Division of Physics of Beams Newsletter

Spring 2008

A Division of the American Physical Society
Edited by Ernest Malamud, DPB Secretary-Treasurer

Report from the DPB Chair

Joseph Bisognano,
University of Wisconsin, Madison

These are not the happiest of times for the U.S. accelerator community, with the reality of lay-offs, project delays, and worse.

The promise of the American Competitiveness Initiative, which rightfully underscored the strong linkage of research in the physical sciences to our national economic success, has found itself caught between the Iraq War and bread and butter domestic programs such as health and education. Although the president's FY 2009 offers us hope, laying out a path for doubling NSF, DOE Science, and NIST budgets between 2006 and 2016, it's likely to be faced with the same fiscal constraints that led, after a promising start, to the debacle of the FY 2008 Omnibus Bill.

Although the ACI and the America Competes Act show that substantial increases in funding of the physical sciences has resonance with both Democratic and Republican law makers, the connection of basic research and its supporting technologies to a strong economy and national security is not in the voters' minds. Do you know the stance of your favorite candidate on scientific research? When was the last time this issue was brought up in a presidential debate?

We need to bring support of scientific research into the national consciousness if there is any chance over the next decade for some of our best ideas in accelerators and beam physics to come to fruition. We must make the connection between science and broad national goals. So I would like to encourage you to be proactive:

- Contact your U.S. representative and senators
- Contact your state and local legislators
- Become active in your political party
- Volunteer to assist with outreach programs at your laboratory and/or university
- Make the case that the physical sciences matter!

In This Issue

Questions? Comments? Visit the DPB web site at http://www.aps.org/units/dpb
Or contact Ernie Malamud, Secretary-Treasurer at 530-470-8303 FAX: 530-470-8456 Email: ernestmalamud@comcast.net

Recruiting New DPB Members

Joseph Bisognano

This is a critical time for the Division of Physics of Beams since our representation has fallen dramatically as a proportion of the whole APS membership. This can ultimately lead to loss of our status as a division. Moreover, it is critical to maintain a large and broad-based division to ensure an accelerator infrastructure in the U.S. that enables the very wide range of basic and applied research represented by the units of APS.

Over the past year, the DPB has intensified its membership recruitment by offering a free 1-year DPB membership to all APS members who are not already members of DPB and a limited-time 50% discount for new APS members who also join DPB. So far, numbers are up by about 5%, but more work is clearly needed. We invite you, as a current DPB member, to contact your non-member colleagues and ask them to join our division. Following is a form to enroll them in DPB. Information on enrolling new APS members with the 50% discount can be obtained from our Secretary-Treasurer, Stan Schriber at schriber@nscl.msu.edu

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APS physics

DIVISION OF PHYSICS OF BEAMS

JOIN NOW!! FIRST YEAR IS FREE

Yes I would like to take advantage of your offer of one-year free membership in the APS Division of Physics of Beams!

Send to:
American Physical Society, Attn: Jennifer Pirnat, One Physics Ellipse, College Park, MD 20740 or fax this form to 301-209-0867 or email to pirnat@aps.org

Name (printed): ____

APS Member ID# (optional):______________________________________

Institution and/or Address: ______________________________________

Email: ____

Signature: ____

DPB Election Results

The newly elected members of the DPB Executive Committee are **Christoph Leemann**, Vice-Chair for a 4-year term in the Chair line. John Cary and Shin-ichi Kurokawa are newly elected Members-at-Large for 3-year terms. **Stan Schriber** is our newly elected Secretary-Treasurer.

Their terms begin at our annual Business Meeting and Reception, on Monday, April 14, from 12:30 to 2 PM during the April APS Meeting in St. Louis.

Particle Accelerator Conference Update

Joseph Bisognano

At the Particle Accelerator Conference Organizing Committee (PACOC) at PAC07 in Albuquerque, a decision was made to coordinate the PAC with the Asian and the European sister conferences, forming effectively an international series with a three year cycle, beginning in 2010. The DPB Executive Committee supported this concept with a formal resolution. In addition, there will be a North American regional conference organized by the PACOC, out-of-phase by 18 months, to address concerns about providing for younger students, scientists, engineers, and technicians, who may not have easy access to international travel. The DPB Executive Committee passed another resolution urging that this regional conference have a distinctive character to complement the international series. Both the international series conference (when in North America) and the new regional conference will be the annual meeting site for DPB. In off years, the DPB will meet at an APS spring meeting.

