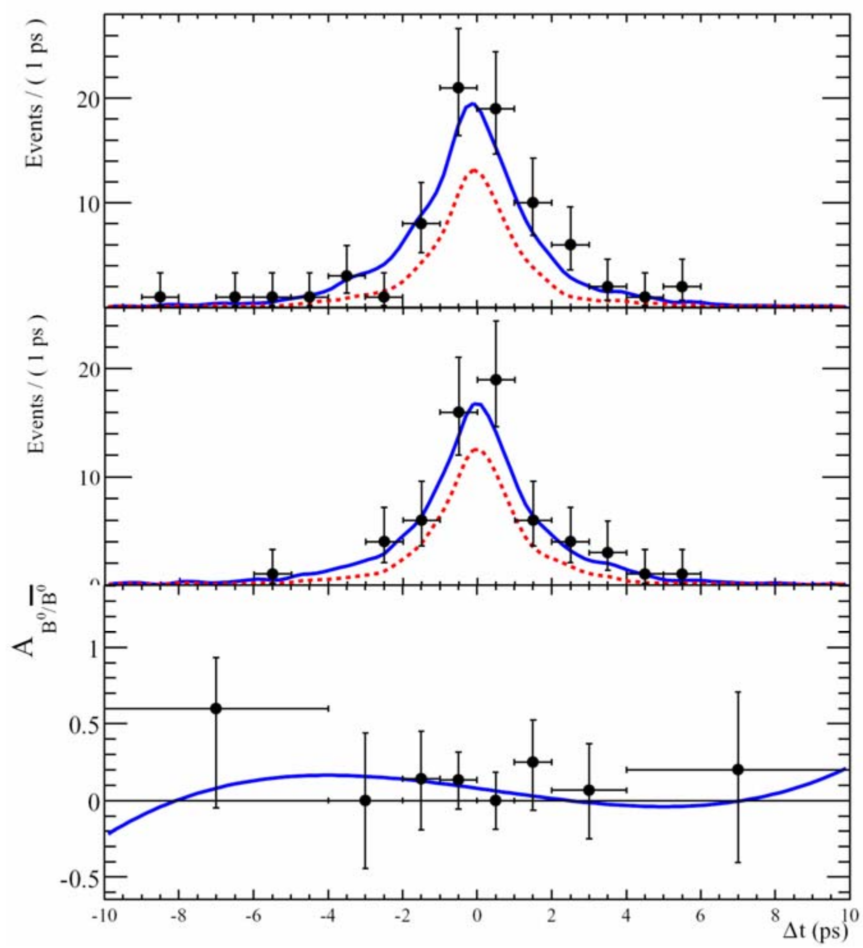


Fig.5. Δt distribution for events enriched in $B^0 \to \rho^+\rho^-$ signal events for B^0-tagged (upper) and $\overline{B}^0$-tagged (middle) events. The dashed line represents the sum of backgrounds and the solid line the sum of signal and backgrounds. The time-dependent *CP* asymmetry is shown in the lower panel along with the projected fit result.

Studies have also been continuing on a host of rare charged and neutral B meson decays that provide a deeper understanding of the role of different "tree" and "penguin" amplitudes in decays to charmless final states. For example, we are now beginning to understand how to use the interference between allowed and suppressed amplitudes to gain information about the third unitarity angle . where first constraints are starting to emerge. Interference between tree and penguin amplitudes can also give rise to so-called direct *CP* violation, which does not involve mixing. This last summer *BABAR* reported the first observation of direct *CP* violation in the channel $B^0 \to K^+\pi^-$. In a total sample of 1606 ± 51 signal events, we observe 856 decays of the type $B^0 \to K^+\pi^-$ but only 750 of the type $B^0 \to K^-\pi^+$. The 13.3% asymmetry is readily visible in Fig. 7 as the difference in the signal height at the B mass for the solid $(B^0 \to K^+\pi^-)$ and dashed $(B^0 \to K^-\pi^+)$ curves. This measurement establishes that direct *CP* violation exists in the B meson system. It also opens up a new window for study of the Standard Model predictions for direct *CP* violation and potential new physics sources.

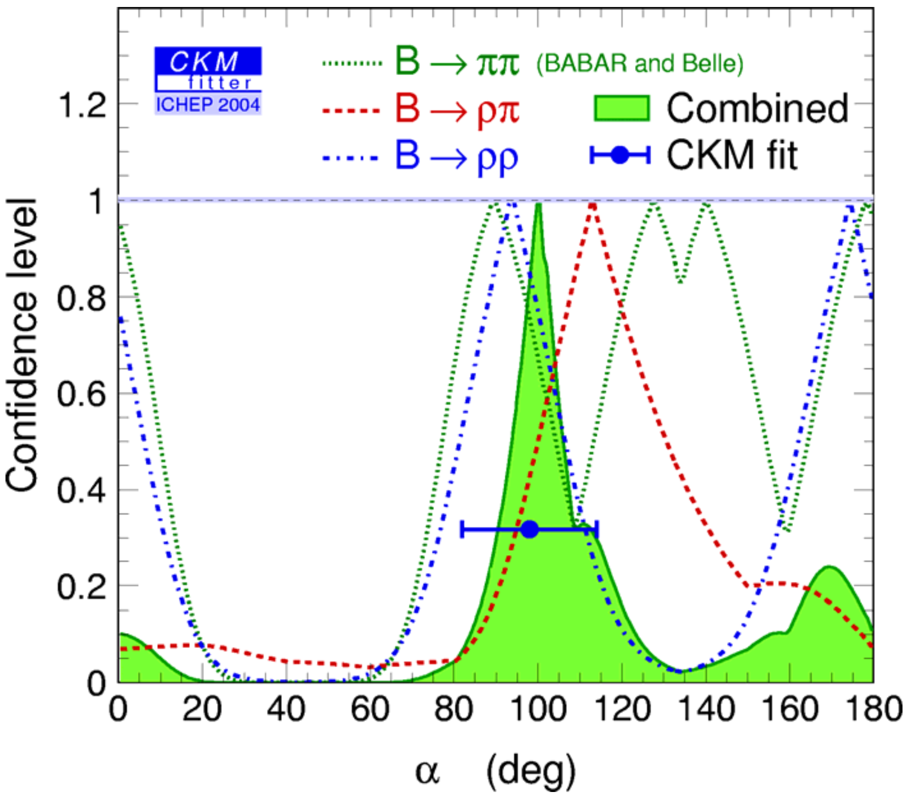


Fig.6. Combined result (shaded region) for direct determination of the unitarity angle , based on measurements of *CP* asymmetry in $B \to \pi\pi$, $B \to \rho\pi$, and $B \to \rho\rho$. The point with error bars in the predicted value for from indirect measurements of CKM matrix elements.

The sides of the CKM triangle can be related to the rates for certain quark transitions and such measurements complement the measurements of *CP* asymmetries, which are related to the angles of the triangle. We are continuing to refine new, state-of-the art measurements of the magnitudes of CKM parameters V_{cb} and V_{ub} using semileptonic *B* decays, and we have studied the detailed dynamical properties of inclusive semileptonic *B* decays to extract key theoretical parameters describing *B* decay. The V_{ub} measurement is particularly interesting in that it exploits the large data sample by using events in which one of the two *B* mesons is fully reconstructed in an hadronic decay mode. In such events, the remaining tracks can be analyzed much more easily, allowing a more inclusive measurement that reduces theoretical model dependence on V_{ub}.

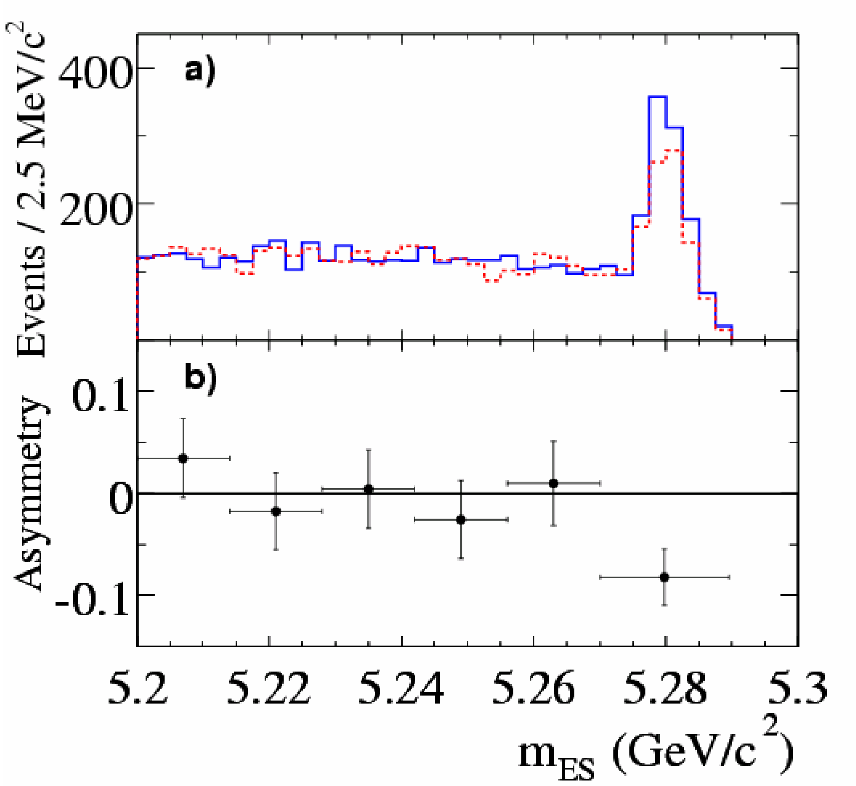


Fig.7. Observation of direct *CP* violation in the decays $B^0 \to K^+\pi^-$ announced by *BABAR* this summer. The solid curve is the mass distribution for $B^0 \to K^+\pi^-$ candidates, while the dashed curve is for $B^0 \to K^-\pi^+$. The lower panel shows the counting asymmetry as a function of mass. In the background region below the B mass peak, no asymmetry is observed. On the peak, a clear difference in the numbers of $B^0 \to K^+\pi^-$ versus $B^0 \to K^-\pi^+$ events can be seen.

One of the most interesting announcements in spectroscopy this year was the claim by several experiments for the observation of two new states that are thought to be the first examples for 5-quark states, or so-called pentaquarks. If true, this would create a whole new spectroscopy of states lying outside our present picture of mesons ($q\bar{q}$ states) and baryons (qqq states). *BABAR* quickly organized a systematic look for pentaquarks, including the claimed $\theta_5^+(1540)$ and $\Xi_5^{--}(1862)$. No evidence for either object was found in our data, or for related states that should appear if these are indeed pentaquarks. We have been able to set limits on production that lie far below those observed for baryons of similar mass as shown in Fig. 8. Our measurements imply either that the new states have a highly unusual production mechanism, or perhaps the initial experiments are wrong. Nevertheless, as with new states discovered by *BABAR* last year, this work is a reminder of the significant potential for surprises in the very large data samples available in *BABAR*. The discovery opens up new territory for exploration of spectroscopy, and it has already led to many other experimental results, as well as much theoretical interest.

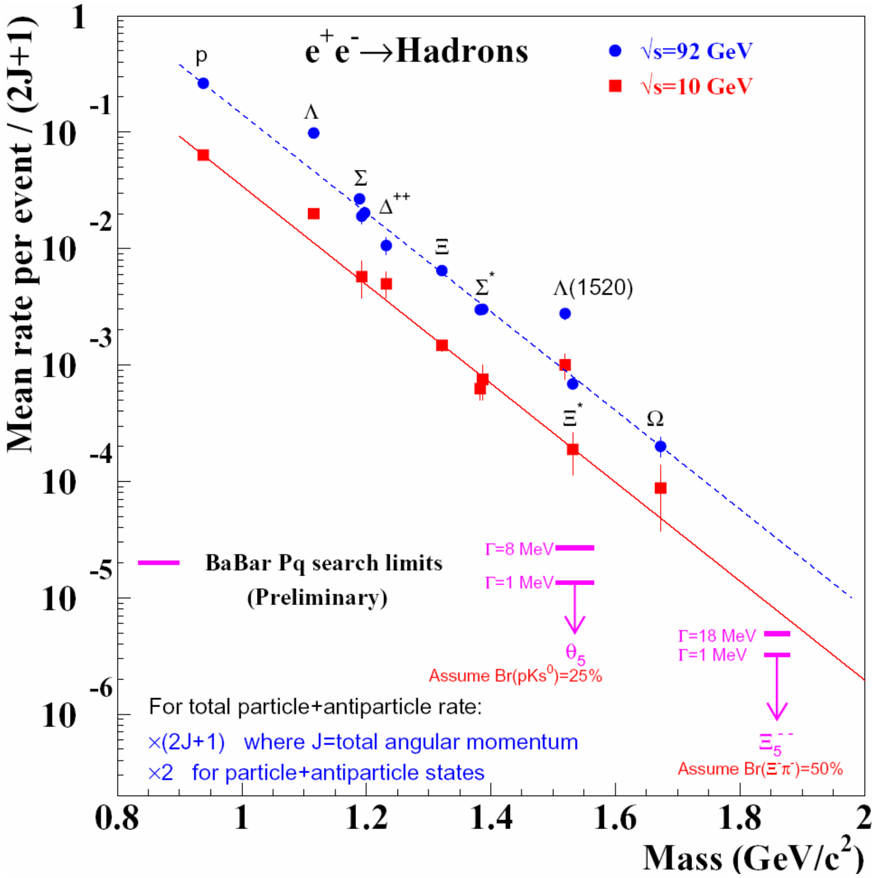


Fig.8. Observed rates for inclusive baryon production as a function of the baryon mass. Also shown are the *BABAR* limits for pentaquark production of the states $\theta_5^+(1540)$ and $\Xi_5^{--}(1862)$, for which other experiments have claimed positive evidence.

BaBar Detector

The *BABAR* Detector completed its fourth data run at the end of July 2004, after collecting 113.4 fb^{-1} (Fig. 9.).The close collaboration between PEP-II and *BABAR* has been a major component of the large increase in recorded luminosity during the last year. The combination of enhanced diagnostic tools for understanding backgrounds in real time along with the unusual level of cooperation between accelerator and detector physicists has allowed us to adapt swiftly to the new environment of continuous filling (trickle injection) of the storage rings. This mode of operation has provided more than 40% increase in luminosity.

The *BABAR* Machine Detector Interface group is developing a detailed Monte Carlo simulation (GEANT4) of the interaction region. This is being used to understand beam related backgrounds with input rays from beam orbit code (Turtle). The group's efforts also include construction of a monitor for beam position and size that uses synchrotron radiation as well as understanding of beam-beam interactions.

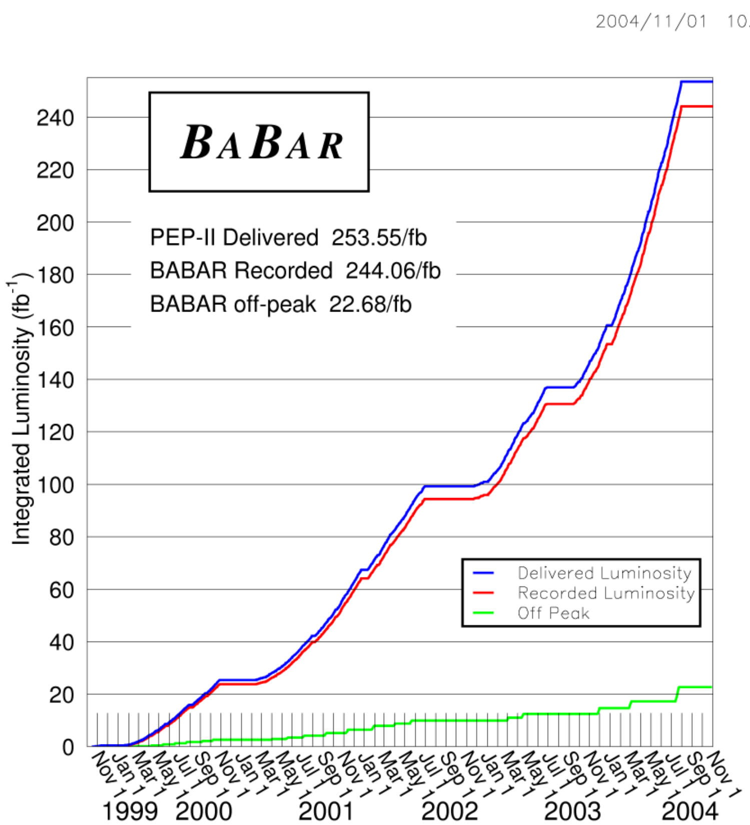


Fig. 9. *BABAR* integrated luminosity (Run 1-4)

The Silicon Vertex Tracker (SVT) has performed well during the past year, though there were two temporarily alarming developments: a threshold increase in some of the readout chips, and bias current growth in some of the modules. The onset of threshold change was found to occur at a radiation dose of about 1 Mrad. Fortunately, the threshold reverts to near normal values as the dose increases beyond 2 Mrad. Procedures have been developed to keep negligible the loss of performance during this transition. The bias current growth, which was found to be unrelated to radiation dose though associated with the steady running provided by trickle injection, was traced to the electric field configuration in the outer layers. Redefinition of relative bias voltages of the layers solved this subtle problem. Measurements of radiation effects for the SVT modules have been completed; they indicate that sensors and readout in all locations but the horizontal plane of the storage rings will last through the end of the decade. The performance of a narrow band of modules will be severely degraded within two years by high occupancy associated with beam backgrounds. Radiation damage from these backgrounds will render this set of modules useless on the same time scale. Spares amounting to 30% of the modules have been built to replace damaged modules and those suffering from radiation damage. The natural time for replacement of these modules would be during the upgrade of the accelerator interaction region at the end of Run 5. However, limitations imposed by the increasing occupancy have led to reconsideration of module replacement at that time.

During the past year it has become clear that the Drift Chamber (DCH) electronics will limit data-taking at higher luminosity (Fig. 10). Beam related backgrounds clog the data pathway from the on-detector electronics to the off-detector readout modules. Fragments produced in the interaction of radiative bhabha event electrons and positrons with beam line elements dominate these backgrounds. This background will grow with luminosity. The fix for this problem is implemented in two steps. In the first phase, whose implementation was completed during the 11 week downtime following the end of Run 4, the programmable array front end chips were reprogrammed to send half of the waveforms. This is expected to reduce the readout dead-time during Run 5 from about 15% to less than 3%, less than the typical dead-time during the majority of Run 4. The effect on the physics performance of the DCH has been seen to be negligible in simulation. In the second phase, to be installed at the end of Run 5, the feature extraction algorithms, which are currently executed in the off-detector readout modules, will be moved into modern programmable array chips located in the on-detector electronics. The data that flows from the DCH will be greatly reduced; dead-time at the highest luminosity projected at the end of the decade will remain acceptably small.

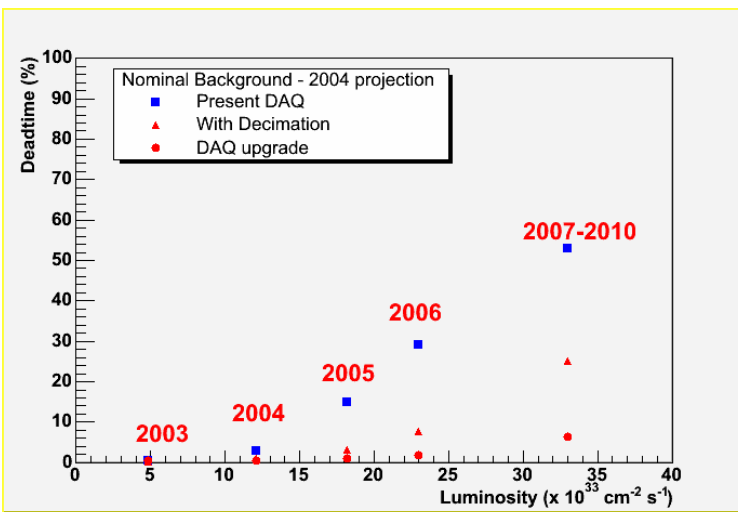


Fig. 10: Dead-time due to DCH readout. Squares show extrapolation of original front end electronics; triangles show extrapolation with phase 1 upgrade; circles show extrapolation with phase 2 upgrade.

The DIRC, which uses Cherenkov light to identify charged particle species, has performed well this year. A work around was implemented to cure a subtle problem in the readout electronics associated with high instantaneous background rates. The Electromagnetic Calorimeter has performed without problems. Effort has focused this year on improvements to the electromagnetic shower reconstruction code.

The new Resistive Plate Chambers (RPCs), installed into the Instrumented Flux Return (IFR) in Summer 2002, performed efficiently during the fourth data run. Additional steel has been added during this year's down to reduce negative effects of beam-related backgrounds on the longevity of these endcap RPCs.

In December 2002 the collaboration selected Limited Streamer Tubes (LSTs) as the replacement technology for the RPCs of the barrel portion of the IFR. The LSTs and associated electronics were developed for *BABAR* during 2003. Production of the wired extrusions for the LSTs began in Italy in Fall 2003, and was completed in Spring 2004. These tubes were assembled into modules at Princeton and Ohio State Universities, with the final part of the very extensive suite of Q/C performed at SLAC before installation. The readout electronics was developed and tested at INFN Ferrara in Italy in parallel with the production of the LST modules. The high voltage system was produced at Ohio State University. The readout strips were produced at SLAC. Installation of twelve layers of LSTs into the top and bottom sextants of the barrel IFR was completed in mid-October. Brass 7/8" absorber replaces the barrel RPCs in six layers in these sextants to improve the π/μ rejection ratio (Fig. 11). All the LSTs are functioning well (Fig. 12). LSTs will be installed in the four remaining barrel IFR sextants at the end of Run 5.

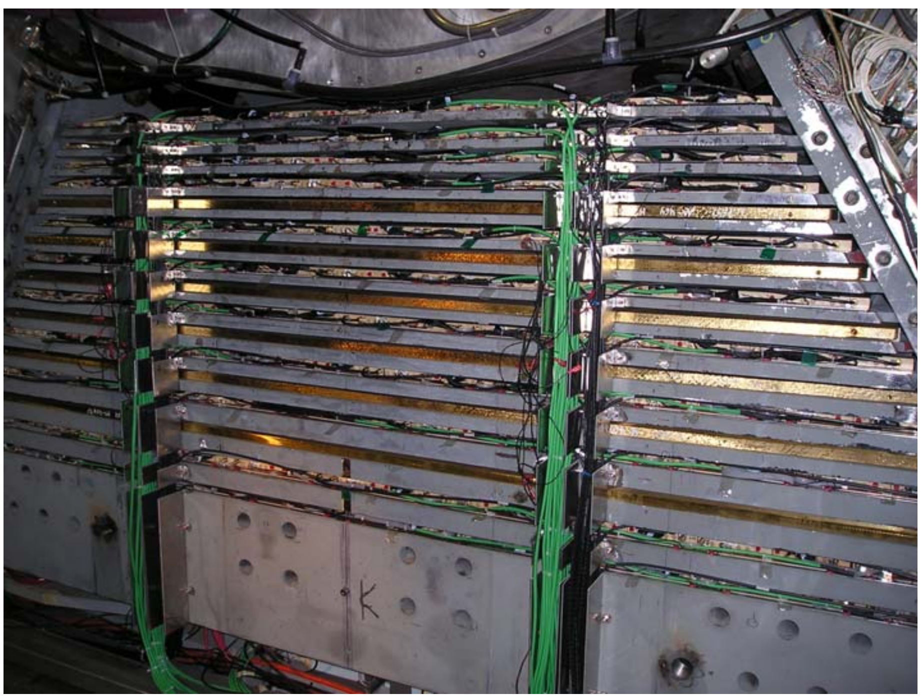


Fig. 11: IFR bottom sextant after installation of LST layers and brass (before re-installation of magnet steel blocks).

The trigger has been upgraded to handle higher luminosity. Additional information from the DCH is used to ensure that events originate close to the interaction point along the beam-line. The new system was commissioned in parallel with the original tracking trigger system during the last month of Run 4, and is ready to be used exclusively in Run 5.

At the end of 2003 *BaBar* deployed a new Computing Model. The main shift in this model was to store the event data in an ensemble of ROOT files with a thin SQL catalogue (not required at run time) as opposed to the Objectivity/DB Object-Oriented Database. During 2004 both newly acquired data and new Monte Carlo simulated events were stored in this new format. In addition earlier simulation and data were also converted. The processing of new data demonstrated both the flexibility of the new system and its utility. New data are passed through a pre-processing step at SLAC to update and optimize calibrations for the hardware systems. The data are then ported to Padova, where one of several available PC-based Linux farms are used to actually reconstruct the events. Within 24 hours of data acquisition, both steps are complete and data shipped back to SLAC for a final quality assurance evaluation. The fast access to physics quality data both ensures a continuous monitoring of detector performance and permits data to enter analysis very soon after it is acquired.

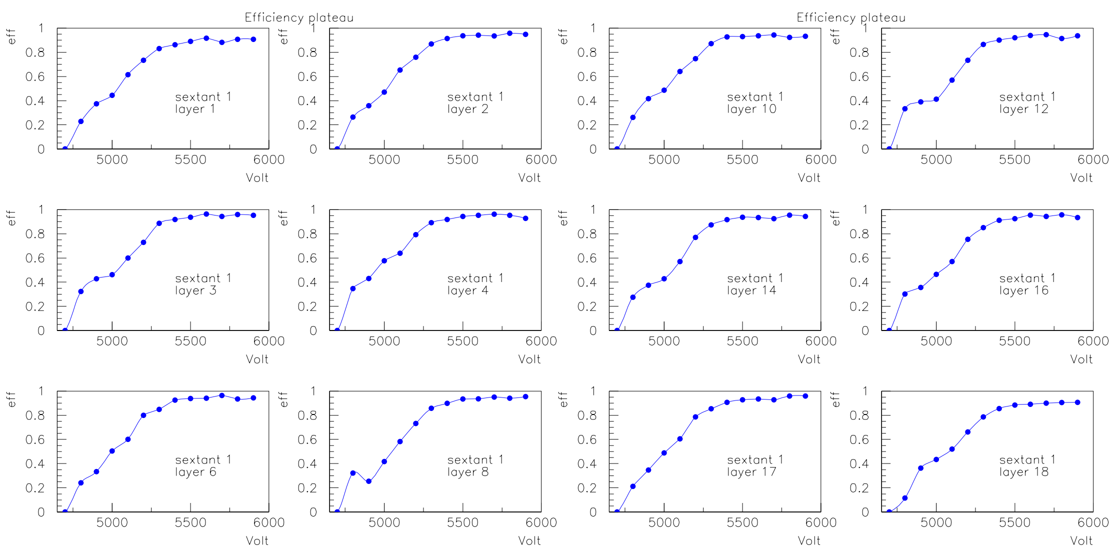


Fig. 12: IFR top sextant layer efficiencies. Each layer is about 92% efficient (inefficiencies are due to geometric dead spaces (tube walls)).

In addition to writing acquired data in the new format and converting old date, all data were passed through a skim process, which applies over 100 physics pre-selections to the data sample and allowed much faster and efficient physics analysis of the full data sets. Specific physics selections of the data are available at each Tier-A site. Our experience with the new data format, in combination with these reduced physics data samples, was very positive and a significant factor in the number of results shown at ICHEP04 with the full data sample. The length of time required for a skim of the complete data sample will allow us to centrally produce new skims several times per year, adding considerably to our ability to quickly attack new areas of physics interest. In addition, next year skimming will be incorporated as part of the normal data processing stream.

BaBar Future Plans

The goal of the experiment is to accumulate a full sample of 500 fb^{-1} by the end of 2006. The collaboration and the laboratory have explored the physics case for extending this rich *B* physics program until the end of the decade and beyond. We have already demonstrated that there is a strong physics case for few ab^{-1} samples, which have the potential of reaching new thresholds in our ability to obtain a complete picture of CP violation in *B* decays. Beyond this, there is a vigorous effort underway to define the physics case for a new facility, capable of luminosities ranging upward toward 10^{36} $cm^{-2}s^{-1}$.

3. FY04 Progress in the Particle Astrophysics Program by Steven Kahn

The Kavli Institute for Particle Astrophysics and Cosmology (KIPAC) has completed its first full academic year. The inaugural faculty team of Blandford and Kahn were joined in fall 2003 by eight postdocs (Baltz, Frolov, Gu, Ho, Marshall, Peterson, Sako and Spitkovsky), three staff members (Althouse, Craig, Marshall). Throughout the year they were joined by several students and visitors and an effective administrative staff led at SLAC by Jennifer Formichelli. In addition, several existing SLAC and Stanford physics faculty members have accepted membership of KIPAC. Two new faculty members, Abel and Allen, have just been appointed, with the former having already started and the latter planning to move to Stanford in January. Tom Abel works primarily in computational cosmology and Steve Allen in the modeling of X-ray clusters of galaxies. In addition, four new postdocs have started in Fall 2004. The current KIPAC membership can be found at http://www-group.slac.stanford.edu/kipac/. It is planned to search for two new faculty members over the coming academic year, one in theory, the other in experimental astrophysics.

KIPAC has become well-integrated into the SLAC-campus physics community. Joint astrophysics seminars occur alternating between campus and SLAC and there is good coordination with other lecture series in theoretical physics. There are twice weekly morning teas where recent papers are discussed and short research presentations are made by group members. These also alternate between campus and SLAC. Looking further a field, serious outreach has occurred into the Bay area astrophysics community (extending as far as UC Davis). A well-attended Kick-Off meeting took place on October 18, 2003 with strong participation from the local community and several collaborations developed as a consequence.

Additionally, KIPAC co-sponsored the international, Third Space Particle Astrophysics meeting in Washington DC on December 10-12 2003 where there were three days of presentations on future programs that would advance our understanding of fundamental physics by performing experiments in space. On February 9-11 2004, an X-ray Polarimetry workshop was held at SLAC. This had a surprisingly large attendance of over 100 including participation from LCLS. The opportunities for carrying out polarimetry enabled by recent improvements in the technology were discussed and the meeting concluded with a sense of optimism about the scientific opportunities in this area. An even larger meeting, on NASA's Beyond Einstein program, took place May 12-14 2004. Here the registration was over 300 which was remarkable support for a program for which NASA had recently chosen to remove most of its support. A theoretical workshop on Force-Free Electrodynamics took place on August 12-14 2004 at SLAC with about 40 participants and was also judged to have been very successful.

The scientific program at KIPAC is now quite diverse. In addition to the work directly related to projects, reported elsewhere, over 80 scientific papers, including conference proceedings have been written by KIPAC members and an even larger number of talks have been delivered. Major research concentrations include the study of clusters of galaxies, combining observations made using X-ray, optical and radio telescopes, a variety of projects in weak and strong gravitational lensing as well as microlensing, investigations of particle dark matter, modeling of pulsars, especially the recently discovered double pulsar, modeling of gamma ray bursts, a new study of the famous cosmic censorship hypothesis, calculations of atomic transitions for use in X-ray astronomy and developing new ideas in black hole astrophysics.

KIPAC look forwards to further growth over the coming year.

GLAST

The Gamma-ray Large Area Space Telescope, GLAST, is a satellite-based experiment under construction to measure the cosmic gamma-ray flux in the energy range 20 MeV to >300 GeV, with supporting measurements for gamma-ray burst transients in the energy range 10 keV-25 MeV. With a sensitivity that is more than a factor 30 greater than that of the EGRET detector on GRO, GLAST will open a new and important window on a wide variety of high energy phenomena, including super massive black holes and active galactic nuclei, gamma-ray bursts, supernova remnants and cosmic ray acceleration, and searches for new phenomena such as super symmetric dark matter annihilations, Lorentz invariance violations, and big bang particle relics. The launch is scheduled for early 2007.

The Large Area Telescope (LAT) is the high-energy instrument on GLAST.
The LAT collaboration is a novel teaming of particle physicists and high energy astrophysicists. The LAT PI and Spokesperson is Professor Peter Michelson (Stanford and SLAC). The LAT is being developed in a partnership between NASA and the DOE, with substantial contributions from Italy, Japan, France, and Sweden. The LAT project is managed at SLAC.

The LAT collaboration consists of approximately 125 scientists, including approximately 40 post-docs and graduate students. There was one full collaboration meeting in FY04, at SLAC in September. Continuing the tradition from past years, accompanying the meeting was a full-day science symposium devoted to specific topic (GeV-TeV Astrophysics in the GLAST Era), providing additional interactions with the broader science community. Two full collaboration meetings are scheduled in FY05, both at

SLAC to be near the hardware. In addition, the Senior Scientist Advisory Committee (SSAC) meets regularly, approximately every six weeks, by teleconference and in person. There is also a monthly "all-hands" meeting for team members resident at, or visiting, SLAC. Science preparation has been proceeding within the context of parallel topical groups, which have been meeting with varying frequency, and an update to that organization was discussed at the recent collaboration meeting.

A highlight of FY04 was the first data challenge (DC1), providing the first end-to-end testing of the instrument simulation, reconstruction, and science analysis tools. A full day of data was simulated (later, an additional five days of simulated data were generated), including a few physics surprises. DC1 was extremely successful: It pulled the international team closer together in many ways, provided valuable feedback to the Science Analysis Software group, and stimulated the further development of many useful tools. DC1 formally began in December, at a meeting at Stanford, and concluded in February at the closeout meeting at SLAC. The experience was covered in the SLAC "Interaction Point" newsletter. Based in part on the lessons from DC1, the LAT team is now planning for DC2 during the summer of 2005. Care is being taken to minimize conflicts with the main focus of the team, building and testing the flight hardware.

Reviews involving the LAT project in 2004 included the following: A DOE/NASA review April 2004, the ISOC CDR August 2004, and the NASA Mission CDR in September 2004. Regular monthly status reviews are held with DOE/NASA.

The LAT Project added key personnel, most notably a second Deputy Project Manager, the ISOC Manager, a Flight Software Manager, and a Production Manager. In addition, manpower in the areas of manufacturing engineering, instrument design engineering, tracker, flight software, integration & test, and quality assurance were strengthened.

An ad hoc group completed plans for the end-to-end tests of the data acquisition system. Detailed system engineering integration and I&T procedure development is underway to execute initial tests with flight hardware the first quarter of 2005.

The focus of the hardware efforts in 2004 has been flight manufacturing and integration & test readiness. All subsystems have begun flight production. The grid will be completed in the first month of FY05, the first flight calorimeter module has been assembled, Tracker flight trays are in production in Italy, and the flight TEM and TEM power supplies are in production. A series of integration & test readiness review peer reviews were conducted, and a great deal of the necessary I&T training has taken place.

Other highlights included:

System Engineering: Tremendous progress on flight drawings has been made. Planning for LAT testing has commenced.

Tracker: Production of multichip modules is well underway. An improved Tracker/grid interface was designed. Nineteen trays were assembled into a tower to validate assembly procedures (including alignment) and provide operator training. During tray panel fabrication, problems were found with bonding kapton bias circuits to tungsten converter foils. An Anomaly Resolution Team was formed, and production will resume early October.

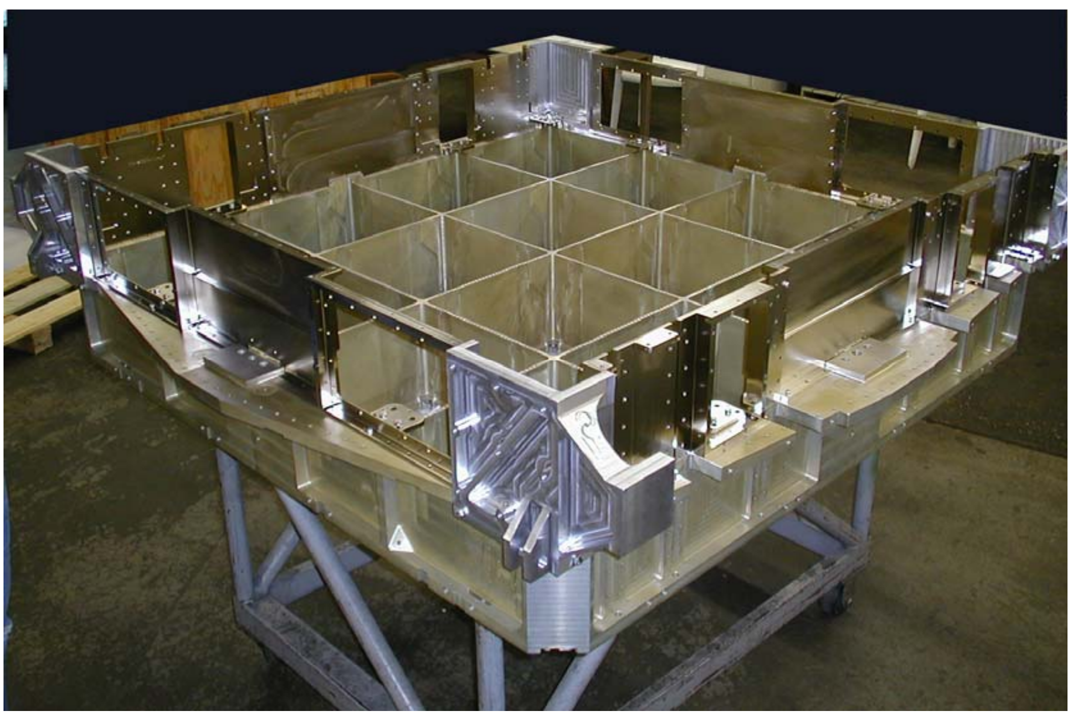
Calorimeter: All CsI crystals have been tested and delivered. All CDEs have been built and tested. The PIN photodiode assembly is complete. Nineteen (of 24) flight structures were manufactured. All flight AFEE boards were manufactured.

Anticoincidence Detector: All tile detector assemblies have been fabricated, as well as all high-voltage bias supplies. Issues with phototube failure and glass cracking were discovered and resolved. Science simulation confirmed that the ACD efficiency requirement is met.

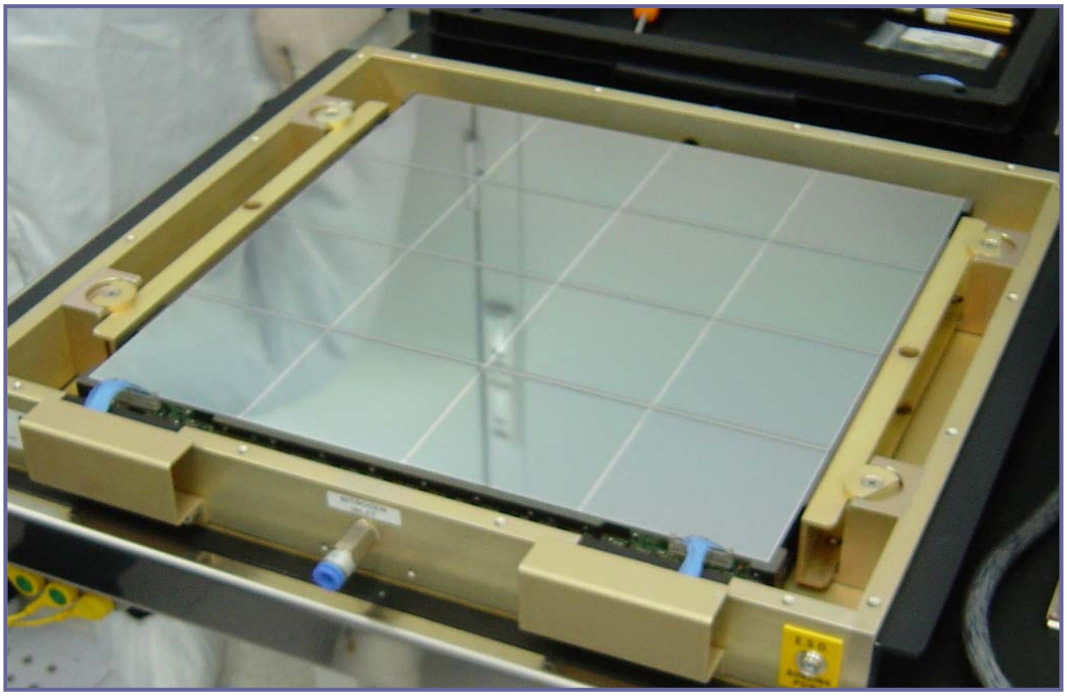
Electronics, Data Acquisition, & Flight Software: All subsystem electronics ground support equipment has been completed. The LAT test bed is assembled and operational. A schedule of monthly flight software demonstrations has been implemented.

Mechanical Systems: The flight grid is nearly completed, including all interface machining. A second grid is in fabrication, for qualification testing.

Integration & Test: Successfully integrated the engineering model Calorimeter with mini-Tracker and mini-ACD.



The LAT Grid Structure



Tracker Silicon Detector

Test Bed for the LAT Data Acquisition System

LSST

The Large Synoptic Survey Telescope (LSST) is a wide-field, large-aperture ground-based telescope designed to provide a faint survey of the optical sky in five color bands every few days. LSST will enable a rich variety of diverse scientific investigations utilizing a common database. These range from searches for moving bodies in the solar system to precision astrometry of the outer regions of the galaxy to systematic monitoring for transient phenomena in the optical sky. Of particular interest for cosmology, LSST will provide strong constraints on models of dark matter and dark energy through both weak and strong gravitational lensing.

A collaboration led by SLAC has been formed to develop the camera for the LSST. This will be the largest digital camera every constructed, with a focal plane covering 3.2 billion pixels, and measuring 60 cm in diameter. The camera also includes three large refractive lenses and a array of five optical filters mounted on a carousel. The mechanical tolerances on the system are tight, owing to a very fast optical beam (f1.2).

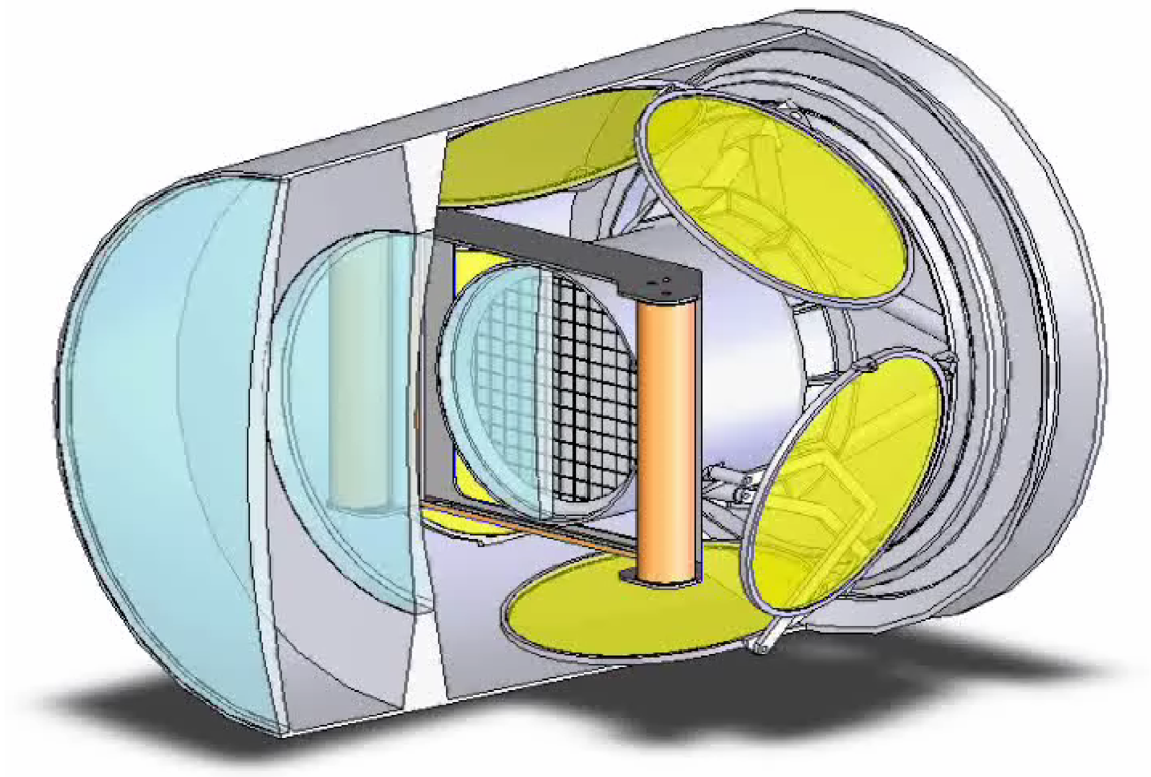
In the past year, substantial progress has been made on developing a conceptual design for the camera which meets the unique requirements for LSST. Early in the reporting period we focused on understanding the sensor requirements and state of sensor technology. We recognized that, to achieve the proposed schedule, CMOS sensor technology was not likely to mature sufficiently to be technically competitive with charged-coupled devices (CCDs), so we chose to develop a conceptual design around CCD sensor technology. Studies of currently available CCD designs and packaging showed that some modest modifications were necessary to meet LSST requirements, particularly segmentation (number of pixels per readout amplifier, adjusted to achieve the fast readout needed) and device thickness (for adequate red response). An R&D plan was developed to produce a demonstration prototype CCD incorporating all the necessary features, optimize the CCD production technology for LSST and prepare the industry for producing the large quantity of CCDs needed. This work is currently being paced by availability of funding.

