Impact of Accelerator Science on SLAC Programs
by
Jonathan Dorfan

SLUO Annual Meeting
18 September, 2009
The Story of SLAC: Exceptional Science Fostered by Innovation

• As our new name attests, Accelerators have been the key technical ingredient at SLAC – in most cases the initiative that led to the marquee science results came from the accelerator builders
  – by pushing the frontiers of accelerator technology, they opened up unchartered territory that revealed unanticipated science

• It is instructive to review SLAC’s history
SLAC Family Tree: Fueled by Technical Innovation

1966
Linear Accelerator

- World's most powerful linac
- Polarized electrons

1972
SPEAR Storage Ring (HEP)

- SPEAR Synch. Light (parasitic)

1974
SPEAR Synch. Light (dedicated)

- Materials, chemistry, Structural biology

1980
PEP Storage Ring (HEP)

- Vacuum, rf
- Beam optics
- Long b quark lifetime

1987
SLAC Linear Collider (SLC)

- First linear collider
- μ-sized, polarized beams
- Emittance Control
- Establish 3 quark generations
- Best limit on Higgs Mass

1987
SLAC Linear Collider (SLC)

PEP-II Storage Ring (HEP)

- Asymmetry,
- Multi-bunch, Feedbacks,
- rf, vacuum, optics
- Discovery of CP
- Violation in B decays
- Discovery of new Charm states, D mixing

1991
Stand-alone Injector

PEP-II Storage Ring (HEP)

- Environmental Science
- RNA Polymerase

1999
SPEAR3 Synch. Light

- Nano-materials
- Complex bio-assemblies

2004
LCLS

SASE
World's First X-Ray Laser

2009
SLAC Family Tree:
Fueled by Technical Innovation

- Heralded Colliding Beam Era
- Discovery of charm quark
- Discovery of tau lepton
- Discovery of jets

1991
PEP-II Storage Ring (HEP)

- Standard Model
- High-energy physics

1991
PEP-II Storage Ring (HEP)

- Standard Model
- High-energy physics
What motivated the building of SLAC (linac), SPEAR (HEP, Synch), etc?
PROPOSALS FOR INITIAL ELECTRON SCATTERING EXPERIMENTS
USING THE SLAC SPECTROMETER FACILITIES

Submitted
By
SLAC-MIT-CIT Collaboration

Particle physicists actively participating in the collaboration at this time:

Stanford Linear Accelerator Center (Group A)
W. K. H. Panofsky, D. H. Coward, H. DeStaebler,
J. Litt, L. W. Mo and R. E. Taylor.

Massachusetts Institute of Technology

California Institute of Technology
C. Peck and J. Pine.
The MIT-SLAC experiment itself was designed to examine resonances produced at high electron energies and momentum transfers, with only a passing look at the deep inelastic region. One theorist even thought these measurements a complete waste of time. Why do you want to measure deep inelastic scattering” he chided David Coward of SLAC, “when CEA has already shown there’s nothing there?”

The Hunting of the Quark by Michael Riordan, pg 132

The Nobel-prize winning contribution from this experiment was the discovery of quarks, and that objective does not appear in the proposal.
So Why Was SLAC Built? -- Because Visionary People Saw the Discovery Potential in Pushing Technology to New Limits. It was the accelerator builders that led the way.

“Dr Ginzton, can you tell me precisely why you want to build this machine?”

“Senator, if I knew the answer to that question we would not be proposing to build this machine.”

