



# SLAC High Energy Physics Research Progress Report—FY00

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## SLAC High Energy Physics Research Progress Report – FY00

### **1. FY2000 Progress for PEP-II (John Seeman)**

PEP-II has completed its second fiscal year delivering colliding beams to BaBar. PEP-II continues to hold the world's record for luminosity and has this year delivered the world's largest data sample of high-energy physics events to a single detector. The luminosity in PEP-II has doubled in the past year to 88% of the design. This increase in luminosity has come from reducing the beam sizes at the collision point and raising the bunch currents. The integrated luminosity per day is now 121% of the design.

The data-taking run started in October 1999 and was stopped at the end of November with vacuum leaks in two high power radiation masks near the interaction region. These leaks were repaired by the middle of January and the run restarted. Since then data collection has been continuous. The present run is to end for maintenance work on November 1, 2000.

The peak luminosity in PEP-II is now  $2.64 \times 10^{33}/\text{cm}^2/\text{s}$  with 1450 mA of positrons and 650 mA of electrons in 605 bunches. In a typical day PEP-II delivers about  $135 \text{ pb}^{-1}$ . The best integrated luminosity in 24 hours is  $164 \text{ pb}^{-1}$ ,  $914 \text{ pb}^{-1}$  in 7 days, and  $3.3 \text{ fb}^{-1}$  in one month. PEP-II has delivered  $23 \text{ fb}^{-1}$  since the installation of BaBar in May 1999.

PEP-II came of age in the past year with many refinements and improvements. The accelerator has become a workhorse for delivering data to BaBar. It is now a true B-Factory.

The optical lattice functions have been optimized in both rings. Beta  $y^*$  for both rings has been set to 1.25 cm which is better than the design. The beam orbits have been corrected within design limits. The beam-beam tune shift values are equal to the design in the vertical plane (about 0.03) and greater than the design in the horizontal (about 0.05).

The bunch-by-bunch feedback systems in both rings stabilize the beam currents to well beyond the present operating levels. There are some heating issues related to the feedback kicker loads and associated couplers and cables. These issues are being addressed.

The detector backgrounds have been suppressed by beam scrubbing and are below (but near) the average radiation doses allowed from the machine to BaBar extrapolated over 10 years. Background spikes in BaBar cause several beam aborts each day mainly from fast but short-term doses to the silicon tracker. A new low pressure vacuum chamber in the HER is being fabricated to suppress these aborts.

Injection has become very efficient at near 100% on a typical day. The filling times are 3 minutes in top-off mode and about 8 to 10 minutes from empty machines. The linac injector has been remarkably stable. Beam aborts due to lost injected particles can

sometimes be a problem. Additional concrete shielding is being installed to reduce these aborts.

The rf system has been stable supporting beam currents of 1.72 A of positrons and 0.92 A of electrons. These systems are now well proven. However, for various reasons, there are still five to eight beam aborts per day cause by the rf system. The various causes of these trips are under investigation.

The positron beam has been observed to enlarge transversely at high currents ( $>1$  A). The enlargement is due to the newly discovered electron cloud instability. Solenoid windings have been added to the straight sections to suppress the electron multipacting and have definitely reduced the beam enlargement. The luminosity has, therefore, increased coming from the reduction of the positron beam size at high currents. Likewise, the optimum bunch pattern used during collisions changes as more solenoids are wound to adjust to the electron cloud density. The solenoid winding of the straight section beam chambers has been done every repair day and is at present about 95% finished. There are about 500 m of vacuum chamber coils wound so far. The attention has now turned to the contribution of the LER arcs to the electron cloud effect. Both solenoid and transverse fields are being considered as a cure. Recently, short test magnets have been installed and beam tests are underway. There are about 1100 m of LER Arc chamber to cover.

In summary, over the past year the luminosity in PEP-II has doubled to  $2.64 \times 10^{33}$  /cm<sup>2</sup>/s. PEP-II remains the world's record holder. Over 23 fb<sup>-1</sup> integrated luminosity has been delivered to BaBar, again the world's largest data sample. The best-integrated day is 164 pb<sup>-1</sup> which is 121% of the CDR design integrated luminosity day. There are development plans underway to provide new equipment including two new rf stations to allow the luminosity to reach  $10^{34}$  /cm<sup>2</sup>/s by the end of calendar year 2002.

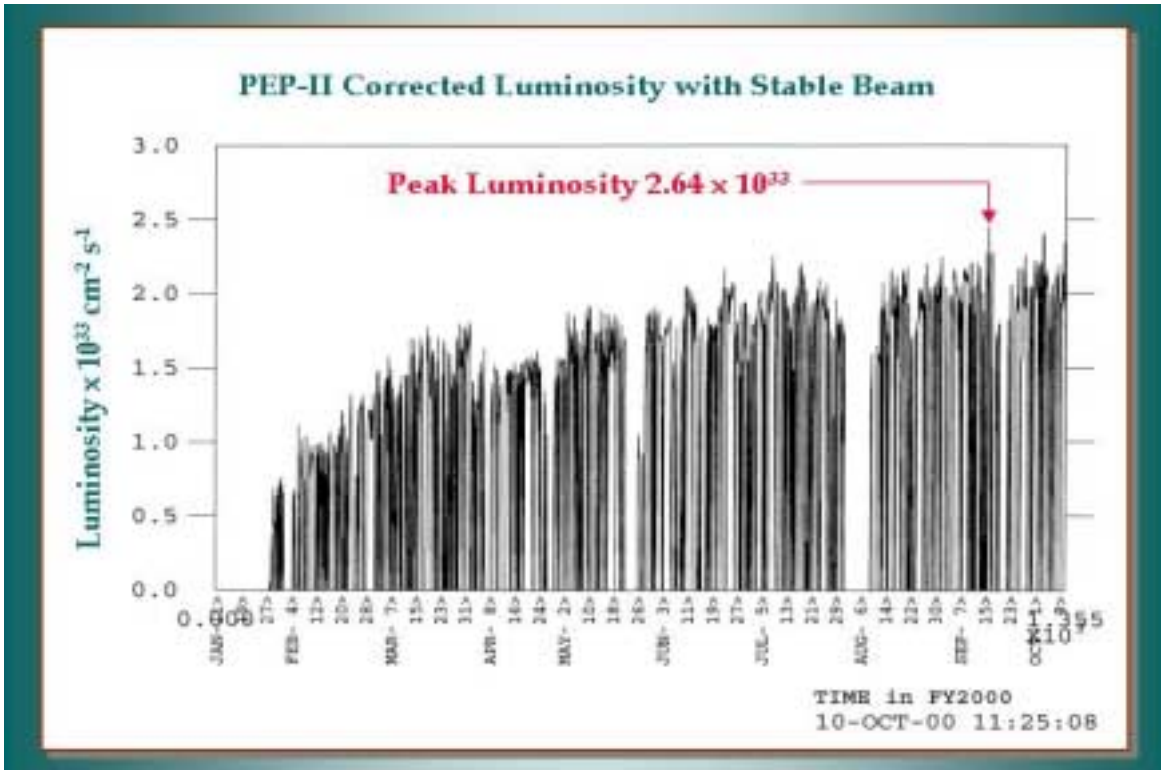


Figure 1 PEP-II luminosity since January 2000.

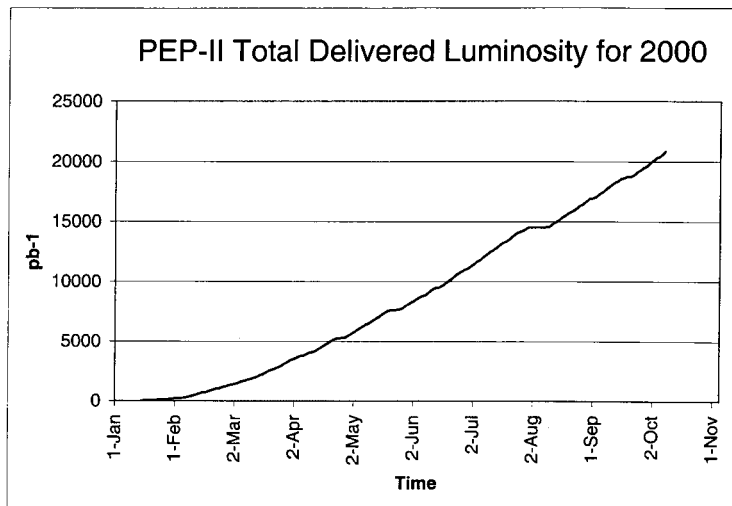


Figure 2 Integrated luminosity delivered by PEP-II since January 2000. PEP-II delivered an additional  $2 \text{ fb}^{-1}$  to BaBar in FY1999.

## 2. FY 00 Progress in BaBar at Pep II (Stew Smith)

The BaBar experiment is performing a comprehensive study of CP violation in the decays of B mesons. With a  $4\pi$  detector and the asymmetric energies of the PEP II beams, BaBar is singularly able to measure precisely the time-dependent asymmetries that in turn lead to determinations of the phases in the CKM matrix. The theoretically unambiguous processes  $B_0 \rightarrow \psi K_s$  will be used to extract  $\beta$ , the most easily measured of these phases. Asymmetry measurements in more rare processes will be used in the future to measure the phase  $\alpha$  and eventually infer the third phase  $\gamma$ . BaBar's very large data samples over the next few years will break new ground in searches for rare decays of B's, and in precision measurements in the charm and tau sectors.

The BaBar program swung into full operation in FY 2000, the detector having been commissioned in FY 1999. Approximately 20 million B events having precise vertex information (approximately twice as many as in the previous world sample of comparable data) were accumulated at the Y(4S), corresponding to an integrated luminosity of  $\sim 20 \text{ fb}^{-1}$ . By the end of FY2000, the accelerator and experiment were operating at or close to the design daily luminosity of  $135 \text{ pb}^{-1}/\text{day}$ . The first physics results from BaBar, based on  $\sim 8 \text{ fb}^{-1}$  of data, were presented in July 2000 at the International Conference on High Energy Physics in Osaka, Japan.

**Detector and computing issues.** By the end of FY 1999 all detector systems had been commissioned during the first data run, in which a data sample of  $\sim 1.2 \text{ fb}^{-1}$  was recorded. A 2-week shutdown then took place in Oct 1999, the main purpose of which was to complete the installation of the DIRC quartz radiator bars (the FY 1999 run took place with only 5 of the 12 bars installed because of production delays at the vendor). Other important tasks completed during this shutdown included the installation of water cooling of the Instrumented Flux Return (IFR), and electronics modifications to reduce noise in the Electromagnetic Calorimeter (EMC). The FY 2000 run began on October 17, but was prematurely curtailed in November by vacuum problems in PEP II. Nevertheless the data taken in this month were invaluable for calibrations and for exercising the computing system. Running resumed in mid-January and continued steadily till the end of FY 2000. Analysis studies confirmed that the performances of the Silicon Vertex Tracker, Drift Chamber, DIRC, and EMC have met or are approaching the specifications of the TDR. However, the efficiencies of the resistive plate chambers in the IFR are lower than designed, and have been decreasing further; this will present a serious issue within a year or so unless the system is stabilized. The collaboration has set up a task force and R&D plan to understand and fix this problem.

To respond to the exciting prospect of steadily increasing PEP II luminosities -- up to 5 times design within the next few years -- the BaBar collaboration conducted an extensive study during the past 8 months to determine what improvements will be necessary to the detector and to the computing system. The resulting plan was submitted to an external technical review that took place on Oct 11/12, 2000. The review committee strongly supported the plan, while pointing out some details that still need to be developed. This

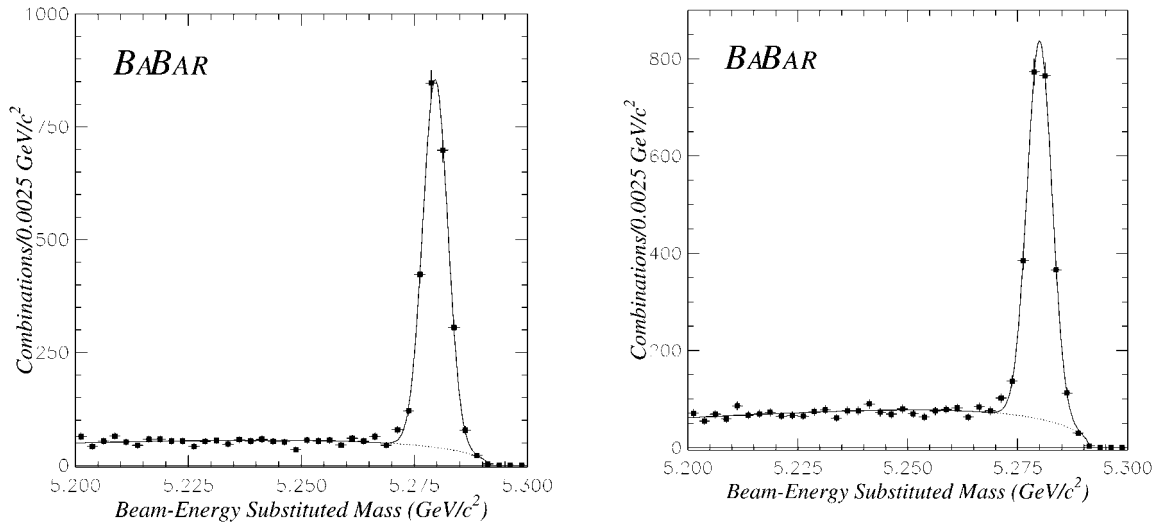
plan will now be submitted to the International Finance Committee in December to secure the needed funding.

**Physics analysis and results.** Enormous activity and progress took place in the areas of physics analysis, including the simulation of physics and background processes in the detector, the generation of large samples of Monte Carlo events, and the processing of both data and Monte Carlo event samples to extract physics results. Approximately 12 % of all data ( $\sim 2.4 \text{ fb}^{-1}$ ) were taken at a center of mass energy  $\sim 40 \text{ MeV}$  below the  $Y(4S)$  in order to understand the continuum events and subtract them from the sample of desired B decays. Thirteen papers containing preliminary results were submitted to the Osaka conference; the results were also presented in 7 talks. The topics included lifetime measurements of charged and neutral B's;  $B^0$ - $B^0$  mixing measurements; studies of radiative penguin decays to  $K^{*0} \gamma$  and  $K^{(*)0} \ell\ell$ ; two-body and three-body charmless decays, charmonium decays, exclusive decays to charm, and a first measurement of the CKM parameter  $\sin 2\beta$  via the time-dependent asymmetry in  $B \rightarrow \psi K_s$  and  $B \rightarrow \psi' K_s$  decays. Many of these measurements are already competitive with previous individual measurements and/or world averages, and will greatly improve in the next few months with larger data samples, better understanding of systematic errors, and the exploitation of additional decay modes to improve statistical uncertainties. Some of the highlights are now summarized in the figures below. First, the main results presented at Osaka are summarized in Figure I, along with extrapolations to the expected results from the full FY2000 data:

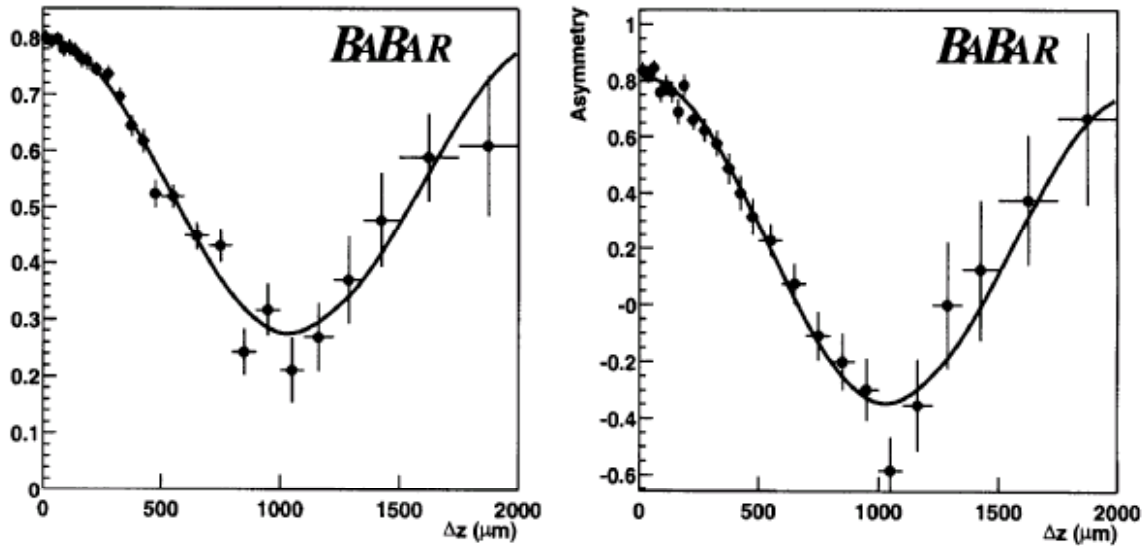
Measurement	Osaka prelim.	Y2K stat.	Y2K syst.	world average [15]
$\tau_{B^0}$ (ps)				$1.548 \pm 0.032(2.1\%)$
hadronic	$1.506 \pm 0.052 \pm 0.029$	$\pm 0.030(2.0\%)$	$\pm 0.022(1.5\%)$	
semileptonic		$\pm 0.016(1.1\%)$	?	
$\tau_{B^+}$ (ps)				$1.653 \pm 0.028(1.7\%)$
hadronic	$1.602 \pm 0.049 \pm 0.035$	$\pm 0.029(1.8\%)$	$\pm 0.027(1.7\%)$	
semileptonic		$\pm 0.022(1.4\%)$	?	
$\Delta m_d$ ( $\hbar \text{ ps}^{-1}$ )				$0.478 \pm 0.018(3.7\%)$
hadronic	$0.516 \pm 0.031 \pm 0.018$	$\pm 0.019(3.7\%)$	$\pm 0.013(2.5\%)$	
semileptonic	$0.508 \pm 0.020 \pm 0.022$	$\pm 0.011(2.2\%)$	$\pm 0.018(3.5\%)$	
dilepton	$0.507 \pm 0.015 \pm 0.022$	$\pm 0.011(2.2\%)$	$\pm 0.010(2.2\%)$	
$\sin 2\beta$	$0.12 \pm 0.37 \pm 0.09$	$\pm 0.2$	?	$0.9 \pm 0.4$

We conclude with a few plots indicating the quality of the data, extracted from papers submitted to the Osaka Conference. Figure 2 shows the data used for the B lifetime measurements, Figure 3 gives the mixing results, Figure 4 shows the samples of charmless 2-body decays, and finally Figure 5 shows the data sample used to extract our result on  $\sin 2\beta$ .

We illustrate the quality of the data with a few sample plots.



**Figure 2:** Beam-energy substituted mass  $m_{ES}$  for all the hadronic modes for (a)  $B^0$  and (b)  $B^+$ . The total numbers of signal events in all  $B^0$  and  $B^+$  modes are  $2210 \pm 58$  and  $2261 \pm 53$  respectively.



**Figure 3:** Time dependent asymmetry between unlike-sign events ( $l^+, l^-$ ) and like-sign events ( $l^+, l^+$ ) + ( $l^-, l^-$ ) for (a) the inclusive dilepton sample and (b) the dilepton sample enriched with soft pions.