DPB Member Bill Foster Elected to the U. S. Congress

Ernie Malamud

On March 8, Foster won a Special Election to fill the remainder of Dennis Hastert's term for the 14th Illinois Congressional District. Bill Foster (D., Ill.) joins two other Ph.D physicists, Vern Ehlers (R., Mi.) and Rush Holt (D., N.J.) in the U.S. Congress. In 1984 Bill moved to the Fox River Valley to raise his family and for the next 22 years to work at Fermilab. Bill played a leading role in several groundbreaking experiments in elementary particle physics and managed several major accelerator construction and research projects. Along the way he designed and built equipment using a number of advanced technologies, including high speed electronics, superconducting magnets, analog and digital integrated circuit design, and high power electronics. Bill has received several awards for these achievements. In 1998 Bill was elected an APS Fellow. His citation reads: "For contributions to development of large scale particle physics electronics, and for a leading role in the design of the permanent magnetic-based Fermilab Antiproton Recycler ring." Bill's campaign was supported by a large number of scientists including many Nobel Laureates. He was endorsed by both Illinois senators, Dick Durbin and Barack Obama. Besides his physics accomplishments, Bill has a successful business background. He and his brother, Fred, created a company that now manufactures over half of the theater lighting equipment in the United States including Broadway shows, the great Opera houses, half-time shows at the Super-Bowl, and at churches, schools, and community theatres throughout the country.

Bill gave me a quote for this newsletter**: "All of you will appreciate the value of having a congressman who understands space charge and superconducting magnets."**

Illinois Accelerator Institute Announces the Inaugural Lee Teng Undergraduate Internship

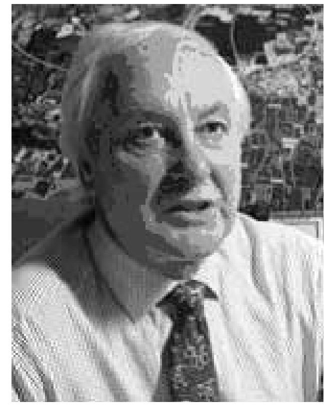
The Lee Teng Undergraduate Internship in Accelerator Science and Engineering has been established by the Illinois Accelerator Institute to attract undergraduate students into the exciting and challenging world of particle accelerator physics and technology.

A limited number of highly qualified students will be selected into this program. Successful candidates will attend the Summer Session of the The U.S. Particle Accelerator School (USPAS), held June 16-27, 2008 at the University of Maryland. They will all take the *Fundamentals of Accelerator Physics and Technology with Simulations and Measurements Lab* for which undergraduate credit is available. For the remainder of the summer they will work closely with a mentor and a project at either Argonne or Fermilab.

The program includes a generous stipend and all travel expenses.
Go to http://www.illinoisacceleratorinstitute.org/ for more information.

Illinois Accelerator Institute

Robert R. Wilson Prize for Achievement in the Physics of Particle Accelerators



To: Lyndon R. Evans, CERN

Citation:
"For a sustained career of technical innovation and leadership in the SPS proton-antiproton collider, culminating in the construction and commissioning of the LHC."

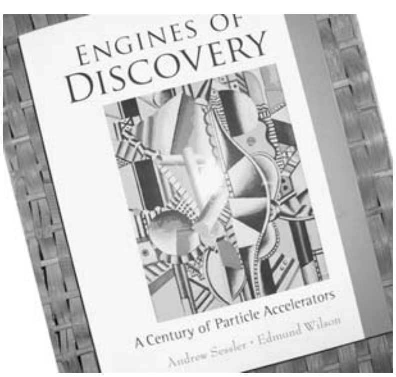
Lyn Evans is of a generation of accelerator builders whose career spans the era of colliders—particular hadron colliders. His research activities started in 1968 with a PhD at the University of Wales, Swansea on the production of plasmas with an intense laser beam. The CO_2 laser, which he build himself, was still in use as late as 1990 in the Swansea Physics Department. This exemplifies a practical approach to the construction and operation of physics equipment which has been his strength throughout his career.