Times To Remember – The Life of Edward L. Ginzton edited by Anne Ginzton Cottrell and Leonard Cottrell pg 121
An Experimental Survey of Positron-Electron Annihilation into
Multiparticle Final States in the Center-of-Mass Energy Range 2 GeV to 5 GeV

(SLAC); G. S. Abrams, W. Chicharly, C. E. Friedberg, G. Golchuber, R. J. Hollebeck,
J. A. Kadyk, G. H. Trilling, J. S. Whittaker, J. Zipse (LBL)

Summary

This is a proposal, using the detector described in Proposal SP-1, to make a sur-
vey of the reaction \(e^+ + e^- \rightarrow \text{hadrons}\) covering the entire initial operating energy
range of SPEAR (2 - 5 GeV in the c.m.). Information on momentum and angle dis-
tributions, masses, and particle species (hadrons, muons, electrons) of the re-
action products would be recorded. Two-body final states will be distinguished
by topology and precise momentum measurement; the constituent masses of multibody
final states will be determined by momentum and time-of-flight measurements. A
search for heavy leptons would also be conducted.

Specific features to be studied are:

(a) Hadron form factors. Assuming one-fifth design luminosity, the dipion yield
could reasonably be expected to lie between 5700 and 2 (events per 100 hours),
depending on the energy and the prevailing dynamics. Muon and electron-pair
backgrounds will be flagged by observing their interactions in the detector.

(b) Baryon form factors. The \(p\bar{p}\) yield should lie between 740 and 0.15 (events
per 100 hours). \(M\) yields might be \(\sim 1/9\) the \(p\bar{p}\). The ability to
separate the two elastic form factors will depend primarily on the number
of events which are accumulated.

(c) The total hadronic cross-section. If the phenomenon is of a point-like
nature, the yields could be as high as \(4 \times 10^5\) per 100 hours. A \(Q^2\) dependence
leads to \(\sim 10\) per 100 hours at \(\sqrt{s} = 5\) GeV. It is planned to separate the
"two-photon" background \(e^+ + e^- \rightarrow e^+ + e^- + \text{hadrons}\) by studying, a \(p\bar{p}\) invariant
the features of the distributions of sensitive kinematic parameters such as
total visible energy and angles relative to incident beams.

(d) Inclusive spectra. Scaling would also be investigated in the deep inelastic
region for \(\pi, K, p\); the ability to separate masses near the elastic limit
will depend on the relative \(\pi, K, p\) yields.

(e) Heavy leptons. Pair production of heavy leptons can be observed by searching
for a final state of non-collinear electron and muon. Rates are estimated
to be as high as 6-hour\(^{-1}\) for a QED-type production.
The Nobel-prize winning discovery of a heavy quark was not anticipated in the proposals.
So Why Build SPEAR? Because Visionary People Saw the Discovery Potential in A Different Geometry.

It was the accelerator that led the way

• The motivation was several-fold:
  – Gain access to higher mass physics by putting the center of mass in the laboratory, albeit with low beam energy
  – Remove the constraints of particle species quantum number conservation – initial state is that of a virtual photon
  – Open up the geometry of the detector to $4\pi$
Opening Up a Port For Synchrotron Radiation

• X-Rays penetrate matter and can image samples at atomic dimensions
  – Spicer and Doniach ‘saw’ the possibilities that a tunable, intense X-Ray beam portended

• It was a leap of visionary faith
  – No one in the early 1970’s could have predicted the remarkable breadth of outstanding science that was to evolve
  – Nor were most of the imaging techniques in common use today available in those days
  – Who would have predicted the Nobel-prize winning work of Kornberg in imaging the RNA Polymerase
The Successes of the 3-6 GeV Machines Motivated a Jump To 30 GeV
The payoff was not as big as SPEAR … true innovation comes with a spectrum of home runs

- The driving scientific arguments were to increase the mass scale to reveal yet higher mass constituents
  - Amongst the biggest “payoffs” were the discovery of the gluon (at PEP’s sister machine PETRA at DESY) and the long b quark lifetime
    - Neither was anticipated, yet both needed the higher center of mass energy
    - The long b lifetime was one of the critical factors enabling CP violation measurements at PEP-II/KEKB
The Lesson from the SLC is different:
Risk Averse Stewardship Forecloses Discovery and Advancement

- The scientific motivation was clear - produce $Z^0$’s and one has a window on all physical processes that lie below its mass – the choice of energy and luminosity were specified by the mass of the $Z^0$ and the ability of the SM to calculate EW cross-sections