A paper summarizing this work, “Study of Silicon Sensor Thickness for LSST,” was prepared for publication and is currently being reviewed internally.

A study was carried out to evaluate whether one of the camera corrector lenses could also serve as a vacuum vessel entrance window in front of the focal plane (which is held at –100°C). Guided by studies previously performed at LLNL for the NIF project, the LSST optical designer and camera mechanical designer worked together to describe a configuration that met the optical and mechanical needs, while also meeting a stringent fracture-mechanics criterion to avoid impact damage to the focal plane CCDs.

Because of the small focal ratio needed to achieve a wide field of view, the image quality at the focal plane is sensitive to position variations of order 10 µm. A study of optical point spread function (PSF) variations with perturbations to the shape and position of the camera optical elements, including the focal plane, due to, say, ambient temperature variations, was carried out so that we could understand the impacts on the mechanical design. The results showed that, while the supporting structures must be designed and implemented with care, the required tolerances fall within existing known practices.

Concepts were developed for the fast (100 Hz) x,y position actuation of the focal plane structure, for the mechanical shutter (exposure times controlled to <1 ms) and for an internal mechanism to exchange up to five bandpass filters stored within the camera body. In addition, a conceptual block diagram of the CCD readout electronics and data multiplexing and handling electronics was developed to permit estimating the mechanical impacts (both internal volume and feedthrough area) and thermal control requirements for camera electronics.



Schematic of the LSST Camera

SNAP

The Supernova Acceleration Probe (SNAP) is a proposal for a space-based wide-field telescope designed to study of the physics of dark energy using Type 1a supernovae as calibratable standard candles. The mission will also enable weak lensing studies with high precision over moderate angular scales. The SNAP design includes a large focal plane tiled with both visible light and infrared imaging sensors, as well as an optical/IR spectrograph suitable for following up detected supernovae.

SLAC/Stanford proposed to join the SNAP collaboration in August of 2003. That application was formally approved in March 2004. Within the collaboration, SLAC is responsible for the design and development of the SNAP Instrument Control Unit (ICU), which performs electronic supervision of the entire SNAP instrument, executes the science mission, manages the operation of instrument mechanisms and thermal controls, and controls the flow of commands and data between the focal plane electronics, mass memory and spacecraft. The ICU includes most of the digital electronics and all of the flight software in the SNAP instrument.

During the past year, an architecture for the ICU was developed which utilizes the experience gained from the GLAST LAT data acquisition architecture. The proposed architecture includes two independent networks (one to service the instrument, the other to service the spacecraft interfaces), which use standardized hardware and data protocols.

The architecture would embed memory with the focal plane electronics, thus eliminating the high speed switching needed to support a central mass memory. The system with distributed memory is inherently more reliable that a localized mass storage unit, since individual failures affect only one of 72 sensor channels. In addition, the architecture would implement functions such as data compression in software. Previously it had been assumed that data compression would be performed in hardware (custom ASIC implementation); a software implementation was chosen because it is more flexible and has less schedule risk.

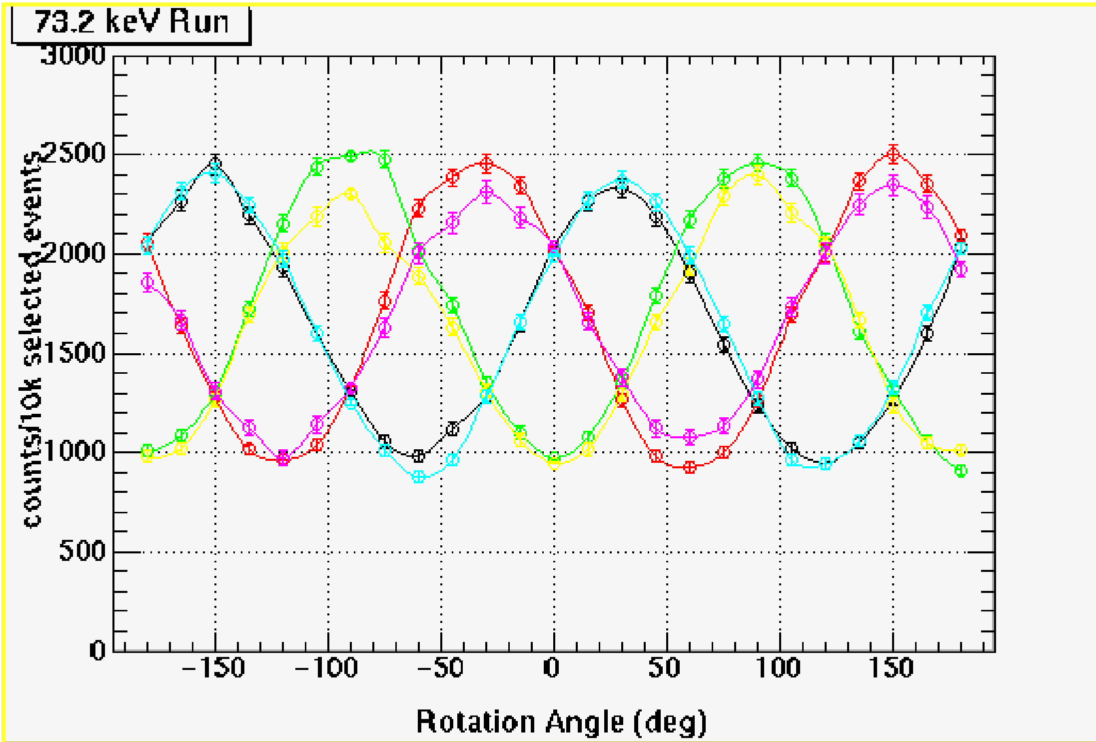
A study of the support and control needs for the visible CCD front-end electronics was initiated. The study resulted in a comprehensive list of commands needed to control CCD bias and clock amplitudes, clock timing, and exposure, readout and reset functions. The list captures the scope of the ICU/front-end electronics interfaces and identifies all variables and allowable ranges.

SLAC scientists have also played a significant role in formulating the detailed scientific program for SNAP, especially with regard to strong lensing investigations. The SNAP database should reveal a large number of new strong lenses. Measurements of the properties of these lensed images will yield a number of interesting constraints on cosmological models.

Other Activities

The Astro-Gamma group has been engaged in a number of research investigations in experimental and observational high energy astrophysics. On the experimental side, the group has been engaged in technology development for the PoGO experiment, a balloon-borne hard X-ray polarimeter for observations of cosmic sources. During the past year, a design for the first prototype detector for PoGO was completed and tested. This work was presented at an IEEE-NS Symposium. In addition, a prototype with seven detector units was tested successfully at the Advanced Photon Source at Argonne National Laboratory. Ten final flight units were later produced.
NeXT is a Japanese X-ray astronomy mission currently planned for launch early in the next decade. SLAC scientists are collaborating in the development of the Soft Gamma-Ray Detector (SGD), which involves an array of actively collimated double-sided silicon strip detectors acting as a Compton telescope. During the past year, a prototype SGD was constructed and tested, proving its background-rejection capability. A proposal for support of this work was submitted to NASA and is currently under review.

On the observational side, SLAC scientists have utilized data from the Chandra X-ray Observatory, the XMM-Newton Observatory, the Rossi X-Ray Timing Explorer and the Compton Gamma-Ray Observatory to study the high energy emission properties of a diverse range of cosmic sources. Topics under investigation include the nature of jets in active galactic nuclei, the hot interstellar medium in clusters of galaxies, and interaction of cosmic ray protons with the dense interstellar medium in the galactic ridge.



Asymmetry measured by a prototype PoGO for 100% polarized hard X-ray at Advanced Photon Source (ANL). The 6 curves correspond to the 6 sets of scatter configuration in the prototype.

4. Experiment E158: A Precision Measurement of the Weak Mixing Angle in Møller Scattering by Krishna Kumar and Mike Woods

Over the last decade, high-energy collider experiments have tested the electroweak theory with great precision, probing at the TeV scale for new physics beyond the standard model. On the other hand, tests of the electroweak interaction at low Q^2 are typically less sensitive by an order of magnitude. In September 2003, the final data collection of SLAC experiment E158[1] was completed, which seeks to determine the weak neutral current coupling of electrons to high precision at low Q^2. This is achieved by measuring the left-right parity violating asymmetry in the Møller scattering of 48.3 GeV longitudinally polarized electrons from the atomic electrons in a liquid hydrogen target. The complete set of E158 data has now been analyzed and provides the world's most precise determination of the electroweak mixing angle $\sin^2\theta_W$ at low Q^2.

[1] SLAC E158 proposal, K. Kumar spokesman and contact person, (1997) (www.slac.stanford.edu/exp/e158/documents/proposal.ps.gz)

E158 Overview

Target electrons, in a 1.5 m long cell of liquid hydrogen (10.5 gm/cm^2), are bombarded by a 48 GeV electron beam, the longitudinal polarization direction of which is changed pseudo-randomly keeping all other beam parameters unchanged. Møller electrons, *i.e.*, beam electrons scattering from target electrons, are isolated by a forward magnetic spectrometer consisting of 3 dipole "chicane" and four quadrupole magnets, oriented with their magnetic axes along the primary electron beam direction. Møller electrons of interest in the full range of the azimuth (spanning the polar angular range 4.5 mrad < □lab < 9 mrad) traverse through the bores of the quadrupoles and are brought to focus in a ring on a calorimeter located 60 m downstream of the target.

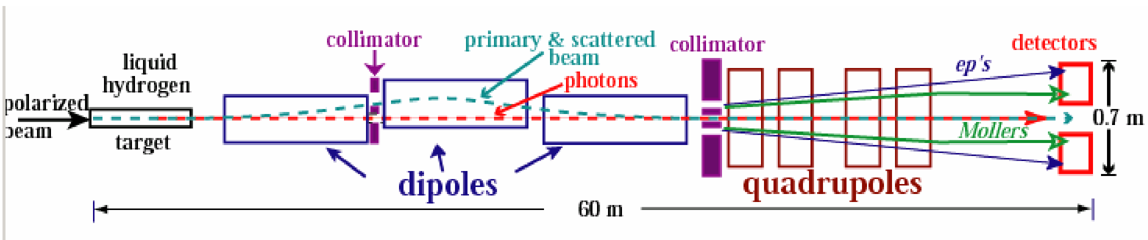


Figure 1: Target, Spectrometer and Detector configuration in End Station A

The experimental asymmetry is measured by averaging the fractional difference in the cross section over many complementary pairs of beam pulses of opposite helicity. In order to achieve the desired statistical error of order 10 parts per billion (ppb) in a reasonable length of time, the integrated signal of more than 20 million electrons is detected each beam pulse.

E158 Physics Runs

E158 performed 3 physics runs in Spring 2002, Fall 2002 and Summer 2003. A summary of the beam delivery for all 3 E158 Physics Runs is shown in Figure 2. Table 1 compares beam parameters listed in the Proposal with those achieved. The average beam delivery efficiency for all 3 runs was 70%. The quality of the beam was excellent, and met all of the goals for the experiment.

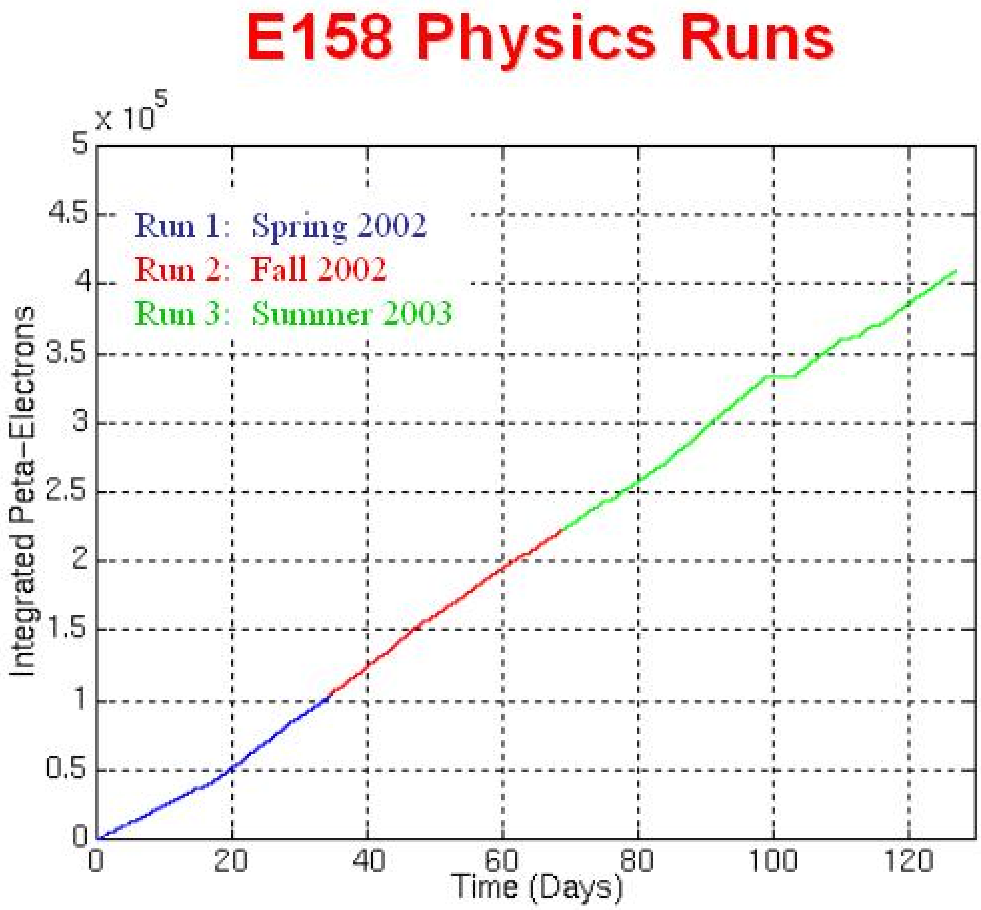


Figure 2: Beam delivery for E158, indicating the total number of delivered electrons in the 3 physics runs. (Run I is indicated in blue, Run II in red and Run III in green.) One Peta-Electron is 10^{15} electrons. A total of 4.1×10^{20} electrons were delivered to the experiment.

Table 1: Beam parameters achieved for the E158 experiment, compared to goals stated in the E158 Proposal.

Parameter	Proposal	Achieved
Intensity at 48 GeV	6×10^{11} / pulse	5.3×10^{11}
Intensity at 45 GeV	3.5×10^{11}	4.3×10^{11}
Polarization	80%	85%
Repetition Rate	120 Hz	120 Hz
Intensity jitter / pulse	2% rms	0.5% rms
Energy jitter / pulse	0.4% rms	0.03% rms
Energy spread	-	0.15% rms
Delivered Charge* (Peta-E)	345K	410K

E158 Analysis

The Run I results are summarized in SLAC-PUB-10270,[2] which has been published in *Physical Review Letters* **92**:181602,2004. Preliminary results from both Run II and Run III data are now available and will be combined with Run I results for publication in Fall 2004. Run II results were first presented at the Fall 2003 Division of Nuclear Physics meeting (DNP03) and are described in SLAC-PUB-10338.[3] Results from the full data sample, including Run III, were first presented at the June *Physics in Collision* Meeting. They were also presented in seminars at SLAC by Yury Kolomensky in late June and again at the SLAC Summer Institute in August. Three E158 students received their Ph.D.'s in 2004: Peter Mastromarino, Klejda Bega and Mark Jones. Two other students received their Ph.D's earlier and two more will complete their theses in the coming year.

The primary E158 goal is to determine the weak mixing angle at low Q^2 from the measurement of parity violation in Moller scattering. The E158 preliminary result is A_{PV}(Moller at Q^2 = 0.03 GeV^2) = -128 ± 14 (stat) ± 12 (syst) parts per billion. The statistical significance is 8σ from zero, proving for the first time ever that parity is violated in the Moller scattering process. From this asymmetry measurement, a value for

[2] *Observation of Parity Nonconservation in Moller Scattering,* SLAC E158 Collaboration, SLAC-PUB-10270 (2003); e-Print Archive: hep-ex/0312035; published in *Phys.Rev.Lett.***92**:181602,2004.
[3] *A New Measurement of the Weak Mixing Angle*, M. Woods (*for the SLAC E158 collaboration*), SLAC-PUB-10338 (2004); e-Print Archive: **hep-ex/0403010.**

the electroweak mixing angle $\sin^2\theta_W$ can be extracted. This is shown in Figure 3, together with results from other experiments at different Q^2. The measurements shown in Figure 3 can all be evolved to the Z-pole for direct comparison and this is summarized in Figure 4. The E158 result gives

$$\sin^2\theta_W (Q^2 = M_Z^2) = 0.2330 \pm 0.0011 \text{ (stat)} \pm 0.0010 \text{ (syst)} .$$

This result is consistent with Standard Model predictions and is the most precise measurement of the weak mixing angle away from the Z pole. The E158 result demonstrates the running of the weak mixing angle from the Z pole to low Q^2 with a significance of 7□. This result sets limits on contact interactions, with a 95% CL lower limit for the compositeness scale $□_{LL}$ ~ 10 TeV. It also sets limits on additional Z' bosons--for example, the 95% CL lower limit for an SO(10) Z' is ~900 GeV.

E158 also accumulated significant transverse asymmetry data and results from these measurements will be published separately. E158 has made the first measurement of a single spin transverse asymmetry in Moller scattering, which arises due to a 2-photon QED process. E158 also measures a transverse asymmetry in ep scattering (of opposite sign to that observed in the transverse ee scattering), where the 2-photon contribution is negligible but QCD effects from intermediate hadronic states are important.

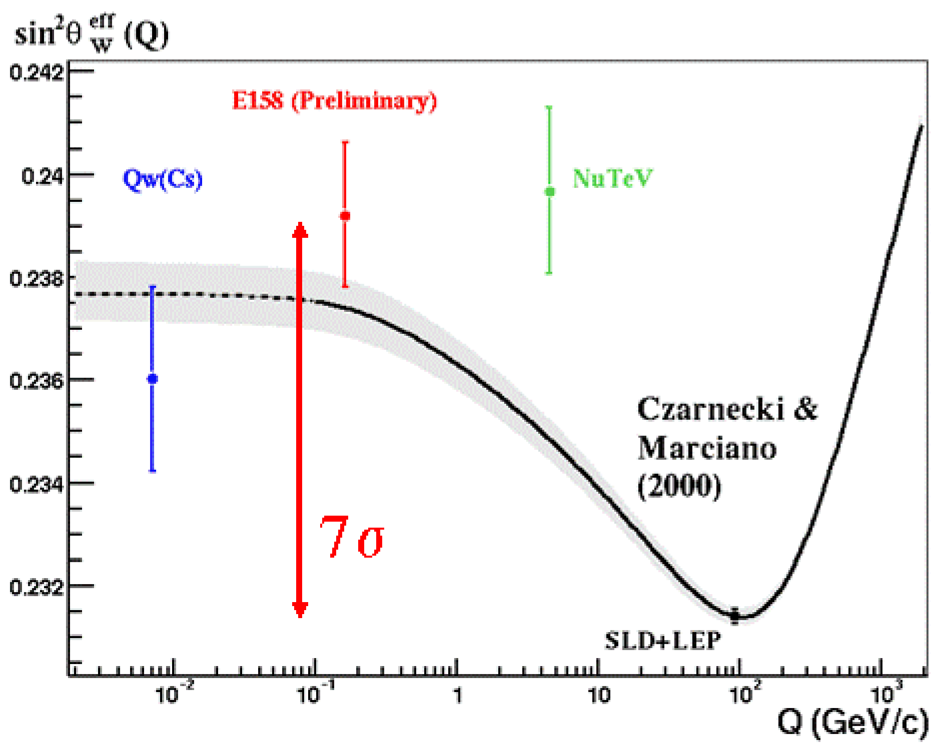


Figure 3: The Q^2-dependence of the Weak Mixing Angle: Theory and Experiment. The black curve is the prediction from Czarnecki and Marciano, with the theoretical uncertainty indicated by the shaded region. The E158 result demonstrates the running of the weak mixing angle with a significance of 7□ from low Q^2 to the Z-pole.

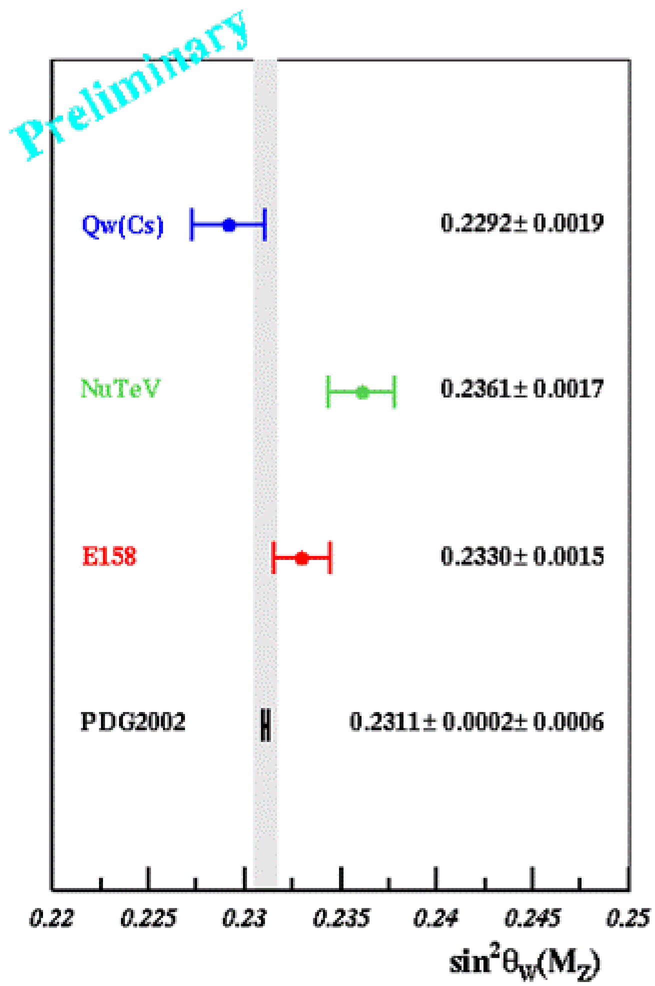


Figure 4: Summary of the Weak Angle measurements shown in Figure 3, but all evolved to the Z-pole for direct comparison. The E158 result is the most precise measurement at low Q^2.

5. FY2004 Self-Appraisal for DOE: NLC and NLCTA by Albe Larsen

In FY2004, several important events occurred related to next-generation linear colliders. Principal among these were the formation by the International Committee for Future Accelerators (ICFA) and the International Linear Collider Steering Committee (ILCSC) of a committee of "wise men." The committee consisted of four members from each of Asia, Europe and the Americas and was designated as the International Technology Recommendation Panel (ITRP). They were charged to evaluate the warm X-band rf technology of KEK and SLAC and the superconducting L-band rf technology developed at DESY and, by the end of the 2004 calendar year, to make a recommendation of which technology to further pursue.

The charge to the ITRP, the minutes of their many meetings, many of the presentations made to them and their final report can all be accessed from their web site.[4]

To prepare for the ITRP evaluation, the US Linear Collider Steering Group formed a task force to compare a design based on the warm X-band rf technology with that of a design based on the superconducting L-band rf technology. Both designs were optimized for a US site and were configured to have similar capabilities. The warm design was very similar to the NLC/GLC design from SLAC and KEK while the superconducting design was a modified version of the TESLA design to improve the design capability and make a simpler comparison. The report from the task force was submitted to the ITRP and can be found at: http://www.slac.stanford.edu/xorg/accelops/.

In addition, to prepare for the ITRP evaluation, the NLC group worked clear as many of the R1 and R2 requirements from the ICFA International Linear Collider – Technical Review Committee evaluation as possible. The most important of these were cleared by the SLAC and KEK teams. However, the ITRP recommended that the cold technology be pursued by the entire LC community. That decision was announced in Beijing in mid-August. Since that time, SLAC has been examining its linear collider program and reorienting its Linear Collider R&D priorities to bring our best skills to the design of a cold machine – cold only in terms of the superconducting rf cavities of the main linacs. Since a thorough, integrated design of a cold linear collider has not been developed, there will be ample work in areas of our expertise including electron and positron sources, damping rings, beam delivery systems and interaction regions, and beam dynamics as well as conventional facilities, and project planning and management. For FY2005 and the years beyond, we will work with the international community to ensure that the technology is in place to build a 1-TeV linear collider using the superconducting L-band rf technology that will meet the luminosity and energy reach requirements of the international high energy physics community.

Over the next months the framework for the first stages of international collaboration will be established, and the newly formed international meetings of the funding agencies responsible for HEP funding around the world will also continue in parallel to ensure that not only the technical and scientific structures are in place to build the International Linear Collider, but also the finances required for a project of this scale.

The Eight-Pack Project

The 8-Pack project presents a demonstration of an entire system design of high-power rf components which enable rf power from klystrons to be combined, manipulated and transported. The power, sent initially to water-cooled loads (phase 1), is now transported to accelerator structures on the NLCTA beamline (phase 2). This system uses a SLED-II power compression scheme which utilizes planar components in an overmoded rectangular geometry to do the rf manipulation and transmission. Phase 1 of the project

[4] http://www.ligo.caltech.edu/~skammer/ITRP_Home.htm.

was fabricated and assembled in FY03. In FY04, phase 1 was commissioned and phase 2 was implemented, commissioned and placed in operation.

In FY04, the 8-Pack project completed the ILC-TRC Technical Options Study R1 goal of demonstrating a full power SLED-2 rf pulse compression system, and operated that system stably for a substantial length of time. In December, the system was operated at a maximum power output of 510 MW, significantly higher than the 475 MW specification in the NLC design. The system ran stably at 500 MW for hundreds of hours.

The system still uses the four XL-4 50 MW klystrons that were installed on the 8-Pack test stand. While these klystrons are not candidates for use in the NLC, they are work-horse X-band power providers which have given thousands of hours of reliable performance in a number of installations at SLAC. The combined power of the klystrons is more than ample for the 8-Pack testing program. In FY04 these klystrons were operated for thousands of hours without incident.

The 8-Pack solid-state modulator is connected to the XL-4 50 MW klystrons and powers them. The modulator operation was improved in FY04 by the addition of a cooling system which allowed it to operate at 60 Hz. The modulator and its control system were commissioned with improvements being made to high voltage connections inside the unit. The modulator operated around the clock, with no significant impediment to accumulating hours of operation for the 8-Pack system.

The low-level rf (LLRF) controls and monitoring system was fully commissioned. The LLRF system provides the drive, amplitude and phase control to the klystrons, and detects and records power levels throughout the 8-Pack rf system. The LLRF system also provides for system interlocks to protect the equipment from rf faults. In reaching 510 MW of power from the SLED2 system, the LLRF system was demonstrated to have the control necessary to operate the 8-Pack system.

In FY04, following the high power demonstration, phase 2 of the 8-Pack project was assembled. All high power rf components needed for installation in phase 2 were fabricated, cold tested and installed, bringing the high power from the SLED-2 system to four NLC accelerating structures on the NLCTA beam line. The components were cold tested individually, then tested together at several stages of system assembly to ensure adequate performance. The klystrons, modulator and LLRF systems, having been tested in phase 1, were fully capable of carrying out phase 2 operations. The installation of components and high gradient accelerator structures was done in the first half of FY04 and phase 2 commissioning and operations commenced. The 8-Pack system provided power to the accelerating structures at full specification. The goal of the tests was to operate the accelerating structures at full gradient for a life test, and this was accomplished. The 8-Pack-powered structures were operated at the NLC specification gradient and breakdown rates for hundreds of hours.

Ongoing R&D

Replacing electromagnets with permanent magnets remains a goal for the NLC Collaboration, and utilizing Fermilab's experience in the area of permanent magnets for accelerator beams is a critical part of this. The testing of Fermilab's latest prototype permanent magnet was completed in FY2004, and while its performance was excellent, it was still below the stringent requirements for the collider. With no source of funding, it appears that some time will pass before another prototype will be constructed. Radiation testing of the permanent magnetic materials in radiation conditions that mimic the backgrounds expected in different areas of the machine continues to be delayed due to funding restrictions.

Electrical systems work included continued advances in a unique solid-state modulator designed for improved energy efficiency, higher reliability, smaller size and lower cost. Significant progress continued on several fronts:

1. The prototype 8-Pack solid state modulator continued supporting the NLCTA with four (4) XL4 50 MW klystrons. With the addition of improved thermal contact heat sinks and a chiller, the repetition rate was successfully raised from 30 to 60 Hz. Structure high-gradient tests were completely successful. A new problem surfaced in that arcing of the HV contacts was found to produce beryllium dust, so special handling controls had to be put in place. This was done successfully, while at the same time contacts that had arc damage were refurbished with a hard brass shim to buffer the aluminum cell casing. The unit has been brought to full operational status but all work in the NLCTA is currently on hold.

2. The new DFM 2-Pack modulator components were delivered from LLNL and assembled into a complete unit at SLAC. The new units have an oil cooling system and more robust board-to-cell 2-piece connectors. The boards have new higher voltage rated IGBTs that run at 4 kV instead of 2.2 kV, greatly reducing the number of boards and cells. The unit was subsequently tested at full rated voltage of 500 kV and full current for two 75 MW XP klystrons of 550 A into a water load. Due to heat rise, the unit could not achieve the full repetition rate of 120 Hz, but did achieve 50 Hz. As before, additional heat sink efficiency was required, so solid copper sinks were recently added and the unit is now ready for a full power run. The unit was not transported to the NLCTA as planned last year due to two factors: The lack of time and funds to complete this installation in FY04, and the lack of 75 MW klystrons. Work has been slowed due to the international linear collider technology decision and lack of resources, but the plan is to complete the full power tests early in FY05.

3. New IGBT topologies were modeled and a new hybrid circuit was tested. This unit has two IGBT chips with an on-board driver, and has rise and fall times below 200 ns, needed for high waveform efficiency of the fast pulse. Future

R&D will continue as appropriate for other SLAC projects, namely kickers and eventual replacement of SLAC modulators and Sub-Boosters with solid state.

4. The 2-Pack modular 4 kW at 4 kV power supply prototype was successfully bench-tested. An single unit will be tested on the 2-Pack as part of completion of this phase of R&D.

5. With the technology decision for a cold machine in place, a new FY05 R&D program is being designed for the following electrical areas, many of which have been on hold for several years due to the high gradient projects: Modulators, Kickers, Controls, Timing and Low Level RF, Instrumentation, Tunnel Electronics and Instrument Standards.

Fast data streaming architectures for NLC continue to be pursued through R&D, aimed also at upgrading the existing SLAC Control System Micro Farm and Front End Processors. The first Front End Crate Controller (FECC) board was designed and constructed but testing was interrupted due to the loss of our consultant to another high priority SLAC experiment. Work will resume in early FY05.

Progress in instrumentation and global controls systems R&D was slow again this year due to diversion of resources to the 8-pack program. The cavity BPM program continues into prototyping and testing on the KEK ATF.

The resolution requirement for NLC linac BPMs is 200-300 nm rms. Bench evaluation of a cold-test prototype for the NLC cavity BPM shows resolution of better than 80 nm for cw excitation, limited by mechanical stability of the test fixtures. Electrical centering with respect to the mechanical center appears to be excellent, but it has not been possible to measure precisely enough to verify that the NLC stability requirement (< 1 micron per 24 hours) is met. Beam tests with three existing (6.4 GHz) cavities at the KEK ATF show resolution of approximately 50 nm. Further improvement of this resolution is expected in the coming year. The theoretical limit of such cavity position monitors for NLC-like beams is about 1nm. Achieving such resolution would allow yet another way of demonstrating mechanical alignment and stabilization at the level needed for a linear collider. The recent realization that cavity BPMs produce a bunch-tilt signal potentially useful for NLC linac emittance control led to confirming measurements at the ATF nano BPM experiment.

Fast data streaming architectures for NLC continue to be pursued through R&D, aimed also at upgrading the existing SLAC Control System Micro Farm and Front End Processors. The first Front End Crate Controller (FECC) board will be tested in the first quarter of FY05. Hardware achievements have included the following: Migration has been completed of the noise-tolerant link, the bus structures, and the CAMAC interface from the Virtex-II FPGA design platform as well as the external SHARC to the Virtex-II Pro with embedded PowerPC. The addition of BITbus support to hardware was completed, and the mode was added to convert this hardware to alternative use as a PNET transmitter for the Master Pattern Generator. FECC board artwork was generated, test circuit boards fabricated and components procured, and loading of the first two test boards was initiated.

Software work has included the following: The real-time operating system was reimplemented on an embedded PowerPC platform, with support for DMA CAMAC interface hardware instead of programmed I/O hardware. Existing support was ported for booting, link message passing, 360 Hz trigger interface, and CAMAC access (local from FECC and remote from PC) to a PowerPC platform. Software support was added for BITbus hardware (local from FECC and remote from PC) on PowerPC platform; local FECC access was added to the PNET transmit mode. Integration was started of PCIL-FECC support into PC-micro CAMAC access software. Ethernet boot support for PC-micro implementation was started. Migration continued of the 360 Hz application code from the PC-micro high priority interrupt routine to the FECC application layer; and conversion continued of the communication between PC-micro iRMX jobs and the 360 Hz application code from a shared memory model to the remote networked link model (TEG).

Progress on an SBIR program that has resulted in a much longer-lived cathode (over 100,000 hours) for the microwave tube (helix TWT) that provides the input rf signal to the klystron did not materialize into a usable tube in FY2004. However, two complete amplifiers were received and are being evaluated in the test lab by utilizing them to operate klystrons that are being processed and tested. Another SBIR project (by Diversified Technologies) produced a high-voltage pulse modulator that is a hybrid of a solid-state switch and a conventional pulse-forming network. The hybrid modulator has been received at SLAC, where it is being integrated into a new high-power test stand that will increase the capacity for klystron testing. An SBIR project continues to work on developing a gridded gun along with a small SLAC activity to design a complete tube for the sheet beam klystron development program. Sheet beam klystrons may some day become a less expensive and more reliable alternative to the conventional, cylindrically symmetric klystrons currently in use for linear accelerators because they allow the beam to be spread out in one dimension, greatly reducing the power density in the device.

Fermilab’s charter on structures has been to develop industrial sources of parts and structures, and they have basically completed both goals. Fermilab can now readily build 60-cm structures at a rate of two per month comfortably and one per week if they push hard. They have independently found sources for all the parts and materials that they require. In addition, the structures produced at Fermilab outperform structures manufactured by SLAC/KEK with respect to the critical metric of breakdowns per hour at a gradient of 65 MV/m. SBIR projects are developing novel devices and technologies to assist in structure manufacturing processes: A noncontacting, interferometric coordinate measurement machine is nearing completion (by Red Cone Research in Colorado); a precision air gauge is being developed for real-time QC of the curved surfaces internal to X-band structure cells (by Surface Manufacturing in Auburn, California); Robotic technology for automated stacking and alignment of accelerator cells is being developed (by Zmation, Inc., in Portland, OR). Novel rf components that may become part of the linear collider's rf pulse-compression system are being developed as well: a multimegawatt circulator, solid state and plasma switches.

In the Main Linac, efforts were concentrated in the three areas of rf sources (klystrons), rf components to compress and distribute the rf power, and accelerator structures that apply the rf to the particles being accelerated.

For the 75 MW PPM klystron program, a milestone was reached when two consecutive klystrons built at SLAC concurrently met all the key requirements for the NLC klystron, including average power, at that time the single remaining undemonstrated parameter. In addition, a tube built by Toshiba with the help of KEK was tested at SLAC and performed very close to full specification, indicating that this klystron is well on its way to being industrialized. It is important to note that this performance represents a world record for average power at X-Band. KEK has three other klystrons either at test or waiting to be tested. SLAC has one more klystron on test with the first version of a newer design due to start test toward the end of calendar 2004. This new version primarily adds margin to the existing design in places that are of concern to the designers, an example being a larger gun ceramic to reduce gradients and the chances of trapped modes in the gun.

An entire system design for the rf components that would enable rf power from the klystrons to be combined and sent initially to water-cooled loads but eventually to accelerator structures was developed. This system uses two electromagnetic modes to reduce the length of round waveguide required, and a compression scheme called SLED-II that utilizes planar components in an overmoded rectangular geometry to perform the rf manipulation. All of the components required for this system have been completed and the system has been assembled and used in the eight pack. Its performance has been significantly above specification and it has run with no problem for many hundreds of hours.

The focus of the structure design program is to arrive at a design that preserves the necessary wakefield attenuation while at the same time providing the accelerating gradient needed without either damage or excessive breakdown events. During the past year, eight structures were operated at the GLC/NLC design unloaded gradient of 65 MV/m with an average breakdown rate below the limit specified for the linear collider. This performance satisfies the X-Band LC structure feasibility demonstration (R1 requirement) defined by the 2003 International Linear Collider - Technical Review Committee (ILC-TRC). More details about these tests are included in the section on the NLCTA below.

Extensive effort was exercised in preparing the Conventional Facilities References Design Summary for Normal and Superconductive Linear Collider Options for the US Linear Collider Steering Group. This effort, in collaboration with the FNAL Conventional Facilities group, included but was not limited to, a description of the salient features of the conventional facilities, defining the vibration, stability, as well as utility requirements for the US Superconducting and Normal Conducting Linear Collider options. This effort has been compiled in Conventional Facilities Design Summaries and Drawings which comprise in excess of 50 drawings.

In addition, design summaries, calculations for electrical energy demand, cooling water loads and drawings for the USLCSG options study were developed in collaboration with the FNAL conventional facilities group.

A comprehensive study was performed to demonstrate that the 3-D vibration simulation/analyses can predict and mitigate the response of the beam tunnel from the cultural noise source located in the service tunnel. The first phase of this effort consisted of 3-D modeling of the Los Angeles twin MTA tunnels where vibration testing was previously performed (F03) for the NLC project. In this phase of the work, the 3-D computer modeling was calibrated and it was demonstrated that the measured vibration responses caused by various cultural and manmade vibration sources can be predicted by analysis. Thus, we have in place a computer simulation program that can be used to evaluate the vibration trade-offs between one tunnel vs. two tunnel, near surface tunnel vs. deep tunnel, etc.

Environmental survey work continued with a focus on characterizing the site-specific surface hydrology and subsurface hydro geologic regime in Northern California. A comprehensive literature search was conducted at the US Geologic Survey, US Department of Agriculture, the California Department of Water Resources, the California Department of Mines and Geology and at other Federal, state and local agencies for all studies related to surface water and groundwater characteristics and quality. A Regional Hydrology Study Preliminary Assessment Report was prepared for the Northern California Site based on this research. Information is being used from that and previous geologic reports to formulate our plan to conduct subsurface investigations at some point in the future.

At the NLCTA, the utility support for Phases 2A and B of the NLC 8-pack was completed. This included coordination with other subsystems, design, and preparation of contract documents and supervision of subcontractors. All work has been completed on schedule and within budget. Further, support was provided for the design and installation of the infrastructure necessary to carry out the R&D efforts for the X-band technology in the NLCTA.

Further work was completed on vibration measurements and their characterization and mitigation in a chiller located in NLCTA, as well as the 8-pack modulator.

The NLC Test Accelerator – NLCTA

The program at NLCTA during the past year was aimed at studying structure reliability where the requirements are very demanding. The NLC/GLC linacs contain about 18,000 structures, which requires the structure trip rate from rf breakdown to be very small ($<$ 0.1 per hour) to ensure essentially 100% full linac energy availability with the planned 2% overhead of spares. Also, the transverse fields generated during breakdown will deflect the beam so there is concern as to the magnitude of the kicks (e.g., do they cause beam loss). Finally, the structures need to be robust in that accidental exposure to air or controlled vents to nitrogen do not severely impact subsequent performance.

To achieve a trip rate below the 0.1 per hour design limit at the 65 MV/m operating gradient required several years of structure development by the NLC/GLC groups. The structure design that resulted is 60 cm long, has a $5\pi/6$ phase advance per cell, and a low group velocity (3-4% c at the upstream end). The breakdown rates achieved this year in a ensemble of such 8 structures operated concurrently in the NLCTA linac is shown in Figure 1 as a function of gradient. The rates show an exponential dependence on gradient with a one decade increase in rate per 7 MV/m increase in gradient (as indicted by the line in the figure). These measurements were made at the design pulse length of 400 ns, although the slope was found to be independent of pulse length. The structures have operated for about 1600 hours at 65 MV/m during which the breakdown rates have steadily decreased. The variation in performance among the structures most likely reflects some differences in their preparation procedures. More rigorous quality control should improve reproducibility.

Measurements of the beam kicks caused by breakdown show them to be large enough to cause some luminosity loss from off-center beam collisions, but not large enough to cause the beams to hit the NLC/GLC collimators. At the 0.1 per hour rate limit, the loss in luminosity would be much less than 1%, which was not considered large enough to warrant lowering the rate limit.

A series of venting experiments were recently conducted to determine the influence of gas exposure on the structure performance. Venting and purging a pair of previously processed structures with filtered, boiled-off nitrogen resulted in almost no degradation of performance. Both structures came up to the design gradient with only a few breakdowns and the subsequent breakdown rate was unchanged for one structure and a factor of 2 higher for the other during the first 24 hours. The structures were then exposed to filtered laboratory air. In this case, they came up to the design gradient after a few dozen breakdowns and continued to breakdown at a rate (~ 0.5/hr) that is 10 times higher than the pre-test levels. However, after 50-100 hours, the rates came down to the earlier values. It appears that the addition of water vapor and the thin oxide layer that results enhances breakdown activity, but only temporarily as these sites are quickly processed. More importantly, a rf conditioned surface doesn’t loose this quality after a exposure to filtered nitrogen or air.