- Like many of his contemporaries he came to CERN, once his PhD thesis was completed, as a Research Fellow.
- 1971—He moved to the newly approved 300 GeV Project for the construction of the Super Proton Sycnhrotron under John Adams.
- He played a key role in the conversion of the SPS into a storage ring.
- Mid 1980s—He worked on the commissioning of the world's first large superconducting storage ring at Fermilab.
- 1989—He was given the task of setting up a new CERN Division responsible for both the operation of the SPS and for the development of the Large Electron Positron Collider (LEP).

In 1994, he was appointed Project Leader of the LHC project, Europe's flagship scientific instrument for the investigation of the high energy frontier in particle physics. The LHC is a huge project with a materials budget of more than 3 billion Swiss Francs, and enormous technical challenges. He was responsible for both the machine design and the development of the unique system of superconducting dipole magnets capable of reaching up to 9 tesla, operating in superfluid helium at 1.9 K. He took this development from a laboratory scale to an enormous industrial production.

In 2001 he was awarded a CBE (Commander of the Most Excellent Orrder of the British Empire) in recognition of his achievements.

Excepted with permission from "Engines of Discovery" by Sessler and Wilson, World Scientific (2007)



"**Engines of Discovery, A Century of Particle Accelerators**," the new book by Andrew Sessler and Edmund Wilson, World Scientific Publishing Company 2007, is available from Amazon and also World Scientific. A web page that gives excerpts, reviews and an order form is at: http://www.enginesofdiscovery.com/

Nominations for the 2009 Wilson Prize should be sent to Steve Gourlay- sagourlay@lbl.gov Chair of the 2008 Selection Committee by July 1, 2008. Guidelines for nominations are at http://www.aps.org/praw/index.cfm.

Award for Outstanding Doctoral Thesis in Beam Physics

To: Rama R. Calaga, Stony Brook University

Ben-Zvi, Calaga, Peggs

Citation:

"For his dissertation about characterization and correction of RHIC's transverse optics and beam dynamics, and about design of an Ampere class SRF gun and cavity."

Thesis Advisors: Ilan Ben-Zvi and Steve Peggs

Calaga writes: "I started my Ph.D. in 2000 at Stony Brook University. After two years of course work, I started my research work in the field of accelerators in Jan 2003 with Ilan Ben-Zvi and Steve Peggs at BNL. My advisors were working in different fields, both very interesting, which ultimately resulted in a combined thesis on beam dynamics and high current superconducting RF cavities. Although difficult, my Ph.D. experience was very rewarding and help shape my scientific career. I was awarded the first Toohig fellowship to work as a U. S. postdoc on the Large Hadron Collider at CERN. The skills acquired during my Ph.D. were invaluable during my postdoc at CERN."

At CERN in the LHC tunnel

Abstract from Calaga's Thesis: The Relativistic Heavy Ion Collider (RHIC) is a hadron collider designed to collide a range of ions from protons to gold. RHIC operations began in 2000 and has successfully completed five physics runs with several species including gold, deuteron, copper, and polarized protons. Linear optics and coupling are fundamental issues affecting the collider performance. Measurement and correction of optics and coupling are important to maximize the luminosity and sustain stable operation. A numerical approach, first developed at SLAC, was implemented to measure linear optics from coherent betatron oscillations generated by ac dipoles and recorded at multiple beam position monitors (BPMs) distributed around the collider. The approach is extended to a fully coupled 2D case and equivalence relationships between Hamiltonian and matrix formalisms are derived. Detailed measurements of the transverse coupling terms are carried out at RHIC and correction strategies are applied to compensate coupling both locally and globally. A statistical approach to determine BPM reliability and performance over the past three runs and future improvements are also discussed.

Aiming at a ten-fold increase in the average heavy-ion luminosity, electron cooling is the enabling technology for the next luminosity upgrade (RHIC II). Cooling gold ion beams at 100 GeV/nucleon requires an electron beam energy of approximately 54 MeV and a high average current in the range of 50-200 mA. All existing e^- coolers are based on low energy DC accelerators. The only viable option to generate high current, high energy, low emittance CW electron beam is through a superconducting energy-recovery linac (SC-ERL). In this option, an electron beam from a superconducting injector gun is accelerated using a high gradient (~20 MV/m) superconducting RF (SRF) cavity. The electrons are returned back to the cavity with a 180º phase shift to recover the energy back into the cavity before being dumped. A design and development of a half-cell electron gun and a five-cell SRF linac cavity are presented. Several RF and beam dynamics issues ultimately resulting in an optimum cavity design are discussed in detail.