- The “genius” was in convincing the scientific and funding community to build an *R&D machine* rather than a “Super PEP” ala LEP
It Was Hard-won Success

• No question, making the SLC work was extraordinarily challenging and lengthy
  – it was a triumph of technical ingenuity
  – it was a testament to the unswerving belief of the proponents
  – it was a testament to the patience of the sponsors
  – it produced a wide variety of accelerator “firsts”

• The improvement in both electron and positron beam capabilities at SLAC were astounding
  – High intensity at very low emittance, transported over distances of miles
  – Control & collisions of micron-sized beams
  – Ingenious implementation of nested feedbacks
The SLC Opened Up New Opportunities that Would Likely Never Have Materialized

• Stimulated the worldwide R&D on Linear Colliders
• The linac $e^+/e^-$ capabilities post-SLC were essential for generating the enormous integrated luminosities at PEP-II
• The unexpected and highly novel science generated by the FFTB and SPPS
• The LCLS!
Final Focus Test Beam: Started as Linear Collider Demonstration Project in 1993

FFTBN (Novosibirsk/Provino)
DESY
Fermilab
IBM
Kawasaki
KEK
LAL(Orsay)
MPI(Munich)
Rochester
SLAC

Fig. 2. (a) Measured fringe pattern in the Compton scattered γ-ray. Solid curve is the least-square-fit of sin-function. (b) Spot size distribution for 3 hours measurement.
10 Years of Novel Science Followed

- E144 collided the FFTB electron beam with a very high powered laser to study non-linear QED

- E157/E162: Plasma Wakefield Studies. Systematic study of intrinsic science and demonstration of
  - Acceleration of electrons and positrons
  - Focusing of electrons and positrons
More Accelerator Magic: Shortening the SLAC Electron Pulse by a Factor of 100!

- Allowed E167 to achieve much higher accelerating gradients: remarkably using only 1m of plasma, they were able to double the 42 GeV SLAC beam energy.
SPPS – The Beginning of Ultra-short pulse, Linac-based, X-Ray Science

- Did outstanding science
- Tested many of the fundamentals for LCLS
  - Short bunch beam dynamics
  - Diagnostics and instrumentation
  - Feedbacks and stability
PEP-II -- Yet a Different Example: A Physics Discovery Looking for a Technical Solution

• The theoreticians and the experimentalists knew what was to be measured. Over time, they developed clever schemes to enhance the very rare CP signals.

• It took some help from Nature (long b lifetime, and B-Bbar mixing) and breakthroughs in technology (silicon vertex detector, asymmetric beams) to get us there.

• Nonetheless PEP-II is a triumph for the accelerator scientists and technologists.

• Since it required such a huge increase in integrated luminosity there was also a “credibility gap” that had to be bridged with the “sponsors”. The kind of leadership that they showed in supporting and funding PEP-II exemplifies what is needed if true innovation is to flourish.
SPEAR 2 → SPEAR 3: Another example of how clever accelerator ideas drive change

- Weidemann and others devised an ingenious optics scheme that not only lowered the emittance by a factor of 8, increased the current by a factor of 5, but also magically preserved the machine and experimental beam-line footprint
  - For a mere $60M, SPEAR leapt from generation 2 to 3
  - Timing was perfect: could use the PEP-II vacuum & RF

Table 1. Source parameters for SPEAR 2 and SPEAR 3.