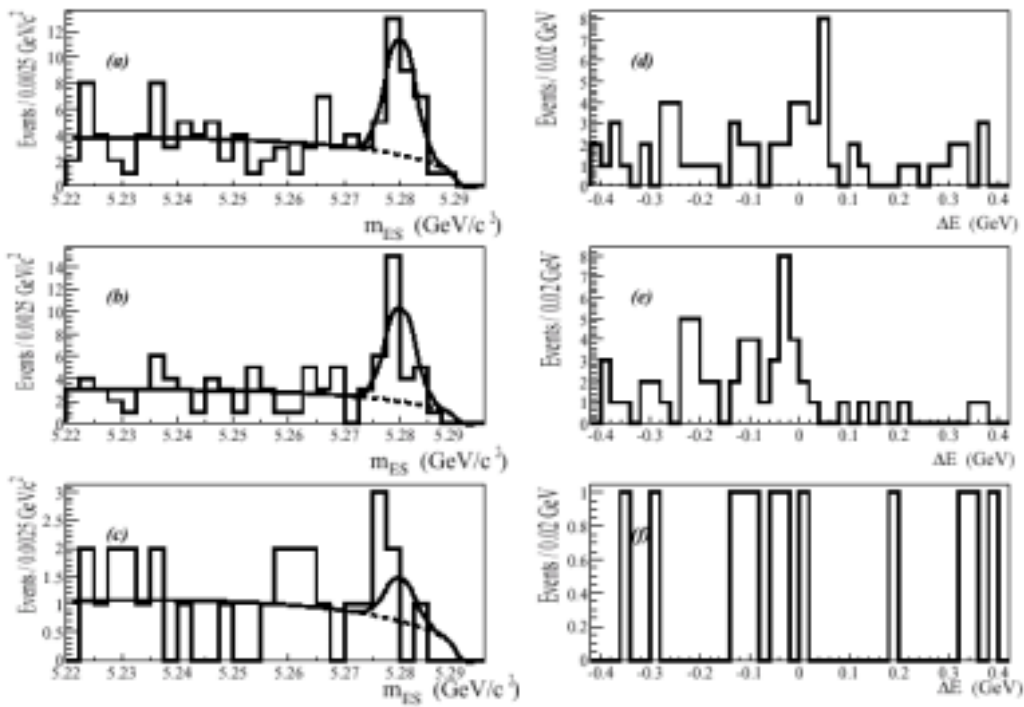


Figure 4: Mass distributions for the samples of B decays to (a)  $\pi\pi$ , (b)  $K\pi$ , and  $KK$ . The classification is done using the DIRC particle identification system.

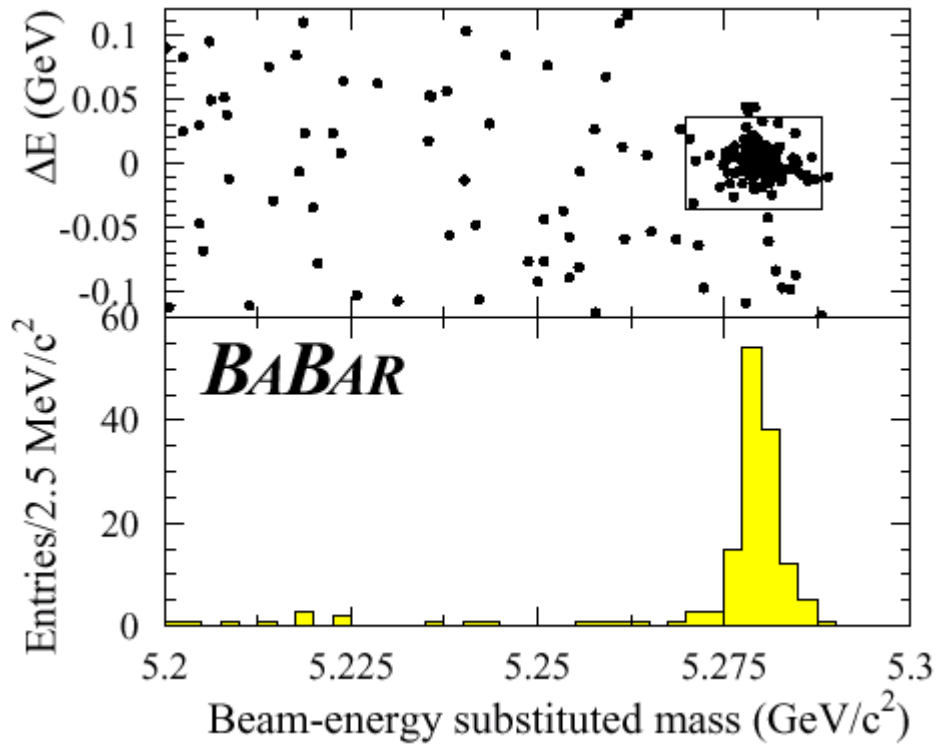


Figure 5: Energy differences  $\Delta E$  w.r.t the center-of-mass beam energy  $E$ , vs. the beam-energy-substituted mass, for candidates in the sample of  $B \rightarrow J/\psi K_s$ . Events inside the box indicated in the figure were used in the measurement of  $\sin 2\beta$ .

### 3. FY 00 Progress in E155X – Spin Structure (Steve Rock)

The deep inelastic spin structure functions of the nucleons,  $g_1$  and  $g_2$ , depend on the spin distributions of the partons and their correlations. The function  $g_1$  can be primarily understood in terms of the quark parton model (QPM) and perturbative QCD with higher twist terms at low  $Q^2$ . There exists no such picture for  $g_2$ . Feynmann claimed that the transverse structure function  $g_T = g_1 + g_2$  had a simple parton interpretation in terms of the transverse polarization of the quark spins which is proportional to quark masses. However,  $g_2$  is sensitive to subtleties of the quark and gluon spins. These include higher twist effect such as quark-gluon correlations, which are not easily understood in perturbative QCD (pQCD) where such effects are not included. By interpreting  $g_2$  using the operator product expansion, it is possible to study contributions to the nucleon spin structure beyond the simple QPM.

Data taking took place in FY99. Electron beams with energies of 29.1 and 32.3 GeV, with longitudinal polarizations of  $(81.3 \pm 2.0)$  % struck transversely polarized  $\text{NH}_3$  or  ${}^6\text{LiD}$  targets. The beam helicity direction was randomly chosen pulse-by-pulse. Scattered electrons were detected in three independent spectrometers centered at  $2.75^\circ$ ,  $55^\circ$ , and  $10.5^\circ$ . The two small angle spectrometers were the same as in SLAC E155, while the large angle spectrometer had an enhanced detector system.

The main work in FY00 was the analysis of the data and presentation of preliminary results at conferences. Three graduate students have been primarily involved in the analysis along the post doc and a few senior people. The SLAC AIX computers have been kept running for this analysis so that we would not have to revamp code that has its origins many years ago on E154. The analysis consists of calibrating our lead glass shower counters for energy and position resolution, optimizing the tracking analysis to maximize efficiency, correcting for known hardware problems, determining the target polarization and composition, and radiative corrections. Data Summary Tapes have been completed and the analysis now consists of fine-tuning cuts and parameters to minimize backgrounds and the final round of radiative corrections. Final results are expected within six months.

#### 4. FY00 Progress for the SLC Large Detector (SLD) (Peter Rowson)

SLD completed its last scheduled run in June 1998, reaching the goal of 350 K Z's for the run. This run added 350 K Z's to the 50K Z's with the new vertex detector VXD3, and to the 150K Z's taken with the old vertex detector.

The past fiscal year has seen continuing demonstrations of the power of VXD3, particularly when combined with the polarized electrons of SLC and the particle identification of SLD. There has been substantial analysis progress and publications on many fronts.

Since 1995, the SLD has provided the single most precise and reliable determination of the electroweak mixing angle, which in turn is the most sensitive probe of higher order corrections in the Standard Model. By testing the Standard Model to high precision, and including the present top quark mass data from FNAL, one is able to constrain the Standard Model Higgs mass and search for the effects of new physics. The measurement determines the left-right polarization cross section asymmetry in Z boson production (ALR), a method with inherently tiny detector systematic effects: using the entire 1992-1998 dataset the total error presently remains dominated by statistics (1.3% compared to a 0.65% systematic error).

The SLD analysis for ALR is now complete and is published (PRL,84,5945 (2000)). The uncertainty of the running SLD average is 1.5%, which translates into a determination of  $\sin^2\theta_{\text{eff}} = 0.23097 \pm 0.00027$ . This result is combined with the SLD measurement of lepton left-right-forward-backward asymmetries, also a final result and as of this writing sent out for publication (to PRL), to yield our current overall average  $\sin^2\theta_{\text{eff}} = 0.23098 \pm 0.00026$ . This number is often compared to the global LEP result, which averages over leptonic and hadronic forward-backward asymmetry measurements and tau polarization results, with a present error of  $\pm 0.00023$ . Interestingly, the assumption of fermion universality inherent in the LEP average has been brought into question by recent data from both sides of the Atlantic regarding the Z to b quark neutral current coupling,  $A_b$ , as mentioned below. The SLD result, by itself, provides an interesting upper bound on the mass of the Standard Model Higgs boson that is more stringent than the worldwide global fit result. The most conservative number is obtained using a particular choice for  $\alpha(M_Z^2)$  (A. D. Martin et. al., hep-ph/0008078), and is 147 GeV/c<sup>2</sup> at 95% confidence.

By virtue of the SLC beam polarization and small and stable collision region, and the high precision and efficiency of the SLD vertex detector, the SLD collaboration is now providing several of the world's best heavy flavor electroweak measurements. These include measurements of  $A_b$  and  $A_c$ , the bottom and charm flavor analogs to ALR (which measures the parity violation of the electron neutral current,  $A_e$ ). Only the SLD experiment directly measures these quantities. SLD also provides competitive measurements of  $R_b$  and  $R_c$ , respectively the bottom and the charm fractions of the hadronic cross-section. Both results confirm the LEP results that are in agreement with the Standard Model. However, as mentioned above, the precision  $A_b$  results from LEP,

which are indirect, deviate from the Standard Model presently by about 2.5 sigma, while the direct results from SLD are consistent.  $R_b$  is mainly sensitive to the left-handed couplings, and  $A_b$  to the right-handed couplings, but there is little theoretical guidance to explain such an effect. It is perhaps more likely that these LEP deviations are due to some combination of statistical fluctuations and unknown systematic effects. The present situation is somewhat troubling, and indicates that purely leptonic data should probably be used to extract the weak mixing angle.

The large 1997-98 data set is also producing world class results in B physics. Experiments around the world are trying to measure  $\Delta m_s$ , the oscillation frequency in  $B_s$  mixing, so far without success. SLD reported  $B_s$  mixing limits at the 2000 summer conferences. The experiment is currently sensitive up to ms about  $14 \text{ ps}^{-1}$ ; this will be extended to  $\Delta m_s = 16 \text{ ps}^{-1}$  with some analysis improvements in the next few months, which will surpass LEP sensitivity. The ratio of  $B^+$  to  $B^0$  lifetimes were determined to be  $1.06 \pm 0.04$ , indicating that lifetime differences in the B sector are smaller than with charm, but that the  $B^+$  may be the longer-lived, as expected. SLD is measuring the branching ratio  $BR(B \rightarrow D\bar{D}X)$ , which may help explain why the semi-leptonic branching ratio is anomalously low, a long standing puzzle in B physics. Using a technique which exploits the decay vertex topology and kaon identification, we measure  $Br(B \rightarrow D\bar{D}X) = .188 \pm .025 \pm .059$ . This measurement relies on the superb resolution afforded by VXD3, and will be improved with additional techniques to become the world's best.

SLD exploits its unique tool kit (polarization, precision vertexing, and particle identification) to test QCD and study hadronization. A new, precise measurement of the B hadron energy spectrum has produced the first clear indication that the shape of the spectrum disagrees with current Monte Carlo predictions. SLD has just published a comprehensive study of inclusive particle production of  $\pi$ , K, P,  $K^0$ , and  $\Lambda$ 's. Gluon jets have been isolated in double-b-tagged  $b\text{-}\bar{b}$  g events and their energy spectrum measured. This measurement allows limits to be set on anomalous couplings. The same events can be used to study parity violation in Z decays and detailed searches for CP and T violation in three-jet events. SLD's particle identification system has been put to good use studying charge and rapidity correlations between various hadron species in hadronic events. The superb vertexing capability of VXD3 has been exploited with a new measurement of the fragmentation of the gluon to  $b\bar{b}$  pairs.

In summary, FY00 has seen the completion of several important SLD analyses, with significant progress on all fronts. SLD is contributing world class measurements to QCD, results in B-Physics that are both unique and the world's best, and an electroweak precision determination of the weak mixing angle that has set the standard in the field for several years and which indicates that the Standard Model Higgs boson should be relatively light. The results have made a significant contribution to particle physics.

## **5. FY00 Progress in Particle Astrophysics Program (William Althouse and Elliott Bloom)**

A program in Particle Astrophysics is the charge of the GLAST Project Group and Group K in the research division. Currently, the GLAST Project group's activities center on GLAST, while Group K's efforts encompass GLAST (focusing on the Tracker, data analysis software, beam tests at SLAC, and general science support), the USA experiment, and R&D for future activities in Particle Astrophysics.

### **The GLAST Effort**

GLAST will be the next-generation space-based gamma-ray telescope designed to provide major advances in observational capability of cosmic sources of gamma rays in the 20 MeV to 1 TeV energy range. Data from the instrument will offer a broad range of physics topics of interest both to particle physicists and astronomers/astrophysicists including, the mechanisms of cosmic particle acceleration, the physics driving the mysterious gamma ray bursts, and the nature of dark matter. This program is primarily supported by the DOE (SLAC) and NASA, as well as with funds from France, Italy, Japan, and Sweden. There is also some support from the U.S. Department of Defense (NRL), the NSF, and Germany (MPE).

During the summer and fall 1999, the GLAST collaboration, an international collaboration of scientists from US (Stanford campus and SLAC, Goddard Space Flight Center, University of California at Santa Cruz, University of Washington at Seattle, US Naval Research Laboratory) and foreign (France, Italy, Japan, Sweden) institutions developed a proposal to build, test and deliver a large area gamma ray detector for NASA's Gamma-ray Large Area Space Telescope (GLAST) mission, which is planned to be launched in late 2005. The project would be managed by SLAC.

The GLAST Large Area Telescope (LAT) flight instrument proposal was submitted to NASA in November 1999 in response to NASA Announcement of Opportunity (AO) 99-OSS-03. Peer reviewers competitively evaluated proposals submitted in response to the AO. NASA announced the selection of the Stanford team proposal at the end of February 2000. DOE approved the LAT equipment development project at SLAC a short time later.

A project team was assembled at SLAC and at the participating institutions during FY00. The Project Office at SLAC is now fully staffed and forms the main part of the GLAST Project Group.

A technical specification for the LAT instrument was prepared, to be responsive to the mission science requirements. Work on the supporting LAT subsystem technical specifications was initiated. These documents will collectively define the project technical baseline. The LAT instrument specification was reviewed and accepted by the GLAST mission Project Office at NASA's Goddard Space Flight Center, and was subsequently presented at the instrument and mission System Requirements Review, a significant program milestone.

Besides continued development of preliminary designs, the LAT team carried out two important trade studies this year. The first one set the final technical configuration for the LAT Tracker sensors (silicon strip detectors), because procurement of these long-lead items needed to be initiated this year. The second study settled the configuration of converters (used for pair-conversion of incident gamma rays) in the Tracker.

Extensive beam tests of the GLAST beam test engineering model (BTEM) were made in December 1999 and January 2000. This was a major effort of the GLAST collaboration, and the personnel. This test came broadly from our international collaboration with about 60 collaborators participating in the data taking and subsequent data analysis. A number of archival publications have already resulted from this effort, with a major publication on the performance of the BTEM soon to be submitted for publication.

A considerable amount of effort went into placing the project effort on a sound programmatic footing. Work was initiated to set up an integrated cost/schedule tracking system and to establish formal cost and schedule baselines. Draft Statements of Work for the various participants and Memoranda of Understanding between participating institutions were prepared. Draft international agreements with the international partners were prepared, and an Implementing Agreement between DOE and NASA was drafted and is being negotiated by the two agencies.

### **USA Experiment**

USA (Unconventional Stellar Aspect) experiment is a satellite x-ray timing telescope designed to measure the energy distribution and time structure of the x-ray flux from the 30-40 brightest x-ray sources in our galaxy and nearby galaxies.

The USA experiment was successfully launched on February 23, 1999 aboard the US Air Force ARGOS satellite. USA science operations began in May 1999. A couple of months after science operations began, two of the redundant proportional wire chamber X-ray detectors were lost due to a micrometeorite impact, halving the effective area of the instrument. Since that time, the telescope has continued to function with no further degradation in the hardware. The observing program has continued over the year with massive amounts of data being brought from space to NRL to SLAC for analysis by SLAC personnel. This data presents exciting opportunities. The NRL colleagues have been working hard to reduce the data, calibrate the instrument and continue the physics results flowing. The experiment is pointed at desired astronomical sources via instructions prepared by the NRL/SLAC collaboration on a weekly basis, as guided by the USA science working group that meets via telecon once per week. These instructions are prepared well in advance of a daily upload to the USA instrument by the Air Force crew responsible for "flying" USA at Kirtland Air Force base, Albuquerque, New Mexico. SLAC personnel have a major responsibility for deciding on the USA science program. Over 3 mega seconds of data from celestial X-ray sources are now in our data base from USA and will be supplemented by data from other X-ray satellites such as RXTE, Chandra, and XMM. As long as USA is operational it will be possible to continue

to seek coordinated observations with ground telescopes radio, IR, optical, and high-energy gamma ray bands. This data will take a number of years to analyse and publish.

A number of papers were presented at conferences on USA progress and preliminary results. One journal paper has been accepted and will be published soon, and work is ongoing on several more.

### **Other Particle Astrophysics**

Two papers on Gamma ray bursts, and a paper on Black hole candidate Cyg X-1, were accepted for publication in the Astrophysical Journal. This work was based on archival data from BATSE (GRB) and HEAO A-1 plus RXTE (Cyg X-1). One Stanford Ph. D. thesis was completed on Gamma Ray Bursts (BATSE data).

With the recent arrival of Dr. Greg Medejski (from Goddard Space Flight center and the University of Maryland) as a permanent physics staff member in the GLAST Project Group, we expect to greatly expand the use of guest observations and archival data from ongoing and past X-ray and gamma-ray missions.

Exploration of possible future Particle Astrophysics projects is ongoing. Some projects with potential interest are Constellation X, a next generation X-ray imaging experiment currently under development at NASA, LISA, a space based gravitational wave experiment currently under development as a joint ESA/NASA project, and OWL, a space based very high energy cosmic ray experiment (energies up to  $10^{21}$  eV), currently under development as a joint ESA/NASA project.

## **6. FY00 Progress in E158 (Emlyn Hughes)**

During FY00 the E158 experiment progressed from the conceptual design stage into that of a full construction project. All detailed designs have been completed or are near completion. Installation of the major components such as the beamline, beam monitoring, the spectrometer magnets and the detector assembly is proceeding rapidly. The large 1.5 meter liquid hydrogen target and refrigerator construction is finished and the target has recently been cold-tested. Hundreds of copper pieces for the water-cooled spectrometer collimators are now being machined in the SLAC shops. Assembly of this state-of-the-art high radiation collimator system has begun in the experimental hall.

The polarized source group has recently successfully activated a strained GaAs cathode in the gun test lab. The installation of this polarized gun on the linac is planned for the beginning of November 2000. During FY00, a large effort on controlling helicity-correlated laser systematics was undertaken, and it is now believed that this project is ready for the first data collection period in 2001. An active feedback between the electron beam diagnostics and the laser optics is now being commissioned. The first full scale test of this laser feedback project will be performed in a one week dedicated 1 GeV beam test during the first week of November 2000.