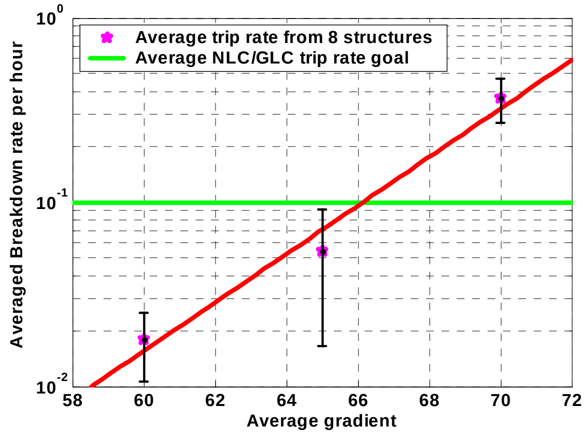


Figure 1: Average breakdown rate for 8 NLC/GLC structures as a function of average unloaded gradient. The error bars indicate the range of rates for the eight structures.

6. Advanced Accelerator Research Department-A by Ron Ruth

Accelerator Research Department-A has worked on a wide variety of topics this past year. The work has three main thrusts: performance enhancement of current accelerators at SLAC such as PEP-II, research and design for near-future facilities such as NLC/ILC or upgrades to PEP-II, and research in fundamental aspects of accelerator and beam physics. The department is divided into several groups: selected topics from each group are discussed below.

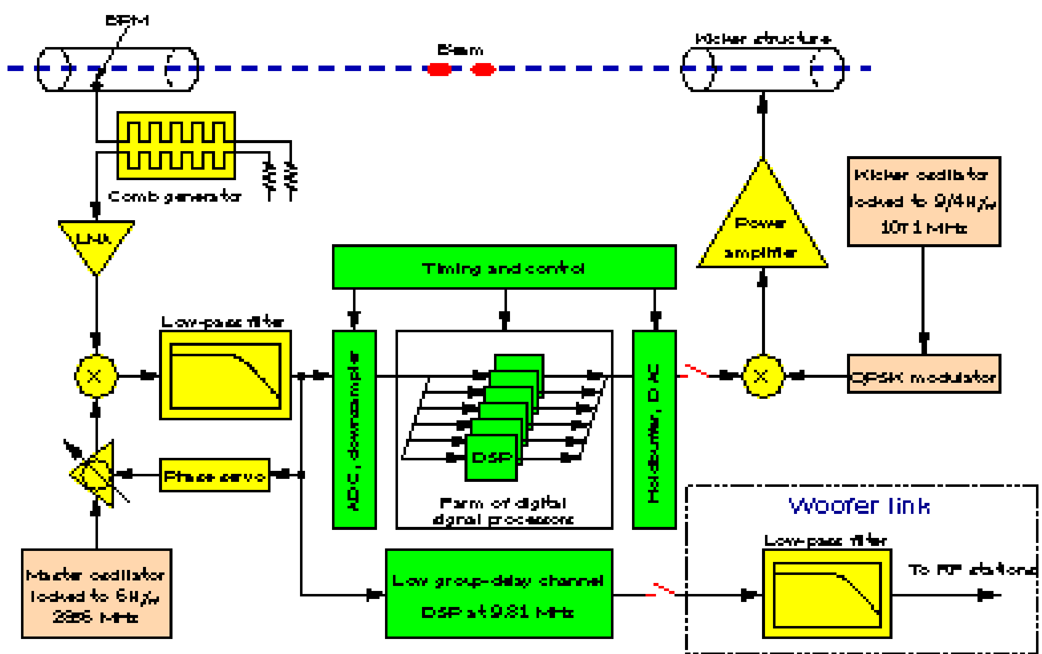
Electronics Research

The Electronics Research group in ARDA combines interests in particle beam dynamics with technology development of fast signal processing and feedback control systems.The group's hardware and software instability control systems have been implemented at labs in the US, Europe and Asia. During the past year the group has presented results via two conference papers and two invited talks at workshops. Dmitry Teytelman was honored with the 2004 APS dissertation Prize in Beam Physics, and John Fox taught a course (RF Engineering and Signal Processing) for the US Particle Accelerator school, as well as Stanford courses in Applied Physics.

The group has been central in machine physics studies to better understand the interactions of the PEP-II RF systems, with their complex impedance-reducing feedback architectures, and the longitudinal dynamics of the machine. This knowledge was transferred to the PEP Accelerator Physics and operations groups via a two day tutorial course on PEP-II RF systems and longitudinal dynamics. This tutorial was developed and presented by Dmitry Teytelman to over 48 SLAC staff. Last year we understood the role that klystron saturation effects have in producing instability growth rates 5 to 20 times the rates estimated during the design of PEP-II. In 2004 we have continued our focus on better understanding and control of the in-cavity longitudinal modes, through machine physics experiments and numeric simulation and analytical studies. In 2004 PEP-II operation has reached the instability control thresholds for these in-cavity modes - further increases in current, or any upgrades to the machine, require new approaches to impedance control.

We have been working on two fronts to combat these instability limits. One effort offers a path to higher gain in the instability control feedback - (The Low Group Delay Woofer). The other path requires changes in the Low Level RF signal processing in PEP-II to better reduce the cavity fundemental impedance via the direct and comb feedback loops.

The low group delay woofer, and the interconnection to the broadband feedback, is shown in the figures. The channel is a separate programmable 9.81 Mhz sampling rate 14 tap FIR control filter, which offers greater flexibility in low mode control via a lower group delay around the control path. A prototype LGDW was constructed in 2004, and commissioned in the HER in May 2004. The commissioning of the LGDW allowed an increase in HER operating current from 1350 to 1550 mA. Of equal importance is the improvement on operating margins, so that the number of RF aborts due to longitudinal instability in the HER was greatly reduced. An AIP project was created 2004 to construct two complete production control channels for both HER and LER. This AIP, managed by the group, is underway. The more complex production systems, with complete operator interfaces, are scheduled for commissioning in fall 2004.



.Figure of the Low Group Delay Woofer Channel and the broadband feedback channel

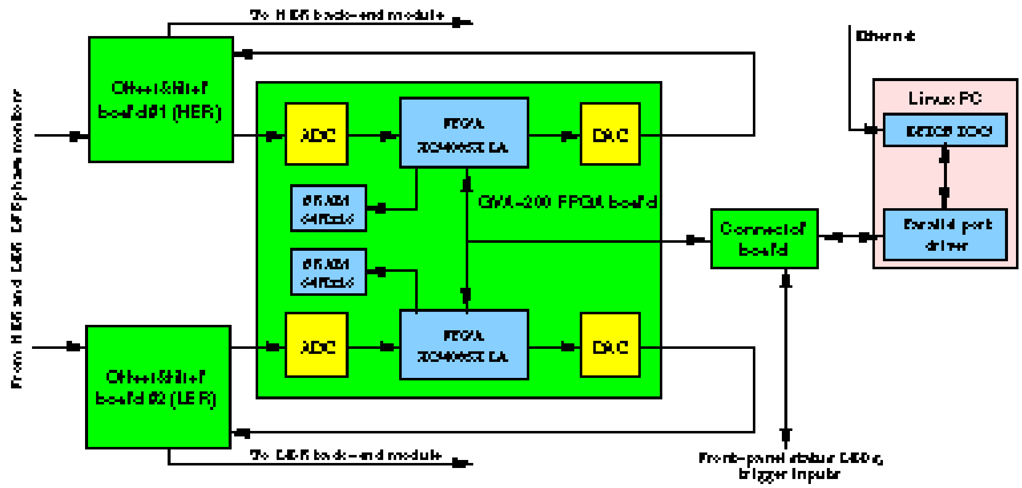
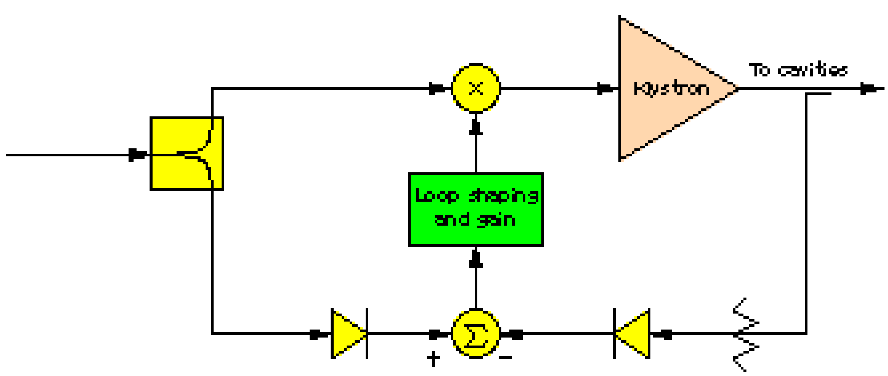


Figure of the Low Group Delay Woofer Implementation

Another PEP-II research area for the group is the Klystron Linearizer. Our efforts in the past two years have led to the understanding that saturation effects in the 1.2 MW PEP-II Klystrons significantly reduce the effectiveness of the impedance control loops. Our modelling efforts have been confirmed by physical measurements of the in-cavity longitudinal modes in PEP-II. The effect of this saturation is so significant that the problem must be attacked at the source in addition to feedback control via the LGDW and broadband systems.

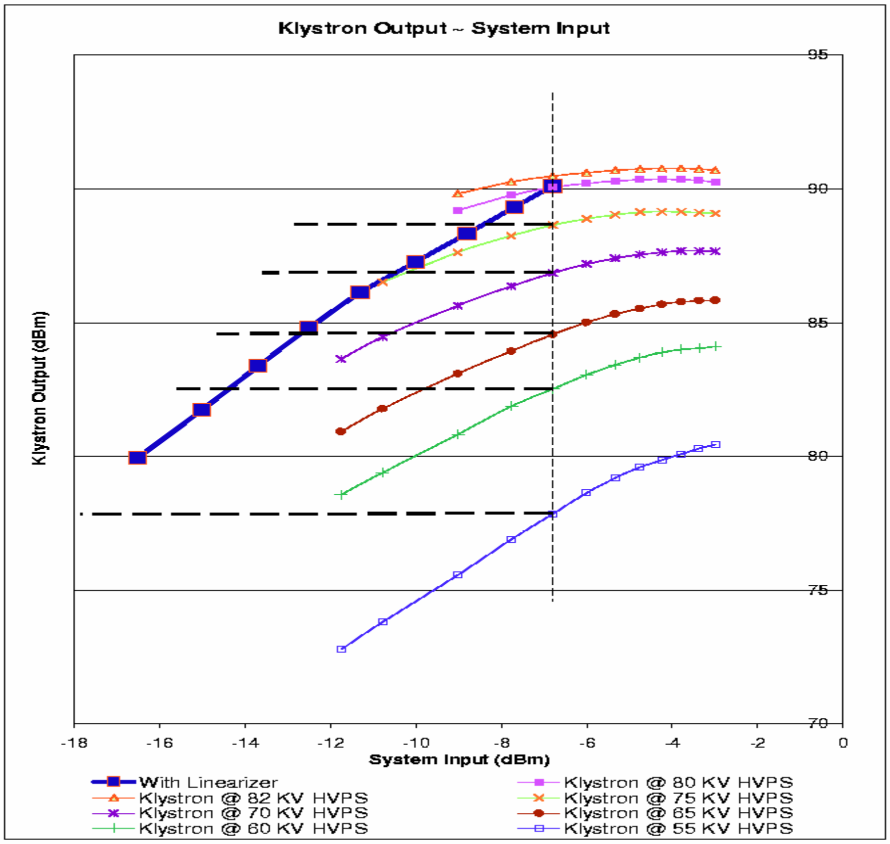
The figure shows the essential idea behind the klystron linearizer. Essentially a feedback loop and compensation circuit is used around the klystron to enforce a linear input to output amplitude gain characteristic. The action of the feedback path is to create a distorted, non-linear input to the klystron, such that after the non-linear klystron gain, the result is a linear gain block.



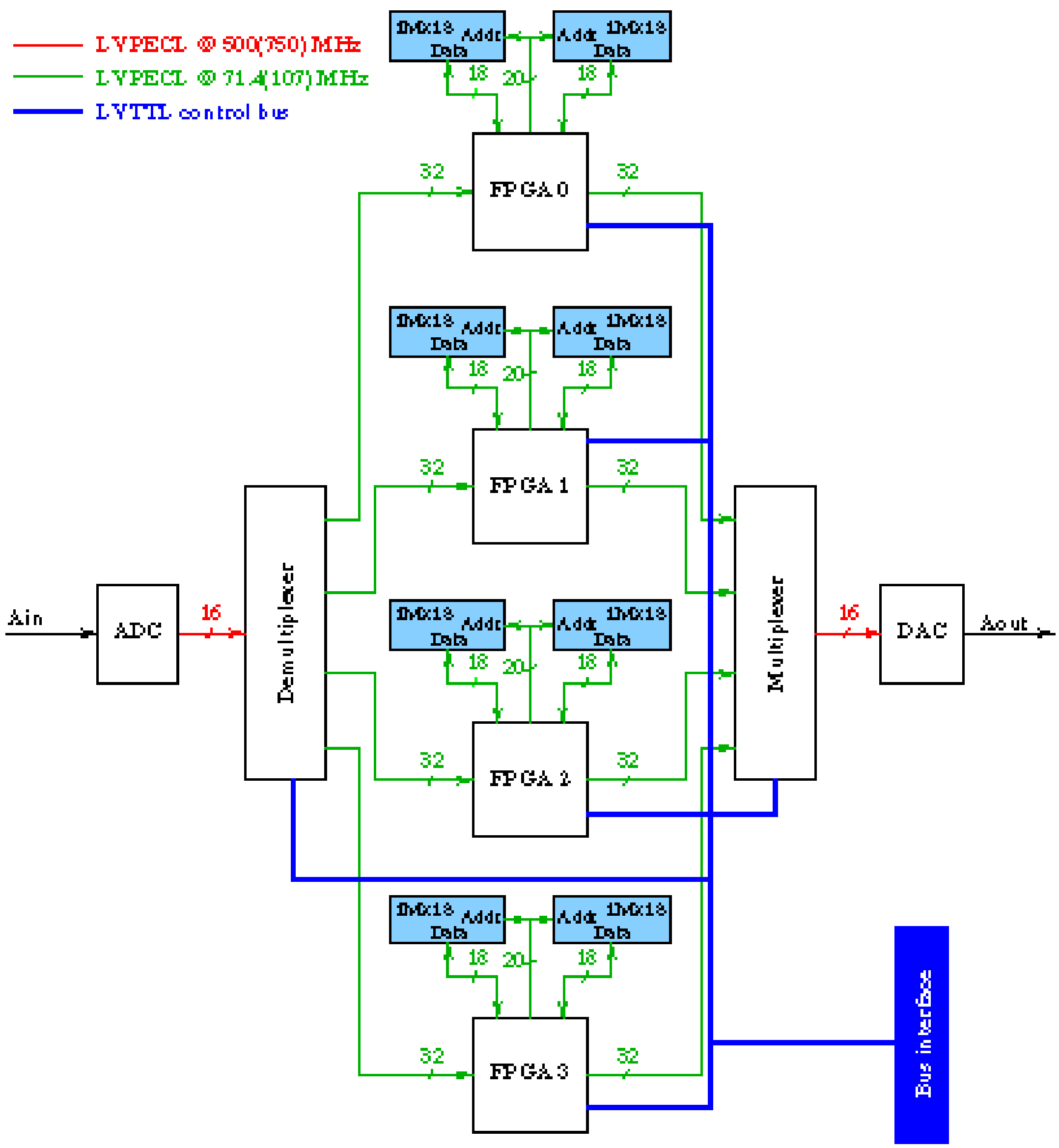
Block diagram of the Klystron Linearizer

Our group has constructed a prototype of this function, in addition to a low-power non-linear klystron test model to evaluate the performance. Efforts have progressed through two test stand tests with full-power klystrons, plus an machine development effort to understand the operation of the linearizer interaction with the complex LLRF systems via installation and operation of the linearizer in a LER RF station. Initial results have led to system development, improvements and understanding of this non-linear analog processor. Our efforts now allow linear operation over the full 10 kW to 1 MW operating range, and allow 630 KHz of control loop bandwidth. We anticipate another round of test stand measurements in fall 2004, followed by construction of 4 test prototypes for machine development testing in the LER in spring 2005.

Linearized Klystron output, and families of Klystron input-output characteristics at various operating points. The linearized output shows operation over the full 100 kW to 1 MW operating range. Due to collector power dissipation limits, the klystron HV power supply is adjusted at each operating point to keep the klystron input power constant. The linearizer circuit must compensate both the change in small signal and large signal gain over this range.



Our group has continued to develop high-speed signal processing systems, and this last year we have continued the detailed circuit and signal processing system designs for a 1.5 GSample/sec. feedback processing channel. This new architecture is of direct applicability to PEP-II and other collider needs, and can implement either longitudinal (downsampled) or transverse (non-downsampled) processing systems. It represents a significant advance in the processing speed and density previously achieved. The initial development has been done in conjunction with Dr. Makoto Tobiyama of KEK, and has progressed to include a significant funding component under the US-Japan Cooperative Program in High Energy Physics.We continue to refine and improve our conceptual prototype - A major design architecture function (the uneven-stepping multiplexer and demultiplexer) was better implemented this year. This refinement removed roughly 50 high-speed ECL components from the design, greatly simplifying the layout task. The figure details the multiplexed signal processing functions which are divided into 4 parallel computational channels. This construction effort is part of our collaboration with KEK and LNF-INFN to build a demonstration system to operate at one of the laboratories. Progress this last year has been unfortunately slower than we would like, as manpower concentrates on the LGDW and Klystron Linearizer projects. We plan on having a proof of concept prototype running for test purposes sometime in spring 2005.



Block Diagram of the 1.5 GS/sec. processing Channel

Our group added a new staff RF engineer - Dan Van Winkle, who is directly involved in RF system analysis and modelling for PEP-II. We also have added a new Ph.D. student, Themis Mastorides, from the Stanford Electrical Engineering department. Themis is working with Yubo Zhou, an Engineer's degree candidate, on the klystron linearizer prototype and measurements.

Collective Effects

The Collective Effects Group continued studies of beam physics in the Linac Coherent Light Source (LCLS) including methods to shorten X-ray pulse duration. We have also studied the problem of single bunch instability and the effect of dark currents in NLC accelerating structures on the beam emittance.

Short X-ray pulses in LCLS. A scheme for producing femtosecond and sub-femtosecond x-ray pulses in the LCLS was proposed in 2003 which involves a slotted-spoiler foil in a bunch compressor chicane. The work was published in Physical Review Letters (PRL, **92**, 074801, (2004)). The latest development of this idea showed a possibility of pushing this scheme into the sub-femtosecond range (P. Emma et al., FEL'04, Trieste, Italy, 2004). The result of computer simulations which demonstrates generation of a 380 attosecond pulse is shown in Fig. 1.

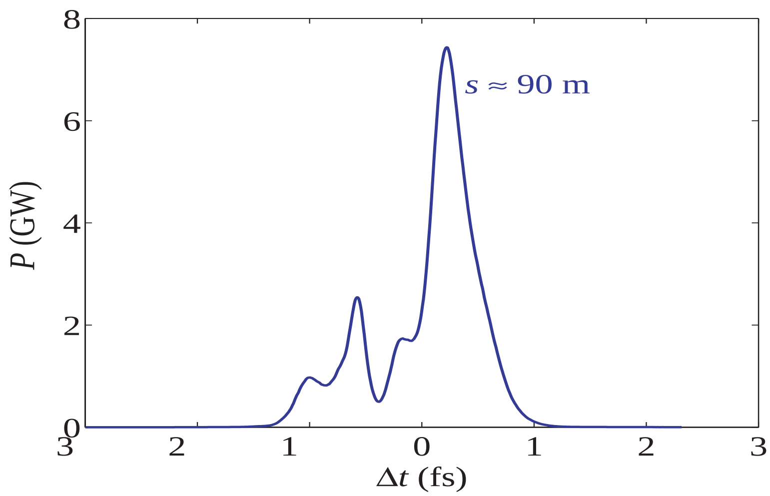


Fig. 1. X-ray power in the undulator at s=90 for LCLS beam with a thin slotted foil. The FWHM duration of the X-ray pulse is 380 attosecond.

Enhanced SASE in LCLS. Following the original proposal by A. Zholents, significant enhancement of the electron peak current entering a SASE undulator was studied which utilizes an energy modulation in an upstream wiggler magnet via resonant interaction with an optical laser, followed by microbunching of the energy-modulated electrons at the accelerator exit (A. Zholents et al., FEL'04, Trieste, Italy, 2004). The x-ray output consists of a series of uniformly spaced spikes, each spike being temporally coherent. Detailed "start-to-end" simulations showed that the output SASE x-ray pulse will be dominated by spikes of a few hundred attosecond or less duration.

Space-charge instability in LCLS. An intensive study of microbunching instability in the LCLS including longitudinal space charge, CSR and linac wakefield was carried out. As the result of this study, it was decided to scrap the super-conducting wiggler in the LCLS design and include a laser-heater system at low energy. This study, and the specific design for such a laser-heater, has been published (Phys. Rev. ST Accel. Beams 7, 074401 (2004)).

Resistive wall wakefield in the LCLS undulator. The largest contributor to energy change in the undulator region of the LCLS is the (longitudinal) resistive wall wakefield of the copper coated beam pipe. The relative energy variation (over the bunch) induced within the undulator region must be kept to a few times the Pierce parameter; otherwise a part of the beam will not reach saturation. Previously, for resistive wall wake calculations in the LCLS, a formula that includes only the dc conductivity of the metal has been used. Recently, more accurate calculations of the wake, ones including also the effect of the ac conductivity in the beam pipe wall were carried out (K. Bane and G. Stupakov, SLAC-PUB-10707, 2004). It was shown that the present LCLS undulator design, with its round copper beam pipe, will result in a relatively large energy variation induced within the bunch over the length of the undulator (0.8%), see Fig. 2. Calculations also show that if, instead, one uses an aluminum chamber, the energy variation can be reduced to within acceptable limits (< 0.2%). It was also shown that the effect of the anomalous skin effect in the beam pipe wall is small, and can be ignored.

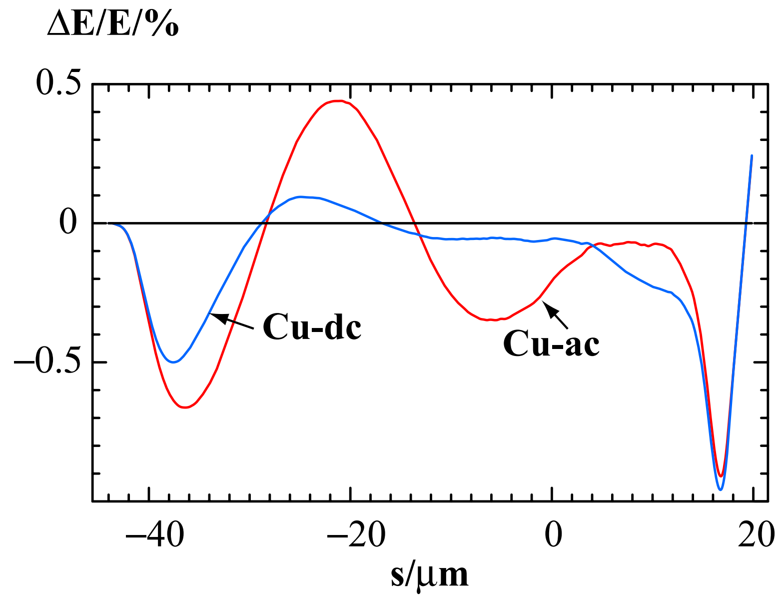


Fig. 2. Energy loss as a function of position within the LCLS bunch resulting from the resistive wall wake in the undulator. The blue line shows previous calculations which account of the dc conductivity only. The red line shows recent result for the ac conductivity—the energy variation within the bunch is increased up to 0.8%.

Laser acceleration in vacuum. A new method was developed which allows calculating laser acceleration in vacuum based on the energy exchange arising from the interference of the laser field with the radiation field of the particle. The method was applied to a simple accelerating structure consisting of a conducting screen with a round hole. Limitations due to material damage threshold and energy scaling of this acceleration method were studied. A paper has been published in PRSTAB (vol. 7, 011302, (2004)).

Numerical study of single bunch instability. A numerical code was developed that solves single bunch stability problem using linearized Vlasov equations (R. Warnock et al., SLAC-PUB-10648). It avoids problems associated with the singularity of the integral equations, and improves the Oide's method currently used for the numerical stability analysis. The linearized Vlasov equation for a bunched beam subject to an arbitrary wake function is rephrased so that it becomes non-singular in the sense of operator theory, and has only regular solutions for coherent modes. The code finds thresholds of instability by detecting zeros of the determinant of the system as they enter the upper-half frequency plane, upon increase of current. Results were compared with a time-domain integration of the nonlinear Vlasov equation with a realistic wake function for the SLC damping rings and showed a close agreement between the two calculations.

*Dark current simulations for NLC structures***.** The metal surface of accelerating structures emits electron currents when operating at rf electric fields higher than 100 MV/m. These "dark currents" may have various deleterious effects, one of which is an interaction with the primary electron (or positron) bunch. Kicks to the beam centroid caused by the field of the dark current may dilute the beam emittance. The transverse kicks induced on the primary beam by a single emitter of dark current (see Fig. 3) in an X-band traveling wave accelerating structure were calculated (V. Dolgashev et al., SLAC-PUB-10666). Those kicks were found to have a maximum amplitude of about 4 V per 1 mA of emitted current. A rough estimate of the emittance dilution for an on-axis beam was calculated which gave a small number compared to the typical NLC-beam wake field deflection.

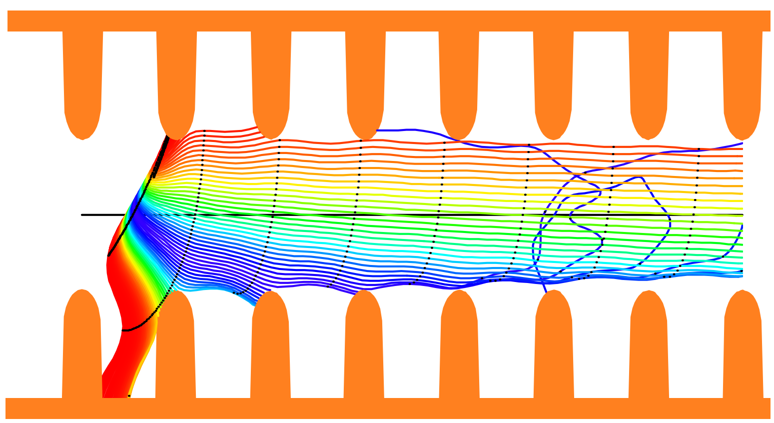


Fig. 2. Secondary electron trajectories in a traveling wave periodic RF structure from a single emitter located at a top iris.

Synchrobetatron stop bands due to a single crab cavity. The stop band due to crab cavities for horizontal tunes that are either close to integers or close to half integers was analyzed (G. Hoffstaetter and A. Chao, PRSTAB, 7, 071002 (2004)). The latter case is relevant for today's electron/positron colliders. This stop band was compared to that created by dispersion in an accelerating cavity and shown that a single typical crab cavity creates larger stop bands than a typical dispersion at an accelerating cavity. It was also found that stop bands can be avoided when the horizontal tune is located at a favorable side of the integer or the half integer. It was shown that the stop bands can be weakened, although not eliminated, significantly when two crab cavities per ring are chosen suitably.

Lattice Dynamics

As the PEP-II luminosity increased to $9x10^{33}cm^{-2}s^{-1}$, which was three times of its design luminosity, we continued the work of improving the optics in the PEP-II accelerators. In addition, we studied the beam-beam effects in e^+e^- colliders and made significant progress in the realistic simulation. As a result of our works, the simulation has become a reliable tool to compute the luminosity of colliders. It is widely accepted as a design and optimization tool for colliders.

Single-particle dynamics. Yunhai has given an invited talk about single-particle dynamics at the ninth European Particle Accelerator Conference, July 5-9, 2004, Lucerne, Switzerland. The talk gave a comprehensive review of existing particle tracking tools to assess long-term particle stability for small and large accelerators in the presence of realistic magnetic imperfections and machine misalignments. The emphasis was on the tracking and analysis tools based upon the differential algebra, Lie operator, and "polymorphism". Using these tools, a uniform linear and non-linear analysis was outlined as an application of the normal form. The work was written as SLAC-PUB-10511 and published in the proceedings of the conference.

Study the beam-beam effects in e+e- collider. We introduce a symplectic method to handle a large and finite crossing angle in the beam-beam interaction. This method is implemented in a parallel computer program to simulate three-dimensional effects in the beam-beam interaction utilizing the technique of particle-in-cell. The results of simulation are compared with analytical solutions, simulations with a well-known existing code from KEK, and experimental observations. This work was written as SLAC-PUB-10401 and SLAC-PUB-10674. In collaboration with Ohmi and Tawada from KEK, we had published the work on Phys. Rew. Lett. **92**, 214801 (2004).

The beam-beam simulation code has been speeded up by a factor of twenty after the implementation of a better scheme for the longitudinal slicing. Each simulation takes only eight hours to complete on a parallel supercomputer. In collaboration with John Seeman, Witold Kozanecki, Ilya Narsky, and Frank Porter, the simulation results are being benchmarked against the experimental measurements at PEP-II. Comparisons of the head-on or small-angle collisions were made with good agreements. The work was written as SLAC-PUB-10527 and published on the proceedings of EPAC 2004.

To model the recent bunch pattern in the PEP-II operation, we added the parasitic collisions into the beam-beam simulation. The simulation has shown a 7% degradation of luminosity compared with 5% observed in the machine. The simulation is used to predict the future performance as the machine is upgraded. These results were shown in the PEP-II MAC meeting, April, 2004.

Build up of electron cloud in the presence of solenoid field. Collaborating with Furman and Pivi from LBL, we have augmented an existing code to include solenoid fields and used it to simulate the build up of electron cloud due to electron multipacting in the PEP-II positron ring. We find that the distribution of electrons is strongly affected by the resonances associated with the cyclotron period and bunch spacing. In addition, we discover a threshold beyond which the electron density grows exponentially until it reaches the space-charge limit. The threshold does not depend on the bunch spacing but does depend on the positron bunch population. This work has been orally presented at the Particle Accelerator Conference 2003 in Portland, Oregon. It was published in Phys. Rev. ST, Accel. Beams 7, 024402 (2004).

Upgrade object-oriented simulation tool: LEGO. Thick lens have been added in LEGO for quadrupoles and dipoles. The treatment is symplectic and six-dimensional. This upgrade allows us to use it as optical design tool in the future. Hard-edge fringe has been added for the quadrupole element.

Precision Measurement for PEP-II Optics and Its Improvement. We have continued to improve Model-Independent Analysis (MIA) for the PEP-II optics measurement [SLAC-PUB-10719, 2004 to be published in the NIM], especially for precision measurement of its linear couplings [SLAC-PUB-10371, 2004]. The speed of obtaining a virtual machine that matches the real machine in linear optics and a machine-fixing wanted model has been enhanced by at least twice during the last year. MIA has become a routine off-line measurement tool for characterizing PEP-II LER and HER optics regularly. It has also become a routine tool to fix the HER and LER beat beats [SLAC-PUB-10369, 2004] and the linear couplings to help PEP-II luminosity steady increase.

Technically, MIA is a high-precision linear optics measurement tool. After resonantly exciting transverse orbit motion twice, one at the horizontal tune while the other at the vertical tune, we obtain 2 pairs of conjugate orbits that makes a total of 4 independent orbits, sufficient for determining the linear optics. Instead of direct orbit fitting, MIA fits the orbit-derived quantities, the Greens functions, the phase advances, and optionally, the eigen-mode coupling ellipses parameters to determine the most probable quad strengths, sextupole feed-downs and BPM gains and cross couplings, thereby, measures the most probable linear optics of the HER and LER and search for the approachable wanted machine model to improve the machine optics.

Lattice design for PEP-II upgrades. The PEP-II upgrade for a higher luminosity requires a lattice upgrade to reduce the Beta* functions at the Interaction Point and decrease momentum compaction factor for a smaller bunch length. Several options of the LER and HER lattices have been designed to satisfy these parameters, and their effect on dynamic aperture was evaluated in particle tracking simulations.

Some of these results had been reported at the PEP-II MAC meeting in April, 2004.

Among the studied HER lattices with a lower momentum compaction factor, two options have been selected for a possible implementation in 2005. These lattices have stronger focusing in the four arcs, where the horizontal phase advance is increased from 60 to 90 degrees per cell, while the vertical phase is 60 and 90 degrees, respectively, for the two options.

This modification reduces the momentum compaction factor by 30% and bunch length by 16% which would allow the proportional reduction of vertical beta* without luminosity loss due to the hourglass effect. The nominal 48 nm emittance is maintained by using a dispersion modulation in the four arcs. Dynamic aperture for both lattices is about 10 sigma for beta*=50/1 cm. These lattices require upgrades of some power supplies and magnets, particularly stronger sextupoles.

In the similar LER study, the higher phase advance options as well as the new 270 degree optics for a much smaller momentum compaction factor have been investigated. However, since the LER nominal optics is stronger compared to HER, it was found that further increase of phase advance significantly reduces dynamic aperture, particularly due to enhanced sextupole aberrations. The higher phase options would also require significant magnet upgrades. At present, these lattices are not considered for implementation.

Several options for HER and LER lattice with a lower beta function at IP have been designed in the range of 12.5 to 7 mm for vertical beta*, and 50 to 33 cm for horizontal beta*. The lattice modification includes a local adjustment of the IR optics and can use the present magnets and power supplies. An alternative method may be used to reduce the vertical beta* using 12 quads in dispersion suppressors next to straights 12 and 4. The latter method is much easier than the IR adjustment, but involves a beta perturbation across the two arcs adjacent to the IR. It was successfully tested in the machine for the HER lattice. Calculated dynamic aperture for the low beta* lattices was found to be sufficient for the present HER and LER emittances, but may need further improvement for a higher LER emittance when wigglers are turned on.

Lattice design for SPEAR-3 upgrade. A realistic version of the SPEAR-3 lattice with double waist low beta optics has been designed for the proposed machine upgrade. The modification of the long straight section includes an asymmetric chicane and a quadrupole triplet to provide low beta locations for two Insertion Devices (ID). In addition, four low beta locations have been created in the matching cells for the small gap IDs. Although the modified lattice has a stronger focusing than in the nominal design, it still provides reasonable size of dynamic aperture (performed by A. Terebilo). This lattice design was evaluated at the SPEAR-3 external review (August 2004) and found acceptable for the proposed upgrade.

Solenoid compensation for a linear collider. A new method of detector solenoid compensation in a linear collider using weak anti-solenoids has been investigated (with A. Seryi who proposed it) and found to be better compared to a skew quadrupole correction. The study was performed for a realistic detector solenoid field overlapped with the final focus quadrupoles and for a beam crossing the solenoid at an angle.

The main conclusion of this study is that most of the correction is produced by that part of the compensating anti-solenoid field which overlaps the final focus quadrupoles. Therefore, relatively weak and short anti-solenoids can be used for the correction of the full detector solenoid. This work is published as SLAC-PUB-10592 and submitted to the Physical Review Journal.

Accelerator Structures

The work on accelerator structures consisted of theoretical design studies, fabrication and experiments. The R&D has been focused primarily on NLC structures. There are two major challenges in designing NLC X-Band accelerator structures. The first is to demonstrate stable, long-term operation at NLC gradient to lower the machine cost, and the second is to strongly suppress the beam induced long-range wakefield to achieve high luminosity. During the past year, the great progress in high gradient operation has been made, and more effort has also been put on dipole wakefield suppression and prototype design of future NLC structures. nOur program involves the collaborative efforts of a number of departments at SLAC, KEK and FNAL.

Structures for High Gradient Tests. Since 2000, more then thirty structures with different length, aperture, phase advance and coupler design have been built and tested at the NLCTA. Work on high gradient testing structures continued to be our high priority task in the past year. The extensive studies and summarization of the results in high gradient research would lead us to select the best possible RF parameters for the NLC prototype structures.

Nine traveling-wave structures with low group velocity (H60VG3R17, two H60VGVG4R17, H60VG4S17-I, H60VG4S17-II, two H60VG4S17-III, H60VG4SL17-A/B) have been designed, built and eight of them were high power tested. Through the thorough comparison and analysis we have selected the following main accelerator parameters: 60 cm of length, 5□/6 phase advance /cell, low group velocity with optimal attenuation factor of 0.5-0.6 for optimal RF efficiency (see Figure 1).

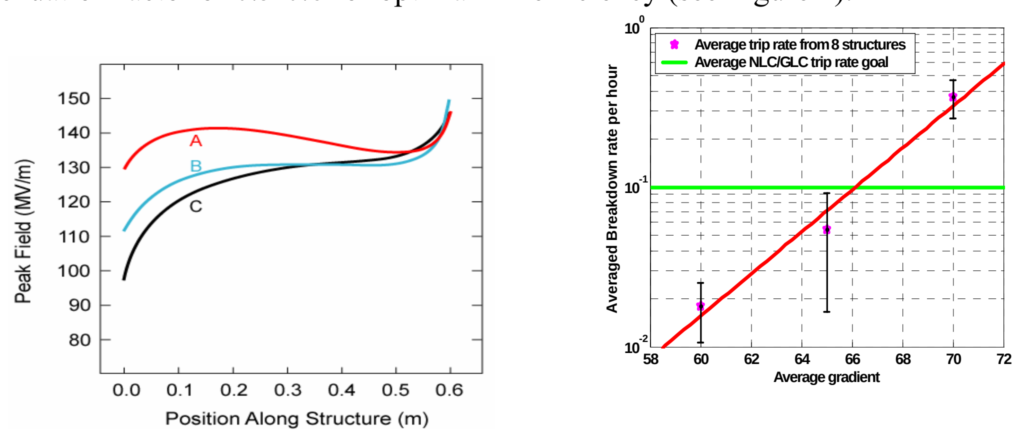


Figure 1. Maximum surface field for three types structures: A (H60VG3S18), B (H60VG3S17) and C (H60VG4S17) at unloaded gradient of 65 MV/m (left) and high power test results for eight structures (right). The horizontal line of the right plot of Figure 1 is the goal line for GLC/NLC stable high power operation – less than 1

breakdown per 10 hours per 60 cm section at unloaded 65 MV/m gradient for 60 Hz RF pulses. The tilted line is a fit for average trip rates for different gradients.

Prototype of NLC Structures

Accelerator Design. As the first generation of full featured HDDS structures, two H60VG4SL17 type of structures have been completed. Figure 2 shows four HOM couplers in both input and output ends. Fundamental input/output couplers are waveguide type. In order to reduce the field in the input end, the dipole mode detuned distribution becomes asymmetric. A $\mathrm{Sech}^{1.5}$ function distribution was adopted for better dipole mode suppression. The predicted wakefield is shown in Figure 3.

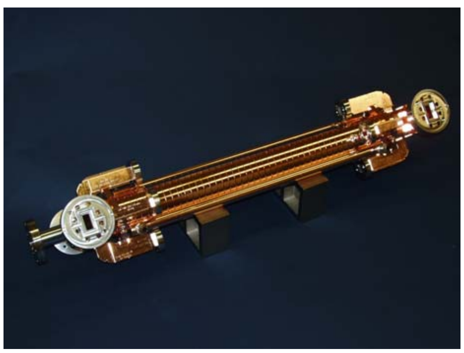


Figure 2. The H60VG4SL17 structure.

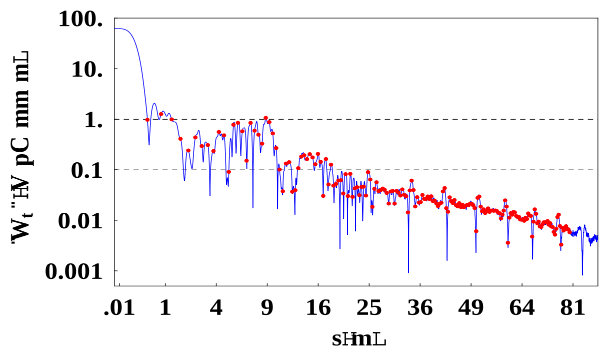
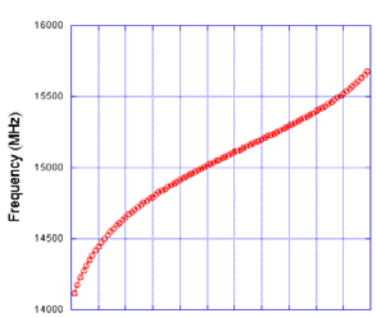


Figure 3: Envelope of simulated wakefield of two fold interleaved structures as function of the distance behind a driving bunch.

Accelerator Cup Fabrication. The accelerator cups for the latest structures, which are fabricated through a combination of precise milling and tuning. For KEK produced cups, final finish was done by single-diamond turning. The fundamental mode (TM01) frequencies and dipole mode (HEM) frequencies were measured by using a single cup microwave QC setup. The results for the first band of dipole mode were shown in Figure 4. The left plot shows the very smooth change for the frequencies corresponding to the cups of two interleaved structures. Right plot shows the distribution of frequencies in comparison with accurately calculated theoretical values.



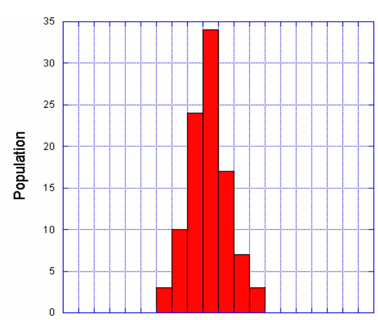


Figure 4: Measured dipole mode frequencies (left) and their tolerances (right).

HOM Coupler Design and Verification. HOM couplers are critical elements to connect each HOM manifold and corresponding WR62 load with good match. A scattering matrix computer code S3P was used to theoretically design the HOM couplers. Figure 5 shows a model with symmetric feeds and better than 0.1 of reflection coefficient within structure first dipole band has been reached with our design. In order to examine the accuracy of the electrical design and mechanical fabrication for those HOM couplers, a cold test assembly of H60VG4SL17B output end HOM coupler was tested. The consistency between measurement and theory gave us the confidence to fabricate such complicated elements.

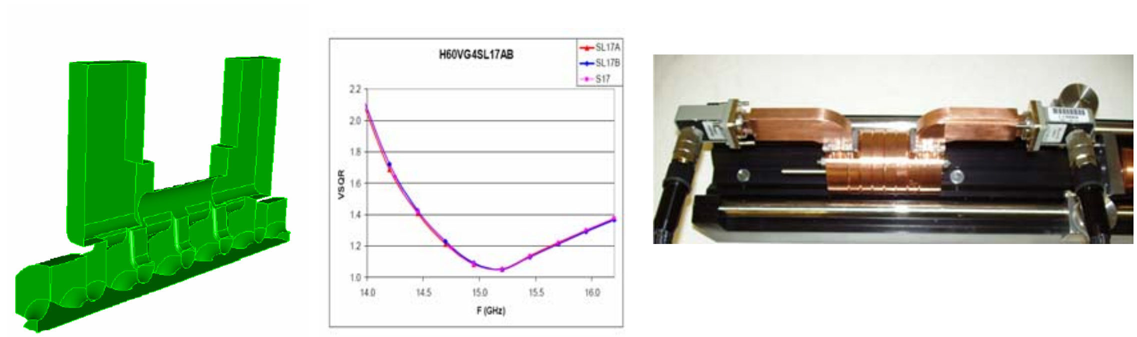


Figure 5. Simulation model for HOM coupler (left), match quality in coupler pass band region (middle) and microwave measurement for a test assembly (right).

<u>R&D for Future Structures</u>

Optimization of Accelerator Disks. To improve the shunt impedance of the structures by 10 to 15%, a structure incorporating rounded cells is being studied and test cups have been machined. The main technical challenge is to machine round-edged pie-shape slots along curved cavity wall. Figure 6 shows test accelerator cups.