Nominations for the next Outstanding Doctoral Thesis in Beam Physics Award should be sent to Gennady Shvets <gena@physics.utexas.edu>, Chair of the Selection Committee. Guidelines for nominations are at http://www.aps.org/praw/index.cfm.

DPB Members recognized as APS Fellows

Congratulations for their important contributions to beam physics are extended to:

Michael Borland, Argonne National Laboratory

Citation: For outstanding contributions to fourth generation light sources, particularly for development and support of the program ELEGANT, the first integrated accelerator code to realistically model coherent synchrotron radiation effects.

Courtesy Brookhaven Natl Lab

Wolfram Fischer, Brookhaven National Laboratory

Citation: For the successful commissioning of high luminosity high energy collisions at the Relativistic Heavy Ion Collider and outstanding contributions to the understanding of high-energy accelerator and collider properties.

Miguel Furman, Lawrence Berkeley National Laboratory

Citation: For his pioneering development and application of simulation tools for the beam-beam and electron cloud effects in colliders and storage rings.

Robert Rimmer, Jefferson Laboratory

Citation: For advances in the science and technology of RF structures and beam stability in high-current accelerators.

DeJan Trbojevic, Brookhaven National Laboratory

Citation: For his original contributions in the design, commissioning and operations of the Tevatron and RHIC colliders, and for the development of new concepts for future accelerators.

Max Zolotorev, Lawrence Berkeley National Laboratory

Citation: For the invention of methods to generate ultra-cold and ultra-fast sources of electron and ion beams using lasers and optical techniques.

DPB Sessions and the 2008 April APS Meeting

April 12, 3:30 PM, Saturday
Session E3 Accelerator Technology and the Physics it Enables (Co-Sponsor: DNP)
Chair: *Lia Merminga, Thomas Jefferson National Accelerator Facility*
Room: *St. Louis E*
Invited Speakers: *Peter Ostroumov, Christoph Tschalaer, Swapan Chattopadhyay*

April 13, 8:30 AM, Sunday
Sess H6 Impact of Major Accelerator Projects on the Development of Emergent Countries (Co-Sponsor: FIP)
Chair: *Satoshi Ozaki, Brookhaven National Laboratory*
Room: *Promenade D*
Invited Speakers: *Vinod Chandra Sahni, Won Namkung, Herman Winick*

April 13, 10:45AM, Sunday
Session J5 The U.S. Particle Accelerator School (Co-Sponsor: FEd)
Chair: *Linda Spentzouris, IIT*
Room: *Promenade C*
Invited Speakers: *William Barletta, Evgenya Smirnova, Michael Syphers*

April 14, 10:45AM, Monday
Session R5 Advanced Acceleration Techniques (Co-Sponsor: DPP)
Chair: *Warren Mori, UCLA,*
Room: *Promenade C*
Invited Speakers: *Chan Joshi, Wim Leemans, Wei Gai*

April 14, 12:30 PM, Monday
Session R18 DPB Business Meeting and Reception
Room: *Director's Row 26*

April 14, 1:30 PM, Monday
Session S12 Accelerator Physics Contributed Papers
Chair: *Thomas Roser, BNL*,
Room: *St. Louis C*

April 14, 3:30PM, Monday
Session T2 Wilson Prize
Chair: *Stephen Holmes, Fermi National Accelerator Laboratory*
Room: *St. Louis D*
Invited Speakers: *Lyndon Evans, Rama Calaga, David Larbalestier*

April 15, 10:45AM, Tuesday
Session W2 The LHC/ILC Era (Co-Sponsor: DPF)
Chair: *Boris Kayser, Fermi National Accelerator Laboratory*
Room: *St. Louis D*
Invited Speakers: *Fabiola Gianotti, Daniel Marlow, Heather Logan*

April 15, 1:30PM, Tuesday
Session X2 **Future Accelerator Facilities** (Co-sponsor: DPF)
Chair: *Young-Kee Kim, Fermilab*
Room: *St. Louis D*
Invited Speakers: *David MacFarlane, A.J. Lankford, Steve Geer*

The US Particle Accelerator School

USPAS sponsored by the University of Maryland
and held in Annapolis, Maryland June 16-27, 2008
Applications to attend this program will be available in spring.