First simulations of the electron beam transport optics have been performed. And the electronics for the beam position monitoring in the beam transport line has been upgraded to handle the higher required resolution on beam position and charge measurements.

Other noteworthy developments during FY00 include a successful test beam in the FFTB used as a check out of a new small quartz tube detector. This scintillator-style detector is particularly sensitive to the passage of charged particles and insensitive to background from photons. This technology developed by the University of Massachusetts group will be used to calibrate the Moller detector during the experiment. In addition, the construction of all the detector segments of the main copper-fiber Moller detector was completed in FY00. Final machining and assembling of this detector at Syracuse will be completed by November of 2000 and then shipped to SLAC for installation. The Saclay group has ordered and designed the pion detector which is a relatively small detector package consisting of 10 large quartz bars. This system should be complete and installed in December 2000.

The schedule for the first E158 data collection periods has now been finalized. The experiment will commission and calibrate the spectrometer and detectors during a dedicated one month run with a low current beam in January 2001. Following this test, the first collection of polarized physics data will occur in March and April of 2001. It is hoped that this data will provide the first publication of a physics result discussed below. One year later, in 2001, a second data and final data collection period is planned.

The goal of the E158 experiment is to perform a precision measurement of the electroweak mixing parameter  $\sin^2\theta_w$  at low  $Q^2$ . For the first run in spring 2001, the goal

is to collect enough data to achieve a precision of 0.002 on  $\sin^2\theta_w$ . This result would already represent the most precise measurement of this parameter at low  $Q^2$ . The competitors come from neutrino scattering at Fermilab and atomic parity violation measurements at the University of Colorado. After the second running period in 2002, it is hoped that the experiment will have achieved its proposal goal of measuring  $\sin^2\theta_w$  to a precision of 0.0008. Combined with precision results from LEP and the SLC, this would establish definitively the running of  $\sin^2\theta_w$  with  $Q^2$  and test via radiative corrections for possible signatures of new physics.

Finally, it is noteworthy that the E158 Collaboration has grown significantly over the past year. The collaboration now consists of 52 physicists from 11 institutes from the US and France. The experiment also has four PhD students who will earn their degree on the experiment.

## 7. FY00 Progress for the Next Linear Collider R&D (Albe Larsen)

This year has been exciting for the NLC collaboration. Fermilab has joined the collaboration as a strong partner with the NLC deputy program manager resident at Fermilab. Research programs have been initiated in several areas that draw on Fermi's expertise. Work toward the NLC has focused in the following areas: 1) further evaluation of strong management tools to allow accurate project cost, schedule, and risk assessments; 2) development of enabling technologies especially rf power delivery where work on klystrons and solid-state modulators is critical; 3) optimizing design of structures that form the tunnel through which the positrons and electrons will travel, and extending studies of techniques to manufacture these structures; 4) development of cost-effective optics decks including beam-position monitors, magnets and magnet movers; 5) reexamination of final focus requirements; 6) evaluation of permanent magnets as possible candidates for many of the NLC electromagnets, offering the possibilities of both initial cost and operating cost reductions; 7) industrialization of structures manufacture. Collaborative efforts continue in the US with the Lawrence Berkeley and Lawrence Livermore National Laboratories, internationally with the KEK National Laboratory for High Energy Physics in Japan, the University of British Columbia in Canada, and Brunel University in Great Britain, and through a number of DOE SBIR awards, which have increased in total number and in the range of technologies being explored.

The basis of the NLC design is found in the *Zeroth Order Design Report*<sup>1</sup> published in 1996. Since then considerable work has been done to flesh out and improve the design. In the past year, following the Lehman review, concerted design evaluation and refinement to reduce costs have had major emphasis.

Achievements in the last year include modifications or redesign of most systems and machine areas with a focus on cost reduction. Lattices throughout the machine have been updated to follow the machine developments and include more detailed descriptions of diagnostics, dump lines and access points. In the injector region, the energy of the second bunch compressor system was lowered to further reduce the system cost. Other configurations are under study including a centralized injector and possible use of C-band rather than S-band for the injector linacs to reduce system length. In the main linac, the XP-1 75 MW X-band klystron was tested successfully at a pulse length of 3  $\mu$ s, twice the original specification of 1.5  $\mu$ s. This allowed a new layout for the rf system, which reduced the number of klystrons and modulators by a factor of two. Lower beam current and slightly better structure performance allowed the linac to be shortened by roughly 8%.

In the beam delivery region, the collimation system has been completely redesigned to reduce the system length by a factor of two. Experimental studies of collimator

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<sup>1</sup> The NLC Design Group, "Zeroth Order Design Report for the Next Linear Collider," LBNL-5424, SLAC-474, UCRL-ID-124161, UC-414, May 1996.

wakefields have begun using a new wakefield test setup installed in the SLAC linac. The initial results indicate that the wakefields are significantly less than predicted theoretically, but consistent with 3-D MAFIA electrodynamic calculations. These studies will continue through FY2001. A prototype 'consumable' collimator, which can be rotated to a new position if damaged by the beam, is being constructed.

In the final focus, a novel optics design has been developed which reduces both the overall length and the number of magnets in a system that is capable of reaching higher beam energies – the best of all worlds. The old design required a length of 1.8 km for a beam energy of 750 GeV while the new design can focus 2.5 TeV beams in a 700-meter length! To take full advantage of this new design, an alternative layout of the two interaction regions is being considered where one region would be dedicated to 'low' energy collisions, between 90 and 500 GeV in the center-of-mass, and the other would be for 'high' energy collisions with the capability of extending from 250 GeV to 5 TeV in the center-of-mass.

Another potential cost reduction under study is the use of permanent magnets where possible throughout the NLC. This would have the added benefits of increasing the reliability of the magnet systems and reducing potential vibration sources from the cooling water needed for electromagnets. Prototype permanent magnets have been constructed at FNAL and will be measured there and at SLAC. A concern with the permanent magnets is the stability of the magnetic center when the strength is varied. Tight stability is required for present beam-based alignment techniques but alternative approaches are under study to relax this requirement.

There have been a number of developments in the simulation and modeling codes including a high-performance parallel version of the Linear Accelerator Research (LIAR) code and of the simulation code to study the fast beam-ion instability, a potential limitation in the damping rings. The NLC version of the Methodical Accelerator Design (MAD) code that includes beam acceleration has been adopted by CERN who will support future modifications and releases. Finally, a code management system, CVS, has been installed for the NLC lattice files and simulation codes to provide better version release control.

Electrical systems work included development of a solid-state modulator to achieve improved energy efficiency, higher reliability, smaller size and lower cost. This work, performed together with LLNL and Bechtel Nevada staff has led to prototype construction, with prototype tests on a partial unit (10-Stack) started in the first quarter of FY00 at low power, and continuing through the fourth quarter with the stack driving a real klystron load (5045) in the SLAC Linac. In addition, a full-scale prototype has been fabricated and assembly started in the third quarter. Full-scale tests on dummy loads are scheduled for the first quarter of FY01. DC magnet power system architecture has been reworked to optimize efficiency and lower system construction and operating costs. Significant cost reduction was accomplished.

Global Controls Systems specification development and optimized controls architectures have been advanced for all major NLC subsystems primarily through studies of new systems and new commercial developments in network architectures. A major effort continues to define requirements. Real-time data requirements are being addressed through new network and controls developments supported through a DOE SBIR program. Models for overall hardware and software architectures are being studied and prototype development has been advanced for the most critical instrumentation and controls subsystems. The low-level rf system to control dynamically and correct the high-power rf drive system has undergone prototype tests for digital detection of phase and amplitude using the ASSET test facility in the main linac. The timing system has been bench prototyped successfully to prove the novel fiber optics and laser technology can achieve picosecond accuracy synchronization as required over the entire accelerator complex. Beam position monitors that drive feedback systems to control the beam position to the micron accuracy needed to achieve design luminosity have been advanced through studies of signal capture and digitization, demonstrating the required signal-to-noise performance. This effort includes advancing a custom analog sampling chip design through a second prototype that is now being tested. Advances have been made in development of non-contact radiation-hard position sensors for magnet movers.

Major cost reduction is achievable if active electronics can be placed in the accelerator tunnel, thereby eliminating massive cable plant and the associated hardware and installation costs. Tunnel radiation models based on a tubular wall electronics enclosure have been studied in detail by Radiation Physics and demonstrate feasibility of using off-the-shelf, non-radiation-hardened electronics in the main linac tunnels. Other areas are more problematic. A tunnel enclosure mock-up has been prototyped and a new approach to vacuum pump electronics has been conceptualized and prototype studies started.

Progress continued in obtaining industrial sources of supply for key NLC components. An SBIR recipient has received and installed a two-spindle automatic machine tool that will perform both lathe and mill operations on both sides of the part without removing the part from the machine. This machine will be used to fabricate prototypes for the one-million precision copper cells needed for the 500 GeV version of the NLC. The first prototype of the structure design for the NLC, the rounded, damped, and detuned structure (RDDS1), was also built and tested successfully by a team effort at KEK and SLAC. Aside from some easily avoidable deformation due to subtle thermal mismatches that occurred during bonding and brazing, the structure performed as intended. The dimensional accuracy on the copper cells for the structure was actually better than that required for the NLC. One of the suppliers of 50 MW PPM X-Band klystrons has completed the first tube and is set to ship it to SLAC at the end of FY00. A 75 MW PPM klystron prototype to be incorporated into the NLC was produced successfully and tested at SLAC, attaining 75 MW of power over a 3-microsecond pulse width, helping confirm that the number of klystrons needed for the NLC could be halved from the prior design concept.

An initial Conventional Facilities design and construction schedule was completed in early FY99, and has been updated regularly. During FY 2000, a consultant prepared a

report on various geologic conditions possible to be encountered during NLC tunnel construction for various tunnel configurations, based on a review of available geologic information from numerous sources and some limited field reconnaissance. Based on this information, the tunnel configuration in some geological conditions might be revised from a shallow bored tunnel to a cut and cover tunnel. For the cooling systems, a concept based on central chiller plants was explored. Although this concept substantially reduced the initial capital cost, it increased power demand and operating cost substantially, so additional options are now being explored. Cooling systems studies will continue under a recently awarded consulting contract. A consultant is currently developing an updated estimate of the underground work, based on the cut and cover configuration, and the actual topography at a representative site. His reports thus far on Main Linac, Injectors and Beam Delivery indicate a slightly lower cost than our earlier estimates. Work is continuing on the estimate for the IR Halls.

During FY00 the SLAC and Fermilab directors established an NLC Machine Advisory Committee (MAC) to provide oversight and guidance to the directors. The MAC has broad representation in both technical expertise and in global distribution, with most of the world's major accelerator laboratories represented. The first meeting of the MAC was held at Fermilab in late May 2000 to introduce MAC members to the machine design concepts. The MAC offered a number of valuable R&D guidelines, and asked that a means of monthly communication with MAC and all collaborators be established. The NLC News fulfills this. A second meeting is scheduled for early FY01. An active preconceptual design R&D program will continue in FY01.

### **The NLC Test Accelerator – NLCTA**

In FY00, the NLCTA accelerator physics program focused mainly on the rf processing of the DDS1 accelerator structure with the goal of achieving gradients comparable to those required by the NLC/JLC designs (about 70 MeV/m). To expedite the program, around-the-clock operation was implemented, which required improvements to the personnel and machine protection systems. With the additional running time, it soon became clear that DDS1 was not going to process above a gradient of about 70 MV/m. More importantly, the continued rf breakdown was found to be damaging the structure. This was manifested as a shift in the phase advance profile at the upstream end of the structure, which was observed by measuring the phase of beam-induced rf. This discovery prompted the examination of the three other NLCTA structures that had been run at gradients below 54 MV/m. The same damage pattern was seen in these structures when bead-pull phase measurements were made. From these results and those from early structure tests, it was hypothesized that the damage is related to the higher group velocity at the upstream end of the structures (the group velocity decreases by about a factor of four along the structure to compensate for the rf attenuation in these nearly constant-gradient structures). As a result of these findings, a series of low group velocity structures are being built and tested: the first was made by cutting off the last 52 cells of one the three NLCTA structures that had been run at lower power (DS2). This end section is currently running in the NLCTA where it reached 70 MV/m in about a tenth of the time as DDS1. Another DDS structure (DDS3) is being processed in a more systematic manner to determine at

what gradient damage begins to occur. This structure has better vacuum pumping than DDS1, and it is being processed in a manner designed to eliminate the multipulse breakdowns that were seen in DDS1. The long-term goal of these studies is to find the structure design parameters and operational procedures to be able to process structures quickly and to continue to run them without damage.

## 8. FY00 Progress in Advanced Accelerator Research (Ron Ruth and Bob Siemann)

### Advanced Accelerator Research 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 or upgrades to PEP-II, and research in fundamental aspects of accelerator and beam physics. The department is divided into several groups, each of which is 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 longitudinal instability control systems have been in operation for several years at PEP-II, the LBL ALS light source, the Italian Phi-factory DAFNE, the German BESSY-II light source and the Korean POSTECH light source. The PEP-II systems contribute to the record luminosity of the B-factory, and are essential for longitudinal control of the 1.5 A beams in the facility. In the past year the group has developed a new set of control techniques, based on IIR (infinite impulse response) control filters. Motivated by the addition of third harmonic cavities to the ALS light source these new filters were optimized to maintain control even in the presence of large tune spreads and increased growth rates resulting from the new impedances the third harmonic cavities added to the ring. The new control approach is based on a model of the machine dynamics, and uses a filter optimization technique to provide good machine control over a wide range of unstable mode frequencies. This analysis and control technique has immediate applicability to the BESSY-II light source, and may be important for PEP-II if bunch-shortening harmonic cavities are installed as an upgrade to increase luminosity. Figure 1 shows the original FIR bandpass and new IIR control filters developed for the ALS. The new filter has a much flatter phase slope in the 7 to 14 kHz region where the reactive tune shifts place the strong unstable HOM-driven modes.

With the five installations commissioned and in operation (and the SPEAR-II system ready for installation), we are encouraging the various users of our systems to develop a shared expertise collaboration. To encourage this transition, a User's Group workshop was held in October, 1999 at the LNF - INFN (Frascati). The workshop included progress reports from the labs, a tutorial covering some of the most recent data analysis tools, and provided a forum to bring the various lab efforts together. We see great benefits to this collaborative sharing of expertise, and are very pleased that the design goal of common hardware and transportable software tools has been established as a working model for the joint development of accelerator technology. Shyam Prabhakar's PhD thesis, "New Diagnostics and Cures for Coupled- Bunch Instabilities", is the second Stanford Ph.D. to come out of the multi-bunch feedback development effort.

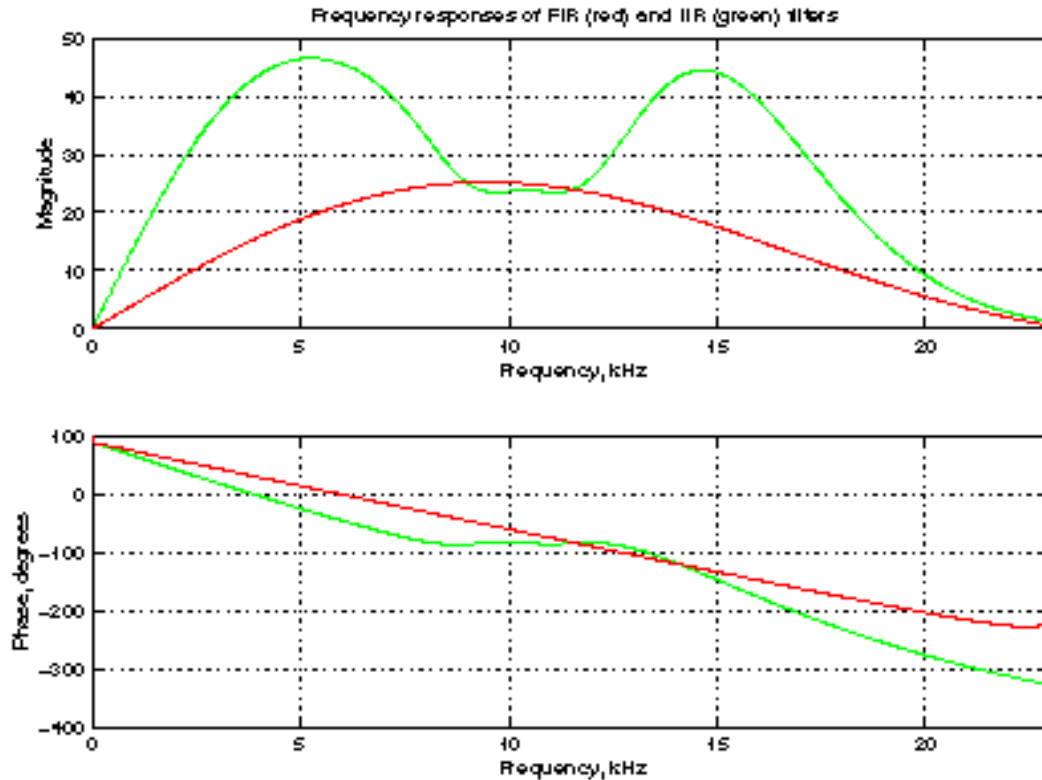


Figure 1. Frequency response of the FIR and IIR filters.

**Collective Effects.** The Collective Effects Group has studied instability problems encountered or envisioned in PEP-II, NLC, LCLS, and the KEKB Accelerator Test Facility, and has made significant contributions to general accelerator physics research. Many of these studies were performed in collaboration with other groups in the ARDA, and other teams in SLAC. Members routinely perform extensive HEP and accelerator physics community service functions.

Examples of items studied last year includes: (a) the continued study of the roughness impedance for the LCLS, with the prediction that the roughness impedance will be much smaller than predicted before; (b) analysis of the effect of energy spread in the train of bunches on the multibunch beam break-up instability in the NLC; (c) participation in the experiment on collimator wakefields measurement; (d) theoretical study of the saturation mechanism of the coherent beam-beam instability; (e) study of connection between the sawtooth instability with a nonlinear mode coupling; (f) theoretical investigation of a monopole mode single-bunch instability; (g) study of beam-current dependent rise of vacuum pressure, as well as multipactoring in PEP-II; (h) participation in the study and operation of PEP-2 single- and multi-bunch instabilities and luminosity improvements; (i) coherent synchrotron radiation in multiply connected vacuum chamber; (j) calculation of narrow band impedance of PEP-2 collimators; (k) proposal of an improved broad band resonator impedance model; (l) a study of laser acceleration of electrons in vacuum, which shows that with a proper choice of the laser, one can obtain an electron beam with a record brightness; (m) development of a simulation code that accurately predicted the

threshold of the sawtooth instability at SLC damping ring; (n) studies of the basic physics processes at the collision point, and simulations of the collision process with the program GUINEAPIG; (o) investigation of the idea of dynamic focusing for linear colliders; (p) participation in the astro-beam physics study group; (q) extraction of the bunch shape from beam spectrum measurements at the SLC; (r) study of high frequency impedance of a periodic rf structure, (s) scattering matrix analysis of the NLC structure, (t) NLC beam break-up emittance dilution, (u) resonator impedance model for a rough surface, (v) 6D phase space characterization of the KEKB-ATF beam, and (w) injector linac design for the NLC.