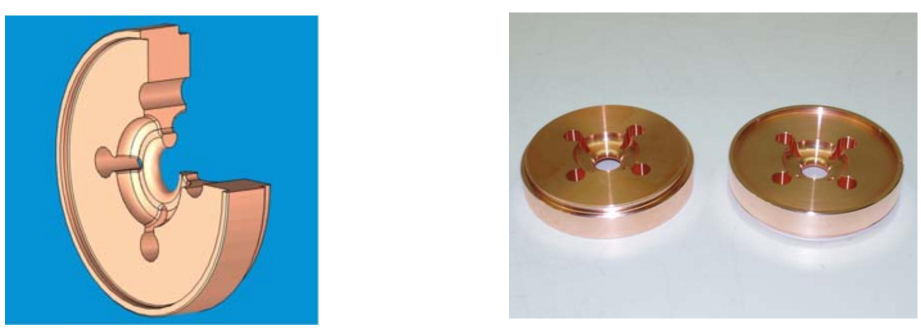
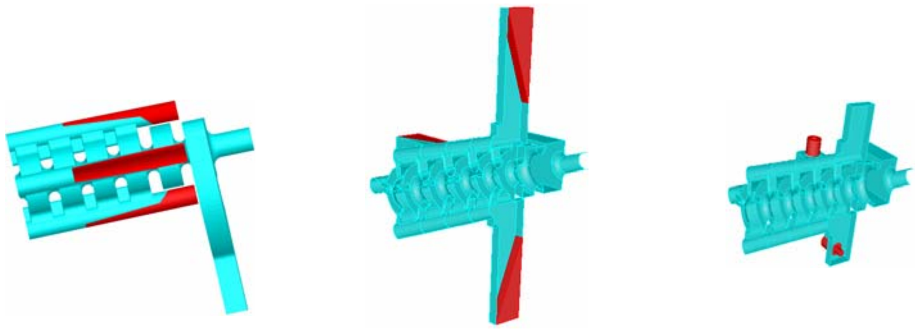


Figure 6. Cutaway view of a simulated accelerator cup (left) and machined test cups (right).

HOM Coupler and load. In order to reduce the complexity and fabrication cost of HOM couplers, there are three proposed and designed configurations for HOM coupler ports as showed in Figure 7. Design A is so called in-line load type, where microwave absorbers are located inside of manifolds. The technical challenges are good broad band HOM matching and low absorption for fundamental mode power. Design B is to braze transverse WR62 loads directly on HOM port. Design C is to use waveguide to coax adapter terminated by a coax load.



(A) (B) (C)

Figure 7: Three types of HOM coupler design

Wire Measurement. A wire-based structure experimental method is being developed to quickly and inexpensively analyze the wakefield suppression properties of accelerator structures. Using a 300-micron thick brass wire, measurements of the structure S-parameters are made to compute the impedances for the monopole band and higher dipole mode bands. The test results for a standing-wave structure, a short traveling-wave structure, and the RDDS1 structure (see Figure 8) show a reasonable agreement with computer simulations.

Figure 8. Wire measurement set-up with RDDS1 structure.

High Power RF

During this fiscal year we built the fully dual-moded high-power rf pulse compression system, see Fig. 1. We have produced 400 ns rf pulses of greater than 500 MW at 11.424 GHz with an rf system designed to demonstrate technology capable of powering a TeV scale electron-positron linear collider (NLC). Power is produced by four 50 MW X-band klystrons run off a common 400 kV solid-state modulator. The system includes a dual-moded transmission waveguide system and a dual-moded resonant-line (SLED-II) pulse compression system. Dual-moding of the transmission lines allows power to be directed through a pulse compression path or a bypass path; dual-moding in the pulse compressor allows the delay lines to be about half as long as they otherwise would need to be. Every part of this RF system performed near perfectly. This includes hybrids, supper-hybrids directional couplers, power dividers, tapers, mode converters, and loads. These components are mostly overmoded to allow for greater power handling.

This experiment is setting high-power records in pulsed rf. The processing time of system was rather short, effectively 4 days. (We subtracted all the time that was needed to debug the electronics and installations errors). The system ran continuously for more than 600 hours. In a period of about 166 hours at a repetition rate of 30 Hz and 99 hours at a repetition rate of 60 Hz, a total of 3.9 10^7 pulses, we recorded 211 trips. Only 29 of them were due to this overmoded system. The rest were due human errors, klystron faults and single-mode rectangular waveguide used after combining the klystrons.

Finally, we added a feedback system to the low-level RF circuits that derives the klystrons. First, the combined output signal of the klystrons is sampled in phase and amplitude. A computer driving two arbitrary function generators, then, modify the drive signals to correct for errors in the modulator, klystrons etc. The result is a high efficacy operation of the SLED-II pulse compression system and a flat output pulse, see Fig 2. The variation compressed signal phase was less than +/- 1 degree, which was limited only by our measurement capabilities during these runs.

During this year also we completed the design of the distribution system do divide the output power of the system to feed different accelerator structures, see Fig. 3. This system was tested successfully by using it to feed several accelerator structures that ran a gradient of more than 60 MV/m.

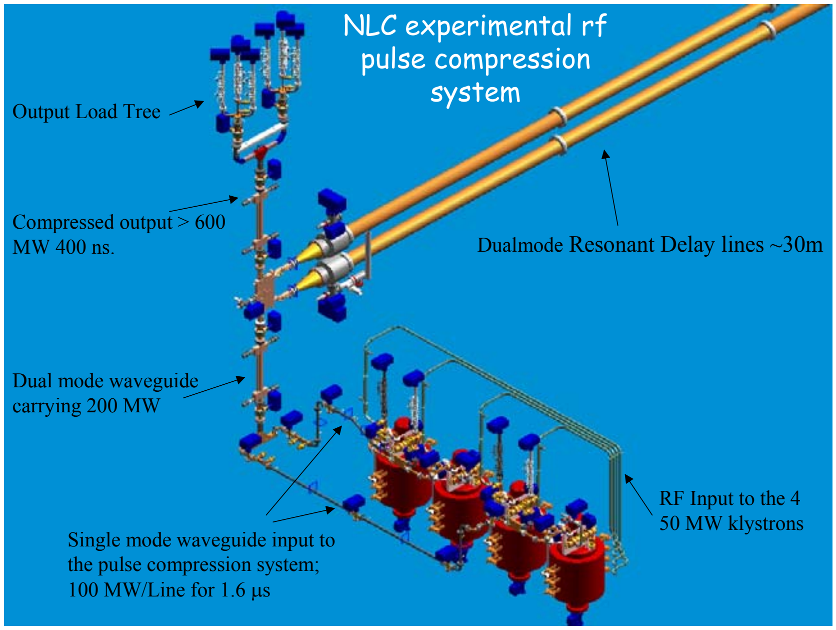


Figure 1: Dual Moded Sled-II System Schematic

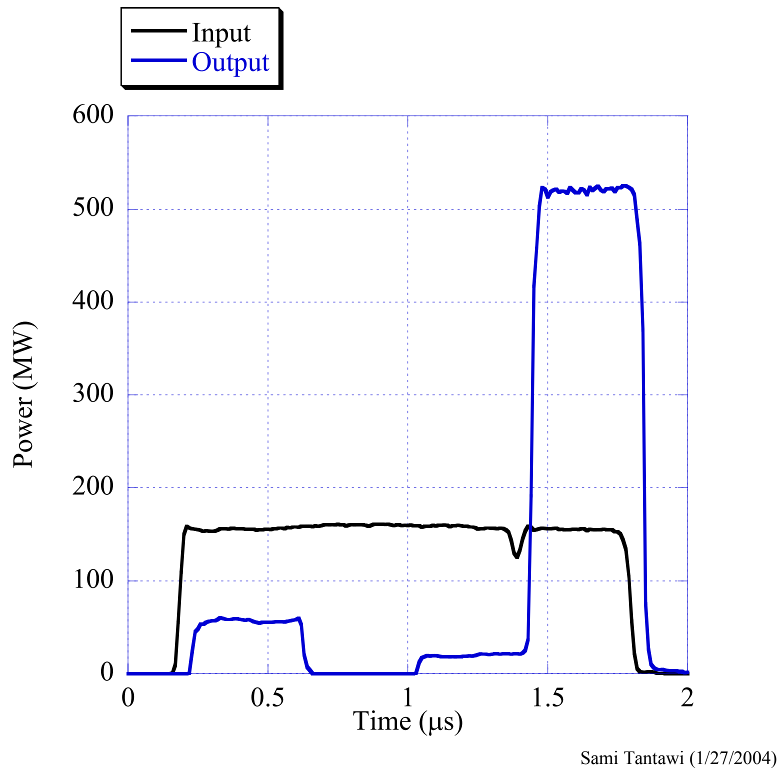


Figure 2. System output with feed forward.

Power Distribution

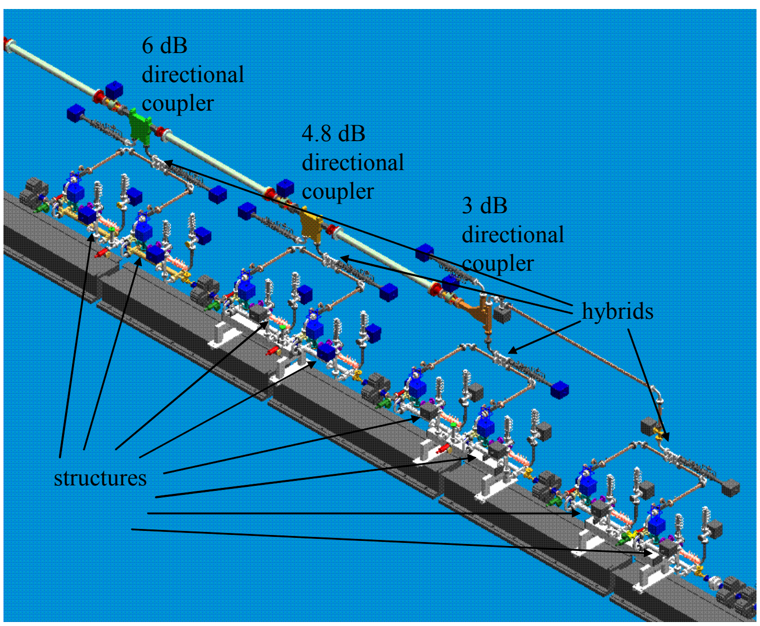


Figure 3. Overmoded power distribution system

Our efforts in extending the art of overmoded systems and components to active devices continued. We tested for the first time an overmoded nonreciprocal device. The device was demonstrated at low power one year earlier, however the high power test performed this year was the first demonstration of such system. The system operated well up to power levels of 2.5 MW at 11.424 GHz. This results in a circulator with power handling capabilities of 5 MW, about 3 times more than the state of the art. However, beyond this power level the system exhibited non-harmonic oscillation. The source of these instabilities is not understood yet. We are currently studying the problem and the physics of these nonreciprocal magnetic garnet material used in the device.

Our efforts in high power solid-state switches for pulse compression systems continued. We have built and demonstrated a new type of fast switches based on an array of PIN diodes on a single wafer. We solved the contact problems exhibited in older versions of the device with a new design of the mounting system. We also reduced the amount of charge injected in the system by a new geometry that only injects the charges in a small ring placed on the wafer at approximately the point of maximum field. The switch geometry is shown in Fig. 4 and the switch performance is shown in Fig. 5.

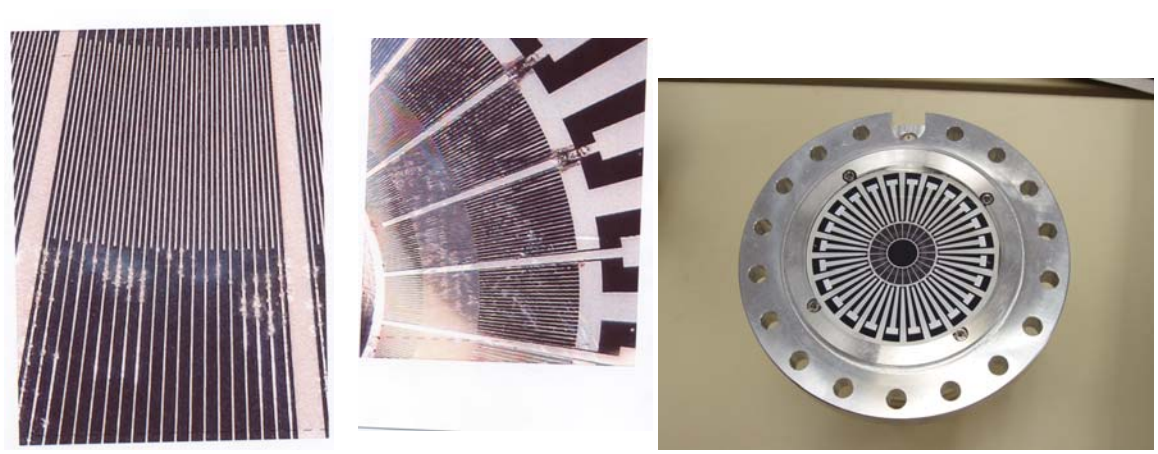


Figure 4. Switch Geometry

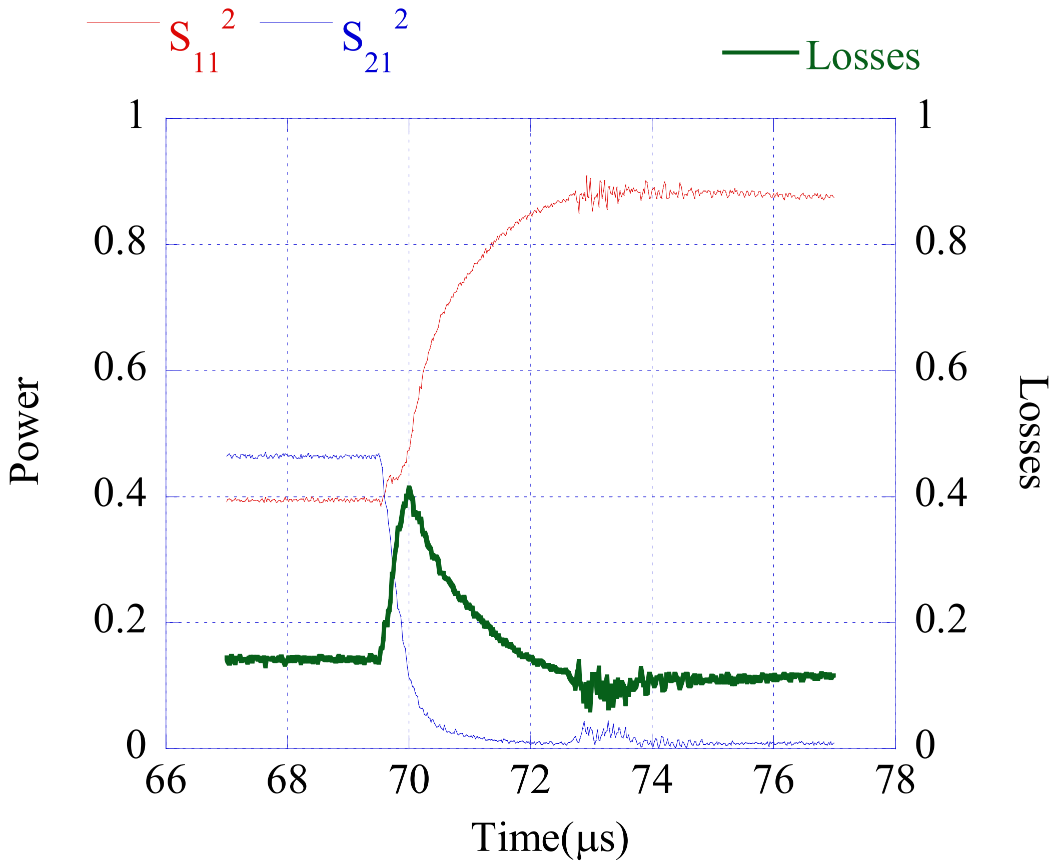


Figure 5. Switch Performance

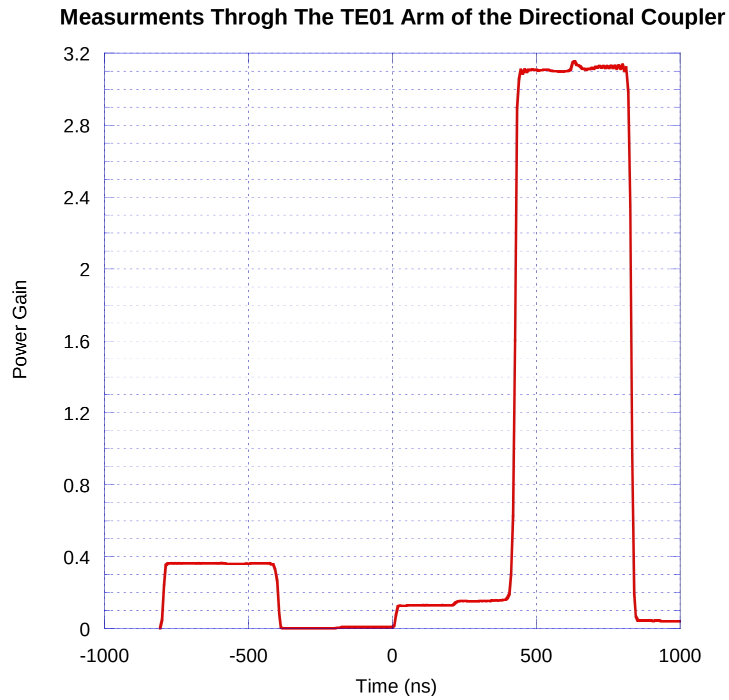


Figure 3. Measured system response thorough the mode selective directional couplers.

Our effort to understand the breakdown phenomenon in RF structures and components continued. We have tested a waveguide made out of molybdenum. The results, to date, indicate the molybdenum is not superior to copper in terms of high field breakdown threshold.

In collaboration with KEK we have build and cold tested several single cavity traveling wave structures. These cavities are going to be fed with rf power using the so called modes converter couplers. We plane to test copper cavities cleaned with high purity water jets and compare them with cavities cleaned with slandered techniques. We are also testing cavities with different materials.

We tested our first nonreciprocal device at high power resulting in an operation at power levels near 3 MW at 11, .424 GHz. This first test revealed several errors in our engineering designs. We have now redesigned the device and we are going to be testing it at high power in the next few weeks.

Our work with High power rf semiconductor devices continues. We have designed P-I-N diode arrays which are specially combined in overmoded waveguides. These hold the promise of an efficient high power source and switch operation. Now, we are examining the detailed physics of their operation modes.

Astrophysics Group

During the past year the group's activities have been on theoretical and experimental studies of particle astrophysics and cosmology. Specifically, the theoretical research has been focused on the nature of dark matter and dark energy, while the experimental activities centered around the program on Laboratory Astrophysics. The group now consists of four senior physicists and two postdoctoral research associates. The group also has one visiting Post-doc and three visiting students from the Center for Cosmology and Particle Astrophysics (CosPA) in Taiwan. Most of the research projects have been carried out in collaborations with world-leading theorists and experimental groups. The major activities are the following.

Theoretical Activities:

- Black Hole Remnants as Dark Matter

Together with R. Adler and D. Santiago (both at Stanford), P. Chen proposed a "generalized uncertainty principle" (GUP) where gravity effects are included. The GUP predicts the existence of a fundamental length, which happens to be the Planck length. By applying this GUP to black hole evaporation, it was shown that BHs cannot evaporate entirely, but should leave with a remnant at Planck mass ($\sim 10^{19}$ GeV). Such remnant from primordial black holes is an interesting candidate for dark matter. The three authors published this work in 2001, and had received the 3rd Prize from the Gravity Research Foundation for this work. R. Adler and P. Chen published another paper this year that further investigates the possibility of such a link between BHR and dark matter. When combining this theory with the "Hybrid Inflation" model of A. Linde and others, P. Chen has recently found that the abundance of BHR is in the right order of magnitude for the dark matter. The very important issue of the stability of the Planck-size black hole remnant, possibly protected by (super) symmetry principle through string theory, has been investigated by P. Chen and M. Shmakova, in collaboration with K. Dasgupta of U. Ill. and two other world experts on string theory. A formal paper is currently under preparation. P. Chen and K. Thompson also collaborate with R. Adler in the study of the cosmology of the post-inflation "black hole" epoch. A formal paper on this project is also been prepared.

- Weak Gravitational Lensing

J. Irwin has developed a novel approach, based on his theoretical expertise in particle beam optics, to the weak gravitational lensing analysis. It is proposed that higher multipole, such as sextupole, moments beyond the conventional quadrupole moment, can in principle be extracted from observation, which would provide extra information in the gravitational lensing studies. Applying this new method to the Hubble Deep Field data, Irwin and Marina Shmakova have found evidence of the existence of sub-galactic dark matter structures. They have posted a paper on the arXiv to report on this finding. P. Chen, J. Irwin, M. Shmakova have been accepted as Guest Memebers of the SNAP collaboration. They expect to contribute to the gravitational lensing and dark energy search efforts in SNAP.

- Dark Energy

P. Chen and a long term post-doc visitor from CosPA, Je-An Gu, have formed a new collaboration on a new theory for dark energy since the summer of 2003. After a year's effort, they have published their new theory in September 2004 (arXiv: astro-ph/0409238), entitled "Casimir Effect in a Supersymmetry-Breaking Brane-World as Dark Energy". By insisting that only the difference, and no the absolute, vacuum energy can contribute to the gravity effect, a la Einstein equations, they demonstrate that the Casimir energy on the 3+1 dimensional brane induced by the boundary conditions of the extra dimensions, with SUSY perfectly preserved in the "bulk", but broken only on the brane. SUSY guarantees the perfect cancellation of the vacuum energy in the bulk. It's breaking on the brane then provides the vacuum energy "difference" between the graviton and the gravitino modes. This new theory looks very promising, and Chen and Gu are continuing the collaboration of the project.

Experimental Activities:

- E-165: Fluorescence in Air from Showers (FLASH) Experiment

Recent observations of ultra-high energy cosmic rays reported super-GZK events above 10^20 eV. However, the two major experiments, the ground-array air shower detector AGASA and the High Resolution Fly's Eye (HiRes) fluorescence detector, exhibit an apparent discrepancy in the observed absolute flux and in the spectral shape. Because of the importance of the physics involved, both groups are currently studying systematic effects that might contribute to the discrepancy. One such effect is the air fluorescence yield.

A proof-of-principle experiment, T-461, using the SLAC FFTB beams to trigger air fluorescence was carried out successfully in the FFTB in June 2002. A formal proposal (E-165) by a five-institution international collaboration, "FLASH", was approved later in November 2002. The first of three runs of this experiment, the "thin Target Phase", has been carried out successfully in September 2003. In June 2004, there was a successful "Thick Target" run, and in July a hybrid run was carried out.

In all, 25 physicists, students, and engineers from the University of Montana, Rutgers University, SLAC, the University of Utah, and the National Taiwan University Center for Cosmology and Particle Astrophysics, participated in the experiment.

- Research and Development of other LabAstro Experiments

R&D effort has been underway in preparing LabAstro experiments beyond FLASH. One major direction is an experiment to investigate into astrophysical dynamics involved in cosmic particle accelerations and jet-plasma interaction. Simulations on the Alfven-wave induced plasma wakefield acceleration has been under development by K. Reil and several international collaborators. Simulations on jet dynamics has been pursued by J. Ng and R. Noble at SLAC, which has yielded exciting results in September 2004. Another possible laboratory astrophysics experiment is the test of the physics of “event horizon” through the Hawking-Unruh effect. Collaboration is forming between this group and the Rutherford Appleton Lab in the UK to investigate this very important piece of physics. It is hoped that by this time next year the group will be ready to look into the designs of these experiments guided by the simulations.

6A. FY04 PROGRESS IN ADVANCED ACCELERATOR RESEARCH Advanced Accelerator Research B by Bob Siemann

Accelerator Research Department B (ARDB) conducts research into the physics and technology of accelerators with a strong emphasis on high gradient acceleration and advanced concepts.

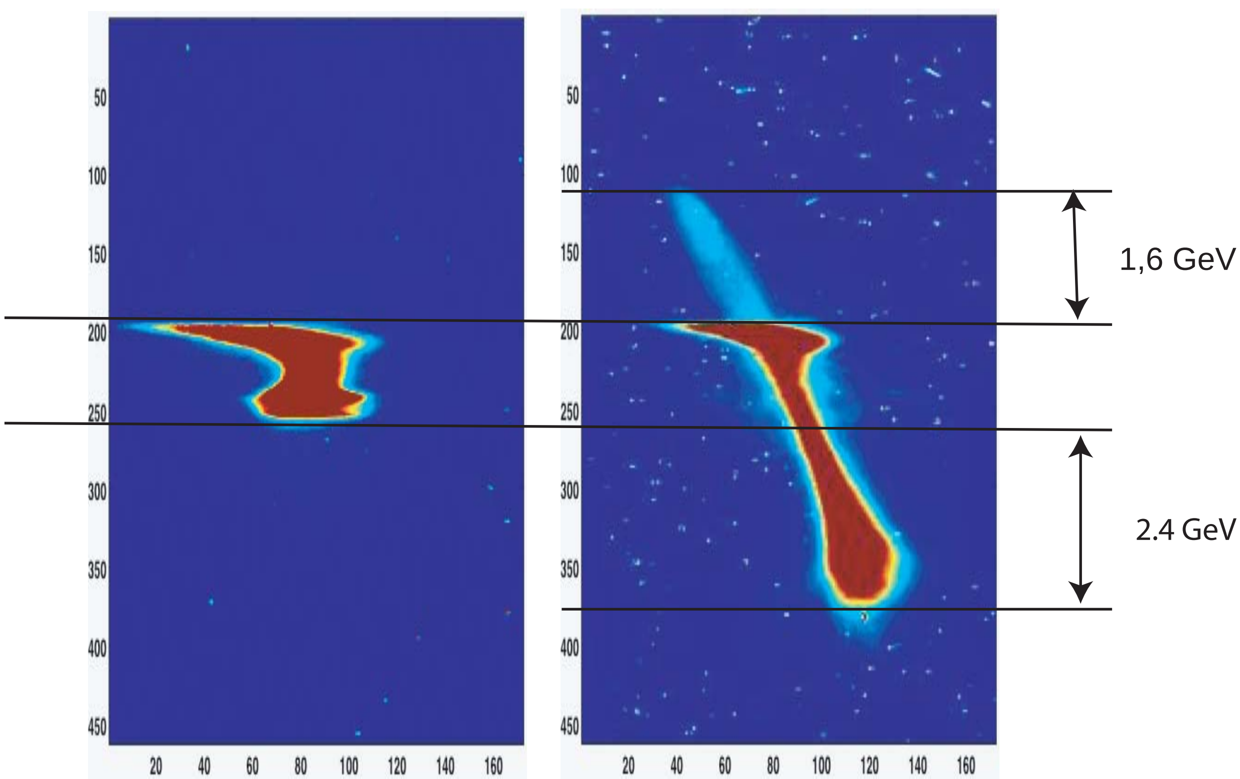
A UCLA, USC, SLAC/ARDB collaboration is continuing with an experimental program to study all aspects of beam driven plasma wakefield acceleration. The SLAC beams offer a unique opportunity for this, and there have been thirteen experimental runs (as experiments E157, E162, E164, and E164X) for over thirteen months of beam time from June 1999 through July 2004. The E157 and E162 data have been analyzed, and the results have been published in thirteen papers in peer reviewed journals. The publications in FY2004 were a general overview of plasma accelerators and the first results on electron acceleration.

- C. Joshi and T. Katsouleas, “Plasma Accelerators at the Energy Frontier and on Tabletops”, s Physics Today, 47 (June 2003).
- P. Muggli *et al*, “Meter-Scale Plasma-Wakefield Accelerator Driven by a Matched Electron Beam”, Physical Review Letters **93**, 014802 (2004).

Experiments E164 and E164X emphasized short bunches made possible by the installation of a compressor chicane in the linac. These experiments were based on simulation and theoretical results that predicted that the acceleration gradient would vary as the inverse of the square of the bunch length provided the ratio of the bunch length to plasma wavelength was held constant. The main features of the experiments were an extremely short bunch length, 0.02 to 0.1 mm, and a 10 cm long, high density plasma source capable of reaching densities above 3×10^{17} cm^{-3}. Innovative instrumentation to measure and monitor the bunch length was also required and was an integral part of these experiments. The first observation, reported in the FY03 Progress Report, was the significant beam generation of plasma. This was unexpected, and it was crucial for the progress this year because it showed the way to making long plasmas.

The results this year have been spectacular with the observation of acceleration gradients in excess of 15 GeV/m sustained for 10 cm. This is illustrated in the figure below that shows one of thousands of events with greater than 10 GeV/m gradient. The E164 and E164X data are presently being analyzed with the objectives of measuring the dependence of the accelerating gradient on plasma density, bunch length, and other beam properties. These results are a milestone in the development of plasma accelerators for extending the energy frontier of particle physics.

Lasers have extraordinary potential as accelerator power sources. Their large fluence leads to the possibility of high gradients. This was realized soon after the invention of the laser, but, until recently, the laser has not been a practical power source because of low efficiency. Recent developments have raised the efficiency of solid state, mode-locked lasers to well above 10%. This has changed the situation, and laser driven accelerators have become a major activity of the ARDB program. The ARDB laser acceleration studies, performed in collaboration with Stanford physicists, are wide-ranging and have both experimental and theoretical aspects.



High-Gradient Acceleration over 10 cm Plasma Length: These are beam profiles taken in a location of large vertical energy dispersion. The horizontal dimension is an image of the beam at the plasma exit, and the vertical dimension is effectively the energy. The panel on the left shows the beam profile with no plasma. The panel on the right shows the beam profile for a plasma density of $2.11 \times 10^{17} cm^{-3}$. Portions of the beam are decelerated by 2.4 GeV and portions are accelerated by 1.6 GeV.

There are ongoing experiments addressing fundamental and practical aspects of laser at the Hansen Experimental Physics Laboratory on the Stanford campus where the Inverse Free Electron Laser and Inverse Transition Radiation interactions are being studied. This work will be moved to SLAC in FY2005 as experiment E163, which will be located at the NLCTA (Next Linear Collider Test Accelerator). E163 will *1)* continue earlier proof-of-principle research, *2)* bunch the beam at an optical wavelength, and *3)* measure acceleration in multiple-cell structures.

Designing and building the E163 infrastructure has been a major activity during the past year, and substantial progress was made during FY2004. An S-band RF system was installed and commissioned and the electron beamline was designed, and magnet fabrication began. Beam commissioning will begin in FY2005.

Photonic crystals are potentially attractive as laser driven accelerator structures because the laser energy is trapped in a small region overlapping the particle beam. Photonic crystals based on either optical fiber drawing or lithography are being designed using computer simulations. Both the underlying crystal lattice and the coupling of energy into the crystal are being studied. A large scale model of a photonic crystal fiber has been constructed and is being tested in the laboratory using RF measurements. In addition, a study of the energy efficiency of laser driven accelerators was completed and published

- R. H. Siemann, "Energy Efficiency of Laser Driven, Structure Based Accelerators"
  Physical Review Special Topics – Accelerators and Beams **7**, 061303 (2004)

The goal of this work is the design and fabrication of practical laser driven structures for that will be explored experimentally in E163.

The ARDB research program would not be possible without collaborations with colleagues from UCLA, USC, and Stanford who are an integral part of every activity. This research would also be impossible without students, and their education is an important part of the ARDB program. There are six ARDB graduate students at the present time, and three students from collaborating institutions are working with ARDB for their dissertations.

7. FY04 Progress in Advanced Computation Researchs by Kwok Ko

Research in Advanced Computations for the past year has focused mainly on the SciDAC project and parallel computing in support of accelerators both within and outside of SLAC. The work included code development, SciDAC collaborations with the Math ISICs and large-scale simulations, all shared among ACD's three groups-Accelerator Modeling, Computational Mathematics and Computing Technologies. Effort has continued on the SBIR projects with STAR, Inc. on developing GUIs for SLAC's software, and the CRADA collaboration with Genencor on computational biology. Progress in each of the major projects is discussed below.

Wakefield Analysis of the H60VG4 DDS Structure

End-to-end simulation of the NLC/DDS prototype, H60VG4, has been carried out using the parallel time-domain solver ***Tau3P*** and the parallel eigenmode solver ***Omega3P***. A computer model of the entire 55-cell structure with exact dimensions is shown in Fig. 1. Using ***Tau3P***, the H60VG4 was simulated for the first time in the time domain with a transit beam. Fig. 2 shows two snapshots in time of the beam-excited fields in the structure. The results were obtained using the IBM/SP at NERSC.

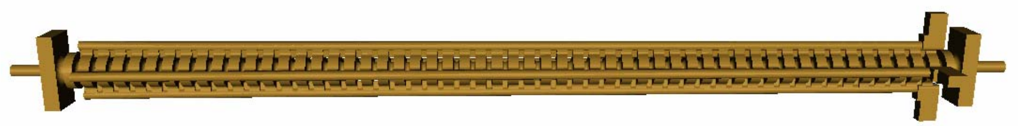


Fig. 1: Computer model of the H60VG4 structure with power and HOM couplers.

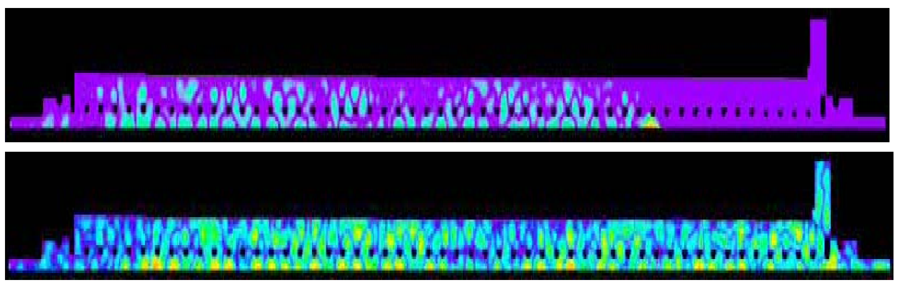
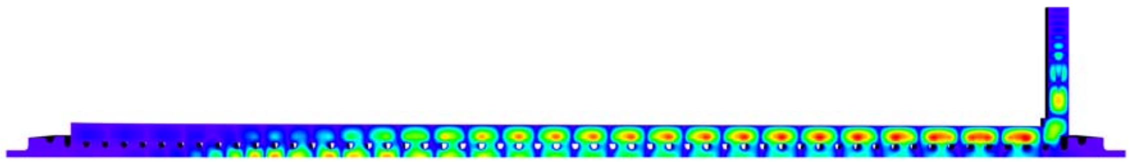


Fig. 2: Beam-excited electric fields in the H60VG4 at two instances in time as modeled by ***Tau3P.***

In the frequency domain, a complex solver has been implemented in ***Omega3P*** for finding damped modes in cavities with lossy materials. It was used to calculate the eigenmodes of the H60VG4 structure in which all waveguides were terminated in externally matched loads. Fig. 3 shows a mode in the first dipole band with high kick-factor but low Q by coupling out through the manifold to the downstream HOM load. A total of 400 complex eigenmodes covering the spectrum up to the 3^{rd} band has been obtained (Fig. 4). The wakefields from summing the eigenmodes are in good agreement with the direct time-domain result from ***Tau3P*** as seen in Fig. 5.

These calculations verify theoretically for the first time the wakefield suppression scheme via damping and detuning on a structure as built, and they can only be done on parallel computers. For example, the Omega3P quadratic element model comprises 2.3 million DOFs that result in a matrix system with 94.5 million non-zeros requiring more than 400 GB of memory. The calculation of 120 eigen-pairs takes 3179 seconds using 512 processors of the IBM/SP3 at NERSC. The SciDAC efforts on solver development have



led to significant improvement for both ***Omega3P*** and ***Tau3P*** that facilitated these large-scale simulations.

Fig. 3: Eigenmode with high kick factor and low Q from ***Omega3P*** in 1^{st} dipole band of the H60VG4.

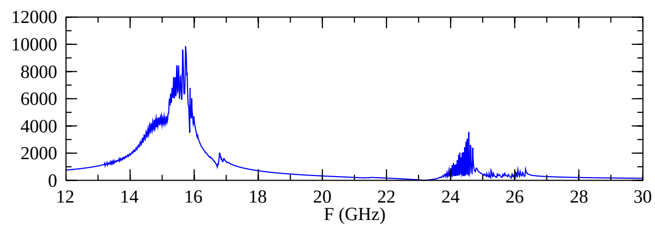


Fig. 4: Impedance spectrum of H60VG4 up to 3^{rd} band from ***Omega3P***.

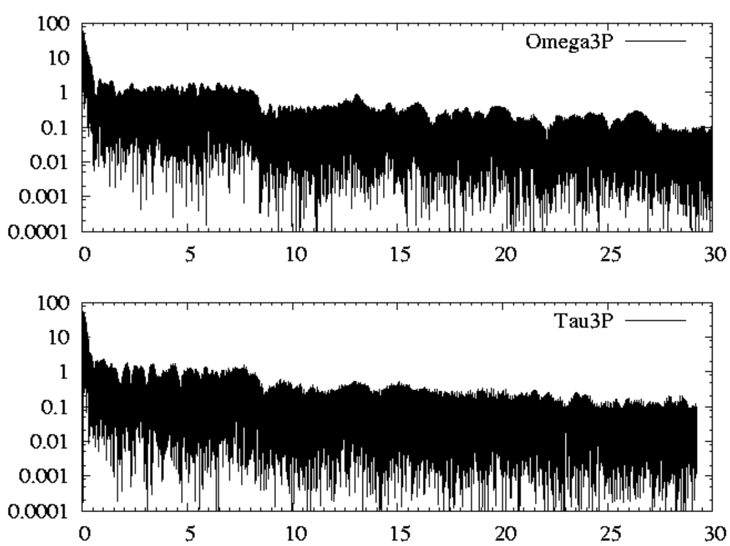


Fig. 5: (Top) Wakefields in H60VG4 from ***Omega3P*** frequency-domain calculation, and (bottom) wakefields in same structure from ***Tau3P*** time-domain simulation.

The Omega3P analysis of the H60VG4 was made possible by treating the coupling to external waveguides as a linear eigenproblem with complex coefficients by terminating the waveguides in matched loads. Work has started on formulating the problem as a quadratic eigenproblem by modeling the waveguides with outgoing waves only and solving the eigensystem by the second order Arnoldi (SOAR) method. Or alternatively, it can be formulated as a nonlinear eigenproblem when can be solved by self-consistent iterations. These methods, under implementation in parallel, will be compared on speed and accuracy on a standard cavity with coupling to an external waveguide through an iris.

Absorber Design for the PEP-II IR

With the complex solver in ***Omega3P***, analysis of the absorber design for damping trapped modes near the crotch region of the PEP-II IR has been carried out. Fig. 6 (left) depicts the ***Omega3P*** model showing the embedded absorber in the crotch regions. It can be seen in Fig. 6 (right) that for this particular absorber design, the reduction in the wall loss for a majority of the modes is about two orders of magnitude. The simulation allows for an optimal design to be reached through an iterative procedure.

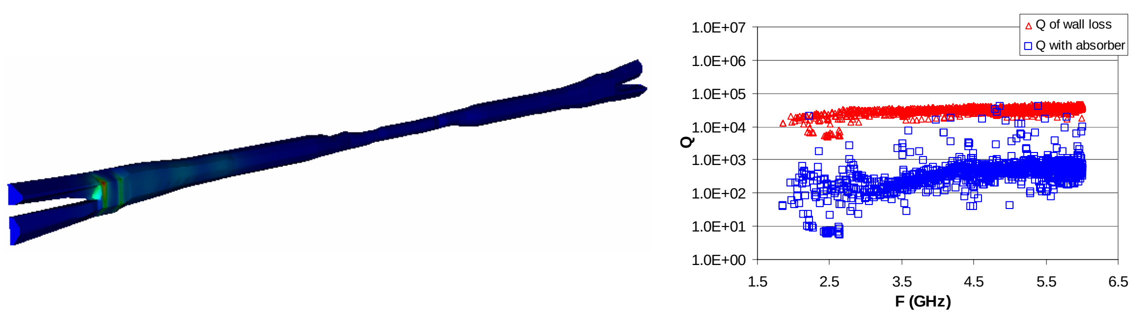


Fig. 6: (Left) ***Omega3P*** model of the PEP-II IR showing absorbers at the crotch regions, (right) Wall loss Q of trapped modes before embedding absorbers (in red) and after (in blue).

Dark Current Simulation for the 30-cell Structure

Using the parallel particle tracking code ***Track3P*** with field input from ***Tau3P,*** the dark current in the X-Band constant impedance 30-cell structure has been simulated for RF pulses with risetimes of 10, 15 ad 20 nanoseconds at a field gradient of 85 MV/m. Fig. 7 shows the pulse propagation in the structure from ***Tau3P*** and the pulse shapes at the three risetimes monitored at the disk of a cell near the output end. The field enhancement at the pulse front is due to dispersive effects which are stronger for shorter risetimes. The ***Tau3P*** field outputs were used in the ***Track3P*** simulations in which both primary and secondary emissions were included and a beta of 40 was assumed for field emission.

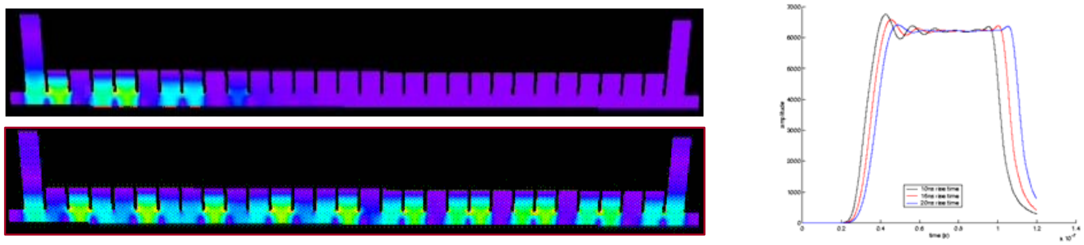


Fig. 7: (Left) Snapshots of pulse propagation using ***Tau3P*** in 30-cell constant impedance structure, and (right) field enhancement due to 10 ns (black), 15 ns (red), and 20 ns (blue) pulse risetime monitored at the disk of a cell near the output end.

A typical dark current distribution at the flat top of a pulse is captured in Fig. 8 with primary particles denoted in red and secondaries in green. The dark current pulse was monitored downstream and the results for the three different risetimes of the drive pulse are plotted in Fig. 9. The dark current pulse showed resemblance to the corresponding field pulse shapes monitored at the cell disk shown in Fig. 7, indicating that field enhancements due to dispersive effects play an important role in dark current generation. The dark current pulses were also compared with measured data from actual high power tests (Fig. 9) and good agreement was found. This is the first-ever dark current simulation of an actual RF pulse in a realistic structure with a complete emission model included.

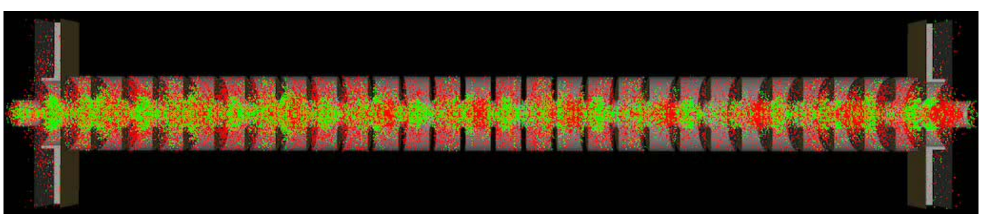


Fig. 8: (Left) Snapshots of pulse propagation using ***Tau3P*** in 30-cell constant impedance structure, and (right) field enhancement due to 10 ns (black), 15 ns (red), and 20 ns (blue) pulse risetime monitored at the disk of a cell near the output end. Drive pulse travels from left to right.