<table>
<thead>
<tr>
<th></th>
<th>SPEAR 2</th>
<th></th>
<th>SPEAR 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>3 GeV</td>
<td>3 GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td>100 mA</td>
<td>200/500 mA*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emittance (w/ IDs)</td>
<td>160 nm-rad</td>
<td>18 nm-rad</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF frequency / h</td>
<td>358.5 MHz/280</td>
<td>476.4 MHz/372</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lifetime</td>
<td>30 h @ 100 mA</td>
<td>&gt;30 h @ 200 mA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Critical energy</td>
<td>4.8 keV</td>
<td>7.6 keV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tunes (x,y,s)</td>
<td>7.18, 5.28, 019</td>
<td>14.19,5.23,007</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e- σ (x,y,s) - ID</td>
<td>2.0, .05, 23 mm</td>
<td>0.43, .03, 6 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e- σ (x,y,s) - bend</td>
<td>.79, .20, 23 mm</td>
<td>.16, .05, 6 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection energy</td>
<td>2.3 GeV</td>
<td>3 GeV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 200 mA phase 1; future increase to 500 mA as beam lines upgraded.
The LCLS – A Massive Step Forward
Could not have happened without the success of SLC

• 1992: Claudio Pelligrini proposed combining the 15 GeV low emittance SLAC e- beam with a precise wiggler magnet and the process of Self- Amplified Spontaneous Emmision to generate a femto-sec, transversely coherent, X-Ray Laser
  – With a brightness about 10 billion times larger than circular sources, it would provide the first simultaneous window on the ultra-small and the ultra-fast
  – Lots of crucial accelerator development followed in the next five years that put the meat on Claudio’s framework

• It wasn’t until the mid-2000 that there were convincing studies to show that one could do revolutionary science with an FEL of this kind
BESAC Meeting October 10 2000: Release of First Study of LCLS Science

LCLS - The First Experiments

- Femtochemistry
  - Dan Imre, BNL

- Nanoscale Dynamics in Condensed Matter
  - Brian Stephenson, APS

- Atomic Physics
  - Phil Bucksbaum, Univ. of Michigan

- Plasma and Warm Dense Matter
  - Richard Lee, LLNL

- Structural Studies on Single Particles and Biomolecules
  - Janos Hajdu, Uppsala Univ.

X-ray Laser Physics

Program developed by international team of ~45 scientists working with Accelerator and Laser Physics communities

Sept, 18, 09

SLAC Users Organization

Annual Meeting
Undulator Girder with 5-DOF Motion Control + IN/OUT

- Beam Finder Wire BPM
- quadrupole magnet
- 3.4-m undulator magnet
- sand-filled, thermally isolated supports
- Wire Position Monitor
- Hydraulic Level System
- CAM-based 5-DOF motion control
- X-translation (in/out)
Undulator Gain Length Measurement at 1.5 Å: 3.3 m

\[ \gamma \varepsilon_{x,y} = 0.4 \, \mu m \text{ (slice)} \]
\[ I_{pk} = 3.0 \, kA \]
\[ \sigma_E/E = 0.01\% \text{ (slice)} \]
There is One More Critical Role That the Accelerator Scientists and Technologists Play

• They are essential in the following roles:
  – Taking the seminal ideas and solving all the challenging ancillary problems to get the idea to the scientific “market-place”
  – Analyzing and solving performance threatening problems that always arise during operation
  – Providing the ideas and knowhow to upgrade the facilities to achieve enhanced performance

• If one doesn’t have free access to these kinds of people, the “miracle” ideas will not turn into reality and the science won’t happen
Will the Innovation That Fueled the Post WWII Technology Explosion Continue?

• The world globally appears to be losing its ability to support true innovation
  – we see erosion in the commercial world
    • no longer do we have the incredible Bell Labs R&D group, the IBM group, etc
  – We see much more focus by governments on risk-averse & short-term investments

• Where is this leading us?
Conclusions

• Meaningful Innovation is that which truly provides the wherewithal to change our world, to transform our knowledge base in fundamental ways
• Innovation requires a complex and delicately balanced eco-system
  – of human and physical infrastructure
  – that is extremely wisely stewarded, with relatively few boundaries
  – that makes long-term commitments to high-risk ventures
  – That is flexible, tenacious, patient
• These elements have all played a crucial role in SLAC’s success
• My hope is that the powers that be have the foresight and boldness to preserve these elements here, so that SLAC science, be it accelerator or non-accelerator, will continue to turn the scientific world upside down with its brilliance