**Lattice Dynamics.** In the past year, the Lattice Dynamics Group has continued the work of improving the performance of the PEP-II. (1) For optics, we reduced the  $\chi$  function at the interaction point (IP) by a factor of two. These upgraded lattices have increased the peak luminosity by a factor of 2. Among these lattices, the ones with  $\beta_y = 1.25\text{cm}$  have been implemented in the machines, and contributed to the recent peak luminosity record of  $2.6 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ . (2) To correct the coupling errors in the machines, we analyzed the beam position data using an object-oriented code we have written (LEGO). Using this analysis, beam-based solenoid compensation has become a routine operation to reduce the beam size at the IP. (3) To prepare for the next phase of the improvement in the optics, we are refining the methods of the Model Independent Analysis (see below). The result of this analysis should allow us to correct the optics to better than 0.1%. (4) To understand the current limitation for the PEP-II and improve the luminosity, we have developed a highly accurate and self-consistent particle code which can simulate the beam-beam interaction. The luminosity obtained with the simulation agrees quantitatively with the measurements from the PEP-II. Using these tools, designed for this asymmetric collider, we are ready to suggest further operating parameter improvements.

**NLC Manufacturing R&D.** The collaboration with the Center for Net-Shape Manufacturing at Ohio State University (OSU) resulted in a series of parts produced using different lubricants recommended by industrial producers of copper forgings. These parts are being studied to determine the viability of these processes for use in mass production of copper parts for the NLC. OSU also measured the stress-flow characteristics of OFE copper. Stress-flow is a parameter required to numerically model the forging process.

The group sponsored a two-quarter Design for Manufacturability project with the Graduate Engineering Department at Stanford. The Stanford team looked at cost and technology trade-off's associated with manufacturing the DLDS tubing. They recommended using aluminum, rather than copper for the tube and suggested that we manufacture the tubes in 40 feet lengths, use a larger (5.1 inch) ID and utilize end-formed flanges with viton O-rings.

The group updated the Quality Function Deployment (QFD) for the accelerator cells and developed specifications for a novel furnace that would combine brazing and bake-out of NLC accelerator structures. We developed a new Design for Manufacturability tool that we call "Cost-Specification Analysis." This is an engineering tool that evaluates

materials, components and processes, to find cost-reducing compromises without trading-off target specifications.

The Phase-I SBIR proposals that were sponsored this year (Automated Diamond Turning Machine and Adiabatic Forging of Accelerator Cells) all received Phase-II awards. A collaborating company received a Phase-I SBIR award to automate the different machine tools used in fabricating accelerator cells. We obtained a first look at forged OFE copper when we chemically and metallographically studied the parts produced during last years Adiabatic Forging Phase-I SBIR.

Overall, technology development resulting from this program has yielded an estimated 85% reduction in the cost of producing accelerator cells. We are now beginning to look at other NLC systems, beginning with the DLDS and expect to have a similar impact.

**Two-Beam Linear Colliders.** An innovative design for a 2-beam linear collider employing drive-beam recirculation was successfully formulated. Drive-beam power requirements were reduced by a factor of four. The design included an earlier feature that made use of a time-slice of the drive-beam klystrons to power all low-energy linacs. A total of 80 long-pulse klystrons power the entire collider. The drive beam and e<sup>+</sup> and e<sup>-</sup> sources are located on a central campus. A first attempt was made to compare the costs with a conventional collider design.

**Low-Emittance Sources.** In order to produce, manage and deliver charged particle beams with ultra low emittance and high intensity, we have been studying regimes close to the quantum minimum-emittance limit. These are extreme conditions for which the current modeling of the beam dynamics is clearly inadequate. Our activities have followed two lines of research. The first is concerned with the fundamental physical behavior of ultra-cold beams. The second aims at studying the processes that may produce or inhibit cooling.

Along the first line we have worked out a complete quantum mechanical description of a single particle motion in an accelerator. We have conducted a detailed characterization of the beam quantum ground-state and related it to the minimum emittance limit. Moreover, we have started to apply the methods of quantum field theory to recognize various possible regimes including that of the Wigner crystal and the Landau liquid. Finally, we have applied both classical and quantum mechanical methods to study the stability conditions of crystallized aggregates.

As for the second line of research, we have been exploring the possibility of using existing or novel cooling techniques to achieve ultra-low emittance for low energy electrons in small low-cost storage rings. These include ionization cooling, wigglers and laser cooling. At the same time, we have run extensive simulations based on existing classical theories to assess the role of intrabeam scattering and ways to minimize its heating effects.

**Model Independent Analysis (MIA) techniques.** The principal goal of MIA is to develop high-precision tools for measuring and analyzing orbits in accelerators and storage rings. While the ultimate intent is to reveal non-linear and subtle system effects, the current objective is to accurately determine linear machine parameters. The result is relevant to PEP-II because of the complex coupling compensation system in the IR region.

After noise floor removal by MIA methods, in a ring the Fourier coefficients of FFTs at the horizontal and vertical tunes specify 4 orbits. Orbit resolution can then be  $\sigma \sqrt{D/PM}$  where  $\sigma$  is the single turn BPM resolution,  $D$  is the number of eigenvectors retained ( $\geq 2$ ),  $P$  is the number of pulses ( $\sim 1000$ ), and  $M$  is the number of BPMs ( $\sim 200$ ). In the PEP-II application  $\sqrt{D/PM} \leq \sqrt{D}/100$ . Present excited orbits are 0.5 mm and  $\sigma \approx 50 \mu\text{m}$ , so the hope is to achieve part per thousand measurements of BPM gain and coupling and normal- and skew-quad strengths.

We have established that in fully coupled symplectic systems the measurement of 4 linearly independent orbits at 2 points (1 & 2) is sufficient to determine  $\partial q_2 / \partial p_1$ . This result holds equally well for BPM outputs, since the map from the trajectory position to the BPM output can be represented by a symplectic map when the BPM output does not depend upon the beam-trajectory slope.

Since there are 4 new pieces of information from each single view-BPM, one can hope to determine the BPM gain and coupling and 1 normal and 1 skew piece of information for each interval between single-view BPMs. One introduces a beamline model and chooses at most 1 normal and 1 skew parameter to vary in each interval. A program to perform a best fit has been written and successfully simulated for the PEP-II lattice. Preliminary data has been analyzed.

**Numerical Modeling.** The Numerical Modeling Group continued to focus on the development of 3D parallel electromagnetic codes, and their applications to the design and analysis of complex accelerator structures and components. The parallel eigensolver, Omega3P, incorporated curved surface features during mesh refinement that resulted in much improved convergence. In modeling the RDDS single cell and the 6-cell section, Omega3P has demonstrated an ability to calculate mode frequencies to within 0.01% of measurements. Similar accuracy was obtained in modeling the APT Coupled Cavity Linac cavity in a joint project with General Atomics. The parallel time-domain solver, Tau3P, has been used to simulate the external loading effect on the dipole modes in the output end of the RDDS section. The calculated mode spectrum is found to be in excellent agreement with measurement. Omega3P and Tau3p now run on the Linux cluster at SLAC as well as both the Cray T3E and IBM SP supercomputers at NERSC. The serial version of the complex eigensolver for Omega3P and that of the wakefield computation for Tau3P have been completed; their parallel implementation has just now started. Work has also begun on a third parallel field solver, Phi3P, which includes electrostatics and magnetostatics calculations and follows a novel field-based finite element formulation for better accuracy. The solver algorithm is being developed in collaboration with Professor Gene Golub of Stanford University. Under a SBIR grant, a graphical user interface for Omega3P has been developed with STAR Inc. for the NT

operating system and was demonstrated this past summer during the USPAS course on "Computational Electromagnetics". This PC version is presently used by other DOE labs such as the Los Alamos National Laboratory. In addition, a new effort towards visualizing fields on unstructured grids has been initiated as a PhD research project with the Computer Graphics group at UC Davis. Finally, the groundwork has been laid for tracking multiple bunches on parallel computers for orders of magnitude improvement in turn-around time. Collaborating with the NLC, a software framework based on a pipeline model has been developed for distributed memory machines. Two beam tracking codes have been parallelized using this framework: Ion-MAD for the study of the fast ion-beam instability in the APS, and LIAR for modeling ground motion effects in linear colliders.

**Accelerator Structure.** The work on accelerator structures consisted of theoretical design studies, fabrication and experiments.

RDDS1, the first round damped detuned structure with optimized cell shape, was fully assembled in April 2000. Compared to the previous DDS, the improvement in shunt impedance was about 19%. A newly developed finite-element parallel-processing code Omega3P was used for the design calculations. A final cell dimensional table was created with a frequency accuracy of better than 1 MHz (in 10 GHz). Frequency deviations of four modes (the fundamental zero and  $\pi$  mode, the  $\pi$  mode of the first dipole band and the zero mode of second dipole band) were measured to be within 0.6 MHz rms. Based on this frequency information, a feed-forward correction in "b" (cavity radius) was applied to the disks in later fabrication in order to correct the integrated phase (less than  $3^\circ$  finally). The disks were manually stacked on a stainless steel V-block inclined  $60^\circ$  from horizontal. The finished stack was pre-diffusion bonded with 600 kg axial force in a furnace at  $180^\circ\text{C}$  for a day. The section was then orientated vertically and fully diffusion bonded at  $850^\circ - 890^\circ\text{C}$  for four hours. Afterward waveguide components, cooling and vacuum parts were brazed in a hydrogen furnace. Final measurement showed that the cell-to-cell misalignment was better than  $\pm 1 \mu\text{m}$  and the book-shelving was within  $50 \mu\text{rad}$ . There was a gentle bow of  $200 \mu\text{m}$  that was straightened after final assembly on the strong back. The structure was installed in the ASSET facility in May. Overall, there is good agreement between the data and predictions from frequency errors caused by the enlargement of few cells near the center and flaring in the ends of the structure due to the differential expansion during bonding and brazing. Theoretical analysis using computer simulations and ASSET results confirmed that for future structures we will use a four-port output coupler for damping the high-Q deflecting modes in the last few cavities and we probably will eliminate upstream HOM couplers.



Figure 2. An RDDS accelerator structure

Recent studies have shown that, after several hundred hours of high-power operation with a gradient of 50 MV/m or higher, rf breakdown has caused surface damage on the disk edges of accelerator structures. The integrated phase change for the accelerating mode can reach few tens of degrees. We plan to study the dependence of surface damage on the structure length, group velocities, rf processing methods and structure cleaning technology. We have designed and are fabricating five types of disc-loaded waveguide structures with constant peak surface electrical field. These structures will be made from either conventional machined cells or single diamond turned cells. Some of the test structures will adopt a new input coupler design to reduce the surface field in the coupler cavity. Two structures are being tested in the NLCTA, and the others will follow. In a parallel effort, we are working on a structure design with larger phase advance (for example, 150 degrees per cell) in order to reduce the group velocity. Both detuning and medium damping of deflecting modes may be needed for short- and long-range wake field suppression. The equivalent circuit simulation calculations have been optimized and improved. The simulations are now faster by a factor of 16 or more.

We presented 16 structure-related papers at the LINAC 2000 conference. They covered a variety of topics in structure design, fabrication, experimental methods and theoretical evaluation and analysis.

**High Power RF.** During this fiscal year, we continued development of the multi-moded rf systems and components. Key components in these multi-moded systems are the tapers from rectangular to circular waveguides. We have shown that these tapers can be designed to support two modes simultaneously. A new design for a taper couples the  $TE_{01}$  mode in circular wave guide to the  $TE_{20}$  mode in rectangular wave guide while at the same time coupling the circular mode  $TE_{11}$  to the rectangular mode  $TE_{10}$ . The simulated efficiency of this taper is better than 99.7% for both modes, and the taper is compact, approximately five wavelengths long. We also developed an array of components with which one can build any rf system using two modes simultaneously. A full rf system for the next linear collider has been designed using such components.

These components include the interconnections between klystrons as well as connections to the long runs of waveguide used to delay and store rf energy. We have begun to build and cold-test these components. The first device to be constructed and tested is the so-called "Cross-potent super hybrid." This device was invented and designed last year; the cold-test results performed this year, showed perfect agreement with simulations.

Along with the development of multi-moded passive components, we are developing super-high-power active and non-reciprocal rf components. These new developments utilize our knowledge and expertise in over-moded waveguide components. The first of these devices is an active rf window operating at the  $TE_{01}$  mode in circular waveguide. This window, shown in Figure 3, contains an array of 400 distributed PIN/NIP diodes. This window was tested up to 13 MW at X-band. This pushes the state-of-the-art of semiconductor microwave switches several orders of magnitude. We are also developing non-reciprocal devices using ferrites and garnets in over-moded waveguides. Several theoretical designs have been proposed for these devices. Again, they use the circular mode  $TE_{01}$ . With these developments, we should be able to push the state of the art of rf circulators, electronic phase-shifters and switches to handle hundreds of MW power levels at X-band and higher frequencies.

Finally, a plasma model for rf breakdown in accelerator structures and in microwave rf components have been developed. This model is the beginning of a theoretical effort to understand the complex phenomenon of rf breakdown.

### RF structure

- DC isolation by  $\text{Al}_2\text{O}_3$  ceramic ring
- No RF choke is needed ( $\text{TE}_{01}$  mode)
- Higher impedance ( $Z_g / Z_0 \sim 4$ , close to cutoff) for this experiment
  - Enhance the effect of window switching status
  - Lower loss at the window during forward bias
  - Huge mismatch without bias

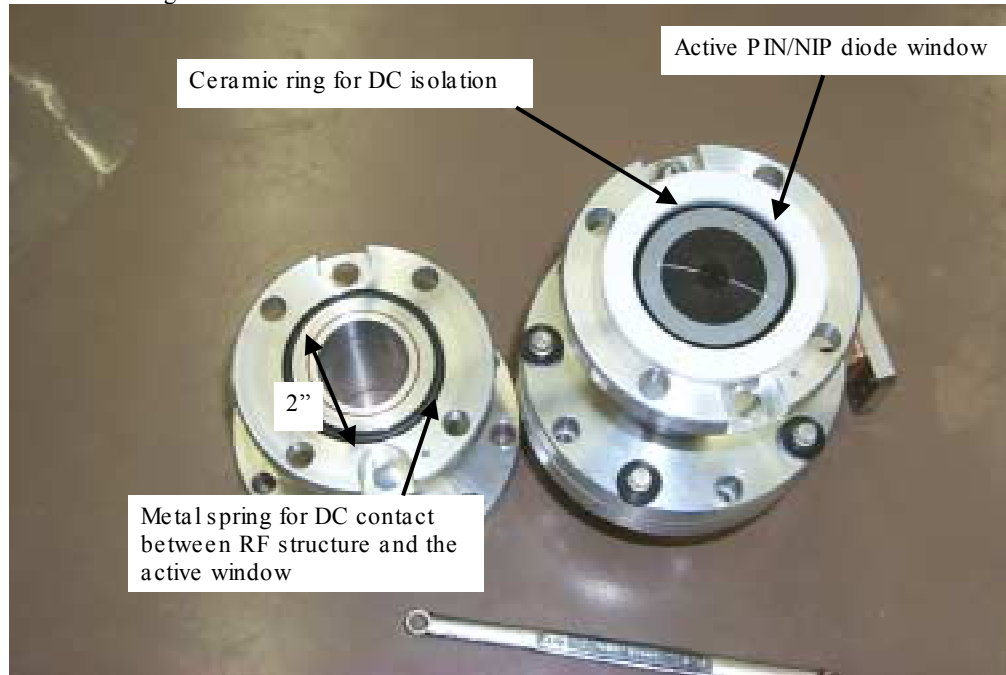


Figure 3. A high-power rf switch

**Advanced Beam Concepts.** One of the major activities in Advanced Beam Concepts during the last year was the E-150 Plasma Lens Experiment at SLAC. The plasma lens was proposed as a final-focusing mechanism to achieve high luminosity for future high-energy linear colliders. Previous experiments to test this concept were carried out with low energy density electron beams.

Recently, the E-150 collaboration has observed plasma focusing of high energy density electron and, for the first time, positron beams. The beams are focused by the plasma lens in both transverse dimensions simultaneously, with a reduction of spot size by about a factor 2 in each dimension at about 1cm downstream from the plasma lens. The focusing fields that produce such a strong focusing are equivalent to several MegaGauss/meter.

The experiment was carried out at the SLAC Final Focus Test Beam facility (FFTB). The nominal positron beam energy was 30 GeV, with  $1.5 \times 10^{10}$  positrons per beam pulse. The plasma lens was produced by laser and beam ionization of a neutral nitrogen gas jet injected into the plasma chamber through a fast-pulsing nozzle. The beam size was measured using a carbon-fiber wire-scanner system.

The results for the laser (and beam) ionization plasma focusing of positron beams are shown in Figure 4. The measured transverse beam size is shown as a function of the distance ( $Z$ ) between the wire scanner and the plasma lens. The axis of the gas jet is at  $Z = -10.5$  mm. The beam envelope is shown converging without plasma focusing (triangle points). With laser (and beam) induced plasma focusing (filled circles), the beam envelope is shown converging towards a reduced waist and then diverging because of the strong focusing. Focusing is also observed for beam-induced plasma with the laser turned off.

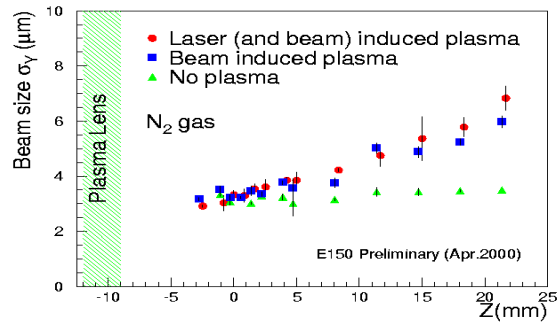
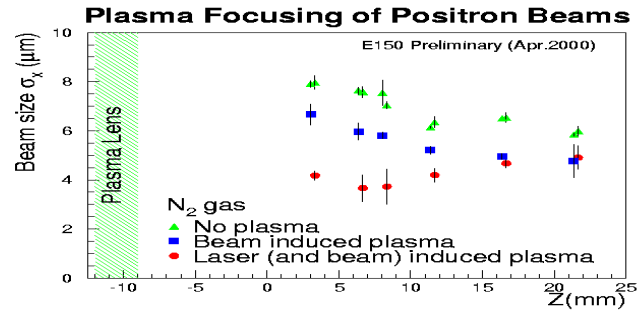


Figure 4. Horizontal and vertical positron focusing

## Advanced Accelerator Research B

The advanced accelerator research in Accelerator Research Department B (ARDB) has concentrated in four areas: mm-wave accelerators, laser driven structures, plasma wakefield acceleration and a facility for advanced accelerator research.

Rf breakdown and dark current trapping limit acceleration gradient. These limits are more favorable at short wavelengths, and this has motivated research in mm-wave (W-band) accelerations. The program this year continued work on fabrication, pulsed heating, rf design, rf power production, and LIGA (deep X-ray lithography).

Last year, a twenty-five cell traveling wave structure that is compatible with constraints from diffusion bonding and electro-discharge machining was designed in collaboration with the University of California, San Diego. This structure has been successfully machined at Ron Witherspoon, Inc. with support from a DOE Phase II SBIR funds. Low power measurements are encouraging in that they show a  $2\pi/3$  mode at the expected frequency and with the expected field profile. However, the match is not good, but will be improved with the second structure currently being machined.