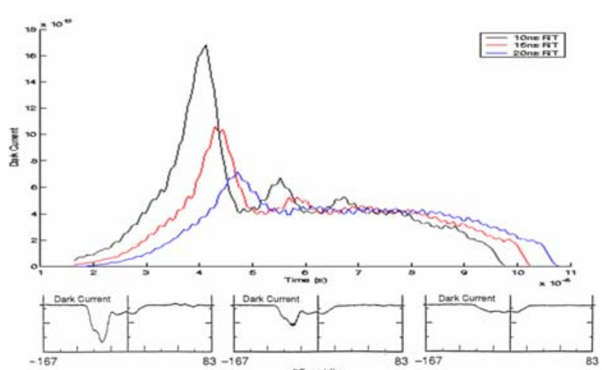
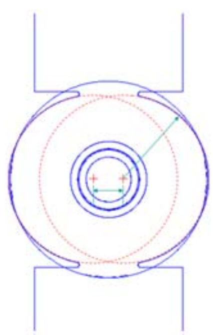


Fig. 9: (Top) Downstream dark current pulses from ***Track3P*** in the 30-cell structure for drive pulses of three different risetimes (black is 10 ns, red is 15 ns, and blue is 20 ns). (Bottom) Downstream dark current pulses from experiment for same three drive pulses in order from left to right, 10 ns, 15 ns and 20 ns, showing good agreement with simulation.

Coupler Designs for the LCLS Injector

ACD has collaborated with the LCLS on optimizing the coupler design for the S-band structure and the 1.6 cell RF gun cavity. In both cases, the goal was to minimize higher order fields and to reduce RF heating. Fig. 10 shows the geometry of the optimized design. The new features included dual feeds to remove dipole fields, racetrack cavity shape to minimize quadruple fields, and rounding of the coupling iris to lower pulsed heating. Fig. 10 also shows the improvement over the single feed design for the quadrupole component in the S-band coupler. The CUBIT mesh model for the 1.6 cell RF gun cavity is depicted in Fig. 11 with the insert showing the wall loss in the coupling iris after rounding. The decrease in temperature rise as a function of the rounding radius is plotted in Fig. 11 (right top) where the reduction in the quadruple field component is also shown (right bottom). These calculations were done with ***Omega3P*** and ***S3P***, a parallel scattering matrix solver. To be able to compute the quadruple fields accurately, 4th order finite element basis functions have to be used in the models. The development of higher order basis (up to 6th) was part of the SciDAC effort in solver improvements. Fields from ***Omega3P*** are being used by LCLS (C. Limborg) in PARMELA emittance calculations.



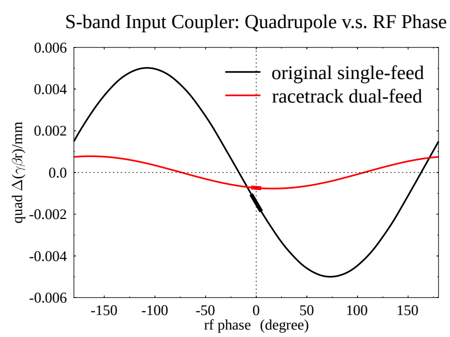


Fig. 10: (Left) Optimized LCLS coupler design with dual feeds, racetrack cavity shape, and rounded coupling iris; (right) Comparison of quadruple field component between optimized and original design.

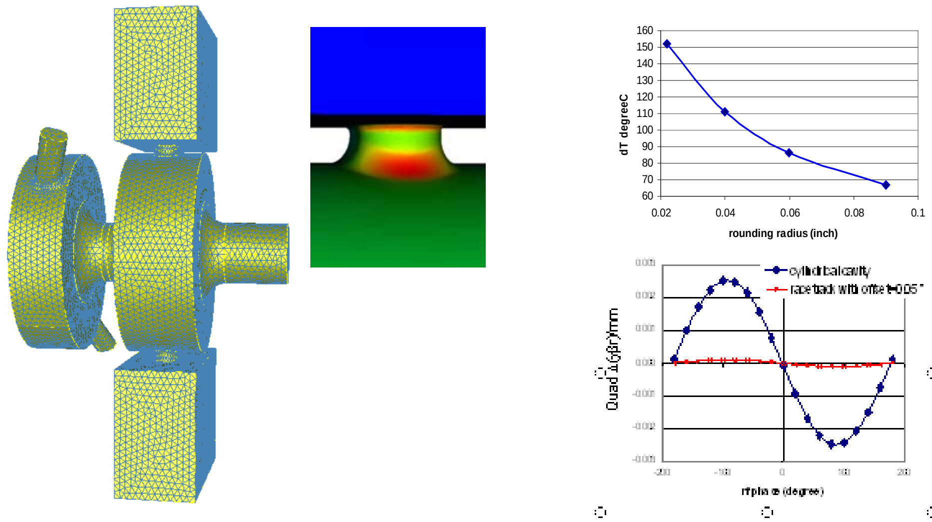


Fig. 11: (Left) CUBIT mesh model of the optimized LCLS RF gun cavity with insert showing the wall loss in the rounded coupling iris; (right top) temperature decrease versus rounding radius; (right bottom) comparison of quadruple component between optimized and original design.

Adaptive Mesh Refinement for the RIA RFQ

Under SciDAC, SLAC and RPI are collaborating on developing a parallel adaptive mesh refinement (AMR) capability in ***Omega3P/S3P*** to improve the accuracy and convergence of frequency and wall loss calculations for cavities of complex shapes. Accurate wall loss determination becomes difficult when the wall currents are localized in a very narrow region of the cavity. The increased wall loss reduces the cavity's quality factor and can lead to surface heating at high power so therefore accurate prediction is needed.

An adaptive mesh control loop based on error estimation has been implemented to provide increasingly refined meshes until a converged result is obtained. The refinement procedure has been applied to the RFQ structure for the RIA project (see Fig. 12). Compared to measurement, results from standard codes on the frequency and Q are off by 1.5% and 30% respectively. With AMR and use of 3rd order elements, ***Omega3P*** results are accurate to 0.1% in frequency and 16% in Q (see Fig. 13) which are significant improvements. At present, tuners have been designed to cover a 1% frequency deviation for lack of better prediction so an improvement by a factor of 10 would significantly reduce the number of tuners and their range, thus leading to lower cost and easier operation. In addition, more accurate wall loss prediction would greatly help in addressing thermal management issues. RIA has many RFQs in its low frequency linacs so this new capability will have a big impact on their design and prototyping.

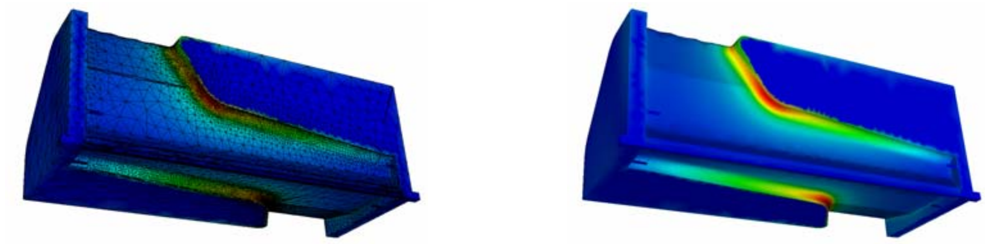


Fig. 12: (Left) Adaptively refined mesh of the RIA RFQ structure; (right) wall loss distribution on the structure from ***Omega3P***.

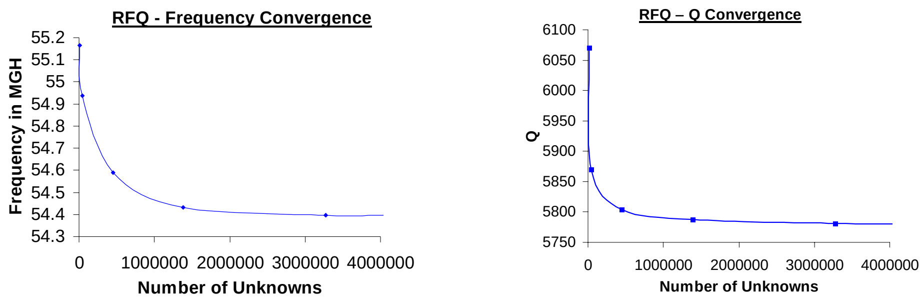


Fig. 13: (Left) Frequency convergence of the RIA RFQ structure from ***Omega3P*** using adaptive mesh refinement; (right) Q convergence in same structure.

Mode Analysis of the PSI Ring Cyclotron

Parallel codes such as ***Omega3P*** has generated new interests in mode analysis of an entire ring cyclotron. Such a task was not previously possible because existing software cannot handle the large problem size. Finding the HOM modes that exist in the machine is useful for better understanding of their effects on the beam dynamics. PSI and SLAC have collaborated on modeling the PSI ring cyclotron with **Omega3P** and determining the HOM effects through an eigenmode analysis. This work constitutes an important part of L. Stingelin's PhD research for ETH/PSI. He had spent three summers at ACD and will graduate in December 2004.

The computations were performed on the 32 CPU IBM/SP4 cluster at PSI using a model with 1.2M elements that corresponds to 6.9M DOFs. It requires 120 GB of memory and 45 minutes to calculate 20 tightly clustered modes using the ESIL solver in ***Omega3P***. A total of 280 modes with frequency close to the beam harmonic have been computed. They can be classified into three types. Forty four of them are cavity modes with low frequency and high gap voltage. There are eighteen vacuum chamber modes having medium frequency and low gap voltage. The rest of the modes are hybrid modes that occupy both the cavity and the vacuum chamber, and these have high frequency and low gap voltage. In Fig 14, sample field pattern of the three mode types in an entire ring cyclotron are shown for the first time. The simulation has been possible only with the advent of parallel computing and use of unstructured grids.

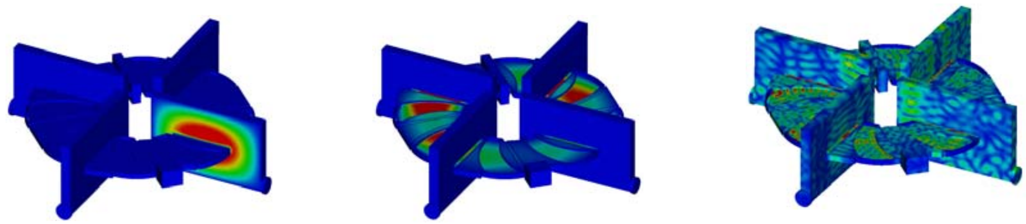


Fig. 14: Eigenmodes in the PSI Ring Cyclotron from ***Omega3P***: cavity mode (left), vacuum chamber mode (middle), and hybrid mode (right).

Parallel Beam Simulations for the PEP-II, Tevatron and LCLS

<u>*Strong-Strong beam-beam*</u> *(With Y. Cai, ARDA)*

A highly parallel strong-strong beam-beam code has been developed to be used for the optimization of current lepton storage ring colliders (PEP-II) and the design of future machines or upgrades. It has been validated through benchmarks on a set of highly demanding parameter sets (Super-KEK B). Due to its superior scalability as compared to similar codes, a complete self-consistent simulation of machines such as the LHC or the Tevatron at collision and in the strong-strong regime is now within reach.

<u>*Weak-strong beam-beam*</u> *(With T. Sen, FNAL)*

Extensive parameter studies of the Tevatron at injection have been performed to obtain the lifetime predictions for different helix openings, chromaticities, emittances, and beam charges. Different bunch train population schemes have also been tested. The results have helped design choices for Tevatron operation. As an example, Fig. 15 shows the result of an aperture/chromaticity scan, displaying an improvement in lifetime below 4 units of chromaticity, which agrees well with observation.

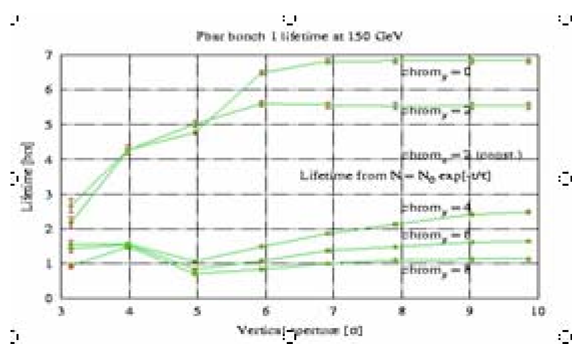


Fig. 15: Lifetime of Tevatron at injection for different apertures and chromaticities.

<u>*Coherent Synchrotron Radiation*</u> *(With P. Emma, ARDA)*

Fully self-consistent, three-dimensional simulations for the Bunch Compression Section of the LCLS facility have been performed to study the impact on beam quality and Free Electron Laser operation of different compression schemes. The results show that the facility can be operated with parameters sets well beyond the original design values; in particular, much shorter bunch length can be chosen while still improving FEL performance. Fig. 16 show the resulting FEL figures of merit for longitudinal slices along the final bunch for different bunch lengths. This is a valuable result for the subsequent operation of the FEL, as it relaxes the beam quality requirements on the electron gun.

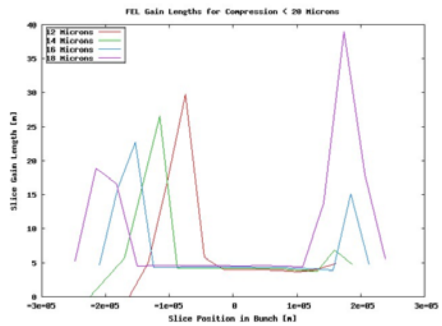
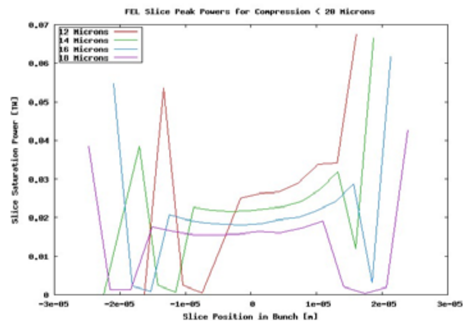



Fig. 16: (Left) Slice gain length (in m) versus position in bunch 9 (in m) in the LCLS; (right) slice saturation power (in TW) versus position in bunch (in m).

8. FY04 High Polarization Electron Source Development by Ed Garwin, Bob Kirby and Takashi Maruyama

The Physical Electronics Group (PEL) contributes to SLAC's accomplishments in a number of areas, by using vacuum and materials expertise to support the development of novel electron sources, detectors and accelerating structures. These areas include high polarization-high current electron sources and surface-analytical research on high electric field structures for advanced accelerator (NLC/ILC) development.

PEL engages in a continuing research program with Experimental Group A, ARDA's Sources and Polarization Group and the University of Wisconsin on the development of **high-polarization high-current semiconductor electron sources**, originally for E-122, then for the SLC and currently for the NLC and End Station A experiments. Polarizations as high as 78% were produced for the Stanford Linear Collider (SLC) from photocathodes based on a thin GaAs epilayer grown on GaAsP. However, after 10 years of experience with many cathode samples at several laboratories, the maximum polarization using the GaAs/GaAsP single strained-layer design cathode remains limited to 80%, while the quantum efficiency (QE) for a 100-nm epilayer is only 0.3% or less. Two known factors limit the polarization of these cathodes: 1) a limited band splitting; and 2) a relaxation of the strain in the surface epilayer. Strained superlattice structures, consisting of very thin quantum well layers alternating with lattice-mismatched barrier layers are excellent candidates for achieving higher polarization because they address these two issues. Due to the difference in the effective mass of the heavy- and light-holes, a superlattice exhibits a natural splitting of the valence band, which adds to the strain-induced splitting. In addition, each of the superlattice layers is thinner than the critical thickness for strain relaxation. Supported by a DOE SBIR Phase II program, strained-superlattice photocathodes based on GaAs and GaAsP have been investigated in collaboration with SVT Associates, who grow such wafers using molecular-beam-epitaxy

(MBE). The principal structural parameters (well and barrier thickness, phosphorus fraction, and the number of superlattice periods) are systematically varied to define the optimum structural details. As large as a 90 meV heavy-hole/light-hole energy splitting is achieved, and the heavy- and light-hole excitations are clearly observed in the QE spectra for the first time. Spin polarization as high as 86% is reproducibly observed with the QE exceeding 1%. The charge capability is measured at the SLAC Gun Test Laboratory. The charge output does not show any surface charge limit behavior, producing a maximum charge of 2.5×10^{12} e^- in 75 ns. The charge output corresponds to more than six times the proposed NLC train charge. The End Station A experiment, E158, required a beam intensity of 8×10^{11} e^- in a 370 ns pulse. A newly developed photocathode was installed in the SLAC polarized electron injector, and ran successfully for E158 Run III. The beam polarization measured by the Moller polarimeter in End Station A was 90%.

To overcome the **surface charge limit effect**, recent photocathodes use the high-gradient-doping technique consisting of a thin (10 nm), very-highly-doped (5×10^{19} cm^{-3}) surface layer with a lower density doping (5×10^{17} cm^{-3}) in the remaining active layer. However, to achieve high quantum efficiencies, a negative-electron-affinity surface is required, which in turn must be prepared on an atomically clean surface. The conventional way to achieve a surface free of all surface oxides and carbon-related contaminants is to heat the crystal to 600° C for about 1 hour. After only one hour at this temperature, diffusion of the dopant in the thin, highly-doped layer results in the re-appearance of the surface charge limit effect. Therefore, high temperature heat cleaning should be avoided. Atomic hydrogen cleaning is a well know technique for removing oxides and carbon-related contaminants at relatively low temperature. An atomic hydrogen cleaning system has been built in the SLAC Cathode Test Lab. Atomic hydrogen is produced by dissociating molecular hydrogen in a 2.5 cm diameter Pyrex glassware surrounded by a helical rf resonator. High quantum efficiency GaAs photocathodes can be prepared at the lower heat-cleaning temperature of 450°C.

Particles and inclusions on accelerator rf components can lead to irreversible **breakdown damage in high surface electric fields**. PEL electron microscopy analysis of particles and grain boundaries on copper have demonstrated an association of the latter with electric breakdowns, showing that vacuum heat cleaning is useful in reducing the number of such events. PEL's FY2004 investigations focussed on two tracks: 1) Autopsy and electron microscopical (SEM) examination of four NLCTA-tested prototype full accelerating structures, 2) measurement of contamination levels and particle-loads on small pieces of structure material (coupons) that have accompanied the manufacture of real structures. A collaboration on structure witness coupons included KEK (diamond-machining of copper coupons) and Cornell University (DC high voltage-generated breakdowns) and showed that breakdowns can occur on surfaces that are free of particles or contamination, at electric field levels achieved in the NLCTA. SEM examination of four RF-tested NLCTA structures showed that near clean-room technique in fabricating structures is essential to reducing gross particle loads that can lead to breakdowns. Further, careful attention must be paid to the structure vacuum bake environment in order to prevent adding non-native contamination (for example, the evaporation of excess sulfur from S/S vacuum components) to the last steps of structure preparation. The autopsies, however, also showed that most RF breakdowns have no visible particle residue or defect in the resulting craters and that most particles do not, in fact, break down. Therefore, most breakdown events must have some not yet-identified cause (presumably sub-surface) for the onset of field emission. Studies of correlation between mass movement inside a grain, hardness of grains with breakdown position, and **(E,H)** field are ongoing.

Electron cloud (EC) disruption of positively-charged beams is a significant problem in high-current positron and proton rings, and is expected to be a problem in the LHC main ring and NLC/ILC damping rings. Secondary electron yield coefficient measurements by PEL provide experimental data for computer simulations (at LBL and CERN) of the EC effect. PEL has extended this yield data to lower incident electron beam energies where the LHC's beam chamber section cryogenic budget may be endangered by a rise in total yield due to elastic backscatter of incoming low energy electrons below 50 eV incident energy. PEL's XPS spectrometer was modified for yield measurements in FY03 at this new lower energy and data collection began on yield-suppressing titanium nitride (TiN) and non-evaporable getter (NEG) coatings for the NLC damping ring, and for clad-copper LHC chamber materials. Yields were measured from as-deposited and electron-bombarded ("conditioned") TiN and NEG-coated flat substrates and from TiN coatings on grooved surfaces of Al. Both grooving and TiN have a yield-lowering effect, which is cumulative. Measurement of re-contamination of clean activated-NEG by residual gases (to simulate long-term evolution of the yield) was found to have a different effect on the yield and surface chemistry than does idealized deliberate dosing with individual contaminating gases.

9. FY04 Progress in Fractional Charge and Massive Particle Research by Martin Perl

A highly automated Millikan oil drop apparatus, with extensive feedback and self regulating controls, has been used throughout much of FY2004 to search for fractional charge elementary particles in meteoritic material suspended in a special mineral oil. The apparatus was developed and first tested in FR2003. This search will conclude in FY2005. When concluded, this will provide a very substantial search for fractional charge particles in meteoritic material and the most extensive search ever carried out in mineral oil.

The reason for searching for fractional charge elementary particles in meteoritic material is that this material that comes from asteroids formed about 5 billion years ago is one of the least processed material in the solar system, and is one of the best candidates for containing fractional charge particles. The experimenters believe that asteroidal material is about one million times more likely to contain fractional charge particles, if they exist, compared to terrestrial material.

Other activities in FY2004 included:

- Initial design work on increasing the throughput of fractional charge particle searches in bulk matter by using a levitometer method.
- Writing and publishing a definitive article for the journal Metrologia on measuring the charge of small drops.
- Preparing a review of all types of searches for fractional charge particles, one of the purposes being to stimulate searches at new Colliders.
- Providing guidance and some laboratory work for workers in the biological and medical fields who want to use oil drop methods in research or manufacturing.
- Obtained a US patent assigned to Stanford University on a document security method using microdrops. This is US 6,786,954

10.FY04 Progress in Test Beam Program

For the SLAC Test Beam Program, FY04 represented a very unusual year; for the first time in SLAC's history no dedicated beam time was scheduled for test beams. Enterprising experimenter's were, however, able to accomplish many tests parasitic to SPPS, E-164X and E-165, which ran in FFTB. Test experiments T-467, T-468, T-470, T-471, T-472 and T-473 were all conducted in this manner in FFTB. In the meantime, a queue of requests has developed for tests to be conducted as soon as beam time can be scheduled. Two such experiments, T-469 (ESA) and T-477 (FFTB) have been approved and prepared and are yet waiting for such time. Other experiments in the queue are still undergoing both budget and beam time considerations before final approval. These tests include T-474, T-475 and T-476 all of which are ILC related tests and when approved would be conducted in ESA.

At present, the FFTB continues to be heavily scheduled for SPPS and E-166 experiments. It should be noted, however, that the SPPS experimenters have demonstrated a willingness to share the area and/or beam time with serious tests during periods that they are not using the beamline. Unfortunately, simultaneous beams in FFTB and ESA are precluded, thus even the approved ESA tests must wait for such shared beam time.

It should be noted that in the last five years, SLAC has run approximately 35 successful tests in support of both HEP detector and accelerator technology. The fact that the two major areas normally used for tests, FFTB and ESA, have not been as readily available resulted in a diminishing number of test beam requests. With SLAC's support for ILC it is expected that demand for tests will resume and that SLAC will be able to continue its effort to provide support for this research.

In January, 2004, the **American Linear Collider Physics Group** held a 4 day workshop, **ALCPG04,** at SLAC on the physics, detectors, and accelerator research related to the International Linear Collider. Among the working groups was a well attended group dedicated to understanding the types of facilities that would be needed and those that were available, at all laboratories, necessary to test the various prototype detectors proposed for the Linear Collider. These participants were given a tour of SLAC's test beam facilities and the various beam capabilities were described. The participants were encouraged by the SLAC staff to consider taking advantage of the SLAC facilities.

T-467 Measurement of FFTB Backgrounds for E-166, R. Pitthan, J. Sheppard; FFTB.

This test ran parasitically to SPPS, E-164 and E-165, taking background data for over one year in preparation for E166, an experiment that is particularly sensitive to backgrounds in the region of the FFTB dump.
The test allowed the measurement of the response to background radiation of the various E-166 detectors and the development of the Data Acquisition System (DAQ).

Generally, the beam conditions for these experiments are not those needed for the experiment E-166 due to the different beam intensities and larger momentum spread of the short pulse length beam, still, in spite of this higher background rate, the experimenters were able to make useful progress toward selection of detectors and the development of the Labview based data acquisition system. The detectors that were tested were 3 CsI detectors, two with PM tubes and one with photodiodes, a pair of Aerogel Cherenkov flux counters and a Silicon Tungsten calorimeter. These tests have allowed the selection of the detector configurations for the E-166 positron and gamma flux measuring calorimeters.

In summary, the T-467 test has facilitated the detector selection and DAQ development, greatly advancing the preparations for the E166 run now under way.

T-468 Diamond Detector Response, B. Petersen, S. Mao; ESA**.**

Next summer, it is planned to supplant the pin diodes, used to measure the radiation dose at the BaBar Silicon Vertex Detector, with diamond detectors. This test was designed to compare the response of the diamond sensors with the currently used silicon pin-diodes. In addition Radiation Physics semiconductor dosimeters will be included for their evaluation with dose. The conclusion found for this test was that the diamond detectors were entirely suitable for this application. They will supplant but not replace the silicon detectors (allowing calibration of old and new data) if an opportunity arises. (see T-473)

T-469 DIRC R&D Program, D. W. G. S. Leith, J. Va'Vra; ESA.

The purpose of this test is research in ring imaging technology for utilization in future detectors such as the Super B-Factory detector. The DIRC (Detector of Internally Reflected Cherenkov radiation) detector is an important part of the BaBar experiment providing hadronic particle identification. During studies for a possible Super-B-Factory detector it was observed that at luminosities much higher than those achievable by PEP and BaBar, the amount of background in the DIRC would severely deteriorate its particle identification performance. To avoid this loss of signal, the background needs to be reduced and the separation of background from signal needs to be improved. A solution to this problem was approached by studying modifications to the detection region: the stand-off box and photodetectors.

A prototype for an improved DIRC has been designed and constructed (see Fig. 1) which reduces the size of the stand-off box and thus will suppress the dominant source of background dramatically. Also used are photodetectors with significantly better timing resolution allowing much tighter selection cuts for Cherenkov photons. Improving the timing resolution from 1700ps for the current DIRC detector to about 50-100ps for the current prototype will also make it possible to determine the wavelength of the photons and correct for the effect of chromatic dispersion in the fused silica radiator material improving the overall performance of the device.

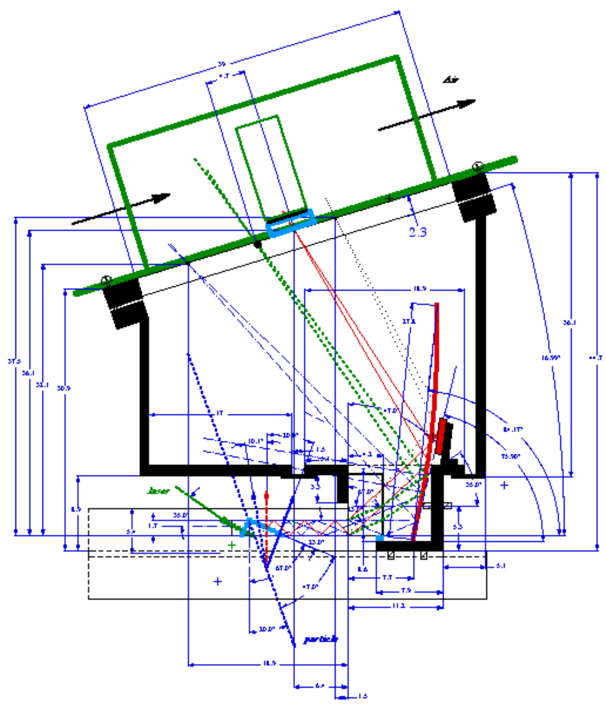


Fig. 1 T-469, Improved DIRC Stand-off Box design

The experiment will utilize a precisely manufactured quartz bar identical to those used in the present BaBar DIRC, which measures 2 x 4 x 400 cm^3. The response of the detector to hadrons transversing the bar at various longitudinal positions (~2-3 cm pathlength) and at various angles will be measured. A large controlled support structure for stable positioning of the quartz rod with respect to the beam is being fabricated. This experiment will utilize the hadron beam developed for the ESA experiment T-436 which tested the response to hadrons of the Gamma Ray Large Area Space Telescope (GLAST) prototype, in FY00.

As a preparation for the beam test, several hardware components have been developed (amplifiers, constant-fraction-discriminator, time-to-amplitude converter, analog-to-digital converter) and installed in End Station A (see Fig. 2). In addition, a data-acquisition system and several data analysis tools have been implemented.

Fig. 2 T-469 DIRC Test Assembly

The upcoming beam tests, will establish the validity of the design and measure the particle identification capabilities.

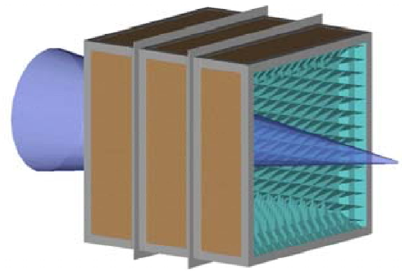
T-469 is prepared for beam. It is expected that beam time will be scheduled in November December 2004 with more time available in February 2005.

T-470 DASH: Diamond Detectors for FLASH, S. Schnetzer, Rutgers U.; FFTB**.**

Test the feasibility of using diamond detectors for measuring shower profiles in the thick target run of the FLASH experiment. The goal is to measure the current produced in the diamond in response to high density particle fluxes of 10^7 to 10^8 per mm^2. Data were taken with a set of 0.8 cm square diamonds mounted side by side, a few cm apart, on an arm that was remotely movable in X- Y- and Z- axes. Dedicated beam tests were carried out during the June and July runs of E-165, each test lasting one to two days. The transverse profile of the 28.5 GeV electromagnetic shower was measured at 2 radiation length steps between 0 and 14 R.L. The results have been compared with GEANT simulations, and evidence was found for a sensitivity loss for the diamond in the most intense center part of shower. This effect is still under study, and may be the first evidence for charge saturation in the diamond, one of the main investigative goals of the experiment. Continuing work involves a pulse-by-pulse comparison with the toroid readout, rather than using run averages, understanding how to compensate for a few millimeter vertical wandering of the beam, and a more detailed GEANT simulation. Valuable experience was gained in handling signals so close to the diamond saturation level using very intense pulses.

T-471 Incoherent Radio Emission from Showers, P. Gorham, U. Hawaii.; FFTB**.**

The purpose of this test is to investigate the radio emission from EM showers, outside the Cherenkov cone, as emitted by thermalizing electrons. The test was carried out during the period of July 21-28 2004. The apparatus was a sheet-copper box, approx. 1.2 meters cube, mounted in the shower "wake" downstream of E-165. The box was designed to be removed from the beam, for PPS reasons, when intensity exceeded $5x10^8$ electrons per pulse.



The test box, a Faraday cage, was lined with RF absorbing material and gave 50-60 dB RFI rejection. There was a set of internal antennae which were coupled, through amplifiers where needed, to oscilloscopes in building 407D. Data were recorded for each set of shower conditions used by E-165, and the oscilloscope traces were transferred to a computer for waveform analysis. In this way a large data set was compiled.

By absorbing the coherent (Cherenkov) RF, and detecting the radio signals at 90-degrees and at the three polarization axes, the incoherent radio Bremsstrahlung signals from the shower were sought. These should be a measure of the shower's intensity. Relatively strong signals were detected and are under analysis. However, there was evidence of phase-coherent background radio signals leaking in. The effort of tracing and separating the components is still in progress. When these are under understood and a subsequent equipment modification has been implemented, a further beam test will be requested.

T-472 Neutron Energy Spectra Measurements, H. H. Vincke; FFTB**.**

A test to measure the neutron energy spectrum near the FFTB during a low power run of E-165 in June and July 2004 (1E7 electrons per pulse, 10Hz). In the past, at SLAC, neutron measurements have been performed outside thick concrete (few meters) shielding but no data are available for “thin” concrete shielding (one meter) walls. For "thick" shielding configurations, mostly high energy neutrons, generated by a high energy photon fluctuating into a hadronic state and interacting quasi-hadronically, reach the detector. With “thin” shielding, a neutron produced in quasi deuteron absorption of a photon followed by an intranuclear cascade and a de-excitation of the target nucleus as well as giant resonance neutrons can contribute to the neutron fluence outside the shielding.

A NE213 liquid scintillator was placed outside of the FFTB. The electronic rack and the DAQ system were placed inside B407. The detector signal was read out to the E-165

DAQ system. Thus, beam charge, target configuration etc. were known during later analysis. The neutron pulse height was measured using two gates with relative delay so that a pulse shape analysis could be used to separate neutron signal from other backgrounds. Analysis: The experiment is simulated with the Monte Carlo transport code FLUKA, post processing of the data, and comparison with the simulation is in progress. This experiment was conducted completely parasitically to E-165.

T-473 Diamond Detector Response, B. Petersen; FFTB**.**

This is a follow up experiment (see T-468) for the planned supplanting, with diamond detectors, of the silicon pin diodes used to measure the radiation dose at the BaBar Silicon Vertex Detector. This is a test of the radiation hardness of the diamond sensor package. Exposure was obtained during experiment E-164x and in four days received in excess of 10 Mrad of dose. A silicon pin-diode survived just fine, however the diamond sensor package made out "G10" (glass-fiber and resin mix) became discoloured and the conducting glue inside failed. It has been concluded that a "G10" package is insufficient and that a ceramic package is needed. Preparation of such a package for further testing is underway.

T-474 ILC - BPM -based Energy Spectrometer, M. Hildreth, U. Notre Dame; ESA**.**

At the Linear Collider, beam energy measurements with an accuracy of 100-200 parts per million will be needed for the determination of particle masses. For such use, we wish to demonstrate the mechanical and electrical stability of a prototype BPM-based Energy Spectrometer. The initial configuration will include 4 BPMs and 1 WireArray on a single girder. Installing these devices in ESA will allow us to determine parameters beyond the single-device resolution such as susceptibility to backgrounds, beam tails, beam tilt and other environmental effects not accessible or reproducible at other facilities. The overall goal for system stability in the face of these adverse effects is ~50 nm over approximately a one hour time scale, a level of electronic and mechanical stability consistent with the expected requirement of 100 nm position stability for an actual energy measurement. We envision this as the first in a series of tests culminating in a prototype spectrometer insertion for a LC.

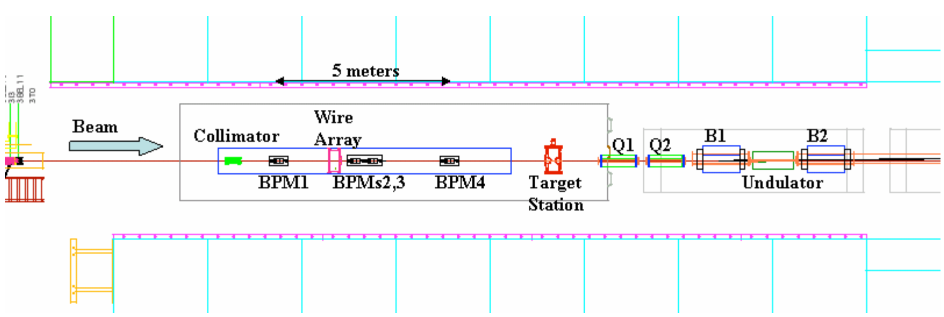


Figure 2. Proposed BPM girder and spectrometer in ESA for T474 & T475

<u>Beam Requirements:</u> Momentum: 25 GeV; Particles: 10^{10} single bunch; (1-5)x10^{11} in 60-300ns train; Rep. Rate: 10 Hz; $\Delta p/p$: <1%

The T-474 request is awaiting budgetary and scheduling decisions.

T-475 Position-sensitive SR Monitor using Quartz Fibers, E. Torrence U. Oregon; ESA**.**

A Linear Collider spectrometer based on the Wire Imaging Synchrotron Radiation Detector (WISRD) design must be able to make precise measurements of the centroid and shape of the SR stripe used to image the primary electron beam. In the WISRD, this SR detector was composed of an array of 75 µm wires spaced on a 100 micron pitch. An alternative detector technology, which may be feasible would use Cherenkov light produced by secondary electrons traversing 100 µm Quartz fibers. This technology has several potential advantages over the wire array, including lower cross-talk, better background rejection due to higher Cherenkov threshold, and simplified high-speed readout made possible by multi-anode PMTs.

The purpose of this beam test is to validate the Monte Carlo simulation of the Cherenkov light production and detection efficiency expected in the quartz fibers, while also directly comparing the signal-to-noise ratio seen in the quartz fibers with that observed in a traditional wire array detector.

The T-475 request is awaiting budgetary and scheduling decisions.

T-476 3D and Thin Planar Silicon for Beam Profile and Luminosity Monitors,
C. Kenney, Molecular Biology Consortium; ESA.

Achieving the desired luminosity at the Linear Collider will be critically dependent on the beam shape and dimensions. Providing real-time feedback will be necessary to optimize the machine parameters. It has been proposed to measure the beam profile using the distribution of background e^+e^- pairs. One possible detector scheme involves using 3D silicon sensors for their speed and radiation hardness. These last attributes would also be useful for a detector able to provide a continuous, direct measurement of the luminosity, ideally on a pulse-by-pulse basis. This detector would be a calorimeter and hence would see a large signal and would not need to resolve individual minimum-ionizing tracks. Either 3D silicon sensors or thin planar sensors should be suitable for this application. The main goal of this test would be to demonstrate fast signal charge collection time of several nanoseconds in a silicon sensor under background conditions having a flux near 10^3 e^-/ cm^2-pulse similar to those expected for a beam profile monitor or luminosity monitor at the Linear Collider. We plan to make measurements using both 3D sensors and thin, planar silicon sensors.

The T-476 request is awaiting budgetary and scheduling decisions.

T-477 Tests of a Tungsten Powder Calorimeter, O. Tsai; FFTB**.**

This is a follow up of test T-466, having the purpose like that of the earlier run, to study the performance of a small prototype electromagnetic calorimeter, which is used to measure electron energy. The UCLA IEP group built this prototype using a new technique that utilized tungsten powder and imbedded scintillating fibers. The main objectives for this R&D were to develop methods which would lead to a very compact calorimeter with good energy resolution, high granularity, good hermeticity, the ability to work in magnetic fields, possessing fast response and affordability.

The result of the first test showed a large variation of response depending upon the position of the beam. Thus it was realized that a better technique to combine fibers with powder needed to be developed. At the same time, the test showed the light yield from the towers to around 400 photoelectrons per GeV, which is approximately 70% that expected.

The group has now completed an improved instrument and are approved and prepared to return for a second test. It is expected that scheduled beam time will become available in February 2005.

11. FY04 PROGRESS FOR THE EXO DOUBLE-BETA-DECAY R&D PROGRAM by Peter Rowson

SLAC groups SLD (M. Breidenbach, C. Hall, A. Odian, P.C. Rowson and K. Wamba) and A (C. Prescott) have been collaborating with the Stanford Physics Department group of G. Gratta, and with others, in an R&D program to test the feasibility of a novel large-scale double-beta-decay experiment. This experiment, known as EXO (for Enriched Xenon Observatory) proposes to use a large quantity (>1 ton) of Xenon enriched in the Xe^{136} isotope as both a decay and detection medium. The double beta decay process,

$$Xe^{136} \rightarrow Ba^{136++} + e^- + e^- \ (+2\nu)$$

can proceed in the two neutrino($2\nu\beta\beta$) mode expected from the Standard Model (and which has already been observed in several nuclei other than Xe^{136}), or possibly in the neutrinoless ($0\nu\beta\beta$) mode. The $0\nu\beta\beta$ process is expected to occur only if neutrinos are Majorana particles, and at a rate proportional to the square of an "effective" neutrino mass, and hence its observation would serve a mass measurement and as the first demonstration that Majorana neutrinos occur in nature. Xenon's excellent calorimetric properties (necessary to distinguish the broad beta spectrum of the electron energy sum in the $2\nu\beta\beta$ process from the line spectrum in the two-body $0\nu\beta\beta$ decay), readily achievable high purity, and lack of worrisome radioactive isotopes make this element an attractive candidate for a low background experiment. In addition, we propose to operate the rare decay search in a coincidence mode, by identifying the Barium daughter nucleus of double beta decay on an event-by-event basis. Barium identification is accomplished by a laser florescence technique that is sensitive enough to observe a single ion and, in principle, to distinguish the various Barium isotopes.

To date, the R&D efforts at SLAC and Stanford have focused on a liquid xenon (LXe) TPC design, where the Barium identification would be accomplished by removing the ion from the LXe using a electrostatic probe, and then delivering the ion to an as-yet-unspecified laser system. The campus group has successfully constructed and operated a laser-illuminated ion trap for Barium and has observed single Barium ions. In addition, they have demonstrated state-of-the-art energy resolution in LXe (which occurs at electric fields >4 kV/cm) and have preliminary results showing resolution enhancement when the scintillation light produced in xenon, in addition to ionization, is collected.

The logistical problems connected with the procurement of a large amount (~10 tons) of isotopically enriched Xe^{136} are being dealt with under the Nuclear-Non-Proliferation programs of DOE. To date, we have obtained 200 kg of xenon isotopically enriched to 80% in Xe^{136}. The site for such an experiment must be deep underground to minimize cosmic ray backgrounds

A prototype that does *not* employ Barium identification is presently being designed and built. It is our intention to construct a 200 kg prototype for use in the DOE operated underground facility WIPP (Waste Isolation Pilot Plant) in Carlsbad NM. This prototype would collect useful data for TPC performance, would definitively observe $2\nu\beta\beta$ in Xe^{136} for the first time, and would accumulate the large number of $2\nu\beta\beta$ decays needed to characterize this important background. . In addition, a design goal is that the prototype has sufficient sensitivity to test with one or two years of data the recent and very controversial claims from the Moscow-Heidelberg Ge^{76} experiment that they have observed $0\nu\beta\beta$ events.

SLAC Activities

At SLAC, we have constructed a xenon purification system that is operated at ultra-high vacuum along with a xenon purity monitor (XPM). The purifier employs a heated Zirconium metal getter to remove non-noble gas contaminants (nominally to the 0.1 ppb level), as well as distillation capability (to remove Argon). The XPM drifts electrons produced from a UV-laser-illuminated cathode in LXe across a gap and measures the transport efficiency. The XPM was upgraded this year to include a longer drift region (60 mm was increased to 109 mm) for improved sensitivity to impurities We have confirmed electron lifetimes as high as 4 ms in purified LXe in this way (more typically, results are ~1 ms), and have reproduced electron drift velocities available in the literature. In addition, we have recently replaced our cold-finger/liquid-nitrogen (LN) cooling system for the XPM with a refrigerator that cools HFE-7000, a hydroflouroether, into which the XPM is submerged. The HFE may serve as both a coolant and a radiation shield for the prototype detector, and also alleviates safety concerns regarding large volumes of LN at the WIPP underground facility. The new HFE-based system is working well.