Pulsed heating could become the physical mechanism limiting gradient at short wavelength. In this phenomenon, a few micron thick layer of the cavity surface is repeatedly cycled to high temperatures, and this could induce fatigue and metal failure. An experiment has been performed in an X-band standing wave cavity. The cavity is driven at high power in a mode that produces a pattern characteristic of pulsed heating phenomenon. The cavity has been exposed to roughly sixty million pulses with a temperature rise of greater than 120 degrees C. There is clear evidence of change in the crystal structure, including slip faults, in the region of high pulsed heating. The most striking evidence of damage has come from electron microscopy where fractures along grain boundaries are clearly seen. The experiment is to be repeated one more time this Fall, with copper to check reproducibility and to improve temperature diagnostics. It will then be possible to use the apparatus to study other materials.

The success of mm-wave accelerators will depend on the availability of power sources. We are collaborating with the SLAC Klystron Department and the University of California, Davis on klystron design. Our emphasis has been on a 1 MW sheet beam klystron. This klystron was designed last year and several objects were fabricated in collaboration with Sandia Laboratories (Livermore). Quasi-optical techniques for non-contact measurement of cavity dimensions are being developed.

There have been three collaborative efforts that have or will substantially increase our W-band capabilities. First, we have worked with the Klystron Department to establish a W-band laboratory based on a commercial network analyzer. As a result all of SLAC's W-band activities will be located in a single, state-of-the-art laboratory. The second collaboration is Dayton Reliable Tools, which is a metal stamping machine shop. They will be working with us to apply their precision stamping techniques to W-band cavity fabrication. The third is a collaboration with Calabazas Creek Research. They have

received an SBIR grant to develop a 10 MW W-band gyrokystron. That tube will be tested at SLAC and then made available to us for powering W-band structures.

ARDB is collaborating on an experiment to study acceleration with a laser driven structure. The experiment is being performed at the Hansen Experimental Physics Laboratory (HEPL) at Stanford University in collaboration with Stanford physicists. The structure is an open structure a fraction of a mm long driven by a synchronized Titanium Sapphire laser. Gradients close to 1 GeV/m are possible. The experiment has been installed, and the electron beam transport, laser beam transport, energy spectrometer, and data acquisition system have been commissioned. Work this year has concentrated on changing and improving all elements of the experiment in response to observations and measurement. The primary improvements have been to the accelerator cell to allow additional measurements of spatial overlap of the electron and laser beams, measurement of the field pattern in the cell, and temporal overlap through the use of a streak camera. Despite these improvements, we still have not observed laser acceleration. However, we remain optimistic because of the number of experimental problems that have been solved.

A second laser acceleration effort has been the design of a laser driven optical fiber accelerator based on the photonic band gap principle. This work has shown that an optical fiber can be designed with a low loss accelerating mode. We hope to pursue this work with the construction of a fiber and measurement of its properties.

A major activity during the past year has been E-157, an experiment on wakefield acceleration in plasmas that is a collaboration of USC, UCLA, LBNL, and SLAC physicists. There have been five experimental runs, and a wide variety of phenomena have been measured, and manuscripts are in preparation or submitted concerning many of them. The results include measurements of refraction at a plasma-gas boundary, Cherenkov radiation based diagnostics, the electron hose instability and thick lens focusing. Acceleration, which is the primary goal of the experiment, has proved to be the most difficult to measure. Analysis of this topic is still in progress.

A tremendous amount of experience has been gained with plasma beam experiments during the course of E-157, and we have submitted a proposal to extend our measurements to positron-plasma interactions. This proposal, E-162, will be the first look at the dynamics of positrons in a long plasma that should be thought of as a primitive prototype of a module of a plasma accelerator. The proposal includes important improvements to the apparatus that will allow even higher quality measurements.

ARDB has been leading the design, and hopefully construction, of a modest facility dedicated to advanced accelerator research. This facility, called ORION, would be a user facility that would welcome faculty and students with wide ranging interests in acceleration techniques. ORION would be based on the NLCTA; facilities and space would be added for experiments. An ORION workshop was held last year, and there was an enthusiastic response from the potential user community. We are now developing a technical design and pursuing possible funding.

All of the ARDB research has an important educational component. Our two senior students are completing their thesis work on an experiment studying a relativistic klystron and experiment on pulsed heating. In addition, we have two ARDB students doing thesis projects on the laser acceleration experiment, and a beginning student working on quasi-optical W-band measurements. In addition, we are working closely with students from other groups or universities in the klystron development, laser acceleration, and E-157 experiments. Post-doctoral associates are also key members of the group. They are leaders in the electro-discharge machining and precision stamping work, the LIGA development, E-157, E-162, the photonic band gap optical fiber accelerator, and the laser acceleration experiment.

## **9. High Polarization Electron Source Development by (Bob Kirby and Takasha 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 NLC R&D programs for the production of particle-free copper surfaces, surface analytical research on high electric field structures for Advanced Accelerator Research, and precision beam size measurements at the FFTB (SLAC experiment E-150, Plasma Lens).

Two-micron wide gold bars on Kapton foil were used for test measurement of focused electron beam sizes in E-150. Results were similar to those obtainable from standard carbon fiber wire scanners. The advantage of gold bars is in their possible use at higher beam current densities, where carbon fibers are destroyed. The successful series of E-150 runs, over a two-year period, demonstrated laser- and electron beam-induced gas plasma focusing of ca. five-micron diameter electron and positron beams. Beam size reductions of up to 50% were measured.

PEL engages in a continuing research program with the ARDA's Sources and Polarization group and the University of Wisconsin on the development of high-polarization high-current electron sources, originally for E-122, then for the SLC and currently for the NLC. We have now completed the first systematic study of the charge limit phenomenon. The charge output and surface charging/discharging time have been measured for a complete set of thin strained-layer GaAs photo cathodes. The active layer thickness is 100 nm and the p-type doping concentration ranges from  $5 \times 10^{18} \text{ cm}^{-3}$  to  $5 \times 10^{19} \text{ cm}^{-3}$  for a set of four samples. The results show that the surface discharging time decreases rapidly with increasing dopant concentration, from 150 nsec down to less than 8 nsec. Therefore, increasing the active layer doping concentration can control the charge limit.

Increased doping level, however, de-polarizes the electron spin. To increase the doping level while maintaining high polarization, a modulated dopant-concentration technique has been investigated. Thin highly-doped ( $5 \times 10^{19} \text{ cm}^{-3}$ ) surface layers were grown on standard single-strained GaAs. The measured polarization increased dramatically from 52% for 35 nm surface layer thickness to 83% for 2.5 nm.

## **10. FY00 Progress in Fractional Charge and Massive Particle Research (Martin Perl)**

A new search for fractional charge particles in silicone oil was begun using a new type of Millikan drop apparatus with horizontal electric fields and upward airflow. Our previous search, now published in Physical Review Letters, showed one drop with anomalous charge among the 40 million drops of silicone oil that were measured. The new search using larger drops will look at about three times as much oil to see if the one drop with anomalous charge was due to an unknown background.

A new apparatus was constructed whose purpose is dual: searches for stable, very massive elementary particles in various fluids and searches for fractional charge particles in meteorite.

In connection with this work, several technical improvements and applications were developed. For example: our drop generating technology was extended to the ejection of drops containing semi-stable mineral suspensions and application was made for a patent using small drop technology for the anti-counterfeiting marking of documents, an invention that may be of particular interest for federal use.

## 11. FY00 Progress in Test Beam Program (Ted Fieguth)

The SLAC Test Beam Program during FY00 included a wide variety of tests involving considerable support effort by many persons at SLAC. Most tests were conducted in ESA and FFTB and benefited many users from other institutions as well as those at SLAC.

For the first time in more than a decade, SLAC provided a usable secondary beam of pions and protons to an experiment. This beam was used by the GLAST collaboration for one of their two important month long tests of their engineering module. The first test (T429) used positrons to measure the silicon tracker position resolution, to calibrate the CsI energy response and to measure its energy resolution. A tagged photon beam of .05 to 16 GeV photons was then used to measure the tracker's angular resolution (point spread function). The second GLAST test (T436) used a 13.5 GeV beam of positrons, pions and protons at an average rate of one particle per pulse. The proton contribution was small with only .0044 protons/pulse, but still a total of 197,000 protons were counted and are being used to test the GLAST pattern recognition algorithms for rejecting protons while keeping gamma rays.

Other notable tests included the test (T438) of the prototype of the Endcap calorimeter for the STAR detector on RHIC at Brookhaven National Laboratory and a test (T444) of coherent Cherenkov microwave radiation from electromagnetic showers conducted for Jet Propulsion Laboratory and UCLA. Physicists from University of California at Davis tested (T443) the performance of a tracking device composed of three planes of silicon pixel detectors.

In addition, SLAC continued the program of testing beam damage in various materials for possible use in applications for NLC (T440, T441, T446 & T447). Finally, tests were conducted in support of SLAC's experimental program. Three of these tests (T437, T439 & T445) were conducted in support of E158 and two tests (T442 & T448) were in support of E157.

SLAC continues to encourage and support research and development in high-energy physics through an active program of providing beams for the purpose of testing detector prototypes and other beam related activities.

During FY00 fourteen test beam experiments were conducted:

T429 Test of GLAST Prototype, R. Arnold, American Univ., ( $e^+$  &  $\gamma$  in ESA); Preliminary run September 1999, Final one month run in December 1999.

T436 GLAST Beam Tests, G. Godfrey, R. Arnold, SLAC, American U. ( $p$  &  $\pi^+$  in ESA); Test Prototype GLAST modules in Hadron beam using Beryllium production target installed in BSY. Ran one month in January 2000.

T437 E-158 Source Commissioning, M. Woods, SLAC (ASSET, Sector 2); Commission Position and Charge Asymmetry Control and Monitoring for E-158. Scheduled to run October 2000.

- T438 STAR Endcap Calorimeter Test, L. Bland, IUCF (FFTB); Test prototype EMC, compare transverse shower profile with GEANT, discriminate  $\pi^0$  photons. Ran October 1999.
- T439 E-158 Detector Radiation Test, K. Kumar, R. Arnold, U. Mass., A. U. (ESA); Test Radiation hardness of E-158 Detector Prototype. Ran February 2000.
- T440 Single Pulse Damage in Copper, M. Ross, SLAC (FFTB); Determine NLC beam parameters that are benign for X-Band RF structures. Ran February 2000.
- T441 Radiation Damage in Magnetic Material, M. Ross, SLAC, (ESA); Determine effect of high radiation on Strontium Ferrite Magnetic Material. Ran February 2000.
- T442 OTR Resolution Contributions in E-157, M. Hogan, SLAC (FFTB); Quantify contributions to Spot Sizes measured with E-157 Optical Diagnostics. Ran February 2000.
- T443 SPARC Pixel Telescope, G. P. Grim, UC Davis (FFTB); Understand Performance of Novel Tracking Device, 3 Planes of Silicon Pixel detectors. Ran August 2000
- T444 Coherent Microwave Cherenkov Radiation, P. Gorham, JPL, Cal Tech (FFTB); Characterize coherent pulsed microwaves from EeV ( $10^{18}$  eV) Electromagnetic Showers. Ran August 2000.
- T445 E-158 Quartz Crystal Test, S. Rock, U. Mass, SLAC (FFTB); Measure response of Quartz-Crystal Detector element and light guide. Ran August 2000.
- T446, T447 Single Pulse Damage in Materials, M. Ross, SLAC (FFTB); Damage test materials (10 coupons) for NLC positron target and RF structures. Ran Sept.-Oct. 2000.
- T448 Magnified Optical Transition Radiation Test, M. Hogan, SLAC, (FFTB); Test new optical setup magnifying electron beam images for E157, Quantify Resolution Limits. Run Sept.-Oct. 2000.

## **12. FY00 Progress in Theoretical Physics (Michael Peskin)**

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. A list of some of the current topics follows:

### **Physics at the Next 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 our 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. Our studies include work on how to measure the parameters of the spectrum of supersymmetric particles and how to study possible strong interactions in the Higgs sector, including strong interactions coupling specifically to the top quark. They also include studies of models with large extra space dimensions (discussed in more detail below), considering specifically how evidence for such models could be uncovered at the linear collider. Complementing these theoretical studies, we have constructed a general-purpose simulation program for linear collider events, which allows a theoretical calculation of any new process to be easily turned into an event generator incorporating realistic beam and polarization effects.

### **Physics at Bottom and Charm 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, the members of our 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, we have intensively studied models of CP violation beyond the Standard Model, and the reactions involving ‘penguin’ diagrams that are expected to probe for these effects most sensitively. We have also studied what can be learned from precision measurements on tau pair production, including probes of CP violation in this sector.

### **Probes of New Physics at High-Energy Colliders**

In support of the past and present experimental electron-positron collision programs at the SLC and LEP and other high energy colliders, the Theory Group designs tests which might validate the Standard Model at high energies or show a weakness that would call for new physical processes. These have included studies of lepton pair production in high-energy collisions and studies of rapidity gaps and color coherence in hadron production. Members of the Theory Group have been involved in the physics studies for

Run II of the Tevatron, pointing out new strategies for Higgs boson searches and novel signatures of supersymmetric particle production. Members of our group have also analyzed the recent evidence for neutrino mass and mixing, giving methods for distinguishing proposed models of this phenomenon.

### **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 which 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.

### **Computational Perturbative Quantum Chromodynamics**

The most challenging aspect of improving methods for QCD is that of devising methods for high-order Feynman diagram calculation. Members of the Theory Group are involved in two programs for computing Feynman diagrams to very high order. The first of these attempts to simplify the computation of diagrams involving essentially massless quarks and leptons participating in high-energy collisions. For the case of one-loop diagrams, information from analytic structure and unitarity, from the use of special gauge choices, and from selection rules of supersymmetry applied to subsets of diagrams have been combined to give a complete accounting of QCD processes involving a total of 5 partons. This work includes the important cases of one-loop corrections of 3-jet production at hadron colliders and 4-jet production at electron-positron colliders. Similar methods can be applied to two-loop diagrams and have already produced dramatic simplifications in model problems in supersymmetric field theories. This program is now being applied to realistic settings such as the analysis of Bhabha scattering at two loops and the two-loop correction to 3-jet production in electron-positron collisions, both processes crucial for the precision determination of the Standard Model coupling constants. The second program aims at the calculation of self-energy diagrams at the 3- and 4-loop order. The technology developed for this study has been applied to the analysis of quark masses in QCD and to a new high-precision QED calculation of the Lamb shift.

### **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 can force the cosmological constant

to be zero, but that solution could work only if supersymmetry were visibly a symmetry of Nature.

Members of our group have devised string models in which supersymmetry is broken but nevertheless that cosmological constant remains zero in perturbation theory. They have also produced models incorporating ingredients from string theory in which the cosmological constant can remain zero in the presence of supersymmetry breaking due to the relaxation of fields living in hypothetical extra space dimensions. Though neither model is realistic, both point to strategies that might be applied to this question in more realistic contexts. At the same time, members of the Theory Group have been involved in studying string models which exhibit a variety of nonperturbative phenomena, including supersymmetry breaking and holographic duality, using the geometric insights of string theory to build new calculational methods.

### **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 our group have explored the cosmology of these theories and their implications for experiments on gravity. They have also devised a wide variety of tests for effects of higher dimensions that can be carried out at present and future accelerators. Among the difficulties of these higher-dimensional theories are problems with possible enhancement of proton decay and other violations of fundamental discrete symmetries. Members of our group have devised models which solve these problems and, in the process, provide a new geometrical framework for understanding the quark and lepton masses.

### **New Theoretical Methods**

Among the other new theoretical methods being developed by the Theory Group are: Applications of object-oriented programming techniques to simulation problems in physics; new methods for solving lattice Hamiltonian systems; a new fundamental theory of discrete physics; foundations of measurement theory; light-cone Fock state methods in non-perturbative QCD; non-perturbative renormalization of QED in light cone quantization.

### **13. FY00 Progress in RF Power Source Development (George Caryotakis)**

Four additional XL-4 solenoid-focused klystrons, which power the NLCTA were fabricated and put in service during the past fiscal year. This brings to ten the total of the XL-4 klystrons. The four new tubes and one rebuild incorporate the new, larger diameter, TE<sub>01</sub> window. The larger diameter window has solved the problem of intermittent window breakdown that plagued the earlier XL-4 klystrons. There have been no XL-4 klystron failures in tubes that include the new window.

The periodic permanent magnet 75-MW klystron, the X75P1, has undergone extensive rework to eliminate gun and output circuit oscillations. The use of strategically placed, selective RF loss was used to eliminate the oscillations. The klystron has been operated successfully (but at very low repetition rate) at 75-MW peak power at 2.8  $\mu$ sec pulse length. The value-engineered, low-cost, DFM version of the PPM klystron is now slated for fabrication and test in the spring of 2001.

Design and development has begun on a multiple beam klystron in the 75-125 MW power range. A six-beam version of the multiple beam klystron (MBK) would be capable of twice the average power of the single beam klystron and would operate at half its beam voltage. This would reduce both the cost and number of modulators required. This work is being done with a small business CRADA partner under SBIR auspices.

## **14. FY00 Progress in Radiation Physics Department (Nise Ipe)**

The Radiation Physics Department investigates and expands knowledge in the areas of radiation production, interactions, instrumentation, shielding and dosimetry.

### **Synchrotron Radiation Dosimetry Research**

The low energy x-ray responses of three ion chambers: the PTW Type 77337, and the Oxford Instruments Long (150 mm) and Short (50 mm) ion chambers, and the feasibility of their use in the energy range between 6 and 30 keV were determined. The dependence of beam size on the responses was also studied.

As part of a four way collaboration between SLAC; the Health Physics Laboratory, Institute of Nuclear Physics, Krakow, Poland; Instituto de Fisica UNAM, Mexico; Department of Physics, Ben Gurion University of the Negev, Israel, the possibility of using a one-hit microdosimetric model for optical absorption studies in lithium fluoride (LiF: Mg, Ti) was investigated. To this end, the lithium fluoride was exposed to high doses of low energy x-rays at SSRL. The results are being analyzed. This could be a step forward in the understanding of the LiF (Mg,Ti) system, which is used for personnel dosimetry because it might be directly related to the cross-section or the distance between active trapping sites. It would also be a good illustration of the application of a "Radiation Physics" model to solid state Physics.

### **Neutron Measurements for Intensity Modulated Radiation Therapy**

In collaboration with the Radiation Physics Division, Department of Radiation Oncology, School of Medicine, experiments were performed at Stanford University with a 15 MV Varian Clinac 2300C/D to determine the impact on neutron dose equivalent to the patient for Intensity Modulated Radiation Therapy (IMRT) since

- a) The beam-on time for IMRT is increased significantly compared with conventional radiotherapy treatments.
- b) The presence of beam modulation devices may potentially affect neutron production.

It was determined that the use of beam modulation devices does not significantly increase neutron production, and that the neutron dose to the patient outside the treatment area increases only because of increased beam-on time.

### **High Level (Mrad) dosimetry in mixed photon and neutron fields:**

Semiconductor dosimeters (MOSFET and P-I-N diodes) were calibrated at Lockheed Martin Missiles & Space Inc. and Sandia National Laboratories. It was found that the semiconductor dosimeters could be used in mixed photon and neutron fields to measure the neutron dose (tissue) from 40 to 8000 rads and photon dose (tissue) from 100 rads to 2.5 Mrads.

The dosimeters were tested in Beam Dump East during the E158 radiation damage test. The measurements agree with the FLUKA simulation to within a factor of two.

**Neutron Measurements**

The commercially available REM500 portable neutron survey meter is a microdosimetric instrument based on the use of a low-pressure tissue-equivalent proportional counter and modern electronics. The neutron spectrometry capability, as well as the dose equivalent response, of the REM500 was evaluated with five radio isotopic neutron sources, 14-MeV neutrons, and tested in three radiation fields with high-energy neutrons ( $> 20$  MeV) at the SLAC.

**Linac Coherent Light Source (LCLS) R&D Activities**

Calculations of energy deposition in micrometric volumes by low energy photons have been done for the LCLS gas cell and mirrors. It was determined that for this kind of calculation, simulation of photoelectron transport by the usual multiple scattering approximations are not sufficiently reliable. Hence, these calculations were performed using full single scattering transport.

**Next Linear Collider (NLC)-related R&D activities:**

The radiation damage to electronics installed in the beam tunnel of the NLC was studied with detailed simulations using the FLUKA Monte Carlo Particle interaction and transport code. The results have a significant impact on the design and cost estimates for the NLC.

The concentration of induced radio nuclides in the soil, groundwater air surrounding the collimation section of the Beam Delivery System of the NLC were also studied with FLUKA. In order to compare the results from FLUKA with experimentally measured data, samples of soil, water, lead, aluminum, copper and stainless steel were exposed in the stray radiation field generated by the interaction of the 25 GeV electron beam with a copper dump in the T-439 Test Beam. The activity of various radionuclides in samples was measured and is being compared with results from FLUKA calculations. Results of these studies are important for the shielding design of the NLC tunnel.

**Developmental Work in FLUKA - Radiation Transport Code**

Various aspects of the particle interaction and transport models in FLUKA are being improved. They include direct  $\mu\text{on}^+ - \mu\text{on}^-$  pair production, which is presently being implemented and Giant Dipole Resonance cross sections for which a new data set based on evaluated measurements has been developed and implemented into FLUKA.

**Developmental Work in EGS - Radiation Transport Code**

Stanford University has acknowledged the EGS4 Code System as an invention disclosure and the Office of Technology Licensing has formally signed a license agreement with the University of California for use of EGS4 in their commercial radiation treatment planning software called Peregrine.

The EGS code has been upgraded into a full FORTRAN version that contains all of the low-energy improvements from KEK.

SSRL Research Progress Report – FY00

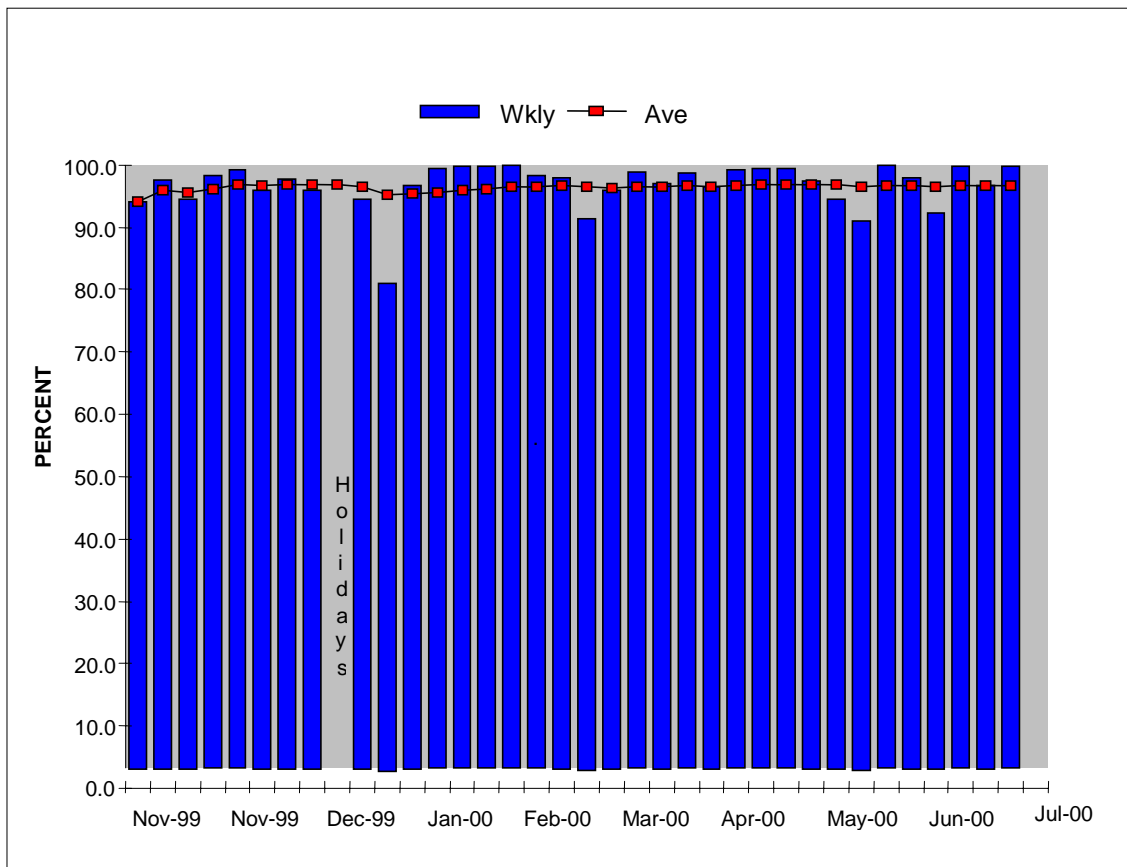
**15. SSRL Overall Operations—FY2000 User Experimental Run  
(Piero Pianetta)**

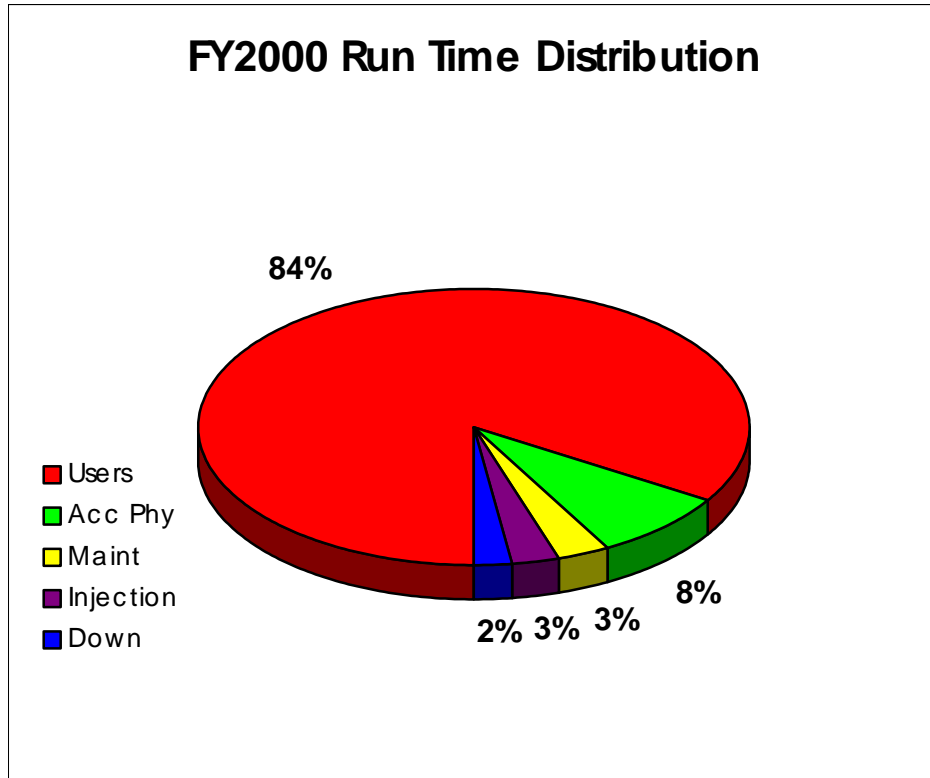
The FY00 user run (November 1, 1999 – July 4, 2000) delivered 96.8% of scheduled user shifts, accommodating the beam-time needs of over 370 unique proposals for 765 experimental starts on 30 beam line stations. The User Research Administration office badged and processed 895 users who came on-site to perform experiments.

Competition for beam-time assignments remains extremely high. When averaged across all beam lines, the over-subscription rate was 40% (user demand is 140% of available resources).

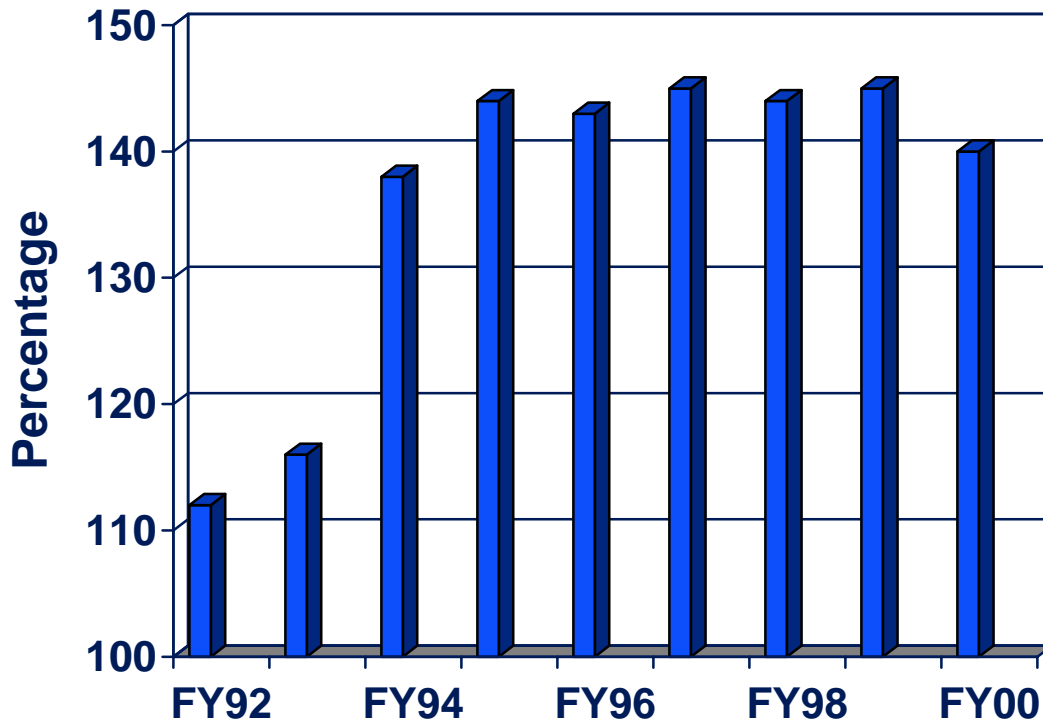
The SSRL user community has grown to 1989 users from over 20 countries. Of the 1624 users getting beam-time in FY00, 89% were from the U.S., spanning 38 states. Users were predominantly from American universities (63%) followed by American laboratories (17%), American businesses (9%), foreign universities (9%), and foreign laboratories (2%).

**FY2000 SSRL Users Weekly Uptime**





SSRL User Demand graph (FY1992 – FY2000)



### Distribution of the 377 proposals receiving beam in FY2000

Life Sciences	48.7%
Materials Science	22.2%
Geosciences	12.5%
Chemistry	6.9%
Applied Sciences	2.9%
Optical	1.5%
Other	5.3%

### SPEAR Improvements and Accelerator Physics

**Upgrade of Pinhole Camera for Vertical Emittance Reduction.** A new pinhole camera system was installed on BL2-0 to provide higher resolution, real-time images of the SPEAR beam. In addition, post-processing of the images can now be done to deconvolve the diffraction functions and resolution function from the profile and thus extract the electron beam sizes and deduce the transverse emittances.

This new diagnostic system has allowed us to perform accurate measurements of emittances. With Insertion devices in, the horizontal emittance is 140 nm-rad, which is in agreement with optics code calculations. The ratio of vertical to horizontal emittance was measured to be of 3.3%.

This system also allowed us to determine that the SPEAR skew quadrupoles were not configured optimally for correction of the horizontal and vertical coupling. The cabling to the quadrupoles was modified to permit further reduction of the vertical beam size, which could ultimately result in higher flux to the user beam lines. Preliminary results showed that a gain in flux of up to 25% was possible on vertically focused beam lines. Additional experiments with users will assess the benefits of this new configuration and insure beam stability before implementation.

**Bunch Motion Monitor System.** As part of our efforts to reduce the vertical bunch size, we used the Beam Motion Monitor (BMM) to study the coupling between planes. The BMM measures the position on two Beam Position Monitors (BPMs) of a single bunch for 1024 turns after deliberately exciting transverse oscillations with a fast kicker. In an ideal, uncoupled machine, the transverse bunch motion would be a superposition of horizontal and vertical oscillation modes, each having its own frequency. The spectral analysis of the BMM position data would show only one oscillation mode in each plane.

Spectral analysis of BMM data in SPEAR showed significant mode penetration between the planes for operational skew quadrupole settings. The relative strength of the 'foreign' mode (oscillation with horizontal frequency in the vertical plane and vice versa) can be interpreted as the measure of local coupling. When we adjusted the skew quadrupoles to

minimize this penetration, we arrived at the setting that closely agreed with those obtained by minimizing the vertical size of the pinhole camera image.

**Average Current Monitor.** The new average current monitor (ACM) printed circuit and packaging design has been completed. A unit was built and successfully tested on the Gun Test Facility (GTF).

**Orbit Feedback System.** The new BPM system is fully installed and BPM data are being collected through the new system. Production digitizer modules have been designed and ordered and will go into production in FY2001.

**Control System Upgrade.** The booster control system has been connected to an EPICS Channel Access Server and now all booster control system parameters are accessible from Channel Access clients. A Channel Access Server to access the SPEAR control system parameters will be implemented as soon as the SPEAR control system is converted from OpenVMS VAX to OpenVMS Alpha.

**BL11 Wiggler.** In FY99, it was discovered that the narrow pole widths of BL11 generate strong nonlinear fields seen along the wiggling electron trajectory. These nonlinear ties decrease the dynamic aperture, making it impossible to inject beam with the wiggler gap closed and decreasing the electron beam lifetime if the gap is fully closed after injecting. In FY00, tracking studies were made to better characterize the nonlinear ties, and specifications were generated for nonlinear corrector magnets (magic fingers) to partially compensate for the wiggler fields. The magic fingers have been designed and built by Danfysik and have been installed.

**Higher Order Mode Resonance Characterization.** Intensive studies were made to complete the characterization of Higher Order Modes in the SPEAR RF cavities and their effects on the beam. The analysis of non-linear behavior of electron bunches in the presence of strong longitudinal cavity modes was continued, both for the fundamental mode and the Higher Order Modes of the cavity. Theoretical and analytical work explaining this behavior for the fundamental mode was completed and published [Limborg, Sebek, *Phys. Rev. E* **60**, 4823 (1999)].

Measurements were done to extend this model to transverse higher order modes. Saturation and relaxation of transverse oscillations were measured for the transverse Higher Order Modes in the cavities. The goal of these studies is to develop an explanation for the saturation mechanism in the transverse direction.

### **SPEAR3 Upgrade Project**

FY00 marked the first full year of design and fabrication efforts for SPEAR3 following the formal project start on July 17, 1999. Major procurements were initiated in the first quarter of this year. These included steel lamination and copper conductors for the main ring magnets and RFP's for the klystrons and RF cavities.

The SPEAR3 magnets are being produced through an Interlaboratory Collaboration with the Institute of High Energy Physics (IHEP) in Beijing. Our Chinese collaborators worked with the SPEAR3 magnet group to complete the detailed designs. In October 1999, the copper conductor procurement was awarded by SLAC and the steel lamination procurement was placed by IHEP. Fabrication of prototype dipole, quadrupole, and sextupole units began in January 2000. In the course of this year, the dipole and quadrupole prototypes have been completed, tested, and approved for production starts. The sextupole unit is near completion. Production completion for the above magnets is scheduled to the end of FY2001. The detailed design of the corrector magnets was completed in September.

Design reviews for the arc girder vacuum chambers were held in the first quarter of this year. Three different copper chambers (QFC, BM1, BM2) thread the magnet apertures of each of the 14 arc cells. The order for machined copper plates was awarded in February and the design and fabrication of tooling required for electron-beam welding at SLAC was initiated. Associated efforts include the design of chamber supports and titanium sublimation pumps. The E-beam welding of QFC is near completion and the first machined plates of BM1 and BM2 have been received. Other vacuum system component design efforts in progress include bellows, photon stops, scrapers, ion pumps, absorbers, masks, kicker magnets, interconnections to insertion devices, transition sections to photon beam lines, and transition sections to the two long straight section –one of which includes the RF cavities.

The new SPEAR3 magnet system requires all new power supplies. A purchase order was placed in April for a 1200 kVA dipole power supply transformer. A review of the overall dipole supply was held in May for the bid process leading to the purchase award in September. A certification test stand for bi-polar supplies was completed. All twenty bulk supplies for bi-polar corrector magnets have been received and tested. For unipolar supplies, development of multi-channel controllers is underway. A design review of the induction kicker magnet supply was held, parts have been ordered, and fabrication of the prototype unit is underway.

In the RF area, the RFP's for four PEP-II style RF cavities and two 650kW klystrons was on the street in October 1999. The order for four RF cavities was placed in January with delivery scheduled the beginning of FY2002. The original plan to power these cavities via two 650 kW klystrons using existing power supplies has been modified due to the extremely high bid prices. A decision was made to use a PEP-II klystron. While this decision requires the purchase of a new power supply, the overall system is more economical. Also, maintenance efforts and spares can be shared with PEP-II. The new location for this klystron near the cavities also allows the system to be installed and tested prior to the main installation period.

The cavity production is on track. Sample aluminum halves of the cavities were machined to verify lathe programming and the machining of actual copper cavity half sections have been completed. Qualification samples by the manufacturer to verify the procedural steps are complete. In addition, associated efforts are in progress to improve

the high voltage power supply design, the low level RF system, and the detailed design of the wave-guide system.

The Instrumentation and Control system efforts involve the computer control system, beam diagnostics, BPM processors, beam timing, and the personal protection system (PPS). Initial efforts focused on refining design concepts together with cost estimates and schedules. Work has advanced in the design and specifications of computer controls, beam monitoring system, RF master oscillator, and the orbit interlock system. The SLAC Radiation Safety Committee approved the design of the PPS access control. The computer control system recently underwent a successful preliminary design review. Work has also been initiated on cable specifications.

In the Cable Plant area, the cable routes within and outside the shielding together with appropriate supports have been studied in detail and are nearing completion. Preparation of the overall design for the SLAC Electrical Safety Committee and the Seismic Safety Committee is underway.

Facilities work has focused on the design of shielding modifications in the East and West straight section areas. The engineering and design was completed in April. Much of this work is to provide shielding enclosures in the straight sections, which is required for SPEAR3 currents to 500 mA. In addition these modifications will meet seismic requirements and reduce tunnel temperature variations. While most of this effort was scheduled for this year's shutdown period, the new funding profile (discussed below) has necessitated some system delays to subsequent shutdowns to conform to available funding and to minimize the impact to ongoing experimental operations.

Unfortunately, only one contractor responded to two separate bidding procedures for the shielding additions and modifications. The contract for this work was awarded in June at a price \$450K above the planned budget. This results in the second Change Control Board action for the project; however the work, with very difficult access, was accomplished approximately on schedule within this year's annual accelerator downtime.

The main SPEAR3 installation period is being reviewed in detail. The current plan calls for demolition of SPEAR2 and installation of SPEAR3 within a 6-month period. This is a very stringent requirement and we are continuing to study methods that will help insure the achievement of this goal. Thus far, actions include pre-assembly of magnet and vacuum system components on new support girders, early installation of new cabling above the tunnel enclosure, and early installation of klystrons in the west straight section area, and straight section shielding modifications in FY 2000.