We have continued a series of experiments to test the feasibility of electrostatic ion extraction from xenon. The "probe-test cell" incorporates a movable electrostatic probe, and an instrumented (PMTs, Si barrier detectors) volume for LXe or gaseous Xe containing a pair of HV electrodes. One of the electrodes holds a weak U^{230} source which undergoes two α decays and emits Th^{228} and Ra^{222} ions into the Xe. We have seen that the probe tip, if set to negative potential, collects radioactive ions (thorium and radium α decays confirm presence of the species). The apparatus has been used to measure ion mobility in LXe, an important issue as the barium ions will be produced in an electric field. The result obtained for thorium ions (0.24 ± 0.02 cm^2/kVs) confirms the low mobility of metal ions in LXe observed by other groups. Recently, the probe was replaced with a "cryoprobe". The cryoprobe is equipped with internal plumbing that functions as a Joule-Thompson expansion cooler, using high pressure argon gas. The probe tip is thereby cooled to below the freezing point of xenon, and ions are trapped in xenon ice. By this means, we have demonstrated that captured ions may be released by thawing the xenon ice, preventing irreversible attachment to a bare metal or dielectric probe tip.

A second approach using a "hot probe" is under study. We have seen in the literature how an appropriately chosen metal surface (eg, platinum) can have a work function that favors the release of adsorbed metal atoms (eg barium) in a ionized state when heated to modest, ~500C, temperatures. An R&D program is underway to test this approach to barium ion release.

Work is underway studying light collection technologies for the prototype. As mentioned earlier, if ionization collection is supplemented by the collection of the 175 nm scintillation light produced in xenon, improvements in energy resolution are possible. The SLAC group has coauthored a paper, submitted to Phys.Rev.B, on observations of ionization and scintillation correlation effects in LXe performed by the Stanford campus group (available in the LANL E-print server at http://xxx.lanl.gov/PS_cache/hep-ex/pdf/0303/0303008.pdf).

We are measuring the performance of large area amplification photodiodes (LAAPDs) and various wavelength shifters that may be appropriate for photodetection. Monte Carlo simulation using GEANT are helping to guide this effort.

The SLAC group has, thanks to assistance from local electrical engineering manpower, designed and started production of the ~200 channels of low noise charge sensitive preamps, and associated digitization and control modules for the 200 kg prototype.

A SLAC group is leading the effort to produce a complete detector monte carlo, and in addition, event reconstruction software to be used for the prototype. A first pass version is ready now.

Work is continuing on all of these topics, but a substantial effort is now focused on development of the 200 kg prototype for installation at WIPP. The prototype detector will incorporate a ~20 cm drift region, a maximum electric field of ~3 kV/cm, and a detection plane consisting of wire grids and/or pads and LAAPDs. For this large effort, more support, both manpower and M&S, will be required.

The SLAC and Stanford groups, in cooperation with WIPP, have proceeded with a layout and design for the anticipated WIPP experimental area, including modular structures housing the apparatus, gas systems, assembly areas, and work areas (all various levels of clean rooms), as well as power and safety systems. The modular clean rooms have arrived at Stanford, and final electrical wiring is underway in the HEPL facility. Assembly of the xenon handling system has started in the SLAC CEH cleanroom left over from the SLD experiment. When completed, this UHV system will be transported down to campus and installed in one of the cleanroom modules, and installation of cryogenic systems will begin with an eye towards a full system test at Stanford in the coming year.

The design of a full scale device incorporating Barium identification will follow pending the results of our R&D and prototyping effort.

12. FY04 Progress in Theoretical Physics by Michael Peskin

Theoretical Physics

The research of the Theoretical Physics Group ranges from the development of fundamental theories such as M-theory, string theory, and higher dimensional theories at very short distances to detailed calculations and tests of theories directly relevant to high-energy physics experiments at SLAC and elsewhere. This section summarizes the current activities of the Theory Group and a few of its important achievements in FY2004.

Physics at the International Linear Collider – The Theory Group is intensively involved in all aspects of physics related to the development of the next-generation linear electron-positron collider. Much of the work involves understanding how to use the unique capabilities of the linear collider environment, such as beam polarization, highly efficient heavy-quark tagging, and the possibility of backward-scattered photon beams, to test aspects of new physics at very high energies that would otherwise be inaccessible. It includes analyses of linear collider experiments on the most familiar models of the next energy scale in physics, including studies of the measurement of the parameters of the spectrum of supersymmetric particles of possible strong interactions coupling to the Higgs sector and the top quark. It also includes exploration of a wide variety of newly-proposed models, some of which are discussed in later sections. Each phenomenon has a specific experimental realization at the linear collider, and we are making an effort to understand the systematic picture of how these effects can be found and distinguished. Complementing these theoretical studies, a general-purpose simulation program for LC events has been created that allows a theoretical calculation of any new process to be easily turned into an event generator incorporating realistic beam and polarization effects.

Over the past year, we have been studying the specific linear collider experiments that might give insight into recent discoveries in cosmology. Cosmic dark matter, in particular, is likely to be produced at the LC. In fact, LC provides an environment for the precision measurement of couplings needed to understand its cosmic relic density microscopically. Many of the techniques needed for these measurements have been developed by members of the Theory Group in our studies of LC physics. In the past year, we have been studying how well the relevant couplings can be measured with these techniques and how these measurements can impact astrophysical observations of dark matter.

Physics at Bottom Factories – The Theory Group is intensively involved in all aspects of physics related to the physics of *B* factories, and the *BABAR* experimental programs in *B* physics and two-photon collisions. On one hand, members of the group have devised new methods for measuring the parameters of CP violation in the Standard Model from analyzing detailed aspects of specific rare *B* decay modes. At the same time, models of CP violation beyond the Standard Model have been intensively studied, as well as the reactions involving 'penguin' diagrams that are expected to probe for these effects most sensitively. In the past year, we have carried out deep theoretical studies of factorization in exclusive radiative and 2-body B meson decays using the tool of soft and collinear effective field theory, clarifying the specific theoretical predictions for the rates of these phenomenologically important processes.

Development of Quantum Chromodynamics – Although there is strong evidence that Quantum Chromodynamics (QCD) is the fundamental theory of the strong interactions, there is much room for improvement in the methods by which QCD is applied to compute predictions for specific processes. Members of the Theory Group have devised improved computational methods for QCD both for high-precision studies and for the extension of QCD calculations to new regimes. These include the development of 'commensurate scale relations' which aid in removing scale and scheme ambiguities from QCD calculations, and the development of renormalization schemes that are analytic in the quark masses. These also include applications of QCD to exclusive *B* decays, charmonium production at high-energy colliders, and hadron and lepton production from nuclear targets. Projects in the current year have included studies of QCD light-cone wave functions and their application to exclusive hadron production and polarization effects in deep-inelastic scattering, and more fundamental investigations into the formalism of light-cone gauge theories. These have included studies of thermodynamics in the light-cone quantization and applications to QCD at high temperature.

Computational Perturbative Quantum Chromodynamics – The most challenging aspect of improving methods for QCD is that of devising methods for high-order Feynman diagram calculations. Members of the Theory Group have been devising methods to simplify the computation of diagrams involving essentially massless quarks and leptons participating in high-energy collisions. In terms of technical difficulties of QCD computations, the frontier now lies in the calculation of two-loop or NNLO corrections. These corrections are essential to interpret the Tevatron and the eventual

LHC data to the few-percent level. For some processes for which perturbation theory converges slowly, the NNLO corrections are even needed to understand experimental measurements to order 1. Over the past few years, members of the group have taken a leading role in the community in developing methods for the computation of QCD processes at NNLO. In the past year, members of the group have completed a fully differential NNLO computation of the Drell-Yan process in hadron-hadron collisions. This work has given the theoretical framework needed to extract the parton distributions of the proton from LHC data at the 1% level of accuracy. Most recently, developments coming from string theory have dramatically simplified the computation of multi-leg tree diagrams. Members of the Theory Group have extended these methods and begun their application to QCD loop diagrams.

Superstring Theory and M-Theory – Members of the Theory Group have been involved in studies of superstring theory and its possible relevance to elementary particle physics. Superstring theory may give a context for the solution of the cosmological constant problem, the question of why the observed cosmological constant is tens of orders of magnitude smaller than straightforward estimates in quantum field theory. Supersymmetry forces the cosmological constant to be zero, but only if it is an exact symmetry of Nature, not one that is spontaneously broken. It is a very important question whether there is an intermediate solution in which supersymmetry is broken but in such a way that the theory still controls the magnitude of the cosmological constant. A new direction of approach to this problem is related to the fact that the observed universe seems to contain a small positive cosmological constant. In the previous year, members of the Theory Group constructed the first solutions to string theory with a positive cosmological constant. In the past year, members of the group have made considerable progress in constructing additional and more phenomenologically attractive solutions. A goal of this study is to understand what range of values the cosmological constant can take in string theory and whether the cosmological constant can be adjusted to a small value.

Another direction for our study of string theory is the application of string theory to models of cosmological inflation. The string models with large positive cosmological constant naturally give candidates for the model of inflation, often with field that implement phenomenologically desirable `hybrid inflation'. Member of the Theory Group have also explored other approaches, including one in which the slow evolution of fields in inflation is related to the nontrivial geometry of the moduli space of the compact dimensions in string theory.

Realistic Models with Extra Space Dimensions – Members of the Theory Group have played a central role in the recent development of models of elementary particle physics with large extra space dimensions. The inspiration for these models came from string theory constructions in which elementary particles are bound to a ‘brane,’ a subspace of a higher-dimensional universe. It was realized that, in theories of this type, the additional dimensions may be large, even macroscopic, and that gravity, cosmology, and elementary particle forces can be affected by the new dimensions at energies as low as those currently being probed in accelerators. Members of the group have explored the cosmology of these theories and their implications for experiments on gravity. A wide variety of tests have also been devised for effects of higher dimensions that can be carried out on present and future accelerators. In the past year, members of the Theory Group have studied the accelerator tests and constraints on two new types of models, first, models of the quark and lepton masses and mixings associated with the location of the associated fields in a highly curved extra dimension; second, `Higgsless' models in which the breaking of electroweak symmetry is due to the boundary condition through which the W boson fields living in a higher-dimensional space couple to a brane. In each cases, there are characteristic tests that may be carried out at the next generation of accelerators.

New Theoretical Methods – Other new theoretical methods being developed by the Theory Group include: applications of object-oriented programming techniques to simulation problems in physics; new methods for solving lattice Hamiltonian systems; light-cone Fock state methods in non-perturbative QCD and non-perturbative studies of QCD in light cone quantization, and explicit Hamiltonian methods for solving quantum gravity problems in black-hole and cosmological backgrounds.

13. FY04 Progress in RF Power Source Development by (George Caryotakis)

Klystron Development

Software

A workshop was held on MAGIC with interested and qualified personnel for the purpose of improving our understanding and operation of our large-signal klystron codes. An effort was begun to verify code releases, track bugs, and check validity against physical models.

We evaluated TRAK (particle tracking code), and EMPIRE (rf and static field code). After about a man-month of effort, neither of these was deemed suitable for our department. ANSYS training was then taken and it is currently used for analyzing sheet-beam klystron magnetic fields.

Hardware

A 75MW klystron (XP3-4) was constructed and tested. This was the first integral pole piece klystron version since XP1. This tube was eventually tested at 120Hz with full rf and pulse width, manned by operators on a 3 shift basis. The tube met spec performance, but began degrading and is currently awaiting autopsy. Another tube, the XP3-5, was constructed and tested. This tube had what appeared to be activity beyond the waveguide couplers. (either in the loads, windows, or mode converters). An attempt was made to investigate the problem using x-ray detectors. We designed and constructed a test set up which currently is on hold.

Test Stand 1 was set up for breakdown experimentations. We designed and constructed waveguides for suitable breakdown quantification. These waveguide experiments are meant to investigate the output waveguide conditions in our klystrons. A collaboration was begun with a small company, Epion, to investigate various coating techniques.

Design

Subsequent to the decision favoring “cold” technology (L band) over “warm technology (X band), an ILC sheet beam klystron (SBK) design parameter space was chosen for a plug-compatible tube for the TESLA baseline (10MW 1.5ms). A design effort was begun. Beam transport and rf interaction looks relatively simple and extremely promising.

Klystron Manufacturing

Fourteen 5045 klystrons were produced (5 new, 9 rebuilds). Two of these failed, but they were experimental tubes and failed due to causes related to the experiment. We usually don't count failed experimental tubes against the yield. On that basis, the yield for the year is 100%. The 5045 MTBF continues to be around 70,000 hours. There are 23 on-line 5045's exceeding 100,000 hours.

Three of the B Factory klystrons were completed, BFK-004, -005, and -006. All tubes were accepted with excellent performance. There are currently manufacturing parts for another 4 tubes.

Ten high gradient X-band test accelerators for use in the NLC Test Accelerator were completed.

In addition we produced many (approx 200) high-power RF components (mode transducers, couplers, loads, etc) for NLCTA, 8-PACK, and Test Lab use.

Work For Others And Collaborations

The development of LIGA-based W-band sheet beam klystron fabrication was done this year. Several cavities for the structure were manufactured and cold tested. The tests show Q’s on the order 1400 with probable improvement after cleaning and firing. MAGIC simulations for the beam transport and cavities were conducted and suggest a complete W-band sheet beam klystron will be realized.

The development of a 100 kW, W-band sheet beam klystron was started this year. Accomplishments were made in several areas pertinent to a high-peak and average-power sheet beam klystrons. These include electron gun design and modeling, beam transport through periodic permanent magnet focusing systems, design and modeling of RF cavities, thermal analysis, and cavity fabrication using normal machining with a high speed spindle. Normal machined cavities have demonstrated Q’s on the order 1400 which is 85% of the theoretical maximum. Three dimensional particle-in-cell simulations were conducted and a complete W-band sheet beam klystron should be available for test in June of 2005.

Compton X- Ray Source

This year the beamline was completed and the laser system was made operational. A series of measurements have been performed to determine the critical parameters of the electron and laser beams in preparation of generating Compton X-rays.

- Using the precision spectrometer at the end of the beamline, electron beam energies of 55 MeV were measured with a dispersion of 0.2 %.
- The beam width at the interaction point was measured to be 94 microns (σ). The laser beam was also found to be approximately this value.
- Using a 100-ps risetime photomultiplier and a 6 GHz scope, temporal alignment of the two beams were obtained to within a few ps.
- Spatial alignment of the two beams was performed using a Tantalum mask with an aperture of 100 microns.

We will be looking for Compton X-rays in the very near future. Improvements in beam focusing will be performed to increase the expected X-ray flux.

14. FY04 Progress in Radiation Protection Department by Sayed Rockni

Radiation Protection Department (RPD) performs applied research in the areas of production, attenuation and interactions of radiation with matter, development and characterization of instrumentation, design of shielding and dosimetry for high radiation environments. Another major area of research in the RPD is the development, maintenance and benchmarking of radiation production, interaction and transport computer codes. Expertise in this area is also provided to others at SLAC in support of their research efforts.

Neutron Energy Spectra and Yield Measurements

Development of experimental techniques used in measurements of high-energy neutrons is an important research goal for the RPD.

Thick target neutron yield measurement and shielding experiment were performed at RCNP (Research Center for Nuclear Physics) of Osaka University, Japan. This experiment was a collaborative project among SLAC and several Japanese institutions. Energy spectra of neutrons from graphite, Al, Cu, Pb bombarded by 350 MeV protons were measured by Time of Flight method using a NE213 liquid scintillator. The experimental data will be very useful for preparing source terms for radiation shielding design calculation. Shielding experiment were also performed using quasimonoenergetic neutron sources by thin-Li target bombarded by 350 MeV protons. The measured data is now analyzed by Ph.D. students of Tohoku University.

A major focus of the experimental research last year was a shielding experiment that performed at the CERF facility at CERN as a cooperative work among SLAC, CERN, JASRI and Tohoku University. Neutron energy spectra generated in the interaction of 120 GeV protons and pions on a copper target were measured behind concrete and iron shield walls using a NE213 liquid scintillator. When the analysis is completed, these shielding experimental data will be used for benchmarking of the radiation transport calculation codes.

Development and Benchmarking of the FLUKA Computer Code

The FLUKA database of total photonuclear reactions has been updated and extended to 190 different isotopes. Many partial reaction cross sections have also been evaluated in order to check consistency. All the evaluated cross section plots will be collected in a comprehensive Atlas and the numerical data will be made available on a SLAC website. The database has been presented at the ND04 Conference on Nuclear Data in Santa Fe 26 September-1st October 2004. A Bézier fit of the total photonuclear cross sections as recorded in the FLUKA database has also been used as a basic ingredient in the FLUKA heavy ion Electromagnetic Dissociation event generator which has been recently developed at CERN, showing a very good agreement with experimental data.

The inclusion of muon photoproduction in the FLUKA code made last year, has been consolidated and results have been found in good agreement with those reported in the original paper of Y. Tsai, and with calculations made with the MUCARLO code by G. Feldman and L. Keller. At the moment only the lowest order process has been implemented, and correlations between the two muons have not yet been taken into account. A more sophisticated treatment is in progress in collaboration with CERN and the University of Milan. A user interface allows to control the biasing parameter and the gamma and muon energy cut-offs.

Development and Benchmarking of the EGS5 Monte Carlo Code

In the past few years, the EGS4 Monte Carlo code has undergone a major and extensive upgrade to EGS5, in particularly in the areas of low-energy electron physics, low-energy photon physics, the PEGS cross section generation, and the coding from Mortran to Fortran programming. SLAC, KEK, and University of Michigan have each contributed to various parts of the upgrade efforts. SLAC's contribution was mainly on the coding language change and benchmark calculations. Benchmark results as well as the other improvements were all presented in the 3rd International Workshop on EGS at KEK on August 4-6, 2004. The results indicate successful upgrade and the goal to have an EGS5 code system that is accurate, reliable and high quality have been achieved. It is planned to release the EGS5 code before the end of 2004.

15. FY04 Progress in SSRL Operations by Piero Pianetta

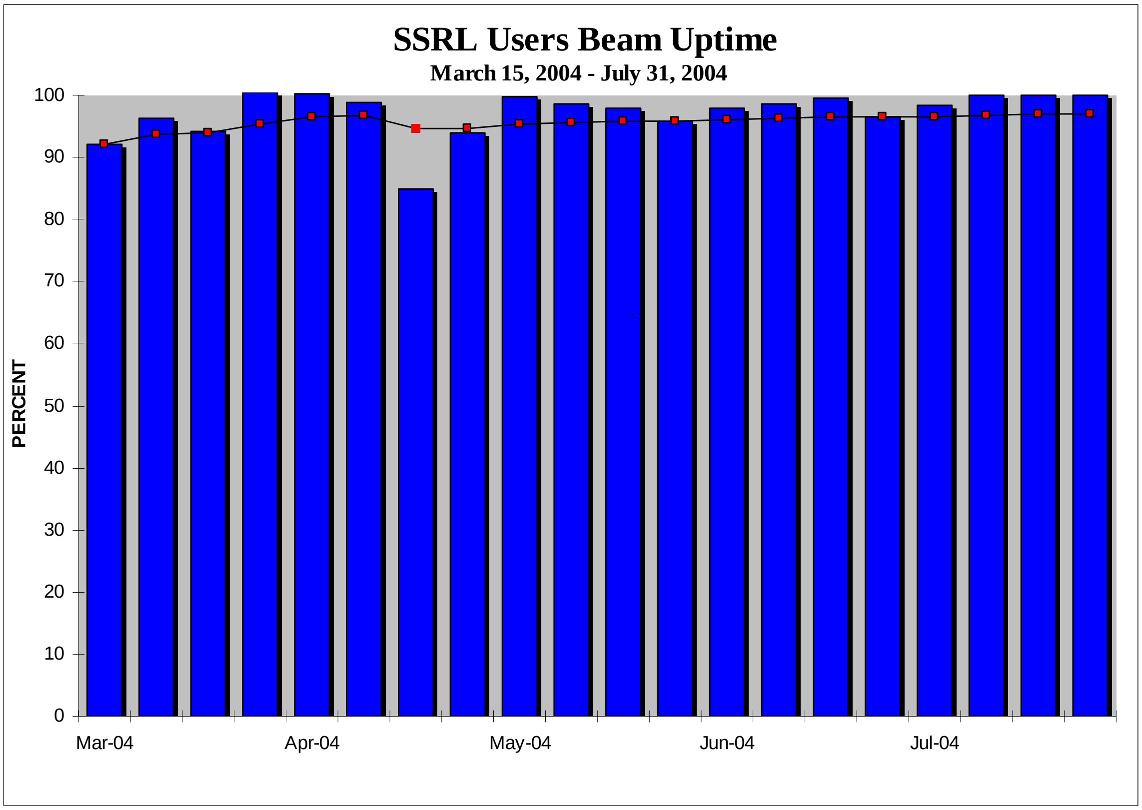
A. FY2004 User Experimental Run

The FY2004 user run (March 15, 2004 – July 31, 2004) delivered 97.1% of scheduled user shifts, accommodating the beam-time needs of 239 unique proposals. During this time, SSRL supported 467 experimental starts on 18 beam line stations that were open for users. The User Research Administration office processed and badged approximately 740 users who came on-site to perform experiments.

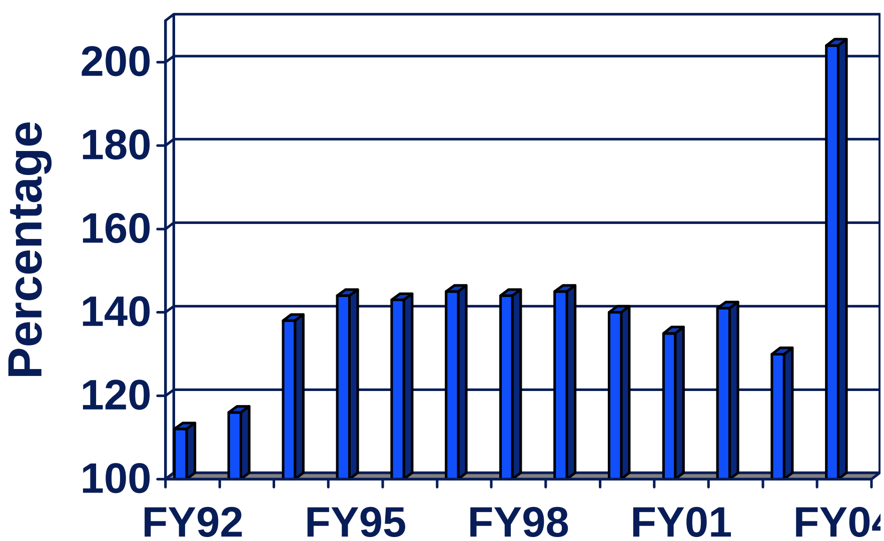
Competition for beam-time assignments remains extremely high. When averaged across all available beam lines, the over-subscription rate was approximately 80% (user demand was 180% of available resources).

In FY2004, users from over 17 countries received beam time at SSRL. Of these users, approximately 89% were from the U.S., spanning 26 states and the District of Columbia. Users were predominantly from American universities (53%) followed by American laboratories (29%), American businesses (7%), foreign universities (8%), and foreign laboratories (3%).

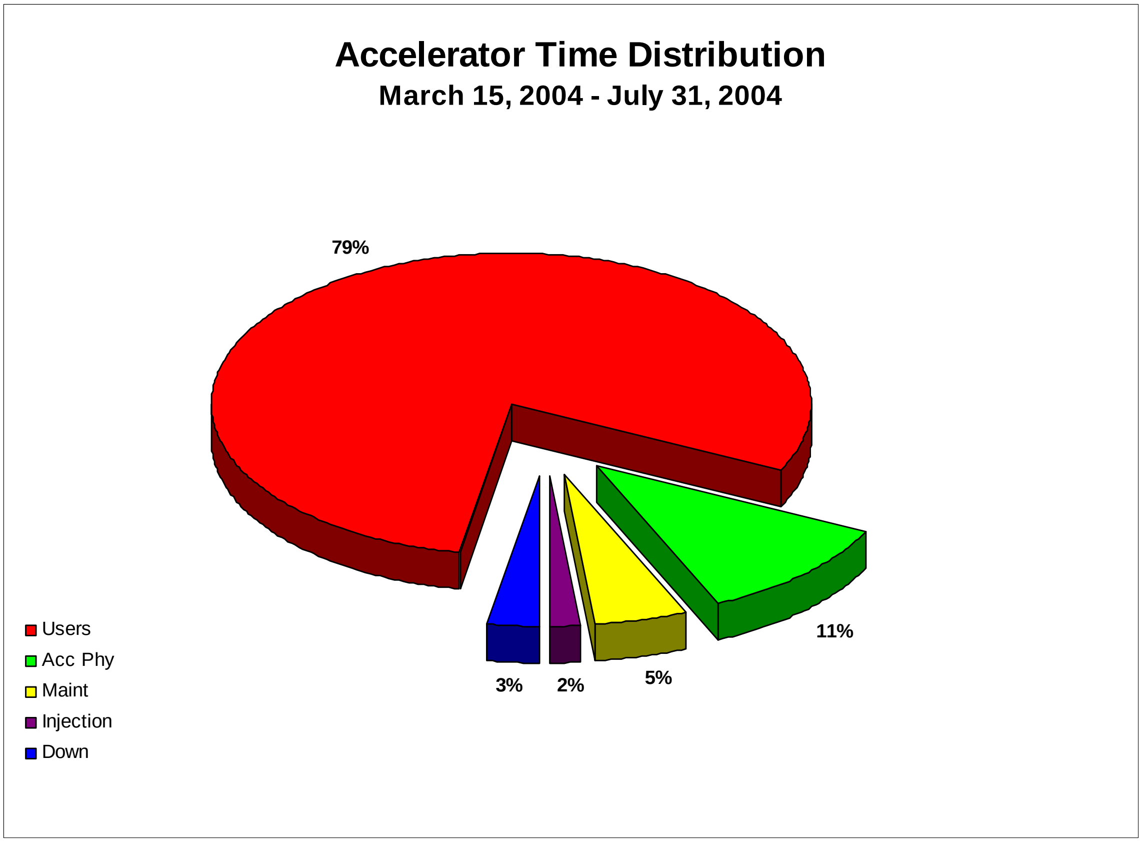
2004 SSRL Users Weekly Uptime



SSRL User Demand (FY92-04):



2004 Run Time Distribution:



Distribution of the 239 unique proposals receiving beam in FY2004:

Materials Science	14%
Physics	5%
Chemistry	16%
Polymers	2%
Medical Applications	5%
Biology/Life Sciences	45%
Earth Sciences	3%
Environmental Sciences	5%
Optics	1%
Engineering	3%
Other	1%

B. SPEAR3 Project

Installation and Turn-on – The SPEAR3 installation was completed in November, 2003, and was followed by preparing the accelerator systems for test and turn-on.

Magnets and Supports – Connections of magnet power supply cables and cooling water hoses were completed in November. Survey and alignment of the magnets and vacuum chambers was completed.

Vacuum System – Fabrication of bellows assemblies, rf transition sections, straight section drift chambers, PPS stoppers, tune driver, and the DCCT current monitor were completed and installed in the ring tunnel in November. Vacuum leak-checking and pump-down continued until the end of November, followed by chamber alignment in the first week of December. The computer-controlled TSP flashing system was commissioned by mid-December as the vacuum chamber was being scrubbed with beam. The TSPs were flashed several times in December during the initial chamber out-gassing, but the flashing rate steadily decreased as the vacuum pressure and "quality" (the product of current and lifetime) improved. The ~ 600 thermocouples installed on the vacuum chamber have been closely monitored to detect any excessive chamber heating, but so far none has been detected as long as the beam is held within the steering limits enforced by the Orbit Interlock.

Vacuum quality has steadily improved with accumulated amp-hours in the ring. As of mid-March, with ~ 60 A-h of accumulated beam time, the lifetime was ~ 18 h at 100 mA (a vacuum quality of 1.8). The lifetime improved approximately linearly with accumulated beam time. By the end of the run, the vacuum quality had risen to 3.5 Ampere-hours at full cavity voltage. A vacuum quality between 5 and 10 is hoped for eventually, but we expect this will take a long time because the thermal out-gassing rate will decrease slowly.

The true integrity of the vacuum system will be tested when the stored beam is increased towards 500 mA. A test run to a current of 200 mA was successfully performed during a machine physics period in June.

Magnet Power Supplies – Magnet power supply control system testing began in September 2003 immediately following restoration of Building 118 AC power. High potential and polarity testing of individual magnets and magnet strings occurred as soon their installation permitted. In early November 2003, prior to PPS certification, installation of temporary barricades closed the ring to off-shift personnel. This allowed for early power supply turn-on. By the middle of November power supply testing was well underway. Successful conclusion of magnet power supply testing occurred by mid-December 2003.

Kicker pulser operation was relatively uneventful for the first two months of SPEAR3 commissioning. However, a February, 2004, maintenance day inspection revealed erosion of the insulated gate bipolar transistor (IGBT) board to pulse transformer connectors. Inadequate contact pressure was suspected to be the cause. Stiffer, more robust IGBT board heat sinks were installed.

There have been occasional problems with the MCOR30 bipolar power supplies. Several MOSFETs and analog switches have failed and the cause is being diagnosed. Engineering staff is closely monitoring the failures and failure rates. At this point the failure rates are decreasing. There have also been nuisance trips of the MCOR30 bulk power supplies tripping off on output over-voltage caused. Engineering has identified possible solutions, one of which has been implemented for the FY2005 user run.

RF System – Once all hardware was installed, commissioning was hampered initially as the circulator and its associated waveguide could not be pressurized. The system is pressurized to provide a Non Ionizing Radiation Protection mechanism for personnel working in the vicinity of the klystron and its waveguide feeder system. The rf system cannot be energized if the circuit is not pressurized. A leak path was identified internally in the circulator and rectified in situ. The rf system was then energized for the first time on November 28, 2003 and each of the 4 rf cavities were initially FM-processed up to a maximum accelerating voltage of 850 kV. By December 8, 2003, each cavity had stably reached 850 kV in CW mode and had run for >24 hours without tripping off the station. At this point, the station had proved its ability to achieve the required station accelerating voltage of 3.2 MV for routine SPEAR3 operation.

In May the temperature of one of the cavity rf windows suddenly increased by a factor of two following a detected vacuum burst in that cavity. Replacing the window was deferred until the summer shutdown, and reducing the total rf gap voltage from 3.2 MV to 2.5 MV reduced the window temperature to a reasonable value while permitting operation for the remainder of the user run. Beam lifetime was consequently reduced by 20%.

Instrumentation and Controls (I&C) – Work on the computer control system continued through the end of the SPEAR 3 installation period and control of the actual accelerator components (power supplies, beam monitors, vacuum instrumentation, timing delay generators, temperature monitors, etc.) was established in November and December, in time for first beam on December 10. Other I&C systems were completed and tested in this time frame as well, including the beam position monitor (BPM) system, tune monitor, DCCT, bunch/current monitor, injection monitors, and the injection timing system. The PLC-based machine protection systems were commissioned during the weeks leading up to December 10. Many of these systems required additional work during the first weeks of beam commissioning to reach the desired level of performance.

Three interlock systems were completed after beam was stored. The Orbit Interlock, a complex system using several BPMs to maintain a tight beam steering aperture so as not to damage vacuum chambers with synchrotron radiation, was activated on January 19, allowing fills above 25 mA. Shortly afterward, the Stored Current Interlock, part of the Beam Containment System (BCS), was commissioned, permitting the first fill to 100 mA on January 22. Further calibration of the Orbit Interlock permitted closing insertion device gaps in early February. Components for the third interlock, the Long Ion Chamber (LION) system, were developed during the user run; this interlock is scheduled to be connected to the BCS during the FY2005 run.

Work continued through the remainder of FY2004 to refine the operation of the I&C systems. Computer application programs are continuing to be embellished and further developed, fast real-time control of the orbit will be established, and beam monitoring systems were being continuously improved.

Environmental Health and Safety – Accelerator radiation shielding installation was completed by the end of November. Concerns identified in the Accelerator Readiness Review, mainly involving minor revisions to safety interlocks and the completion of system safety procedures, were addressed and permission to begin operation in early December was granted by the DOE. Shielding required for 500 mA operation was installed during the July-September shutdown.

Accelerator Physics – Work in the first quarter of FY2004 focused on completing accelerator control and characterization application programs in MATLAB and preparing a detailed commissioning plan. A series of meetings was held to train operators and accelerator staff to use the new SPEAR3 software, diagnostics, and hardware. Actual commissioning took place between December and March (see Commissioning section) during which the control programs were further developed and the accelerator parameters were characterized and optimized. Studies of beam stability, dynamic aperture, coupling, injection and lifetime continued through the user run.

Commissioning – In early December, beam was established in the Booster, the beam containment interlocks were certified for the Booster-to-SPEAR (BTS) transport line, and the first beam signals were seen in SPEAR3 on December 10. The first complete turns of the injected beam around the ring with rf off were seen the following day. These activities demonstrated that most of the major systems were working as planned.

The rf system was turned on December 12 and the first accumulated beam in SPEAR3 occurred on December 15. The ring was operated at low current (<20 mA) for a few weeks before commissioning the Orbit Interlock, but this current was more than enough to commission the diagnostics, correct the orbit, and correct and control the linear optics.

After the Orbit Interlock (which permits operation above 20 mA) and the Stored Current Interlock (which permits operation above 70 mA) were commissioned, the ring was filled to the operating limit of 100 mA for the first time on January 22. The lifetime at the time was ~ 4.5 hr. In the following weeks the vacuum pressure steadily improved and, as of mid-March, at 18 hrs at 100 mA.

Most of the commissioning work in February and early March focused on characterizing the linear and non-linear lattice properties, studying the limiting apertures in the ring, developing the orbit monitoring and control programs, and measuring and correcting the effects of insertion devices. The linear optics functions have been corrected to within a couple of percent of design. Measurements of the nonlinear optics distortions are also quite close to predictions, which have resulted in good injection efficiency and lifetime (for this stage of vacuum conditioning).

Measurements of the electron orbit show that it is very stable. The absolute orbit can be placed in the storage ring magnet centers to within several tens of microns. The fill-to-fill reproducibility of the orbit at the beam positions monitors (BPMs) is about 1 micron. Without feedback, the orbit drifts only a few tens of microns over the course of many hours. With orbit feedback, this is reduced to about 1 micron, as measured by the BPMs.

The final days of storage ring commissioning before beam delivery to users on March 15 were dedicated to investigating minimum apertures for future insertion devices, developing the LION beam containment system, delivering beam to BL9, the first and only beam line available to users on March 15.

The commissioning effort was assisted by several visitors from national and international synchrotron light facilities, including the ALS, NSLS, CAMD, APS, Soleil, ESRF, Swiss Light Source, DESY, Taiwan Light Source, and the Australian Light Source.

C. Accelerator Improvements

Injector – Work continued in FY2004 to improve the reliability and operation of injector at 3 GeV. Improved vibration damping was installed for the White circuit pulse choke, and other improvements to the pulser enclosure were made. A plan for replacing the kicker pulser high-voltage delay lines with lumped-element pulse-forming networks is being investigated to improve system reliability. A White circuit cell tune monitoring system is being designed. The Accelerator Physics group will study and hopefully improve the injection and extraction efficiencies of the booster.

Injector Pulsed Signal Monitoring – Testing of system components will be completed in FY2005. The prototype buffer will be tested on the bench. Assuming it meets specifications the complete set of buffer amplifier boards can be ordered. The multiplexor will be tested with real signals in the lab to measure the effects of electrical noise and crosstalk on the performance of the multiplexor.

Turn-Turn Beam Position Monitors (BPMs) – The basic BPM data acquisition software residing in EPICS IOCs has been completed and tested. The software for continuous and turn-turn data acquisition is complete. The general purpose user interface for turn-turn acquisition and post-processing display is being developed. Test tone signal couplers have been installed in the ring tunnel. The turn-turn BPM processors will be commissioned early in FY05. This will include verification of signal quality, power levels, timing, noise rejection, signal integrity and gain control, and completion of the software.

Synchrotron Light Monitor (SLM) – The SLM M_0 mirror and cold finger vacuum chamber assemblies, other in-tunnel components and radiation shielding were installed in the July-September shutdown. Final connection to the storage ring is planned by the end of the calendar year, pending approval of the shielding by the Radiation Safety Committee. The rough vacuum components and optical elements for the optics room will be completed and installed in this time frame as well. SLM commissioning is scheduled for early calendar year 2005.

Beam Scrapers and Tune Driver – Low-impedance beam scraper vacuum chamber modules were installed during the July-September shutdown. The scrapers will be commissioned at the beginning of the FY2005 run. They will enable studies of beam size, lifetime, injection apertures, and minimum apertures for future insertion devices. An rf amplifier for the tune driver will be procured in the first quarter of FY2005.

Orbit Control – Work is underway to implement fast orbit feedback based on the combination of multiplexed and turn-turn BPMs. High speed data transmission and processing hardware, real-time control programs, system application programs and additional orbit monitoring and control hardware needed for fast orbit feedback are being developed. First tests of this system are planned during the FY2005 user run.

500 mA Shielding – Additional localized shielding in the ring tunnel needed for higher current injection and 500 mA stored beam operation was installed during the July-September shutdown. Final review and approval of the shielding by the Radiation Safety Committee is expected in October.

Control System and Application Programs – Work continued through FY2004 to extend and refine the functionality of the control system by adding more sophisticated control and application programs. Programs were developed for automatic bucket-filling, TSP flashing, accumulated beam monitoring, temperature monitoring from over 600 thermocouples, Orbit Interlock steering verification, kicker bump compensation, orbit feedback with photon beam position monitors, and many more. Work will continue in the next fiscal year to provide an operator interface and data acquisition applications for the new fast orbit feedback system.

SPEAR3 Performance and Lattice Upgrades – The accelerator physics and engineering groups will continue to study and tune the SPEAR3 accelerator to maximize its performance and stability. Measurements of transverse beam stability at higher current will be made to determine if a transverse feedback system is required. Lattice modifications that will enable smaller gap insertion devices have been studied and reviewed, and a double vertical waist lattice for the east long straight section has been selected for implementation by the FY2007 user run. Studies of top-off injection will commence in FY2005.

Gun Test Facility (GTF) – After substantial rf processing with the Mg cathode the maximum field obtained was 107 MV/m with sustainable fields of 95 MV/m, still below the LCLS requirement of 120 MV/m. The quantum efficiency (QE) of the cathode was measured and found to be only a factor of 2 higher than the previous Cu cathodes. Additional measurement showed the QE to vary across the cathode by over an order of magnitude. Attempts to clean the cathode to improve the QE and reduce the QE variations were unsuccessful. Subsequent emittance measurements demonstrated nearly identical longitudinal emittance when compared with Cu cathodes but Mg showed a factor of two increase in the transverse emittance at very low charges. Other measurements showed the presence of an undesirable quadrupole field at the gun exit, possibly a consequence of the single rf feed for the gun, that degrades the beam quality in the emittance compensation process. More experiments are planned in FY05 to study this problem. The new gun design incorporates a dual rf feed which eliminates this quadrupole effect.

A prototype electro-optic bunch length monitor was installed. The diagnostic was tested without electron beam and the first e-beam tests are scheduled in FY05.

A new rf amplifier was built to drive the GTF gun klystron. The amplifier can rapidly vary the rf output amplitude and phase to control the time required to fill the rf gun. This will be used to reduce the heat load in the gun as required by LCLS. Initial testing is scheduled for FY05.
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Planning for future GTF operation has also begun. Alternate sites will be explored that would permit GTF operation after SPEAR implements top-off injection, precluding ready access to the existing GTF vault. In addition to rf gun and cathode development, new programs are being considered for the GTF, including ultrafast electron diffraction, terahertz radiation sources, Compton scattering and electron beam diagnostic testing and development.

D. Beam Line and Facilities Improvements

At the beginning of the year the focus was on completing the alignment of the beam lines to the SPEAR3 source points, followed by a commissioning period where the performance of the beam lines was brought up to SPEAR3 specifications. In addition, most of the general beam line improvements were merged with the Beam Line Upgrade Project described below. Improvements beyond these included the implementation of photodiodes for the I_0 measurement on insertion device beam lines to overcome the nonlinearities associated with ion chambers at high fluxes, upgrade of the digital signal processors on the beam line steering system, development of microfocus capabilities (in particular on BL6-2 and BL11-2), upgrade of detector electronics to higher speed performance, and implementation of CCD detectors on materials diffraction end-stations.

Beam Line Upgrade Project – Since it was determined that the SPEAR3 accelerator would run at 100 mA during the FY2004 run, the installation of most of the 500 mA upgraded beam line components was delayed until the summer 2004 down. This delay had the major positive impact of reducing resource allocation conflicts during the SPEAR3 installation and reduced the probability of user operations delay on a given beam line owing to lack of availability of some component. Thus in FY2004, the beam line upgrade program concentrated on the assembly and installation of the remaining components of the BL5, 6, 10, and 11 ID beam line 500 mA upgrades. Fabrication and assembly of some of the components necessary to upgrade ID BL4, BL7, and BL9 were accomplished. With the exception of radiation shielding related activities, bend magnet beam line upgrades saw relatively little activity in FY2004 due to resource limitations.

One significant aspect of the beam line upgrade program was the decision by the SLAC Radiation Protection Department to conduct a full radiation safety review of every beam line prior to 100 mA operations. While such a review was anticipated for 500 mA operations, it was not anticipated for 100 mA operations of beam lines with no increases in source power and/or critical energy (i.e., all beam lines save the bend magnet beam lines BL1, 2, 3, and 8). Significant resources have been allocated to this effort to date and will continue to be allocated throughout the fiscal year. This will delay the 500 mA upgrade of some beam line components.

BL1, 2, 3, and 8 – Owing to resource limitations, upgrade activities on the bend magnet beam lines were limited largely to re-commissioning the beam lines with the new SPEAR3 source location and upgrade of a few key components and radiation protection systems required for operation with SPEAR3. Notably, new beam transport hutches were completed on BL1 and 2 and a new experimental hutch was erected for BL1-4. The JUMBO monochromator on BL3-3 was decommissioned and the old double crystal monochromator from BL6-2 is being adapted to function in its stead. Beam line shielding will be modified according to current shielding protocols to permit 500 mA operations. By the end of the summer shutdown most of the bend magnet stations were upgraded sufficiently that they can be operated with 500 mA. In many cases the performance of the beam line will be sub-optimal until the full 500 mA upgrade of the beam line is completed.

BL4 – As noted above, BL4 upgrade activities in FY2004 will be largely limited to fabricating hardware that BL shares in common with other similar beam lines. These include the BL4-1 and 4-2 LN monochromators, the monochromator entrance slits, graphite filters, and Be windows for all three branch lines. BL4 shielding was modified according to current shielding protocols to permit 100 mA operations of BL4-2. The BL4-2 upgrade is funded by DOE BER.

BL5 – The gratings for the BL5-1/2 monochromator have been delivered and installed in the SGM. The SGM and associated entrance and exit slits have been installed on the experimental floor. First light through the monochromator was obtained in July with the 9^{th} through 43^{rd} harmonics being clearly visible and quite sharp. Final assembly and installation of the remaining BL5-1/2 500 mA upgrade components will be completed in early FY2005. The BL5 shielding was modified according to current shielding protocols to permit 500 mA operations of BL5.

BL6 – The 500 mA BL6 upgrade including the 500 mA masks, the M_0 and M_1 mirrors and radiation shielding were completed during the summer shutdown.

BL7 – BL7 shielding was modified according to current shielding protocols to permit 100 mA operations of BL7-1 and 7-2 during the 2004 run. Fabrication of the BL7-1 monochromator has started with installation anticipated during the 2005 shutdown. Mechanical testing of key components of the BL7-2 sagittal focusing monochromator has commenced and initial results are promising. Fabrication of the M_0 mirror systems for all three branch lines has commenced with installation scheduled during the summer 2005 shutdown. The remaining masks and other components for BL7 were designed in FY2004.