A further measure is to replace the existing asphalt tunnel floor with a new re-enforced concrete slab that will support shorter magnet Support girders. This is already in the plan for the transition areas to the straight sections. This plan would minimize the complex roof block removal and re-installation and allow the smaller girders to be rolled into their tunnel positions without the requirement for heavy-duty cranes in very confined areas. A special review committee recommended that we consider this course of action.

During this Quarter, the SLAC Earthquake Safety Committee and the Radiation Physics Group gave approval for the shielding modifications noted above. The Fire Safety Committee has approved the preliminary Fire Hazards Analysis for SPEAR3. Work is continuing on the Preliminary Safety Analysis Document. Another accomplishment was the DOE approval (January 6) of the SLAC Davis-Bacon Committee recommendations with regard to defining SPEAR3 work that is subject to the requirements of the Davis-Bacon Act.

The accelerator physics group has focused on corrector magnet performance, injection kicker magnet design, tracking studies, and software development for orbit control. The corrector magnet studies involved field uniformity requirements and have been in concert with the vacuum chamber design group. This has resulted in final design of the CuNi insert together with an adjacent slot in the copper chamber to allow optimum penetration of (ac) corrector fields for orbit stabilization. Control system application developments have included graphical/interactive orbit control programs, fast feedback system simulations, pinhole camera development for vertical emittance measurements, and development of field uniformity requirements for vertical corrector magnets.

At the beginning of the year, appropriate milestones were incorporated into our detailed schedules for project tracking. The detailed schedules were assembled in "Primavera" and the project baseline established in "Cobra". These programs were used for providing the Performance Measurement System (PMCS) for the PEP-II project. In March, the SPEAR3 PMCS was in operation providing BCWS, BCWP, and ACWP information with associated cost and schedule variances for the project WBS levels.

In March, the project was officially informed that the DOE funding profile for SPEAR3 would be stretched out resulting in a possible one to two year delay in completion. As a result, the recently completed costs, schedules, and milestones would require substantial revision. An immediate slow-down of the project in nearly all areas was required to match the availability of funds.

The impact of the new funding plan was presented at the June 13-14, 2000 DOE Lehman review. Following the review DOE provided a modified profile that was estimated to cause only one year's delay with a cost increase of \$5M. This was reviewed and accepted as the new project baseline. New detailed costs, schedules, and milestones were developed. It is planned that the PMCS will be reporting for this new plan in the 4<sup>th</sup> Quarterly report for this year.

Lastly, the executive summary report from the above noted DOE review provided the following evaluation of the project:

"The project team has made very good progress on the development of designs for the technical components and conventional facilities. This was especially true for the vacuum system. The accelerator design has matured as indicated by the thoroughness of accelerator physics analysis of the SPEAR3 design. The magnet systems team was

congratulated for a large volume of excellent planning and design. The magnets and girders appear to be sound and the production schedule looks quite realistic. There were some concerns by the committee that the girders do not have adjustable supports, and that the storage ring would require additional maintenance time to keep the ring aligned. In the areas of Power Supplies, RF Systems and Instrumentation & Control all appear to be moving along well and show evidence of close collaboration between SSRL and SLAC, which recently completed the PEP-II project successfully. The project presented an installation plan to the committee that had everything installed in eight months rather than the six months allotted by the shutdown schedule. Adequate time remains to work the installation schedule to allow for the appropriate planning and staging of technical components, and to adjust to the new funding profile."

"The management structure and dedicated staff are in place to effectively execute the project. The team has implemented a Project Management Control System (PMCS) that was used on the PEP-11 project. The project management understands its ES&H responsibilities. They are aware of ES&H policies and have implemented them to ensure ES&H is integrated into the planning of activities, and hazards are identified, evaluated and integrated."

#### **Fourth Generation Source Development**

**LCLS.** The Linac Coherent Light Source Project made significant progress in several areas in FY00. A Scientific Advisory Committee (SAC) was set up to address the science that can be done with the LCLS. At the first meeting, held on Oct. 15-16, 1999 at SLAC, the SAC discussed the potential for major scientific achievements in several areas and provided directions for the machine design. Some of the conclusions of the meeting were that the present specifications offer unique opportunities for exciting science, that shorter FEL pulses (down to 50 fs from the nominal 230 fs) are desirable for some important applications, and that the synchronization with an external laser is very important for pump-probe experiments.

The LCLS team responded to the SAC recommendations by intensifying the exploration of ways to achieve very short bunches in order to make sure that the design can accommodate such options. A report on this subject was issued in the summer of 2000.

The development of the Conceptual Design Report, including the cost estimate, is on schedule and is expected to be completed by spring 2001.

The VISA experiment at NSLS started taking data. A gain of 2 orders of magnitude has been measured. Several components have been upgraded, resulting in more stable and reproducible operation. Saturation is expected to be measured before the end of calendar year 2000.

The FEL Physics Group improved the FEL simulation code GINGER to include realistic electron beam parameters and distributions. An "electron beam collimation and matching insertions" was studied with a view to clip part of the unwanted tails in the electron

beam, allowing the machine to operate under a lower electron charge and lower emittance configuration. This would allow an easier transport with reduced negative effect of wake-fields in the Linac and undulator. This configuration is considered a promising alternative to the nominal working point.

A new and improved design of the LCLS photo-injector was completed. This design offers increased brightness, with a computed emittance below the  $1 \pi$  mm mrad.

A new layout of the LCLS injector takes advantage of an existing side tunnel on the SLAC Linac at the right location. It allows access to the photo-injector while the Linac is in operation.

Improved parameters were established for bunch compression and a study of the rf phase stability was carried out. The compression mechanism was linearized by the addition of a short x-band accelerating section. This leads to a more relaxed tolerance of the gun laser timing and, potentially, a shorter FEL pulse length.

A Workshop on Bunch Length diagnostics was held at NSLS in March 2000. One of outcomes of the meeting was that the short FEL pulse (230 fs) can be measured by deflecting the electron bunch with a transverse rf structure. A prototype of this diagnostic tool is being developed and will be tested on the SLAC Linac in 2001. Calculations and simulations indicate that the resolution of the system will meet the LCLS requirements.

The magnetic and mechanical design of the undulator was completed and a short engineering mock-up has been built to check the dimensional compatibility of the various components. An intensive study of the electron optics along the undulator was completed. It showed that focusing with a triplet is not suitable for x-ray FELs. As a consequence, it was decided to retain the FODO optics. An optimized version of the latter was developed.

In the X-Ray Optics field, progress was made in the design of the instrumentation and in the calculations of the absorption cell. Computer models to calculate the FEL electric field downstream of the undulator and the diffraction downstream of optical elements were completed. The general layout of the experimental areas was defined. The CDR will include both a “near experimental area” and a long beamline for a “far experimental area”. The latter offers several advantages in terms of reduction of power density on the optical components and flexibility in the manipulation of the photon beam. Methods to produce shorter FEL pulses (down to  $<50$  fs) by optical pulse compression and slicing have been developed.

**Gun Test Facility.** The Gun Test Facility (GTF) is dedicated to the development of the high brightness electron source necessary to drive the LCLS. The source under test at the GTF is an rf photo-cathode gun developed as a result of a SSRL, SLAC, Brookhaven National Laboratory (BNL) and UCLA collaboration. In FY00 the effort was directed towards improving the hardware and making the system sturdier and more reliable.

A dual head laser configuration was installed, providing increased pump power to the laser.

A new sub-picosecond resolution streak camera was commissioned. The streak camera was employed to measure the laser pulse shape and duration and will also be used to measure the electron beam bunch length and shape.

The GTF can produce Gaussian laser pulses with a continuously variable pulse length from approximately 2–10 ps FWHM. Temporal pulse shaping experiments were begun using both a time domain technique of splitting, delaying and summing pulses (pulse stacking) and a frequency domain technique using an amplitude mask in the Fourier plane. The emittance of the electron beam is highly dependent on the electron bunch length and shape. The expected optimal pulse shape to produce the lowest possible emittance is an approximately flattop pulse with 1 ps rise and fall times and 10 ps width.

Emittance measurements in 1999 had been hampered by the lack of an available laser and a contaminated copper cathode. The end result was a beam with very high emittance due to the non-uniform emission off the cathode. The cathode was replaced with a new electro-polished copper material under strict cleanliness control to eliminate contaminants. Preliminary results indicate that a cathode with near uniform emission can be produced. The lowest emittance measured so far at the GTF is about  $3 \pi$  mm mrad at 0.5 nC electron bunch charge and 4 ps FWHM bunch length. This emittance number is reduced to less than  $2 \pi$  mm mrad when it is corrected for the limited resolution of the YAG crystals that have been used to produce optical images of the beam. It is planned to replace the YAG crystals with Optical Transition Radiation (OTR) monitors soon. The computed emittance value is  $2 \pi$  mm mrad, given the particular field, solenoid position, electron beam dimensions and beam charge used during the measurements.

During FY2001, the GTF will be modified to obtain a gun configuration that is expected to produce emittance values equivalent to less than  $1 \pi$  mm mrad at 1 nC charge.

**Selection of First Scientific Experiments for the LCLS.** The Scientific Advisory Committee (SAC) for the Linac Coherent Light Source (LCLS) has selected six scientific experiments for the early phase of the project. A document describing these experiments was submitted to DOE BES in early September 2000.

This document presents descriptions of the early scientific experiments selected by SAC in the spring of 2000. They cover a wide range of scientific fields. The experimental teams consist of many internationally recognized scientists who are excited about the unprecedented x-ray capabilities of LCLS that surely will lead to new scientific frontiers.

More generally, this document serves to forward the scientific case for an accelerator based x-ray free electron laser source, as requested by the BESAC subpanel on Novel Coherent Light Sources, chaired by Stephen R. Leone.

Two general classes of experiments are proposed for LCLS. The first class consists of experiments where the x-ray beam is used to probe the sample without modifying it, as is done in most experiments at current synchrotron sources. In the second class, the LCLS beam is used to induce non-linear photo-processes or matter in extreme conditions. The same source can be used for both types of experiments by utilizing six orders of magnitude changes in photon flux density by focusing the LCLS beam, and by exploiting the strong dependence of the photoabsorption cross section on photon energy and atomic number.

The first five experiments (not in priority order):

- Atomic Physics Experiments
- Plasma and Warm Dense Matter Studies
- Structural Studies on Single Biomolecules and Particles
- Femtosecond Chemistry
- Studies of Nanoscale Dynamics in Condensed Matter

are based on the design parameters of the LCLS:

- Wavelength 15 Å 1.5 Å
- Peak sat. power 11 GW 9 GW
- # coh. photons/pulse  $2.2 \times 10^{13}$   $2.2 \times 10^{12}$
- Energy bandwidth 0.42% 0.21%
- Pulse width (FWHM) 230 fs 230 fs

specified in the “LCLS Design Study Report”, prepared for DOE by the Stanford Linear Accelerator Center in 1998. Some of the experiments assume that the x-ray beam can be focused to  $100 \times 100 \text{ nm}^2$  with 50% of the full photon flux, which is today’s state-of-the-art.

All LCLS experiments involve the interaction of a high power x-ray beam with atoms and so the first experiment is aimed at understanding this process at a fundamental level. This basic knowledge is important for the second experiment which uses the high power of the LCLS to create an interesting state of matter, so-called warm dense matter and proposes to probe it by a second delayed LCLS pulse. The third experiment is tied to the first two in that it depends on the time scale over which a biological molecule disintegrates after it is hit by the LCLS beam. Radiation damage is one of the main obstacles today in determining the structure of proteins that cannot be crystallized. The experiment is based on the use of LCLS pulses that are fast enough to determine the structure by x-ray scattering before radiation damage sets in. The fourth experiment goes to the very heart of chemistry, aiming at obtaining molecular pictures, i.e. atomic positions, bond length and angles, during chemical reactions or transformations at femtosecond time scales, previously reserved for ultrafast lasers. Finally, experiment number five pushes the envelope in probing ordering phenomena in hard and soft condensed matter on the important nanometer length scale, which cannot be seen by optical photons, over a broad range of time scales. Nanoscale dynamics is not only

scientifically interesting but it constitutes the competitive arena of advanced technological devices.

The above five experiments, even at this early proposal stage, already instill dreams of improved XFEL characteristics, for example, shorter pulse lengths. Like the application of conventional lasers has been accompanied by R&D on lasers themselves, there needs to be an R&D program to explore new accelerator and optics concepts with LCLS. This is the goal of the sixth experiment: X-ray Laser Physics.

The history and experience of three generations of synchrotron radiation sources has taught us that the above experiments are at best the tip of the iceberg of scientific opportunities. It is safe to predict that we have not yet thought of the most important experiments that eventually will be done with this new class of radiation sources – x-ray free electron lasers!

### **New Beam Line Facilities and Beam Line Improvements**

**BL1:** In preparation for the SPEAR3 shielding installation discussed in the context of BL2 below, the under-utilized BL1-1 grasshopper was decommissioned. The motion control system on SAXS branch line 1-4 was upgraded for improved performance and greater hardware commonality with other SSRL beam lines. The BL1-4 user control station ergonomics was improved with the addition of new furniture, noise reduction partitions, etc. A new solid/liquid sample temperature control stage (25-450 °C with +/- 2 °C control) was added to the BL1-4 instrumentation. BL1-5 ran in a first come-first served mode as a test bed for rapid access beam time for multi-wavelength anomalous dispersion experiments in macromolecular crystallography. This approach proved to be very useful for the macromolecular crystallography community. A plan is in the design phase whereby BL1-5 will be remodeled. The major improvements include extending the hutch, increasing the user area and implementing the same experimental hardware and software as found at all other macromolecular crystallography beam lines.

**BL2:** The SPEAR shielding enclosure was significantly modified to improve the radiation shielding at the BL2 exit port from the SPEAR tunnel. This new ratchet wall was necessitated by and designed for SPEAR3 beam operations and 3.0 GeV injection. The SPEAR pinhole camera diagnostic on BL2 was upgraded to provide improved source imaging and resolution. The BL2-1 M<sub>0</sub> mirror system was replaced with a new optical system which provides improved focus quality and enhanced mirror manipulation capabilities. The BL2-1 experimental hutch was equipped with computer-controlled slits.

**BL3:** The commissioning of the BL3-1 LIGA station was completed early in the FY00 run. Since the completion of commissioning, the beam line has been in regular production servicing the Sandia National Laboratories and Jet Propulsion Laboratory user communities. The M<sub>0</sub> mirror on soft x-ray BL3-3 was replaced with a mirror providing better power filtering and improved focus fidelity. The BL3-3 Jumbo monochromator controls were upgraded to the standard SSRL instrumentation control suite (which consists of a DEC-Alpha work station, Kinetic Systems Grand Interconnect interface, and

SSRL Instrumentation Control Software [ICS] package). Initial conceptual design studies of the BL3-3 SPEAR3 upgrade were completed.

**BL4:** The user control stations for the BL4-1 and 4-2 branch lines were altered to provide a more ergonomic work environment including background noise reduction at station 4-1. Reconfiguration of the floor space near BL4 permitted construction of a storage facility for BL4-2 SAXS equipment adjacent to the experimental hutch. The BL4-2 rear hutch was extended to facilitate segregation of SAXS experiments to the rear hutch and XAS experiments to the front hutch. This segregation will reduce the operational burden associated with changeovers from one technique to the other resulting in more efficient utilization of the BL4-2 beam. Relocation of the SAXS program exclusively to the rear 4-2 hutch necessitated the design and fabrication of a new SAXS hutch table and associated control system. The assembly of this system will be completed before the FY2001 user run. A new multi-layer crystal set was purchased for the BL4-2 monochromator. Finally, the procurement of a new 20 pole, 2.0T wiggler magnet to replace the existing 8 pole, 1.8T wiggler was initiated. The new wiggler is being designed and constructed by Danfysik who produced the BL11 wiggler magnet. The conceptual design review for this new wiggler is scheduled for early FY01 while delivery is anticipated late in the first quarter of FY01.

**BL5:** The BL5-2/5-3 end station controls were upgraded to the standard SSRL instrumentation control suite. The original float glass M1 mirror on BL5-4 was replaced with a polished ULE mirror. The improved focal properties of the ULE mirror result in a three-fold increase in flux delivered to the experiment when the monochromator is operated in low-resolution mode. The flux gain approaches ten-fold at high resolution.

**BL6:** The major redesign of BL6-2 for SPEAR3 operations is proceeding. Fabrication of the front-end components started at the end of FY2000. Several long lead optical components including the new Si M<sub>0</sub> and M<sub>1</sub> mirrors are have been ordered as is the liquid nitrogen (LN) chiller for the new LN monochromator. Several slits and filters are in various stages of design.

**BL7:** BL7-1 was optimized for fixed energy (~1 Å) monochromatic experiments in macromolecular crystallography. By shortening the positioning rail for the experimental equipment (and subsequently shortening the experimental energy range obtainable), users could more easily access the equipment. Staff saved time by not having to re-optimize the beam line at different energies. Users that required wavelengths > 1 Å were scheduled on BL1-5 or BL9-2. The beam line was also equipped with 2 new Silicon Graphics Octane computers each with a set of dual high-performance graphics boards.

The central element of the new high magnetic field facility on BL7-2, a 13T superconducting magnet, was commissioned and installed in the BL7-2 rear hutch along with the associated in hutch x-ray instrumentation. Initial x-ray measurements were conducted with the magnet operating at low field. A new high speed, single element Ge detector for BL7-2 x-ray scattering applications was commissioned while a second similar detector was purchased. BL7-2 in hutch hardware was augmented with the

addition of computer-controlled slits. The BL7-2 control station was reconfigured to provide users greater space and reduce background noise.

A new computer-controlled optical rail and Ge detector array alignment carriage was developed and implemented on BL7-3. A new VXI based motor control system for this instrumentation was evaluated and implemented and specific software for communication and control was developed. BL7-3 will serve as the first test bed for this system, which has been chosen as the successor to the current CAMAC-based beam line systems. A set of computer-controlled motorized slits was also implemented, as well as a new alignment system for detector and slits for an ionization chamber-type fluorescence detector system. Delivery was taken of a 30-element Ge detector array, with processing electronics in procurement. Software for the control of this electronics was further enhanced, and the system will be fully implemented during FY01.

The procurement of a new 20 pole, 2.0T wiggler magnet to replace the existing 8 pole, 1.8T wiggler was initiated. This new wiggler, which is the sister wiggler to that discussed under BL4 above, is being designed and constructed by Danfysik. The conceptual design review for this new wiggler is scheduled for early FY01 while delivery is anticipated late in FY01. SPEAR shielding was modified to provide the high bay required for installation of this new wiggler. Conceptual design of the major SPEAR3 upgrade of BL7 started at the end of the fiscal year. Procurement of several long lead components was initiated.

**BL8:** The BL8 machine protection system (MPS) was updated with new front-end valves and the SSRL standard Allen Bradley MPS control system. The instrumentation control systems on both BL8-1 and BL8-2 were upgraded to the SSRL standard instrumentation control suite.

**BL9:** A large ADSC Quantum-315 3x3 matrix CCD detector was procured for BL9-2 with delivery anticipated in February 2001. This new detector has a greatly increased active area of 31.5 x 31.5 cm<sup>2</sup> and a significantly decreased readout time of 1 second. The experimental hutch table was modified to accept heavier loads to accommodate the new CCD and new detector positioning systems. A new style cryostat, a CryoJet on loan from Oxford Instruments, was tested at BL9-2 for cryo-cooling samples. The device performed extremely well and a CryoJet has been procured for this station. A new fully automated beam scatter guard shield and beam stop were designed and implemented. These devices can now be positioned easily and reproducibly via computer control. Plans were developed for upgrading BL9-1 with the standard detector positioning system, the Huber kappa goniometer developed on BL9-2, and the new standard software package BLU-ICE (described below).