BL9 – BL9 shielding was modified according to current shielding protocols to permit 500 mA operations of BL9. The BL9-1 monochromator is currently in fabrication with installation scheduled in December 2004. The BL9-2 LN monochromator has been completed with installation also scheduled in December 2004 along with the remaining masks to permit 500 mA operation.

BL10 – BL10 shielding was modified according to current shielding protocols to permit 500 mA operations of BL10. All the remaining 500 mA upgrade components will be installed during the summer 2005 shutdown.

BL11 – The final shielding modifications for the 500 mA operations of BL11 were completed during the summer shutdown.

E. New Beam Line Development

BL12 – The performance specification for the in-vacuum insertion device for BL12 will be developed and procurement of the ID initiated. The beam line optical concept will be developed. Design of front end components will commence. The funding for BL12 is from Caltech, through a gift from the Gordon and Betty Moore Foundation.

BL13 – The performance specification for the insertion device will be developed and the procurement of the ID initiated. The beam line optical concept will be developed. Design of front end components will commence.

SSRL Instrumentation and Control Software – The SSRL ICS program development continued during FY2004 and the new software was installed and tested on several beam lines.

Several changes were implemented on the XAS data collection program XAS-Collect. The new software has been developed for the Microsoft Windows XP operating system, but will also be available on the OpenVMS and Linux operating systems. In order to take advantage of the higher flux available under SPEAR3, the XAS data collector has been modified so that it can take data in a continuous manner. In this mode of operation, the monochromator is moved continuously, and the data is taken in a rapid manner as it moves.

The implementation of VXI based instrumentation continued during FY2004. This included the new V535 stepper motor controller as well as real-time clocks, counters, analog and digital input and output devices. In addition, the VXI platform can accommodate both VME and the legacy CAMAC modules by using adapter cards.

Computers and Networking – The remaining tier 3 network infrastructure was upgraded to Gigabit Ethernet in FY2004. The demand for Gigabit connections to high-end servers is growing and more fiber optic installations to end-nodes are being installed and managed. The design and installation of a redundant network infrastructure to support mission-critical servers began in FY2004. The network has been extended into new buildings and the network installation to operate SPEAR3 has been completed.

All SSRL staff PCs have been migrated to the SLAC-wide Microsoft Active Directory Domain. Applying Microsoft patches is a major ongoing job to prevent computer virus infections and vulnerabilities.

Facilities and Infrastructure – As this was the first year of SPEAR3 commissioning and operation, the facilities and infrastructure activities have been limited to those that do not require an extensive SPEAR shutdown. SLAC has been replacing smoke detector systems in the accelerator housings with a very early warning smoke detector system (VESDA) to improve the overall safety of the laboratory. The SPEAR ring and the SSRL Booster have been upgraded to the new standard. Building 221 is a modular building located within the SPEAR complex which was found to have a substandard foundation. This building was upgraded to current seismic codes. A liquid nitrogen distribution system was installed that will ultimately serve all of the liquid nitrogen cooled monochromators and experimental hutches. Finally, a plan is being developed as part of the SLAC infrastructure project to address structures within the SPEAR facility requiring reinforcement to meet seismic bracing standards. This project will continue through FY2008.

F. Facility Research and Development

Inelastic Scattering and Advanced Spectroscopy Facility for SPEAR3. The main focus in FY2004 was the design and fabrication of the first component for a dedicated XRS spectrometer. This includes development, testing and purchase of new Si and/or Ge analyzer crystals, design and purchase of multi-crystal goniometer and corresponding control units as well as detector. In addition to the R&D efforts, studies on water, ice, photosystem II as well as other transition metal compounds and aqueous solutions continued at the APS.

Molecular Environmental and Interface Science. The Brown group continued its studies at SSRL in the following areas (1) abiotic and biotic oxidation pathways of pyrite surfaces; (2) formation of ternary surface complexes of dicarboxylic acids and metal ions on metal oxide surfaces; (3) interactions of metal ions with biofilm- and organic polymer-coated metal oxide surfaces under in-situ conditions; (4) XAFS spectroscopy studies of heavy metal contaminated soils; and (5) XAFS, micro-XAFS, and micro-XRD studies of uranium in the Hanford Vadose Zone.

The kinetics and molecular mechanisms of bacterial Mn(II)->(IV) oxidation were investigated. Mn(III) was found to occur as a transient reaction intermediate, with enzymatic participation occurring at both oxidation steps. These results indicate that bacterial Mn(II) oxidation can be a source for Mn(III), which is a powerful oxidant in the environment. The structures of bacteriogenic Mn oxides collected from the field (Pinal Creek, Arizona, Black Sea, and Saanich, Inlet, British Columbia) and produced under systematically varied laboratory conditions were studied using a combination of WAXS and XAS techniques. Mn oxides were found to occur as nanoparticulate hexagonal phyllomanganates (sheet structures). These oxides are believed to be the dominant sources and sinks for Mn in the oceans and the oxic zones of soils and sediments. Bacteriogenic Mn oxidation was studied in the presence of uranium(VI) to investigate the ability of Mn oxides to sequester this toxic metal. In the presence of uranium, bacteriogenic Mn oxides were found to exhibit defected tunnel structures that retained U(VI) in their structures as the uranyl cation. These results demonstrate a scientific basis of using bacterial Mn(II) oxidation for remediating uranium-contaminated ground water.

Strongly Correlated Materials. A systematic investigation of many families of cuprate compounds, has revealed the consequence of competing order or disorder in the lightly doped regime: opening of an energy gap even along the node of a d-wave superconductor [Shen et al. Phys. Rev. B **69**, 054503 (2004)]. Such a behavior is expected in some theories but never observed before. We are in the process of pursuing this problem further. At the same time, we have also used other materials to gain further insights on the impact of disorder on superconductivity [Eisaki et al., Phys. Rev. B **69**, 064512 (2004)].

Significant progress has been made in understanding the unconventional electron-phonon coupling in cuprates. Electron-phonon interaction is usually expected to be independent of momentum, energy and doping. Experiments indicate that none of these is true for cuprates (at least for the p-type where more extensive investigations have been done.) [Cuk et al., Phys. Rev. Let. **93**, 117003/1-4 (2004); T. Devereaux et al., Phys. Rev. Let. **93**, 117004/1-4 (2004)]. This explains the strongly anisotropic and temperature dependent mode coupling effect seen in cuprates, this may also provide a way to understand the universal velocity seen all p-type materials.

Significant progress is expected in understanding the electronic structure evolution and chemical potential behavior in $Ca_{2-x}Na_xCuO_2Cl_2$ [Shen et al., preprint]. A long-standing puzzle in the cuprate research is the peculiar behavior of the chemical potential position as a function of doping. From the very beginning, it was identified that the chemical potential does not drop to the valence band maximum upon hole doping as expected from almost all theoretical models. Instead, the chemical potential appears to shift systematically, but inside the “gap”! It has been clear that the cracking of this puzzle will allow considerable insights on the nature of these novel materials to be gained. Through cleverly designed experiments, the chemical potential was determined with a precision that was not possible before. The peculiar behavior of the chemical potential position was found to be intimately tied to the anomalously broad spectra at the valence band maximum of the insulator. Due to strong interaction, the quasiparticle weight is dramatically suppressed. The peak of the spectrum, previously identified as the quasiparticle pole, is actually due to "incoherent excitations" reminiscent of the polaron picture (either spin or lattice, or both). This finding provides a comprehensive understanding of the doping evolution of the cuprate electronic structure, and resolves one of the most important puzzles in the field, and will have a lasting impact.

Important progress is also expected in understanding the anisotropic quasiparticle dynamics and nature of charge ordering. An intriguing connection between Fermi surface nesting with $\mathbf{q} = \pi/2$ in $Ca_{2-x}Na_xCuO_2Cl_2$ and the striking charge ordering phenomenon with a periodicity of 4a seen by STM has been observed [Shen et al., preprint]. The data provide an exciting opportunity to understanding the nature of charge ordering in cuprate–an important current issue in the field–especially as it will allow understanding of the dual personality of the charge ordered state, in terms of momentum space and real space descriptions.

Progress in the study of other strongly correlated materials is expected. Experiments have been started on the Fermi liquid to non-Fermi liquid evolution via doping through van-Hove singularity (VHS) in $Sr_{2-x}La_xRuO_4$. The importance of VHS in 2D solids has been recognized for a long time, but has never been directly observed by tuning via doping, and has never been connected to the Fermi liquid to non-Fermi evolution. The limit of ARPES experiment will be pushed in this case. Further progress is expected in understanding the charge density wave materials such as $CeTe_3$, $CeTe_2$, $LaTe_3$ and many others.

Chemical Physics of Surfaces and Liquids. N_2, CO, NO and O_2 adsorption on stepped Pt and Ru crystal surfaces related to the fundamental understanding of active sites in catalysis was studied. XAS measurements of water at different pH provide new information to address structure, hydrogen bonding and electronic structure of protonated water. Another aspect of research is the adsorption and thin film growth of water on different metal and metal oxide surfaces. What is the structure and nature of bonding in the first interface layer and does water grow in an ice or liquid like configuration?

Development of Resonant Coherent X-ray Scattering. In late spring of FY2004 the experimental setup was shipped back from BESSY to be located at a dedicated branch line of SSRL's new spherical grating BL5-2, which has an elliptically polarizing undulator as a source. Initially, further investigation is being made into using the 70 nm spatial resolution image reconstructed from the spectro-hologram as input for the Gerchberg-Saxton like algorithm, which tries to retrieve the phases from the very same data set–which is time viewed as a speckle pattern.

In parallel to this technique development, the parts necessary for the investigation of magnetic fluctuations will begin to be incorporated into the experimental setup: in-situ sample manipulation, temperature control, earth field compensation, and an optical MOKE system to characterize the magnetic properties of the thin films.

One critical component for this project is the preparation of defect free, few monolayer, thin ferromagnetic films and their characterization. Process development is underway and will continue into FY2005.

Imaging with Coherent X-rays. A new 3D algorithm has been applied to the reconstruction of a single GaN quantum dot from 25 experimental diffraction patterns. A 3D image with a resolution at ~ 35 nm is expected. Then on to the next step to improve the 3D imaging resolution, which is currently limited by coherent x-ray flux, exposure time and the distance between the sample and the CCD detector. In collaboration with Dr. Tetsuya Ishikawa, a focusing mirror already has been installed on the coherent x-ray beam line (BLX29) at SPring-8 to increase coherent flux. The experimental apparatus is being modified by shortening the distance between the sample and the CCD. The new instrument will be able to determine the 3D structure of nano-sized materials at better than 10 nm resolution. Due to the longer penetration length of x-rays compared to electrons, the imaging technique can determine the 3D structure of thick material science samples at a few nanometer resolution, which is not accessible to scanning probe microscopy and transmission electron microscopy.

Small and Wide Angle Scattering Studies of Soft Matter. An expansion of the capacities of the materials science scattering program is being undertaken to incorporate simultaneous SAXS/WAXS analysis. This has necessitated a physical expansion of the beam line hutch area and the installation of a second detector; making the scattering facility one of very few in the world to offer real-time SAXS/WAXS scattering. Combined with the uniquely small beam cross-section available at SSRL's BL1-4, this offers a unique facility for SAXS/WAXS for small (e.g., capillary mounted) solutions and gels. Experimental groups with existing projects outlined to benefit from simultaneous SAXS/WAXS include scientists from Stanford University, University of Texas (El Paso), University of Michigan, IBM, and BASF (Germany).

New science that is afforded from this development includes the ability to observe in real-time the formation of macromolecular networks, as occurs with gel complexation from a solution or with the cross-linking of a gel to form a polymer network; observing both the nucleation of crystalline junctions that form the basis of rheological stress relief in the network and the larger macromolecular assemblies that such crystals adopt. These issues are fundamental to the understanding of the kinetics of the formation of ordered fluids and plastics, and are immediately applicable in the computer (data storage) and automobile industries.

Structural Properties of Novel Materials

Non-crystalline Materials. The x-ray analyzer developed at SSRL and used for the measurement of the structure of amorphous materials was used to measure the structure of liquid water. In order to improve the r-space resolution of the radial distribution function (RDF) x-rays of ~ 20 keV were employed, allowing measurements out to a scattering vector (q) of ~ 19 Å^{-1}. Even though the experiment was done at an absorption edge, the analyzer is necessary to separate the Compton scattering from the elastic scattering. Data analysis is underway.

Water at Interfaces. The arrangement of water molecules at solid-aqueous solution interfaces is profoundly important for understanding the chemical, physical and biological processes occurring at these interfaces. A concerted effort has been started to determine the structure of water at solid–aqueous interfaces using x-ray and neutron diffraction. Initial studies have focused on the difference between D_2O and H_2O at hydrophilic surfaces (SiO_2) in collaboration with J. Stalgren at Stanford as well as the structure of H_2O at ZnS(110) in collaboration with J. Waychunas at LBNL.

Ultra-trace and Microanalysis. Starting in FY2004, the efforts of the group presently working on the total reflection x-ray fluorescence, TXRF, project has been expanded to include a microscopy effort to take advantage of the SPEAR3 brightness. Initially, an experimental system incorporating Kirkpatrick-Baez (KB) optics has been used in conjunction with an entrance slit to provide microbeams for fluorescent microanalysis and micro-XANES. This system was installed in FY2004 during a preliminary commissioning run in which a spot size of 1x3 microns was obtained. Additional commissioning is planed in FY2005 to reach the goal of tunable spot sizes ranging from 1 to 10 μm.

In order to make room for this system, the existing TXRF station on BL6-2 was decommissioned early in FY2004. A more compact TXRF system will be designed and installed upstream of the KB optics to continue to provide TXRF capabilities at SSRL. However, the system will not be designed to take full wafers but rather concentration on the more specialized samples being brought by users such as the interplanetary dust particles (IDPs) originally studied in FY2003 and biological materials for trace element detection.

X-ray Physics. The SPPS has been operational for more than a year. During this period there has been approximately 5 months of beam delivered. Significant progress has been made in the technology for the characterization of ultra-short (~ 80 fs) electron bunches. There has been considerable progress in the commissioning of new instrumentation, in particular a KB mirror system contributed by a new collaboration with the ESRF and a dispersive x-ray crystal spectrometer aimed at near edge x-ray spectroscopy for the Ni and Cu k edges. Finally, experiments that hold the promise of giving new insight into the nature of laser induced non-thermal melting of semiconductors have been completed.

A significant challenge for linac based ultra-short x-ray sources is the characterization of the temporal profile of the electron bunch with the ultimate goal of developing a non-invasive on line bunch length diagnostic. Led by Adrian Cavalieri and the University of Michigan team SPPS has demonstrated sub 300 femtosecond resolution from our first generation electro-optic sampling instrument. Using this diagnostic the arrival time jitter of the electron bunch with respect to the laser synchronized to the master oscillator for the linac has been measured to be less than 200 fs rms for periods of minutes. Based on the results of these initial measurements a second-generation instrument is being installed for the upcoming running period that should have resolution approaching 100 fs.

The ESRF team led by Olivier Hignette has installed and commissioned one of their state-of-the-art KB mirror systems at SPPS. The aberration-induced errors are of order 100 nm yielding sub-micron spot sizes that are limited by the geometric demagnification of the SPPS source. The intensities observed in the commissioning phase approached 10^6 photons per pulse.

The 1% bandwidth of the SPPS beam is well matched to near edge x-ray spectroscopy, but pump-probe jitter requires a new instrument for these studies so that the full near edge region can be measured in a single shot and then successive pulses are binned by the measured pump-probe delay and then pot processed. There is a complication for SPPS however: the angular divergence of the incident beam is not sufficient for a simple Bragg spectrometer. Peter Siddons and the Brookhaven National Laboratory team have designed and built an asymmetrically cut bent crystal spectrometer designed for the Cu K edge and its resolution and bandwidth have been measured yielding the predicted performance.

Finally a team led by Aaron Lindenberg of SSRL has completed a series of experiments looking at laser induced non-thermal melting. The intensity from the SPPS beam is sufficient to measure not only the short time response of the Bragg scattering from the lowest Bragg peak from InSb, the (111), but also from the (220). The preliminary analysis of the data indicates that the initial motion of the atoms immediately following the laser arrival is inertial but the details of the evolution of this initial step await further analysis of the data.

These steps in both science and technology using the SPPS are stimulating increasing interest in ultra-fast x-ray scattering and are laying the ground work for experiments to come at the LCLS, the world's first x-ray free electron laser.

XAS Studies as a Probe of Electronic Structure / Contribution to Function

Copper. Cu K- and L- edge and EXAFS studies have been initiated for a monomeric Cu^{III}-O_2^{2-} peroxo system, which clearly demonstrate its unusual Cu^{III} nature. These data will be compared to Cu K-and L- edge data of a closely related Cu^{II}-O_2^{-} superoxo system. Computational L-edge simulations will be used to obtain a ligand field description of the Cu^{III}-O_2^{2-} system, which in combination with DFT calculations will shed light onto the contribution of the ligand system in stabilizing a Cu^{III}-O_2^{2-} electronic structure. S K-edge, metal K- and L-edge XAS studies have also been initiated on disulfide-Cu_2(II) complexes in both the end-on and side-on S-bridged forms. These studies will be used to correlate to the biologically relevant Cu_2-O_2^{2-} end-on and side-on model complexes. Preliminary S K-edge and Cu L-edge studies indicate that the ground states of the side-on $Cu_2(S_2)/Cu_2(O_2)$ complexes are more covalent than those of the end-on $Cu_2(S_2)/Cu_2(O_2)$ complexes. This derives from the larger σ-donor interactions in the side-on structure, which has four Cu-disulfide/peroxide bonds, relative to the end-on structure, which forms two bonds to the Cu. A detailed spectroscopic study involving Cu K-edge and EXAFS and S K-edge data has been performed on the active site of the "red" blue copper protein nitrosocyanin. The EXAFS analysis reveals a 5-coordinate active site in the oxidized form and a 3-coordinate Cu^{I} in the reduced form. This can have important implications to the electron transfer reorganization energy. The S K-edge study reveals the presence of a weak Cu-S(Cys) bond with a less covalent thiolate-Cu interaction (20% S 3p). This study is being complemented by resonance Raman, MCD, EPR and DFT calculations to obtain a detailed ground state description of the ψ^* (HOMO).

Heme-Copper Oxidases. A detailed EXAFS, K-edge and L-edge study for both Cu and Fe has been initiated on a series of heme-copper dimeric complexes that structurally mimic the active site of cytochrome c oxidase to elucidate the nature of peroxide binding and cleavage at the active site in the protein. The focus is to understand the electronic and geometric structure in the peroxide bridged complex and to shed light on the ground state wave function of the antiferromagnetically coupled $Cu\text{-}O_2^{2-}\text{-}Fe$ system. Quantitation of the Cu and Fe electronic overlap with the peroxide will be achieved from the metal L-edge spectrum and a ligand field description of the heme-peroxo moiety in the complex will be pursued using computational simulations. This study will be complemented by studies on model complexes with an oxo bridge and monomers with innocent ligands (H_2O and OH^-), which emphasize the effects of increasing covalency.

Iron. The study of compounds in which Fe and NO interact is generally important to inorganic chemistry. NO is isolectronic with O_2 yet will in general form much more stable compounds. In the absence of other experimental data, NO has been used to mimic the behavior of O_2 toward numerous heme and non-heme iron enzymes. Since the metal center and the ligand can both gain and lose electrons, systems which contain an Fe-NO component can be difficult to describe, and referred to more generally as $\{FeNO\}^x$, where x =6,7,8 and describes the number of metal d and NO π* electrons. In order to gain insight into the $\{FeNO\}^7$. S=1/2 compound, $[Fe(Papy_3)NO]^{2+}$, a model based on spectroscopically calibrated density functional theory has been proposed. The model would imply that the compound is best described as a $Fe^{II}\text{-}NO^{\bullet}$ system with most of the unpaired electron density located on the NO unit (spin density of 0.74). The interaction of Fe with NO can be established experimentally by examining the shift of the Fe-K-edge energy position, whose primary determinant is the effective nuclear charge on the iron. This technique will also be applied to a number of other $\{FeNO\}^7$ and $\{FeNO\}^6$ compounds.

Structural studies of HPPD has continued. In addition to structurally characterizing HPPD with and without substrate, studies will focus on the interaction of both of these systems with NO as a good oxygen mimic as described above. Fe-NO bonds are ideal to study by EXAFS because they are typically much shorter than those usually present in the coordination sphere. Thus the studies should provide important insights into the behavior of these enzymes.

The catalytic cycles of many heme and non-heme iron enzymes involve species containing Fe-O bonds. In some cases the metal centers in these species are thought to involve Fe in a formal oxidation state of Fe(IV) or higher. The newly developed L-edge technique for the determination of differential orbital covalency (DOC) provides a unique way of studying these systems. Studies began by examination of a series of relevant Fe(IV), Fe(IV)=O, Fe(III)-OH and Fe(III)=O compounds.

Iron-Sulfur and Heterometal Clusters. The differences in S K-edge XAS of the active sites of the HiPIP and ferredoxins were pursued to understand the fundamental reason for these proteins to use two very different redox couples of the specific cluster. The environmental effects on the covalency of [Fe_4S_4] clusters was studied by systematic perturbation of the protein environment and in model complexes with H-bonding counterions. The [Fe_4S_4] cluster study was complemented by that of heterometal MFe_3S_4 model complexes. Studies were also initiated in defining the active site structure of the enzymes nitrile hydratase and will be complemented by parallel studies of relevant model complexes. The contribution of the Fe-S bond to the reactivity of superoxide reductase, which reduces superoxide to peroxide, will in addition be studied in proteins and model complexes.

PES Studies of Electronic Structure Contribution to Function. We have measured VEPES data on a series of model iron complexes–high spin $[FeCl_6]^{4-/3-}$ and low spin $[Fe(CN)_6]^{4-/3-}$ and $[Fe(tacn)_2]^{2+/3+}$. These redox couples will be analyzed using the methodology (VBCI [Valence Bond Configuration Interaction] model and DFT calculations) developed in the studies on $[FeCl_4]^{2-/1-}$ and $[Fe(SR)_4]^{2-/1-}$ (R= Ph). The effects of increased coordination, high spin vs. low spin and back bonding will be investigated. We will address the issues of changes in effective nuclear charge (Z_{eff}) at the metal center, metal-ligand interactions, and geometric and electronic relaxation upon oxidation. This study is critical as it provides a framework for understanding [$Fe_4S_4(SR)_4$] iron sulfur clusters that model the active sites of the electron-transfer ferredoxins and high potential iron proteins (HiPIP's).

Inorganics in Living Tissues. The development of capillary-based optics has been augmented by that of K-B optics approaches, as described in the microscopy section. Chemically selective, spatially resolved x-ray imaging techniques of inorganics in living tissues is planned to proceed at enhanced spatial resolution. The investigations of metal distribution in insects will continue in collaboration with G.N. George and I.J. Pickering, University of Saskatchewan. In particular, investigations of the Drosophila melanogaster models of various human neurological diseases will be expanded, and also used to test various drug candidates (e.g., the flavinoid quercetin as a treatment for Hallervorden-Spatz syndrome). The major advantages of the Drosophila systems stem from the short life cycle of the fly, its physiologically robust nature, and its ideal size for XAS imaging experiments.

G. Materials Research

Research carried out by SSRL faculty and staff and associated Stanford faculty and students is described in below and covers a broad set of disciplines: (1) Complex Materials; (2) Magnetic Materials; (3) Scientific and Educational Gateway Program; (4)

Nano-scale Ordering in Complex Oxides: Model Systems for Local Probes; (5) Nano-scaled Magnetism in the Vortex State of High-T_c Cuprates; (6) Nano-scale Electronic Self-Organization in Complex Oxides; (7) Nano-Magnetism; and (8) Linac Coherent Light Source R&D. Areas (4) through (7) are collaborative efforts of the SSRL X-ray Laboratory for Advanced Materials and the Stanford University Geballe Laboratory for Advanced Materials.

1. Complex Materials. For Shen's programs, an important progress milestone has been to test a new way to analyze photoemission data and extract the collective mode information. This work, done in collaboration with Shi, Plummer, and Zhang of Oak Ridge National Laboratory, [Shi et al., Phys. Rev. Lett. **18**, 186401/1-4 (2004)] is influencing the way one looks at the photoemission. A related progress is the experimental finding of fine structures in the abrupt kink in the dispersion that is indicative of collective mode coupling (i.e., the kink is now found to have several substructures) [Zhou et al., submitted to Science]. This is the first time such a fine structure is observed which was due to a greatly improved signal-to-noise ratio. This effort benefits greatly from discussions with Laughlin.

Laughlin is searching actively for exactly-solvable models of quantum phase transitions of potential relevance to the correlated-electron problem [Science, **303**, 1475 (2004).] He is also exploring new ways to cull unimportant information from experimental results degraded by quantum criticality effects. Laughlin had a major breakthrough with his invention of Gossamer Superconductivity [Laughlin, *Phil. Mag.*, cond-mat/0209269], [B.A. Bernevig *et al., Phys. Rev. Lett.* **91**, 147003 (2003)], a simple mathematical model showing that correlated-electron behavior induced by Coulomb interactions does not need to have anything to do with the mechanism of superconductivity in the cuprates. He identified the cause of the unusual normal state properties as proximity to a zero-temperature phase transition [B.A. Bernevig *et al., Ann. Phys.*, *Phys. Rev. Lett.* **91**, 147003 (2003)].

Although the vast majority of high-T_c research has focused on the hole-doped systems, the electron-doped materials such as NCCO have presented an important challenge to our understanding. Following a successful crystal growth effort of the electron-doped superconductor NCCO as well as prior new insights into the two-dimensional quantum percolation problem, Greven was able to test the degree to which quantum percolation physics pertains to NCCO [P.K. Mang *et al.*, Phys. Rev. Lett. **93**, 027002/1-4 (2004)]. These data for the spin correlations and ordered moment are in good agreement with recent theory for the Hubbard model, which in turn is based on Shen's earlier ARPES work [Armitage *et al., Phys. Rev. Lett.* **88**, 257001 (2002)]. These results constitute significant progress toward a full understanding of the normal state of the electron-doped superconductors. Since superconductivity in high-T_c cuprates appears in close proximity to the antiferromagnetic phase, it is essential to understand the nature of nearby magnetic ground states. Through careful x-ray and neutron diffraction work, Greven discovered that the oxygen reduction process, required to render NCCO superconducting, transforms a fraction of the crystals into cubic $(Nd,Ce)_2O_3$, and that the field-effects observed by others and ascribed to a quantum phase transition of NCCO are not intrinsic, but due to this secondary phase [P.K. Mang *et al., Nature* **426**, 139 (2003)]. Consequently, the question of genuine magnetic field effects in NCCO remains an interesting, unresolved research topic. The discovery of spurious magnetism in NCCO is a good example of the benefits of a synergistic growth and scattering effort like that by Greven. Furthermore, successful growth of sizable, high-quality single crystals of the bismuth-based and electron-doped superconductors by Greven's effort has enabled valuable collaborative research with Shen's ARPES effort.

Greven's crystal growth efforts will be extended to other high-temperature superconductors with the long-term goal of obtaining a deeper understanding of antiferromagnetic and charge/structural degrees of freedom using neutron and x-ray scattering, and to correlate such information with complementary collaborative ARPES and STM work on the same samples. In a major recent breakthrough, Greven [separate support through SSRL, together with Beasley, Geballe, and Fisher] has succeeded in growing samples of the mercury-based superconductor $HgBa_2CuO_{4+\delta}$ (Hg1201) that are two orders of magnitude larger than the previous world record. Hg1201 exhibits the highest superconducting transition temperature of all the single-layer cuprates, and it is the material with the simplest crystal structure. The new samples are large enough to allow the first detailed scattering, ARPES, and STM experiments of this model superconductor.

Doniach has continued to work on correlated electron systems and other complex materials. Work on a bosonic theory of electrical conductivity on transition metal oxides has started. This is expected to provide a model of high temperature conductivity in compounds such as the ruthenates and nickelates. In addition, simulations of the molecular dynamics of liquid water have led to the discovery of dynamic defects, or "nano holes", with lifetimes on the order of a picosecond. Such transient structures are of interest in connection with the photo-ionization threshold of water, where they may be responsible for the observed lowering of the threshold by around 1eV. The current focus of the theoretical research is on computations of the expected x-ray scattering from these defects which may be observable using the Sub-Picosecond Pulse Source.

2. Magnetic Materials Research. The general program on x-ray studies of magnetic materials concentrated on three areas that will be described in sequence below,

1. Exploration of the ultimate speed of magnetic switching.
2. Refinement of our understanding of the important exchange bias phenomenon.
3. Development of resonant soft x-ray methods for lensless imaging of magnetic domains.

(1) Ultrafast magnetic switching has been explored by means of the fast and strong field pulses provided by the electron bunches of the SLAC linac. These experiments gave unexpected and important results regarding the ultimate speed limit of magnetic recording.

Magnetic recording and memory applications require a bistable bit consisting of a single magnetic domain in which the magnetization M can be "up" or "down". It has become clear lately that the fastest and most efficient recording is achieved by precessional switching, where M precesses about a magnetic field Bp present for a duration τ. The condition for such switching is that Bpτ reaches a certain value. Substantial shortening of the switching time τ seems thus possible by increasing the write pulse amplitude Bp. The speed of precessional switching was explored with perpendicular media that support high bit densities. In these experiments, the SLAC linac was used as a giant hard drive writing head to probe the limits of data recording. In such exploratory experiments magnetic field pulses with a width of 1 picosecond (10^{-12} s) and amplitudes Bp up to 3 Tesla (or 30,000 Oe) can be created. These pulses are faster by a factor of 1000 and larger by a factor of 10 than the writing head field pulses used today in technology. Hence this technique can explore the future limitations of magnet recording.

These experiments revealed that at ultrafast speeds the switching no longer occurs at a well-defined Bp but becomes random within a rather wide range of switching fields. The importance of this observation lies in an unexpected “fracture of the magnetization” under the load of the fast and high field pulses. It puts an end to deterministic switching as we know it today.

This result points out an unexpected speed limit for magnetic recording [I. Tudosa et al., *Nature* **428**, 831 (2004)]. The encountered limit is at speeds that are about a factor of 1000 slower than the ‘ultimate speed” previously expected from established knowledge and physical principles (about 1 femtosecond (10^{-15} s) corresponding to the size of the exchange energy).

(2) The use of x-ray linear dichroism has enabled experiments to gain unique information for antiferromagnetic materials, which, because of their vanishing magnetization caused by their compensated magnetic structure, are difficult materials to study. Particularly interesting effects occur at the boundary of an antiferromagnet (AFM) and a ferromagnet (FM). A prominent example is exchange bias, which was discovered half a century ago and which is used today in magneto-electronic devices to pin the magnetization of a ferromagnetic layer. This work addressed an important assumption made in theoretical models of exchange bias and more generally for the interaction of a ferromagnet with an antiferromagnet.

Using x-ray spectroscopy, it is now possible to investigate the microscopic structure of these fascinating systems right at the interface. These studies revealed that an exchange-coupled ferromagnet/antiferromagnet system behaves like an antiferromagnetic exchange spring magnet, very similar to ferromagnetic spring magnets that consist of coupled soft and hard-magnetic ferromagnets. Like in a ferromagnetic spring magnet, a planar domain wall is wound up in the antiferromagnet when the magnetization of the ferromagnet is rotated or switched. The existence of such a wall is a key assumption of models describing exchange bias, but it had never been confirmed experimentally [Scholl, et al., Phys. Rev. Lett. **92**, 247201/1-4 (2004)].

(3) The Linac Coherent Light Source (LCLS) at the Stanford Linear Accelerator Center will be the first operational x-ray free electron laser. It will provide fully transversally coherent x-ray pulses from 100 fs down to 1 fs in duration, which will open up a new time regime in the investigation of magnetization dynamics. At the same time, the transverse coherence of the x-rays will enable a new imaging technique based on x-ray scattering, which does not require any lenses. It is therefore often referred to as "lensless imaging". The key advantage of this new imaging technique is that only the wavelength limits the achievable spatial resolution, and not the performance of any lenses. This lensless technique is being developed to investigate spatially resolved dynamics like magnetization switching, fluctuations near phase transitions, and non-equilibrium processes occurring in thin magnetic films. The principle of the lensless x-ray imaging technique is compared with a full field imaging technique in Figure 3.

When coherent light is scattered from an object, the far field scattering pattern (Fraunhofer regime) is the exact two-dimensional Fourier transform of the electric field scattered by the object. Therefore, if the amplitude and phase of the scattering pattern could be measured, the structure of the object in real space could be easily retrieved. However, the phase is not directly experimentally accessible, half of the information is lost in the measurement, and this is the so-called phase problem. It was proposed in 1952 by Sayre that this loss of information can be overcome by measuring additional, non-redundant intensities in the scattering pattern ("in-between" the Bragg peaks). This so-called oversampling technique, which involves an iterative numerical algorithm to extract the phase from the additional intensities, has been developed over the last decades, and a first reconstruction of the real space structure from the x-ray scattering pattern of a simple test structure was demonstrated in 1999 by Miao et al.

The reconstruction of the magnetic domain structure is being investigated in thin films from their coherent scattering patterns, which are made visible via the X-ray Magnetic Dichroism effect. To facilitate this reconstruction ideas developed in the optical regime in the context of holography are being pursued. When a small scattering center is placed near the sample, a holographic scattering pattern is detected. This reference structure will scatter light which will interfere with the light scattered from the sample. The inverse Fourier transform of the detected interference pattern is the spatial autocorrelation of reference structure and the sample. The experimental apparatus has been developed and recorded first images both without and with a reference hole [Eisebitt et al., *Appl. Phys. Lett.* 84, 3373-5 (2004)].

3. Scientific and Educational Gateway Program

Research Training – During the period of the SPEAR3 upgrade, $CERIUS^2$ simulation skills were strengthened through course work, application to ongoing problems and, through the extension of the Internet II. Additionally, Gateway students have access to CIMAV, a major materials laboratory in Mexico.

In addition, students were familiarized with other national synchrotron facilities (ALS) and neutron facilities (LANL) which provided an opportunity to expand the scope of the project by exposure to the capabilities in the softer x-ray regions.

This period was used to enhance analytical capabilities and introduced mini-courses in Rietveld powder diffraction analysis and other techniques. This opportunity was also used to further integrate the SSRL/UTEP participants in the Gateway program.

The Chianelli group continued to address a number of important areas started in FY2003. These areas included: 1) structure/function relations in transition metal sulfide hydrodesulfurization (HDS) nanocatalysts in order to improve the performance of these important environmental catalysts; 2) study of the nature of the stable organic-inorganic complexes moving into new areas of application for these materials; 3) study of amorphous and disordered materials since they are proving to be superior catalysts for hydrotreatment and for fuel cell electrodes; 4) with Dr. Gregory Lush's group, complete the study relating the performance of multilayered display devices to diffraction and XAFS information; 5) with a CIMAV group under the direction of Luis Fuentes, continued to study the structure of $BaBi_4Ti_4O_{15}$ Aurivillius phases.

The Gardea group continue investigations on the the metal binding properties of the "hyperaccumulators" as well as the bonding of heavy metal ions to biomaterials.

The Pingitore group continued to study trace elements in human bone, as well as the speciation of arsenic and lead in air filters, slag, and soil from El Paso and Juarez.

In a new project, Professor Stec will bring protein crystallography to the Gateway Program. His main research interest is in structural enzymology, i.e., how chemical reactivity is generated in biological macromolecules. Several projects are designed to determine three-dimensional structures of important proteins and study details of their catalytic reactions, especially in metallo-proteins. Several protein crystals have been grown and are ready for study. Projects include:

- The structure and mechanism of proteins involved in inositol processing.
- The structure and mechanism of the E. coli replication complex.
- The structure and function of C. caldarium rubisco.
- Quantum mechanical origins of ligand discrimination in myoglobin.
- Catalytic details and substrate recognition in C. griseus abasic nuclease.

4. Nano-scaled Ordering in Complex Oxides: Model Systems for Local Probes

It is the goal of this program both to develop model systems for studying nanoscale phenomena in highly correlated materials, and to prepare these materials in forms that lend themselves usefully to real- and k-space probes ideally suited for studying their physical properties.

DOE funding for this research program began in September 2001. Synthesis routes for the materials of interest were improved and detailed characterization work was begun. Progress in each of these areas is summarized below:

Heavy Ions and Negative-U Interactions. Over the course of the last two years a multi-step synthesis route to produce high-quality single crystals of $(Pb_{1-x}Tl_x)Te$ with Tl concentrations up to the solubility limit has been established. This is a model system to study the effects of negative-U interactions. The crystals have remarkably sharp superconducting transitions, and the variation in T_c with Tl concentration was determined. In addition, smaller Tl concentrations, too dilute to induce superconductivity, cause an anomalous upturn in the resistivity for decreasing temperatures below approximately 10 K. Such behavior is reminiscent of the Kondo effect for dilute magnetic impurities, though the magnetization measurements imply that the Tl ions have fully disproportionated. It is possible that the low-T behavior results from a more exotic "charge Kondo" effect, in which the Tl^{+} and Tl^{3+} states correspond to the degenerate spin "up" and "down" states of the traditional magnetic case. The progression from charge-Kondo to superconductivity for higher concentrations of the negative-U centers would follow naturally, somewhat analogous to long-range magnetic order in Kondo lattice compounds. While such a charge Kondo state is theoretically possible, to date there has been no experimental confirmation. Ongoing experiments seek to establish whether such an explanation is appropriate for Tl-doped PbTe.

Systematic studies were begun to determine the progression from charge-Kondo like behavior at low Tl concentrations to superconductivity for higher Tl concentrations. Collaborations with H. Manoharan (Stanford) to measure local changes in the density of states over Tl impurities, Z. X. Shen (Stanford) to obtain an understanding of the electronic structure via photoemission, and S. Dugdale (University of Bristol, UK) to obtain a measure of the Fermi surface via positron annihilation (for larger Tl concentrations quantum oscillations are damped) have been established.

Charge-Density Waves in Layered Rare Earth Tellurides. Motivated by a desire to better understand the nature of electronic structure and Fermi surface reconstruction in an incommensurate charge density wave state, a new set of compounds was studied. The RTe_3 family has a layered structure, based on pairs of square-planar Te sheets separated by RTe slabs, and forms for R = Y and La through Tm, excepting Eu. The Fermi surface is simple, formed from the p_x and p_y orbitals of Te atoms in the square sheets. Hole and electron sections are partially nested by a single wave vector, and a charge density wave is observed via TEM with $q_{CDW} \sim 5/7$ Å— 2π/a. The resulting gap can be observed via ARPES, and varies around the Fermi surface, with a large maximum value of approximately 400 meV [Brouet et al., Phys. Rev. Lett. 93, 126405/1-4 (2004)]. This is a model system for studying the electronic structure deep in an ICDW state because (a) the material has a very large gap, allowing direct observation of the gapped and ungapped portions of the Fermi surface via ARPES, (b) the material has a very simple electronic structure, allowing for an intelligible description of the reconstructed Fermi surface, and (c) the ability to grow exceptional quality crystals of a very large size (up to a cm in-plane), allowing complimentary Fermi surface studies via quantum oscillations. In fact, this material promises to be an ideal test-bed for comparison between dHvA and ARPES data.

Using these crystals, a careful study of quantum oscillations in this material was initiated. Initial de Haas van Alphen (dHvA) measurements, show at least three frequencies which vary with angle according to 1/cos(theta), consistent with minimal z-axis dispersion. Comparison with the areas obtained via ARPES implies that a 500 T frequency is likely associated with the ungapped piece of Fermi surface centered around $(0,\pi/a)$, whilst a 1.6 kT frequency arises from reconstructed regions of Fermi surface formed from the other ungapped sections. Additional x-ray diffraction experiments are planned at SSRL to probe the charge density wave–we anticipate measuring the correlation length both in-plane and between adjacent planes, and will begin to plan subsequent inelastic experiments to look at excitations.

Charge Segregation in CuO with the Rock Salt Structure. CuO is a Mott insulator that normally forms with a monoclinic crystal structure. The goal of this work is to synthesize this material as a model system in a cubic rock-salt structure using epitaxial growth, and then study its electronic transport properties as a function of doping using k- and r-space probes. Contrasts with the cuprate superconductors are of obvious interest. Evidence for nano-scale charge stripes has already been reported for this material, which heightens our interest.

The installation and modification of a new MBE-grade molecular beam synthesis system (MBS) in the Geballe Laboratory for Advanced Materials has been completed. The new version combines multi-source electron beam thermal evaporation and pulsed laser deposition in the same UHV chamber. The system also includes in situ RHEED for structural determination, FTIR for measurement of the absolute temperature of film during deposition and XPS for determination of the composition and chemical state (e.g., oxidation state). This new thin film deposition system has been built up using resources from DOE, NSF and AFOSR. The system is now ready for concerted effort on the synthesis of CuO epitaxial thin films.

Electronic Transport in Bad Metals. $SrRuO_3$ is unusual in that it is a rare example of a 4d itinerant ferromagnet. As documented in earlier work at Stanford, it is also what is commonly referred to as a bad metal, in that its resistivity increases with increasing temperature beyond the Ioffe-Regal limit, and its optical conductivity shows distinctly non-Drude behavior. Both of these properties are reminiscent of those seen in the cuprate superconductors.

Recent theoretical calculations based on dynamical mean field theory as applied to highly correlated systems predict qualitatively the observed dc and optical properties. Quantitative tests are lacking, however. According to these theories, there should also be an associated suppression of the electronic density of states at the Fermi level. One long-term goal of this work is to look for this suppression of the local density of states using scanning tunneling spectroscopy. Toward this end, in the present year it has been shown that good scanning tunneling microscopy can be done in air on these $SrRuO_3$ thin films after simple cleaning by heating the films in a vacuum system in an oxygen atmosphere.

Advanced Superconductors. The effects of chemical inhomogeneities in the bismuth-based family of copper oxide superconductors, $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+1+\square}$ [H. Eisaki et al., Phys. Rev. B **69**, 064512 (2004)] have been investigated.The double-layer variant (n = 2; "Bi2212") of this homologous series has been of great interest to the ARPES and STM communities, and it has also been a candidate material for possible technological applications. One discovery was that certain local disorder effects seriously impact the electronic properties of Bi2212. All Bi2212 data reported in the literature are plagued by this problem. These results point the way to a new generation of experiments on Bi2212 and other, related transition metal oxides. Under typical ambient growth conditions, the actual Bi:Sr ratio of single crystals is not 2:2, but around 2.1:1.9. We investigated how this kind of off-stoichiometry affects the superconducting transition temperature (T_c) of single crystals. By substituting Y on the Ca site it was possible to study systematically the site dependence of disorder effects for $Bi_2Sr_2Ca_{1-y}CuO_{8+\square}$ substitution for Sr is reasonably thought to have large local effects, because the Sr site is next to the apical oxygen, and random substitution therefore affects the CuO_6 octahedra tilts. On the other hand, Y doped on the Ca site has a smaller effect, because this crystallographic site does not bond directly with the Cu-O layer.

The maximum attainable value of T_c, T_c(max), is highest for smaller Bi/Sr disorder. Most interestingly, it was determined that Tc(max) can be increased to a new record value of 96 K for a small amount of Y doping, i.e., Ca-site disorder, which, in effect, leads to a Bi:Sr ratio of 2:2 and hence zero Sr-site disorder. These results have the important implication that the degree and the type of disorder are very important experimental parameters that can and should be controlled: a new generation of experiments on such optimized samples is clearly called for. Collaborative work on Ca-free and Ca-doped Bi2212 has led to, respectively, the observation of periodic density-of-states modulations from STM.