Beam line 9-3, dedicated for biological x-ray absorption spectroscopy, was fully operational as a user beam line during the 2000 run. The equipment includes a Canberra 30-element Ge solid-state detector array system, which, together with a liquid helium cryostat, enables the collection of spectra from dilute metalloproteins. Users reported success collecting data from samples more dilute (low sub-millimolar) than hitherto possible on previously available beam lines. In addition, the small spot size on beam line

9-3 was exploited to carry out micro-X-ray absorption and chemically specific imaging measurements on biological samples. This has been achieved in two ways. The first uses double slits to aperture the beam to 100x100 micron<sup>2</sup>. The second uses the novel technology of a tapered metal capillary optic to condense the beam line focus down to a spot size in the order of 5 microns in diameter. The advantages of such an optic are that it is more reflective, stable and robust than corresponding glass optics, and that it can be simply added into the beam line at the experimental hutch. A prototype motorized optic alignment stage was developed and implemented and preliminary results obtained.

**BL10:** Like the other VUV beam lines, BL10-1 was also converted to the SSRL standard instrumentation control system. Additionally, a new  $I_0$  monitor was added to BL10-1. A new  $M_0$  mirror was ordered for BL10-2 with delivery anticipated in early FY01. The motion control system for the BL10-2 diffractometer was modernized and the alpha axis refurbished. New computer controlled in hutch slits were installed.

**BL11:** As mentioned above, pair of corrector magnet modules were designed, fabricated, and installed on the BL11 wiggler to compensate for field non-linear effects discovered during the wiggler commissioning. While most of the beam line was designed for 500 mA power levels, the decision to build SPEAR3 for 500 mA postdated the BL11 front-end design. Consequently, the design and initial fabrication activities for 500 mA capable replacement front end components was undertaken in FY2000.

The new PRT beam line BL11-1 (PRT members: The Scripps Research Institute, Stanford University and SSRL) was constructed last year. It is a wiggler side station with a vertically focusing mirror followed by a horizontally focusing single Si(111) crystal monochromator. The detector positioning system and Huber kappa goniometer, originally developed on BL 9-2, were also installed on BL11-1. Several weeks at the end of the run were devoted to commissioning this new macromolecular crystallography station. A series of data sets were collected from P6 myoglobin crystals. The statistics for data reduction and for the anomalous scattering signal of iron in myoglobin were of excellent quality. During the last week of the run, the Wilson group (from The Scripps Research Institute) helped in the commissioning phase by collecting data and reporting problems. Specific problems with the stability of the optics were discovered and solutions were quickly defined, which also included the design of a mirror feedback system. Despite the minor problems with the optics, the Wilson group collected several very good quality data sets. During the commissioning phase, a MAR345 detector was used for data collection, however, a second ADSC Quantum 315 3x3 CCD detector has been procured for this station with delivery anticipated in March 2001.

The BL11-2 liquid nitrogen (LN) cooled monochromator was installed early spring with first monochromatic light extracted in March. Since this is the first LN monochromator at SSRL, the monochromator was extensively tested during a two-month commissioning period. The monochromator performed quite well with no observable thermal degradation of performance at power densities greater than expected for a properly filtered beam line under SPEAR3 and approximately 60% of the total power. Mechanical stability and energy reproducibility results proved equally encouraging. Following the

monochromator commissioning, the 1.2 m  $M_1$  refocusing mirror was installed and first focused light conducted into the BL11-2 hutch in May. After a brief additional period of optics commissioning, the beam line was turned over to user commissioning. BL 11-2 transitioned to hutch commissioning mode in May 2000 when focused monochromatic light was threaded into the end-station hutch. Approximately 5 weeks of commissioning time were available leading up to the summer SPEAR shutdown, some of it with users who collected publishable K- and L-edge XAS data. Instrumentation tests were scheduled between user beam periods and focused on installation and testing of the LN cooled monochromator, x-ray mirrors, the dedicated 30-element high-throughput/high-resolution Ge detector array, computer control for the detector and beam line, and a gas mixing/delivery systems for dedicated ionization chamber detectors. Test performance data collected during this period has proven invaluable to planning for phase II of commissioning activities, to resume in Nov. 2000.

Design of the BL11-3 side station optics commenced during FY00 and the long lead optics were procured for delivery in FY01.

**BLU-ICE:** The graphical user interface for beam line control and experimentation (BLU-ICE) was developed primarily on BL9-2. The design concept for this software required it to be: highly intuitive, easy to use, robust, distributed, and provide full control and flexibility. The software was successfully refined over the running period with input from our user groups. The software fully controls and integrates the experimental setup and data collection. Multi-wavelength anomalous dispersion (MAD) experiments have been made extremely easy to perform with little overhead for user training and startup. The distributed nature of the software allows many processes to run simultaneously anywhere on the network. This gives staff remote access from their office or home to the user's experiment increasing the efficiency of user support. Many synchrotron facilities have made inquiries about the specifics of BLU-ICE and several are planning to implement the software at their protein crystallography stations.

## Highlights of the 2000 Scientific Program

### Structural Molecular Biology

**Macromolecular Structures and MAD.** Roger Kornberg's group (Stanford University) determined the three-dimensional structure of the 450 kDa, multi-subunit complex RNA polymerase II (pol II), the primary enzyme for the transcription of DNA into mRNA for the expression of proteins. The collection of very high quality diffraction data at BL9-2 allowed the unambiguous tracing of the entire structure. Several high quality data sets were collected at BL9-2, which led directly to the phasing of this extremely large and important macromolecule, including MAD data with ~50% selenomethionine (SeMet) incorporation. It was possible to clearly identify ~80 of the possible 120 SeMet peaks in the structure. This SeMet data greatly aided in the tracing of pol II. [*Science* **288**, 635 (2000)] In another important development, the SSRL staff collected MAD data from a cryo-cooled myoglobin crystal that had been incubated with 400 psi krypton gas. The incorporation of Kr was achieved with a short incubation time of 2 minutes and with a subsequent depressurization of ~10 seconds before flash-cooling. Although it does not bind as well as xenon, Kr has a more easily accessible absorption edge (~16 keV) and by collecting redundant data, a sufficient signal can be obtained. MAD data were collected at the Kr edge and a significant peak ( $22\pi$ ) was found in the anomalous Patterson map. Kr MAD will be implemented as a standard experiment at our MAD beam lines in the upcoming run. New methods and techniques geared towards high throughput structure determination were also investigated in more detail, especially with regard to data quality and required anomalous signal for a successful structure determination experiment. The results confirm that a complete data set at the edge inflection point and single remote wavelength are sufficient for phasing of most structures. After density modification procedures or refinement of the phases, neither an increase of the multiplicity nor an extra wavelength improved the quality of the maps tested. This result implies a shorter data collection time to collect MAD data for structure solution. The use of auto-tracing routines for tracing new structures quickly was also explored and the wARP procedure was successfully used to trace the majority (~95%) of several new structures. The refinement and application of these structure determination methods and techniques will be extremely useful for producing a high-throughput structure determination system that could lay the foundation for projects such as structure based drug design and structural genomics.

**Small-angle X-ray Scattering/Diffraction Station BL4-2 Highlights.** A low-resolution single crystal diffraction data set recorded on BL4-2 was essential in solving the diffraction phase problem in the determination of the 3.6-Å resolution crystal structure of the Hong Kong 97 bacteriophage mature empty capsid [Wikoff *et al.*, *Science* **289**, 2129 (2000)]. HK97 is the first double-strand DNA virus structure whose atomic structure has been solved. The unusual topological linkage of polypeptide chains in a way similar to chain mail suits worn by medieval knights was found with HK97 for the first time. Solution x-ray scattering data were used effectively to study quaternary structures of a couple of large protein complex systems in solution, complementing respective crystallographic studies. The quaternary structure model, previously proposed by crystal

structures of individual components, of the HslUV chaperon complex was corrected using the low-resolution structure information driven from solution x-ray scattering. This study confirmed the quaternary structure seen in the crystal structure of the entire HslUV complex (Sousa *et al.*, submitted to *Cell*). The other known example is the hexameric ring structure of RuvB DNA helicase, whose atomic resolution structure turned out to be a form of screw instead of a ring structure that had been thought to be more consistent with biochemical results. Solution x-ray scattering results confirmed that the hexameric ring structure reassembled computationally using the atomic resolution protomer structure, was the quaternary structure that exists under physiological conditions in solution (Putnam *et al.*, in preparation).

**New capabilities for XAS-Imaging.** Novel tapered metal capillary optics were used in preliminary experiments on beam line 9-3 for XAS-imaging and micro-XAS of selenium in plant materials. Measurements were done with optics giving spot sizes of 10 and 5 microns diameter, and resolution at the cellular level were achieved in transverse sections of a seedling stem and in longitudinal sections of a mature plant stem. Specifically it was observed that the selenium is predominantly localized in the outer layers of both of these types of specimens. Micro X-ray absorption spectra were also successfully collected from specific locations in these samples.

### **Molecular Environmental Sciences (MES)**

Growth in the SSRL Molecular Environmental Sciences (MES) user program continued in 2000, with MES activities occurring on 13 XAS, x-ray scattering, and VUV beam lines during the user run. In response to ongoing growth in the community, SSRL significantly increased scientific support for MES activities during FY 2000, including the hiring of a support technician, training an engineering physicist for BL11-2 and general MES scientific program support, design of several major instrument packages for BL11-2, and design of a joint MES/VUV sample preparation laboratory. Preparation for commissioning BL11-2 dominated activities for all MES personnel, with actual characterization of the beam line commencing in May. Of the 5 weeks available for commissioning activities, about 42% of this time was scheduled for users, who measured publishable K- or L-edge x-ray absorption spectroscopy (XAS) data for Ce, Fe, Cu, As, Hg, Pb, Sr, U, and Rh in a number of MES experiments. Instrumentation tests were scheduled between user beam periods and focused on beam line optics, computer control of motors, and testing of the 30-element high-throughput/high-resolution Ge detector array. The array performed beyond expectation, with excellent energy resolution (e.g., 250 eV FWHM at Zn  $K_{\alpha}$ ) and clean data at count rates in excess of 500,000 Hz. Other major MES projects in FY 2000 included detailed design of two major new instruments (initiated in 1999), including a spectrometer for grazing incidence EXAFS, XSW, and reflectivity measurements, and new high-flux liquid helium cryostats for cryogenic XAS measurements.

A taste of the capabilities of BL11-2 was demonstrated in a joint SSRL/USGS XAS study to determine the mechanisms of uranium attenuation in engineered barriers installed to remediate contaminated groundwater at Fry Canyon, Utah. Prior XAS measurements in

this system were limited to synthetic analog samples having artificially high (>1,000 ppm) uranium concentrations. Natural field samples have eluded XAS characterization due to their low uranium concentrations and high strontium contents, which greatly interfere with uranium data collection. However, full XAS characterization of a dilute field sample (190 ppm uranium) was obtained in June at BL11-2 by combining the capabilities of the 30-element detector array with the high flux of the 26-pole wiggler and the stability of the BL11-2 liquid nitrogen cooled monochromator. This result is highly significant for MES scientists at SSRL. The ability to measure such natural samples, which are typically much more dilute and chemically heterogeneous than synthetic laboratory analogs, is fundamental to the development of risk assessment and remediation strategies for environmental contamination. XAS analysis of the Fry Canyon field samples indicates the dominant mechanism of uranium attenuation in the barriers to be adsorption of uranium on particulate surfaces (as opposed to precipitation of solid uranium compounds). Knowledge of this fundamental characteristic is central to optimization of the barrier design.

## Materials Science

**High-Resolution Small Angle Scattering on Soft Matter.** Using a combination of x-ray scattering, performed on BL10-2, confocal microscopy and electron microscopy, the Safinya group from UCSB has described a distinct type of spontaneous hierarchical self-assembly of cytoskeletal filamentous actin (F-actin), a highly charged polyelectrolyte, and cationic lipid membranes. On the mesoscopic length scale, confocal microscopy reveals ribbon like tubule structures that connect to form a network of tubules on the macroscopic scale (more than 100 micrometers). Within the tubules, on the 0.5- to 50-nanometer length scale, x-ray diffraction reveals an unusual structure consisting of osmotically swollen stacks of composite membranes with no direct analog in simple amphiphilic systems. The composite membrane is composed of three layers, a lipid bilayer sandwiched between two layers of actin, and is reminiscent of multilayered bacterial cell walls that exist far from equilibrium. Electron microscopy reveals that the actin layer consists of laterally locked F-actin filaments forming an isotropic two-dimensional tethered crystal that appears to be the origin of the tubule formation. [*Science* **288**, 2035 (2000)]

**Signature of Superfluid Density in the Single-Particle Excitation Spectrum of  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ .** The doping and temperature dependence of photoemission spectra near the Brillouin zone boundary of  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  exhibit unexpected sensitivity to the superfluid density. In the superconducting state, the photoemission peak intensity as a function of doping scales with the superfluid density and the condensation energy. As a function of temperature, the peak intensity shows an abrupt behavior near the superconducting phase transition temperature where phase coherence sets in, rather than near the temperature where the gap opens. This anomalous manifestation of collective effects in single-particle spectroscopy cannot be reconciled by models based on a Fermi liquid, but rather may be more naturally explained by models based on the doped Mott insulator, such as Resonant-Valence-Bond type of theories, stripe theory, and theories based on quantum critical point phenomena. [*Science* **280**, 277 (2000)]

**Inelastic X-ray Scattering as a Novel Tool to Study Complex Insulators.** The electronic structure of Mott insulators continues to be a major unsolved problem in physics despite more than half-century of intense research efforts. The discovery of high-temperature superconductivity and colossal magnetoresistance in doped Mott insulators is a highlight of this intellectual crisis. Well developed momentum-resolved spectroscopies such as photoemission and neutron scattering cannot directly address problems associated with the Mott gap as angle-resolved photoemission can only probe the occupied electronic states whereas neutrons do not couple to the electron's charge directly. Hasan *et al.* reported the observation of highly dispersive (up to 1.3 eV) charge excitations across the Mott gap in a parent cuprate insulator using high-resolution resonant inelastic x-ray scattering (RIXS). This reveals the anisotropy of full Mott-gap which sheds light on the momentum resolved structure of the unoccupied upper Hubbard band for the first time. Given its deeply bulk-sensitive and weak-coupling nature and the ability to probe dispersive behavior of the unoccupied bands over several Brillouin zones inelastic x-ray scattering has the promise, as demonstrated, to become an important experimental tool to study the electronic structure of complex insulators. [*Science* **288**, 1811 (2000)]

**Nature of the Electron Ordering in  $\text{La}_{(1-x)}\text{Sr}_{(1+x)}\text{MnO}_4$ .** An understanding of the electron ordering in manganese oxides will ultimately shed light on the mechanisms responsible for the unusual magnetic properties of these materials, which are becoming important to the high-density magnetic memory industry. Manganese oxides containing other metals can form crystal structures with different effective dimensionalities for the Mn atoms: perovskite (cubic) structures, double-layer structures, and single-layer structures like the compounds described below. All show a rich variety of electronic and magnetic phases depending on doping, temperature, and magnetic field. Colossal magnetoresistance, in which huge changes in electrical resistance are induced by external magnetic fields, has been observed in the perovskite and 2-layer manganites, but not in the single-layer manganites. The desire to understand complicated correlated-electron systems like the manganites has inspired a significant amount of theoretical work recently, requiring new experimental work to determine which theories work best.

The Greven group at Stanford University has used synchrotron x-ray scattering to investigate the low-temperature structure (believed to be driven by ordering of the  $e_g$  electrons) of the single-layer manganese oxide  $\text{La}_{(1-x)}\text{Sr}_{(1+x)}\text{MnO}_4$ . A number of similar compounds with different levels of Sr doping were studied, covering the range  $0.33 < x < 0.67$ . Three distinct structural regimes were found as a function of doping (or of  $e_g$  electron concentration  $n_e = 1 - x$ ): a disordered phase ( $x < 0.4$ ), a phase with "Wigner-crystal-like" polaronic order ( $x > 0.5$ ), and a mixture of these phases in the intermediate regime ( $0.4 < x < 0.5$ ). The phase diagram is reminiscent of that of the manganese perovskites. In all manganites, the structure of the ordered phase appears to primarily depend on  $n_e$ , to be insensitive to the dimensionality of the lattice, and to result from a sinusoidal ordering of  $e_g$  polarons. Also, there is a remarkably similar phase competition/separation for  $x$  approximately equal to 0.5 in single-layer and perovskite manganites. However, the macroscopic electrical and magnetic properties of single-

layer and perovskite manganites in the mixed and the disordered regime, *i.e.*,  $n_e > 0.5$ , are dramatically different.

This work is important for two reasons. First, it clarifies our understanding of the structural phases of  $\text{La}_{(1-x)}\text{Sr}_{(1+x)}\text{MnO}_4$ . There had been inconsistency in previous experimental results, resulting in disagreements about the role played by the  $e_g$  electrons. Second, the resulting phases seem to fit into a pattern shared with other manganites. There seems to be a significant amount of structural similarity, even though the electrical and magnetic properties are very different. These results will put some important constraints on the theories.

## Science Education

SSRL, as a national synchrotron radiation source, contributes directly to the education of a large number of undergraduate students, graduate students and postdoctoral fellows in a wide range of fields, from physics, materials science, geology and environmental sciences to biochemistry, biology and medicine. To date, >400 Ph.D. or M.Sc. theses have been reported to being awarded based partly or fully on work performed at SSRL. SSRL expects report between 20-30 theses earned in 2000.

During the summer of 2000, SSRL again sponsored six of the SLAC Summer Internship in Science and Engineering (SISE) Program students, and hired an additional eleven college and high-school students directly as summer employees. They were involved in as diverse areas as heavy atom derivatization and data collection for the crystal structure determination of bungarotoxin, creation of user interface documentation for MAD data collection, assembly and installation of beam line electronics, inventory and installation of system software for PC systems, and develop assays development and optical characterization of metalloenzyme forms.

SSRL also held several workshops during the year to disseminate new methodologies and make users acquainted with new instrumentation. Subjects included "Fundamentals of X-ray Absorption Spectroscopy Data Analysis", "Small-Angle X-ray Scattering Studies at SSRL" focusing mainly on materials science applications, and "Techniques for Automated Mounting, Viewing and Centering Pre-cooled Protein Crystals" with the main emphasis on robotics developments.

## **FY00 Progress on Technical Information Services (TIS) (Patricia Kreitz)**

SLAC continues to provide full text electronic access to its scientific and technical information. New publications are made Web-readable within 24 hours of their clearance through the Technology Transfer/Patent Review Office. This year, SLAC published 320 papers which were transmitted to OSTI per their requirements. We also are continuing to convert older materials from paper to electronic format. The most heavily used publication series are already fully converted and Web-accessible (items with a SLAC-PUB or a SLAC-R[eport] number). As funds permit, we convert less-used series. This year, the legacy conversion project posted 332 publications to the Web, for a total of 6,099 publications since Fall 1998.

World-wide use of the SLAC SPIRES-HEP databases continue to grow. We constantly receive email testimonials about how useful the databases are to the particle physics community. We will be establishing the fifth mirror site in Russia next year. This year we have been involved in three development efforts--building Web accessible conference proceedings, collaborating with IBM's TeXExplorer group to improve Web displays of mathematics, and working with the Santa Fe Open Archives Initiative. All of these efforts are developmental at present, but feedback has been extremely positive to date.