The mercury-based copper oxide superconductors $HgBa_2Ca_{n-1}O_{2n+2+\square}$ can be viewed as model materials due to their relatively simple, nearly undistorted crystal structure, because they appear to be least affected by chemical disorder, and because of their record superconducting transition temperatures (e.g., for n = 3, T_c = 134 K at ambient pressure and 164 K at 31 Gpa). However, the synthesis of this homologous series has remained a serious challenge until now. Consequently, rather few experiments have been done on the Hg family of superconductors. In a major breakthrough, single crystals as large as 10 mm^3 were grown, about two orders of magnitude larger than the previous world record. Neutron diffraction confirmed the single-grain nature of these samples. Initial resonant inelastic x-ray scattering (RIXS) experiments at the Advanced Photon Source (APS) reveal a rich charge-excitation structure in the 2-10 eV range.

Field-effect Doping of Correlated Electron Materials. By applying a large electric field to strongly correlated systems that are close to an electronic instability, such as superconductivity or a metal-insulator transition, it is anticipated that it will possible to

continuously tune through the transition and hence gain a much deeper understanding of the complex electronic behavior in these materials. The research is of interest from both a fundamental viewpoint and also in terms of potential technological applications. The initial research efforts seek to demonstrate that it is indeed possible to modulate the charge density in correlated electron materials by the required amount to produce an observable effect.
ZrO_2 films have been produced using both reactive deposition and pulsed laser deposition. Survey measurements of the dielectric constant and breakdown fields show that these films are capable of inducing charge densities approaching 10^{14} carriers/cm^2, sufficient to begin limited field-effect doping applications. Specifically, breakdown strengths of 12MV/cm with a relative dielectric constant of 16 have been achieved. More advanced deposition approaches may permit much better performance. In any event, in the mean time, the present ZrO_2 films will be used for field-effect tuning of the superconductor/insulator transitions in the indium oxide thin films being studied by Kapitulnik.

Pair Density Waves. It has long been known theoretically that in the presence of a large exchange field, or even a large applied magnetic field, a superconductor should form pair density waves because Cooper pairing now involves electrons with different k vectors. There is now convincing experimental evidence that such a state exists in the superconductor/ferromagnet (S/F) proximity effect in which a spatially decaying pair density wave is induced into the ferromagnet. Still quantitative agreement between theory and experiment is lacking. Even more dramatic are the various predictions that under certain circumstances the induced pairs can be in a triplet spin state in the presence of spin flipping processes at the SF interface, when the magnetization of F is spatially varying or when F is a half metal. These striking predictions are completely untested experimentally as far as we know.

A program to study this phenomenon systematically was initiated. As a start in this effort, a new measurement system that includes a variable temperature, rapid turn around insert for transport and tunneling measurements in a split-coil, transverse-field superconducting magnet was assembled. This system also has precise and automated angular control of the sample in the transverse magnetic field. Using a simpler system (PPMS) available in GLAM, preliminary measurements of the critical magnetic fields of some SF bilayers have been made.

5. Nano-scaled Magnetism in the Vortex State of High-T_c Cuprates.

This work explores fundamental physical processes which give rise to novel collective phenomena and self-assembled nano-structures resulting from high magnetic fields or complex synthesis processes. A proper understanding of these processes requires new experimental tools and radically different theoretical concepts. This project combines material synthesis, neutron scattering and theory to investigate the antiferromagnetic vortex state of the high-transition temperature superconductors. The research program has recently been broadened to include quantum spintronics.

A major accomplishment of this program was the first observation of magnetic field induced antiferromagnetic (AF) scattering in the electron doped material $Nd_{1.85}Ce_{0.15}CuO_4$ in 2003. One of the central issues in the field of high T_c superconductivity concerns the interrelation between antiferromagnetism and superconductivity. In 1997, the P.I. of this program (S. Zhang) and his collaborators (Science, **275**, 1089 (1997)) predicted that a magnetic field would induce antiferromagnetism in the vortex state of high T_c cuprates. A particular advantage of the NCCO compound is its low Hc2, the upper critical field where superconductivity is completely destroyed. In the NCCO material, it is about 7 T, while the Hc2 for most of hole doped materials is above 60 T. Dai's group performed extensive neutron scattering experiments on this material, and found that the field induced AF moment increases linearly with the applied field, saturates near Hc2, and decreases as the field is further increased from Hc2 to about 14 T. This discovery has recently been confirmed by Yamada's group at the Tohoku University, in a similar electron doped PCCO superconductor. The qualitative aspect of this experiment was predicted in earlier theoretical work by the P.I., reported in Phys. Rev. Lett., **79**, 2871 (1997). Soon after the experiment, the focus of the research was turned on the quantitative understanding of the observation. The result of this work was accepted for publication in Phys. Rev. Lett. In this paper, it was shown that the entire magnetic field dependence of the induced antiferromagnetic moment, ranging from low to high field regimes, can be quantitatively explained by the SO(5) theory of high T_c superconductivity.

Another major milestone accomplishment of this project is the completion of a commissioned review article on the “SO(5) theory in strongly correlated systems”, to appear in the Review of Modern Physics. This review article we summarizes the status of the theoretical understanding of high T_c superconductivity based on the unification of antiferromagnetism and superconductivity. This review paper received high praises from the referees and expected to be cited as a classic in the field of high T_c superconductivity.

The work on the microscopic structure of the antiferromagnetic vortex cores will be continued. In addition to working closely with Prof. P.C. Dai’s group at the DOE lab at ORNL, work with experimental groups using STM and magnetic cantilevers to probe the charge and spin orderings in the underdoped cuprates and in the vortex state is also planned. In particular, a proposal has come out of this research that Cooper pairs form a crystal in underdoped cuprates, with a unit cell of 4a x 4a, and the ordering of the pairs can be directly imaged by the STM tip. Close work with the experimental groups to test this theoretical proposal is planned.

A new direction of research on quantum spintronics was also begun. T he semiconductor industry has been progressing steadily along the Moore's law trajectory for the past 40 years. However, fundamental limitations face Moore's law as the industry moves into the nano-domain. Heat dissipation inside a semiconductor chip is now the limiting factor in scaling ICs. Conventional microelectronic devices are based on the storage and flow of electrical charge. In the past several years, there has been considerable interest in the possibility of developing novel nanoscale devices based on the generation, manipulation and detection of spin polarized current. Spin-based transport in semiconductor systems has been proposed as the foundation of a new class of low power electronic devices. While Ohm's law governing the flow of charge current describes the inevitable dissipation of power, our recent work predicted that the generalized Ohm's law governing the generation of spin current by an electric field can be reversible and non-dissipative.

As a result of this work, a paper, entitled "Dissipationless quantum spin current at room temperature", was published in Science, **301**, 1348 (2003). According to Science Magazine's news service, this paper was among the top ten most accessed papers in FY2003. This work generated tremendous interest in the semiconductor industry. The managing director of Applied Materials, the world's largest semiconductor equipment company, calls it a discovery which could compare with that of the transistor. IBM decided to form a joint center on spintronics with Stanford University, to rapidly accelerate the research, development and commercialization of this new discovery. Most importantly, our theoretical prediction has been confirmed by an experimental group at UC–Santa Barbara. The experimental confirmation was announced on March 16, 2004. The work on quantum spintronics will continue, developing novel theoretical methods to predict the behavior of spin transport in semiconductor devices. Closely with IBM, within the framework of IBM/Stanford spintronics center, the theoretical predictions on the dissipationless spin current will be tested experimentally.

6. Nano-Scale Electronic Self-Organization in Complex Oxides

Nanoscale ordering in complex oxides, where the valence electrons self-organize in ways qualitatively different from those of conventional metals and insulators, is one of the most important outstanding problems in physics today. Our research is inherently multi-disciplinary as we present below.

ARPES Program. A distinct change of electronic structure and phase equilibria with doping of K_xC_{60} monolayers was observed. A series of K_xC_{60} monolayers using ARPES were studied. Phase separation with stable K_3- and K_4- phases was clearly revealed, and the doping behavior is not a rigid band filling. I nsulating phases with $x \geq 4$ exhibit distinct difference from metallic ones on both band structure curvatures and spectra line shape. The former indicates a change on molecular orientation with doping, and the later could be explained by fundamentally different roles played by many-body effect for metallic and insulating phases.

Magnetic Imaging Program. Using novel scanning techniques the study of several high-T_c systems was continued with an emphasis on the study of the interplay between magnetism and superconductivity.

Mesoscopic Magnetic Imaging of Very Underdoped $YBa_2Cu_3O_{6+x}$. Many researchers believe that the pseudogap phase holds the secret for understanding cuprate materials. In the underdoped regime, the transition temperature is low or even zero, the pseudogap temperature is high, and the superfluid density is low. Images of individual isolated flux quanta in very underdoped samples of $YBa_2Cu_3O_{6+x}$ from UBC were obtained. The characteristic size of individual flux quanta in very underdoped samples, those with critical temperatures below 20 K, is much larger than expected, possibly indicating a lower superfluid density. However, the possibility of nanoscale structure along the long axis of the vortex is a complicating factor. It is well known that vortex flux is quantized in units of hc/2e. Usually, the fluxoid quantization implies magnetic flux quantization in isolated vortices in the bulk of a superconductor. In the very anisotropic superconductor $YBa_2Cu_3O_{6+x}$, however, partial flux quanta were observed, as shown in a scanning Hall probe image of a T_c = 14 K sample, taken at 4 K. These fractional fluxes are interpreted as subsurface-terminated pancake vortex stacks. This work appears in the thesis, submitted recently, of Janice Guikema. The possibility of wandering pancake vortices that we invoked in these studies of YBCO complicates the interpretation of the penetration depth measurements, and further work on both the YBCO samples and on very underdoped samples of Hg-1201 in collaboration with Martin Greven of the parallel program is needed to sort out the contributing factors to the apparent vortex size.

Nanoscale Ferromagnetism, Antiferromagnetism, and Superconductivity in $ErNi_2B_2C$. $ErNi_2B_2C$ is a superconductor below 11 K, an antiferromagnetic superconductor below 6 K, and a ferromagnetic antiferromagnetic superconductor below 2 K. The effect of the antiferromagnetism on vortex pinning was studied. Scanning Hall probe images were taken at T = 6.7 K, just above T_{neel}, and at T = 5 K, just below T_{neel}. Below T_{neel}, the vortices are pinned in one-dimensional stripes that may be domain walls. This work is currently being conducted by two students: Hendrik Bluhm from the Moler group in collaboration with Suchitra Sebastian from Ian Fisher's group, and are reported for the first time in March 2004. Work has started on studying the ferromagnetic state, where the existence of a spontaneous vortex lattice is predicted theoretically.

Single-fluxoid Dynamics in Rings of Very Underdoped $YBa_2Cu_3O_{6+x}$. The existence of vortices, or individual quanta of magnetic flux, is one of the most fundamental and striking features of superconductivity. Although the energy of a vortex can be calculated simply in Ginzburg-Landau theory, the direct measurement of the energy of a single vortex has historically been extremely difficult. With SQUIDs and Hall probes, it is possible to observe individual vortices enter a mesoscopic ring by observing telegraph noise coming from single-fluxoid jumps in the magnetic screening signal. These measurements allow the energy of a single vortex to be inferred.

High Resolution STM Studies. In order to fully investigate nanoscale ordering phenomena in a variety of materials, these studies seek to uniquely combine both momentum-space and real-space detection techniques for a complete measurement portfolio. The capabilities of STM have been extended by measuring low-energy vibrational and magnetic excitations, and to couple these new techniques with atomic manipulation. The constraints these combined efforts place on the apparatus are extreme and part of our ongoing work is to integrate these tools with the complex materials that are the focus of this project. The design and prototype testing of the instrument has been completed. The system performs at low temperature (down to 500 mK) and in the presence of a magnetic field up to 11 T.

Nanoscale Self-organization in Novel Superconductors. Work has concentrated thus far on the most easily cleavable materials to perfect surface preparation in the STM system. Clean surfaces of $Bi_2Sr_2CaCu_2O_{8+\delta}$ have been demonstrated and tunneling measurements on these samples grown by Greven's group were prepared.

Nanoscale ordering in correlated magnetic materials. Since part of this effort involves the measurement of the two-point propagator or Green's function via a single-point (STM) measurement and employing knowledge of the local scatterers, a theoretical analysis of the quantum mirage effect via this formalism was completed. This work, done in collaboration with Heller's group at Harvard, exploited a scattering approach into which Kondo correlations were introduced by the addition of a resonant scattering phase shift. Through the application of this theory, it became clear that our experiment was also a direct measurement of the Kondo phase shift for a single magnetic moment. It also appears that an earlier theoretical prediction that "two-tip" data can be extracted from "one-tip" data is validated by these results.

Current work is progressing in an external collaboration with Philip Stamp's group at University of British Columbia to investigate the competition between Kondo and RKKY coupling in magnetic nanostructures, with an aim to assemble artificial structures that might mimic the interactions in real materials. Likewise, a related collaboration with Barbara Jones at IBM has resulted in an analysis of our STM data on nanoassembled Kondo lattices, another model for real interactions in complex materials. This work demonstrated evidence for the direct observation of a correlation hole (the "Kondo hole") in an artificial Kondo lattice of Co atoms. Proposed work will extend these studies synergistically to new magnetic correlated materials. Prime candidates are the colossal magnetoresistive (CMR) manganites. Promising to technology as well, these materials have revealed themselves to be fertile ground for novel correlated electron physics potentially involving effects such as double-exchange and charge localization via polaron formation.

STS of Ordered Structures on High-T_c Materials. This program concentrated on the study of ordered nano-scale structures on the surface of cleaved BSCCO:2212 crystals produced by Martin Greven and will extend it to the single layer material BSCO:2201. Studies of Charge Density Waves in tellurides made by the group of I. Fisher were also started.

Ordered structures in the LDOS of BSCCO. Theoretical and experimental evidence has been mounting in support of the possibility that their ground state exhibits spin and charge density waves (SDW and CDW), which are primarily one-dimensional (i.e., stripes) with characteristic wave-vector in the Cu-O bond direction of $q_{\square} = 0.25(2\square/a_0)$. In STM measurements, such modulation was first seen by Hoffman et al. as a 2-D checkerboard pattern of DOS modulations, aligned with the Cu-O bonds, around vortex cores in a magnetic field. The reported modulations showed a checkerboard ordering vector of $q_{\square} = 0.25(2\square/a_0)$ extending to large distances when measured at bias energy ~ 7 meV. Shortly afterwards this same effect in zero field on similar BSCCO crystals was observed and reported as part of this work. The observed modulation with ordering wave-vector $q_{\square} = [0.25\pm0.3](2\pi/a_0)$ was found at all energies exhibiting features characteristic of a 2-D system of line objects. Moreover, the LDOS modulation manifests itself, for both, positive and negative bias, as a shift of states from above to below the superconducting gap. The fact that a single energy scale (Δ) appears for both superconductivity and stripes suggests that these two effects have the same microscopic origin.

In a new study of optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ in zero field, the differentiation of dispersive and non-dispersive spatial DOS modulations as a function of energy was studied. The main finding is that a spatial map of the superconducting coherence peak heights shows the same structure as the low energy DOS. To obtain this result a map of the density of states at the gap energy was made (i.e., the DOS at the peaks of the conductance). Examination of the data shows that while gap inhomogeneity may have some degree of alignment with the superstructure, when the conductance (i.e., LDOS) at the gap energy is plotted, the periodicity of approximately 4-lattice spacing which is 45 degrees to the superstructure is observed. This periodicity is similar to the one most prominent at low energies. The fact that the LDOS at the gap energy (Δ) shows a periodicity similar to the low energy periodicity (i.e., G(E), $E \ll \Delta$) lends support to the fact that the 4-period is a robust feature, independent of dispersive features such as quasiparticle scattering interference.

An analysis of the location of the defects in the 2-D structure of stripes (checkerboard) reveals that the defects are concentrated in regions of low gap and large coherence peak. This is the first study of the topology of CDW-like structures in strongly correlated systems.

STS Studies of the CDW State of $CeTe_3$. $CeTe_3$ is a layered compound where an incommensurate Charge Density Wave (CDW) opens a large gap ($\approx$ 400 meV) in optimally nested regions of the Fermi Surface (FS), whereas other sections with poorer nesting remain ungapped. Using STM it was possible to observe the CDW as well as observe the signal from the ungapped part of the Fermi surface.

7. Nano-Magnetism

Over the past several years, this research has focused on the implementation of pump-probe techniques for the study of nanoscale magnetic structures. Such experiments use magnetic excitations triggered by picosecond current pulses through lithographically fabricated wires. The current pulse is launched by a laser triggered optical switch and the time evolution of the magnetic excitations are probed with 50 ps x-ray pulses from the Advanced Light Source in Berkeley. X-ray excited images are recorded with a photoemission electron microscopy (PEEM), an x-ray scanning microscope or an x-ray imaging microscope. The ultimate goal of this work is to study the switching of nanoscale structures by injection of a spin polarized current.

Significant progress has been made in two areas discussed below.

1. The pump-probe technique has been used to study time dependent magnetization processes with sub-nanosecond resolution;
2. Spin injection structures have been fabricated and imaged.

(1) Time resolved magnetization dynamics in micron-sized planar magnetic structures have been recorded. These results show that the magnetization dynamics of the whole structure is dominated by the tiny nanoscale vortex that is formed at its center. In particular, the initial motion of the magnetization is determined by the vortex handedness or chirality. These experiments demonstrate that the out-of-plane magnetization in the nanometer-scale vortex core dominates the nanosecond magnetization dynamics of micron-size vortex patterns. This reveals that handedness, which is of well known importance in biological systems, also plays an important role in the dynamics of microscopic magnets. The results have been published in the journal Science [Choe et al., Science **304**, 420-2(2004)].

(2) Lithography capabilities on the Stanford campus for the manufacture of spin injection structures have been established. In the process, three graduate students were trained in nanofabrication techniques.

A typical sample is made by optical and e-beam lithography on a SiN coated Si wafer. After building the desired spin injection structure a 100 x 100 μm^2 picture frame is etched from behind into the Si wafer, leaving the SiN membrane, so that the spin injection structure on front of the SiN membrane can be viewed with a scanning x-ray transmission microscope. A Cu lead delivers the current to the center of the spin injection structure where the current runs upwards through a small pillar consisting of a Co/Cu/NiFe sandwich structure. The Co layer spin polarizes the current, the Cu layer decouples the Co reference layer from the to-be-switched NiFe layer. The current then exits through another Cu lead. Magnetic contrast in the pillar structure has been successfully seen. Future experiments will concentrate on observing magnetic switching in the pillar structure caused by spin injection.

I. Structural Molecular Biology

The primary purpose of program is to further develop synchrotron radiation facilities and provide access for the national scientific community through a strong program of user support. Such synchrotron resources are a powerful and versatile tool for research in structural molecular biology. The scientific proposal and technological focus of this program includes the applications of synchrotron radiation to macromolecular crystallography, small-angle x-ray scattering (SAXS) and x-ray absorption spectroscopy (XAS) These efforts are led at SSRL by Professors K.O. Hodgson, S. Doniach and B. Hedman, and Drs. S.M. Soltis and H. Tsuruta.

Key aspects of the program being provided by BER funding include:

1. Continued availability to, and support of users on, state-of-the-art beam lines and instrumentation on the newly upgraded SPEAR3 storage ring for SMB research for a significant fraction of a given year (~ 9 months or more depending on core operation funding levels).
2. Enhanced user support and training for SMB scientists using up to 10 existing stations at SSRL (of which eight are on high-intensity, multipole wiggler beam lines).
3. Full operation and user research program on all three stations on the Beam Line 9 facility dedicated to SMB research.
4. Continued development and implementation of advanced optics, experimental facilities, detectors, computer resources and software to enable optimal advantage to SMB users of the new 3rd generation SPEAR3 storage ring.
5. Continuation of Phase II capital improvement projects in areas such as electronics and detector data acquisition systems for SMB stations.
6. Continued synergistic research and user support in the SMB area with the NIH National Center for Research Resources (NCRR)-funded Biomedical Technology Program (BTP) and the National Institute of General Medical Sciences (NIGMS)-funded macromolecular crystallography operations support and Structure Determination Core of the Joint Center for Structural Genomics.

Beam Line Operations and General Developments – As part of the SPEAR3 commissioning, with the approval of the SLAC Radiation Safety Committee, the first SPEAR3 beam was brought into one beam line, BL9-3, on March 8, 2004. The light observed on the monitor inside BL9-3's hutch showed banding which is consistent with the effect of the separated pole pairs in the wiggler viewed at the 5-mrad off-axis observation angle of BL9-3. This effect could not be seen with the old SPEAR2 ring as its source size was so big that the radiation from each pole pair could not be resolved, so the effect of the reduced source size on SPEAR3 was immediately seen. After an intense week of optimizations, the first user data, of biological x-ray absorption spectroscopy, were measured on March 15, 2004. Beam also has been established in BL9-1 and BL9-2. For the first myoglobin test data set taken on BL9-1, the diffraction spots looked excellent, the beam divergence was better qualitatively than SPEAR2, and the iron anomalous scattering peak was 17σ. This compares to an iron anomalous scattering peak of 13σ in similar myoglobin tests last year under SPEAR2 on BL9-1. Beam line operations on other SMB beam lines will continue to resume in stages, paced by completion of electrical work, hutch upgrades, PPS checkouts and certification, shielding, Radiation Physics approval and commissioning.

The overall highest priority in FY2004 was to bring all SMB beam lines and equipment into user operation under SPEAR3 operations, and to introduce the users to the new instrumentation that has been implemented during the shutdown.

All macromolecular crystallography beam lines were equipped with robotic auto-mounting systems and training in their use, including new software, was a major focus. BL11-3, which was commissioned at the end of the FY2003 run (mainly funded from BES and external industrial sources), was brought up as a shared user beam line, 50% of the time for SMB and the balance to materials science scattering. The upgrade of BL1-5 was completed and progress was made on further enhancement to the instrumentation and software for high-throughput and remote access.

For XAS, while BL7-3 was unavailable during the FY2004 run, instrumentation and software was transferred on a time-shared basis to wiggler beam lines BL6-2 and BL10-2, which brought a significant increase in operational activity for the staff, as well as the training of users in new optics and use environment. A collaboration with Prof. John Rehr, University of Washington for the development of new methodology for the analysis of XAS data was initiated, and single crystal instrumentation and software development for acquisition and analysis was pursued.

The commissioning of new instrumentation and the characterization of new beam capabilities for BL4-2 was the major focus, as well as the training of users upon their return to the beam line. Software for data acquisition and analysis was developed, and novel electronics for time-resolved scattering experiments implemented.

Also during FY2004, developments were conceptualized, plans defined, advice sought from outside scientists, and a proposal developed and submitted for peer-review for the continuation of the overall Structural Molecular Biology Program at SSRL.

Beam Line 4 and 7 Upgrade Projects – BL7 shielding was be modified according to current shielding protocols to permit 100 mA operations during the FY2004 run. Fabrication of the BL7-1 monochromator was started with installation anticipated in the summer 2005 shutdown. Fabrication of the M_0 mirror systems for BL7-1 and BL7-3 has commenced with installation scheduled during the summer of 2005. The remaining masks and other components for BL7 will be designed, fabricated and assembled in FY2004 for installation during the 2005 shutdown. Design of the BL7-0, 7-1, and 7-3 hutches will be completed and these new hutches fabricated. The remaining BL7 shielding will be modified according to current shielding protocols to permit 500 mA operations of BL7 in the FY2006 run.

While progress on upgrading the beam line components for all three stations on BL4 will be limited by funding constraints in the BES budget (the BL4-2 upgrade is dependent on the timing of the work on the other two stations), optical components such as the LN_2 monochromators and associated entrance slits, graphite filters, and Be windows will be fabricated in parallel with similar components on other beam lines to exploit fabrication cost reduction from quantity discounts. BL4-2 was, however, operational in FY2004, and dedicated 100% to biological SAXS, with the new 20-pole 2-T wiggler in place and new front-end components for SPEAR3 operations. It will be used with existing optical components while operating the wiggler at reduced magnetic fields. Beam characteristics superior to those previously provided by SPEAR2 are expected due to the low emittance of SPEAR3 and its much greater beam stability. For example, the flux density of the 9-keV beam on a typical SAXS sample will be a factor of 3 to 10 higher than the current flux density, depending on actual wiggler field and ring current. The full upgrade of the

BL4-2 optics for high-current SPEAR3 operation is expected to be completed in FY2006 depending on DOE-BES funding.

Beam Line 9 Upgrade Project – The BL9-1 monochromator is currently in fabrication with installation scheduled for December 2004. Final assembly of the BL9-2 LN_2 monochromator should be completed by the spring with installation also scheduled for December 2004. Most of the remaining slits, masks, filters, and windows for BL9 are currently in fabrication. Design of the remaining components, the pivot masks for BL9-1 and 9-3, will commence this spring with summer fabrication in time for an early fall installation. BL9 shielding will be modified according to current shielding protocols to permit 500 mA operations of BL9 and, once installed; this will complete the BL9 upgrade project.

16. SCIENCE EDUCATION by Helen Quinn

Pre-College Education

The pre-college outreach program Quarknet workshop continued in 2004 with three one day workshops open to teachers who had participated in the prior years program. Approximately 10 teachers participated in each day. SLAC continues to support local schools through its surplus equipment donation program and through tours for students in physics or physical science classes. Over 200 pre-college students toured SLAC in 2004. In addition, SLAC staff volunteer to assist local schools in a number of ways, including invited presentations, judging at Science Fairs, answering e-mail science questions etc. The Young Physicists Program at SLAC continued outreach, mentoring a small number of local high school students was continued this year and introducing a question answering interaction with the classes of Quarknet teachers. SLAC Kids day bought over 234 students ages 9-16 to SLAC for a day of science activities and lab visits.

Undergraduate Students

In summer 2004 25 undergraduate students from all around the country students undertook summer research internships at SLAC, under DOE's Science Undergraduate Laboratory Internships program each year. These students are housed on Stanford campus and carry out individual projects under mentors who are scientists working at SLAC. In addition a number of user groups bring undergraduate students to SLAC each summer, while a few more students are hired directly to work on specific tasks, such as programming. The communications office continued its program to bring science-writing and science-illustrating student interns to SLAC, with six interns participating over the past year.

Postdoctoral and Graduate Students

SLAC continues to be the host for the research of large numbers of graduate students every year. These students either work with SLAC faculty, or with faculty from other institutions who carry out research at SLAC as users of the facility, either in the high-energy physics (HEP) program or within the SSRL laboratory. Students working at SSRL come from a broad range of disciplines including physics, chemistry and the biosciences. Many non-US students also come to SLAC with faculty from their home institutions who are members of the BaBar collaboration.

Likewise at the postdoctoral level SLAC remains a major training ground with young scientists either working as SLAC employees or coming here as members of user teams. This training plays an important role as can be seen by looking around the world and noting how many leaders in the field spent time at SLAC in their student or postdoctoral years.

Science Education at SSRL

Training opportunities at SSRL play an important role in teaching students as well as working scientists from diverse disciplines how the tool of intense x-ray beams can be used to extend knowledge within their realm of interest. Several science education events were held at SSRL within the last year to further this objective and to meet the needs of current and potential future users.

Over 300 people participated in the 30th annual users' meeting on October 9-10, 2003, which provided a forum for the presentation and discussion of new data, developments, other research activities from SSRL and the synchrotron community. Fittingly, Keith Hodgson's presentation included a brief retrospective of the key accomplishments over the last 30 years and focused on the exciting new opportunities for the future. A special session was held to honor Iran Thomas, a long-time Deputy Director in the DOE Office of Basic Energy Sciences who passed away in February 2003. Iran recognized the value of education and diversity and became a champion of both; he realized that the light sources could be used as a bridge to create opportunities in these areas and supported the SSRL and University of Texas El Paso (UTEP) Gateway program (sponsored by the DOE Materials Science Program) as one such effort to ensure that the workforce of the future is trained in science and engineering. In this special session, three students from UTEP presented talks on their research which was enabled by this innovative program. The remaining sessions included a number of scientific talks which were selected to represent interdisciplinary applications of a variety of synchrotron-based techniques of interest to the broad scientific community of synchrotron users. Areas included small angle x-ray scattering, macromolecular crystallography, microspectroscopy and diffraction, and surface spectroscopy. Over 40 user research posters were presented during the poster session on October 9, with five graduate student receiving awards for their outstanding poster presentations.

In conjunction with the annual users' meeting, SSRL staff coordinated five concurrent workshops on October 8, 2004 (each summarized below): 1) Synchrotron Techniques for Environmental Microbiology and Biogeochemistry, 2) Probing Mechanical Deformation and Failure via Synchrotron X-rays, 3) Sub-eV Inelastic X-ray Scattering Facility with SPEAR3, 4) Recent Advances in Soft- and Hard X-ray Microscopy, and 5) Crystallography Beam Line Automation--Work Smarter Not Harder.

Along with ALS and DOE-NABIR, SSRL hosted a workshop on "Synchrotron Techniques for Environmental Microbiology and Biogeochemistry" focusing on these emerging fields which have cross-cutting research themes emphasizing the interplay and energy flow between microbial communities, inorganic and organic contaminants, (bio)minerals, groundwater, and other solutions. Synchrotron(SR)-based techniques are beginning to play important roles in these research areas because of the utility of SR methods for characterizing metal ion and organic molecule speciation under in-situ conditions in complex environmental materials. The purpose of this workshop was to introduce synchrotron techniques to graduate students, post docs, and other researchers in the fields of environmental microbiology and biogeochemistry, and to bring together scientists from these and the synchrotron communities to share ideas. The workshop was attended by 70 participants from academic institutions and national laboratories around the U.S.

The "Probing Mechanical Deformation and Failure via Synchrotron X-rays" workshop involved scientists interested in investigating mechanical properties of materials via synchrotrons. Sessions focused on salient issues in mechanical deformation and failures, such as crystal plasticity models, fatigue, crack propagation, etc. A brief survey of relevant synchrotron methods including parallel beam geometry for mesodiffraction, microdiffraction, and phase contrast imaging, as well as talks on actual experiments done at synchrotrons were also included. At the conclusion of the workshop, participants brainstormed future projects and developments.

The "Sub-eV Inelastic X-ray Scattering Facility with SPEAR3" workshop covered plans for a dedicated facility for sub-eV inelastic x-ray scattering in the 5-15 keV range at SSRL. Twenty-seven participants registered for this workshop, including eight speakers. The workshop introduced the various techniques that can be carried out at the proposed facility, including: X-ray Raman scattering, resonant inelastic x-ray scattering, selective x-ray absorption and x-ray emission spectroscopy.

A joint SSRL/ALS workshop on "Recent Advances in Soft- and Hard X-ray Microscopy" was held at ALS. In recent years there have been many advances in scanning and full field x-ray imaging techniques such as improved spatial resolution, more stable instruments for spectromicroscopy and time resolved microscopy, phase contrast imaging techniques as well as high resolution tomographic capabilities in absorption and phase contrast. These techniques enable novel nanoscale research in various fields of materials science, environmental science and biology. This workshop discussed these new capabilities in order to identify the scientific direction for soft- and hard x-ray microscopy at both light sources.

The Workshop on "Crystallography Beam Line Automation: Work Smarter Not Harder", discussed new technologies for high-throughput crystallography at SSRL, ALS and other synchrotron facilities. The workshop consisted of a beam line tour at the ALS on Oct. 7, and presentations and discussions at SSRL on Oct. 8 followed by a hands-on session at SSRL in the afternoon the same day. Over 80 people attended the talks and discussion sessions which focused on new technologies for high-throughput crystallography at synchrotron light sources, emphasizing the benefits for and concerns of general users. Four main topics were covered: automated sample mounting systems, automated crystal centering, data backup approaches, and crystal screening interfaces. Experts in these areas gave talks that addressed specific issues such as system efficiency, information management, remote accessibility, and cross compatibility between light sources. Each series of presentations was followed by facilitated discussions and anonymous 'voting' on the importance of issues raised and agreement with points made by participants.

The fifth annual Structural Molecular Biology Summer School (SMB) was held at SSRL from August 16-20, 2004. The school focused on three synchrotron-based techniques: small angle x-ray scattering, x-ray absorption spectroscopy, macromolecular crystallography, and the application of these techniques to biological problems. This year's summer school was attended by 23 students and was lead by a team of 18 tutors. It consisted of three days of lectures, followed by a day and a half of rotating practical sessions.

In addition, SSRL staff arranged several activities as part of the 3rd Annual SLAC Kids Day on Thursday, August 19, 2004. Approximately 230 boys and girls ages 9 to 16 years registered for this event with each kid attending workshops in the morning and the afternoon and a science lecture presented by Dr. Graham George (former staff SSRL scientist, now at the University of Saskatchewan). Each participant completed a hands-on project in the mechanical, welding and electronic workshops. There were also science workshops in astrophysics, waves and biology. Other technical workshops included magnetics, cryogenics, radiation, vacuum and metrology. The most unique aspect of the SLAC Kids Day was that each kid had the opportunity to work one-on-one with a technician, engineer and/or scientist, providing a rewarding experience for both the kids and the staff volunteers.

17. Scientific and Technical Information Management 2004 DOE Assessment by Pat Kreitz

Announcement records for all appropriate scientific and technical information (STI) publication products were submitted in electronic form to DOE's Office of Scientific and Technical Information (OSTI). Overall, Technical Publications' processed documents increased 28% over last year resulting in 1590 announcements. This improvement results from an active program of extended leak outreach efforts, process improvements made in identifying leaked papers and reporting corrections, and a change to the way reprints are reported. All appropriate STI was made available on SLAC's publicly accessible web server on average within 4 hours of release notification by the Technology Transfer/Patent Review Office.

Technical Publications reports its STI publication products as preprints, preprint leaks, and reprints defined below:

Preprint	*Original manuscript submitted to SLAC for publication. When we publish preprints, we assign a preprint number and send an electronic report announcement to OSTI along with a link to the electronic version.*
Preprint leak	*Manuscript submitted to SLAC after publication elsewhere, but the original manuscript is available to SLAC. We assign a preprint number and report it to OSTI along with a link to our electronic version.*
Reprint	*Manuscript first published elsewhere—typically a journal—and the original manuscript is not available to SLAC. SSRL makes up the bulk of reprints. As required by the ethics of their scientific collaborations, SSRL scientists and users publish their papers in scientific journals before releasing them for SLAC publication. When we publish reprints, we assign a reprint number and report it to OSTI, but we do not provide a link to the text from the SLAC publications server. When the SPIRES-HEP literature database record for the paper has a link to the journal article, we link through that to the journal's version.*

In FY03, Technical Publications reported reprint announcements by calendar year to provide additional time for papers to be published in journals and subsequently processed. While investigating the new XML harvesting method this year, it became apparent that the most efficient way to report all announcement records is by fiscal year. Therefore, all records will be reported based on when they are posted to the web (preprints) or registered in the publications system (reprints). Table 1 and Table 2 reflect this change.

Table 1. OSTI Preprint Announcements

	FY01	**FY02**	**FY03**	**FY04**
Preprints	260	305	299	417
Preprint Leaks	69	207	435	438
Total preprint announcements to OSTI	329	512	734	855
Leaks as percentage of total:	*21%*	*40%*	*59%*	*51%*

Table 2. OSTI Reprint Announcements

	FY01	FY02	FY03	FY04
SSRL Reprints	57	499	176	528
SLAC-HEP Reprints	500	145	334	207
Total reprint announcements to OSTI	557	644	510	735

FY04 Accomplishments

Increased author submitted preprints and decreased leaks

This year Technical Publications reported a 39% increase in author submitted preprints, and a 16% decrease in the total number of leaks. This was accomplished in large part by focusing efforts on

- educating authors about the importance of submitting their papers to prevent leaks
- developing automated methods to make registration and submission of documents easier for authors
- and, continuing improvements to the internal workflow processes and systems involved in finding and correcting leaks

Continued efforts to establish paperless publishing

Technical Publications continued efforts to go paperless, resulted in FY04 printing and distribution costs totaling 20% of FY98 figures. These efforts included efficiently managing electronic access to STI, providing print-on-demand service, replacing hardcopy distribution with online distribution, and providing STI to the SLAC Archives and History office in electronic format only.

Researched OSTI XML harvesting and investigated federated searching

While investigating OSTI's new XML harvesting methodology this year, Technical Publications learned from OSTI that their search tool can only index and thus search single PDF documents. Due to accessibility issues, Technical Publications does not always provide full-text documents in the single file format. We are currently investigating federated searching, a method OSTI already uses on their Science.gov site. Federated searching would allow OSTI to perform full-text searches directly from our document server along with the metadata we submit to the Information Bridge database. Once the single PDF issue is resolved, we plan to implement XML harvesting or, if it can't be resolved then we will encourage OSTI to use federated searching.

Improved registration and publishing workflow

Technical Publications worked with authors and the Office of Technology Transfer to improve workflow related to registering, reviewing, and releasing SLAC's STI. As you can see in Table 3 below, these efforts significantly reduced the average processing time for documents this year.

Table 3. FY2004 Process Improvement for Document Review and Release

Processing step	Owner	Time
From registration to document submission to TechPubs	Authors	16 days (before improvements) 8 days (after improvements)
From TechPubs to Office of Technology Transfer	TechPubs	1 day
From submission to Office of Technology Transfer to receipt of patent release	Office of Technology Transfer	5 days
From receipt of patent release to posting to document server	TechPubs	1 day

We anticipate that our continued efforts, coupled with additional initiatives described below, will even further reduce processing time for SLAC documents.

FY05 Plans

Continue outreach efforts

Technical Publications will continue to develop and implement methods to educate authors on the processes involved in registering and submitting STI.

Enhance scientific publishing support for SLAC

To save time and effort for authors and Technical Publications staff in DOE STI management, we plan to continue developing the following enhancements as time and resources allow:

1. Automate creation of title pages for newly registered documents
2. Automate publication of preprint notifications on web and via e-mail
3. Allow electronic file submission at time of paper registration
4. Automate collection of keywords at time of paper registration
5. Submit author papers to arXiv
6. Automate selected internal reporting and tracking tasks

18. FY04 Progress in Linac Coherent Light Source

Fourth Generation Source Development

Project Authorization Milestones

The Project successfully completed an External Independent Review during May and June of 2004. In addition, the Project underwent an SC-81 review in August. Results of both reviews were favorable and should result in approval of CD-3A (authorization to begin long-lead acquisitions) and CD-2B (approval of project baseline) in support of planned project activities in FY2005 and FY2006.

Environment, Safety and Health

The Project carried out a preliminary safety assessment, documenting its findings in a Preliminary Safety Assessment Document. This draft document is currently under review by DOE.

Management

The Linac Coherent Light Source Project became a division of SLAC, effective 10 August 2004. As a result, the LCLS Project Director reports directly to the SLAC Director to enable better integration of LCLS priorities into SLAC activities.

A key management responsibility in the LCLS organization, Controls Systems Manager, is now borne by a world-recognized expert. As a result of filling this critical post, plans for integration of LCLS controls with the SLAC linac control system are maturing rapidly.

The integrated, resource-loaded schedule has been prepared for the entire Project as part of defining the baseline.

A Project Execution Plan and Project Management Plan have been prepared for the Project.

Scientific/Technical

LCLS accelerator researchers have developed a concept for a "laser heater" device to control the intrinsic energy spread in the electron bunch. This device, installed in the injector, will replace the superconducting wiggler originally planned for installation at the 4.5 GeV point in the linac.

The injector design has been brought to maturity. Detailed specifications have been developed for the gun laser. Modifications of the RF photocathode gun have considerably improved the field quality and power handling capability of this component. Both items are ready for release to procurement.

Comprehensive measurements of the performance of copper and magnesium cathodes have been completed; confirming that copper is the better choice for the LCLS.

A broad-spectrum study of the future capabilities of the LCLS has been published[5], describing the options for further development of the capabilities of the facility. It covers

[5] M. Cornacchia, et al., "Future Possibilities of the Linac Coherent Light Source", SLAC-PUB-10133, also published in *Journal of Synchrotron Radiation* 11, pp. 227-238 (2004)

extension of operating wavelength from the 5 nanometer range to the sub-Angstrom range. It also presents options for seeding to achieve enhanced brightness and temporal coherence. It also describes techniques for producing x-ray pulses of duration as short as 1 femtosecond. This paper describes a particularly elegant and simple way to produce short pulses, using a thin foil to make time-dependent adjustments to the emittance of the electron beam[6].

Prototype testing of the LCLS undulator has continued at Argonne National Lab. The Argonne team has successfully tested a concept for fine adjustment of the undulator field, using a "canted pole" undulator configuration. This concept also makes it possible to move the undulator about 10 cm from the beam path, an important capability for commissioning the FEL.

The Lawrence-Livermore team has developed a simplified design for the x-ray attenuator. By coordinating the operation of a gas attenuator cell with a solid attenuator, it will be possible to implement a more compact and reliable system.

The LCLS-SLAC team has initiated a collaborative effort with researchers at Cornell University to determine the feasibility of building a pixel array detector matched to LCLS performance. The ultimate goal of this collaboration is to develop a detector with sensitivity and dynamic range suitable for detection of single x-rays, along with 120 Hz readout capability. This effort will supplement additional detector development activities to be carried out as part of the LCLS experiment design effort.

"Title – 1" design of LCLS conventional facilities was completed in April. The facility design provides six experiment stations in two experiment halls to support LCLS science. The design also provides a lab/office facility for the user community and support staff. The facility layout permits the addition of a second undulator and FEL source within the initial construction. Possible future expansion to six "hard" x-ray lasers can be accomplished without loss of the facilities and function of the original construction.

Proposals for LCLS experiments and experiment stations were solicited by SSRL in a wide-reaching call to the international x-ray and laser community. The response from these communities was formidable; thirty-two letters of intent to prepare proposals, prepared by 256 researchers, were received. These letters were reviewed by the LCLS Scientific Advisory Committee in July. The outcome of the review was the identification of five major areas of research thrust:

- Coherent scattering at the nanoscale
- Pump/probe diffraction dynamics
- Pump/probe high-energy density physics
- Nano-particle and single-molecule imaging

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[6] P. Emma, et al., "Femtosecond and Subfemtosecond X-Ray Pulses from a SASE Free Electron Laser", SLAC-PUB-10002, also published in *Phys. Rev. Lett*. 92, 074801 (2004)

- Atoms, molecules and optical science

The signatories of the letters of intent will be organized into five groups which will prepare specifications for experiment programs in these areas. The specifications will be used as the basis of design for five LCLS experiment stations. SSRL will be responsible for the preparation of the design and, ultimately, the construction of these experiment stations. SLAC will seek Critical Decision 0 for construction of LCLS experiment stations.

18. FY04 Progress in Linac Coherent Light Source

The Linac Coherent Light Source (LCLS) will be the world's first x-ray free electron laser when it becomes operational in 2009. LCLS is currently in the detailed project engineering and design phase, with a construction start planned in FY2005. Pulses of x-ray laser light from LCLS will be many orders of magnitude brighter and several orders of magnitude shorter than what can be produced by any other x-ray source available now or in the near future. These characteristics will enable frontier new science (click box below to explore LCLS science) in areas that include discovering and probing new states of matter, understanding and following chemical reactions and biological processes in real time, imaging chemical and structural properties of materials on the nanoscale, and imaging non-crystalline biological materials at atomic resolution. The LCLS project is funded by the U.S. DOE and is a collaboration of six national laboratories and universities.