Two-week courses: June 16-27, 2008
(each of the following full courses earns 3 credits from the University of Maryland)

- **Fundamentals of Accelerator Physics and Technology with Simulations and Measurements Lab (undergraduate level)** Ying Wu and Stepan Mikhailov, Duke University and Juhao Wu, SLAC
- **Accelerator Physics** Waldo MacKay and Todd Satogata, Brookhaven National Lab
- **RF Superconductivity: Physics, Technology and Applications** Jean Delayen, Jefferson Lab
- **Beam Dynamics Experiments on the University of Maryland Electron Ring** Rami Kishek, Santiago Bernal, Ralph Fiorito, Mark Walter, David Sutter, Patrick O'Shea and the UMER Staff (This class is limited to 12 students)
- **Beam Physics with Intense Space Charge** John Barnard and Steven Lund, Lawrence Livermore Ntnl Lab

One-week courses:
(each one-week half course earns 1.5 credits from the University of Maryland;
students may attend one week and earn UMD credit)
<u>One Week 1/2 courses: June 16-20, 2008</u>

- **Medical Applications of Accelerators** Jay Flanz, Massachusetts General Hospital
- **Laser Plasma Accelerators** Carl Schroeder and Eric Esarey, Lawrence Berkeley National Lab
- **Vacuum Electron Devices** Alain Durand, Thales Electron Devices, Michel Langlois, ALBA Synchrotron
- **Beam-Based Diagnostics** Christoph Steier and Greg Portmann, Lawrence Berkeley National Lab and James Safranek, SLAC

<u>One Week 1/2 courses: June 23-27, 2008</u>

- **Radiation Detection and Imaging for Medicine and Homeland Security** Thomas Budinger, UC-Berkeley and Lawrence Berkeley National Lab
- **Laser Applications to Accelerators** Yuelin Li, Argonne National Lab
- **Microwave Sources** Bruce Carlsten and Steven Russell, Los Alamos National Lab
- **Control Room Accelerator Physics** John Galambos and Chris Allen, Oak Ridge National Lab

Participation is open to both U.S. and non-U.S. citizens. International participants not currently residing in the U.S. may apply to attend the program and may request financial sponsorship but they may not earn credit from the University of Maryland.

MORE INFORMATION at uspas.fnal.gov

LCLS Commissioning

Paul Emma, John Galyda and others

The Linac Coherent Light Source (*LCLS*) is a SASE (self-amplified spontaneous emission) x-ray free-electron laser (FEL) project under construction at SLAC [1]. The project is supported by a multi-laboratory collaboration including ANL, LBNL, LLNL, and UCLA and is presently in its second phase of electron beam commissioning. The first phase occupied the months of April through August 2007 with a focus on the recently installed injector, including drive laser, RF photocathode gun, S-band and X-band RF systems, first bunch compressor chicane, and the various beam diagnostics. The second phase of commissioning began in December 2007 after a 3-month installation period. This phase includes the second bunch compressor chicane and the full 1-km long linac (the last one third of the SLAC linac). The final FEL commissioning phase for this new generation of light source begins in 2009 with project completion in early 2010.

First electrons from the new RF photocathode gun, which was designed and built at SLAC [2], were observed on April 5, 2007 and beam was quickly established to the nominal injector energy of 250 MeV in the main SLAC linac. Over the next five months in 2007 all injector systems were commissioned and the beam accelerated to as high as 16 GeV using the last 1/3 of the SLAC linac [3]. During this time the RF gun operated with a cathode field of 115 MV/m at a 30-Hz repetition rate with no significant down-time. In April of 2008, an upgrade of the gun RF probes will allow 120 Hz operation at more than 120 MV/m.

The photocathode drive laser system, purchased from *Thales Laser*, has performed extraordinarily well with 98% up-time and energy delivered to the cathode, ex-

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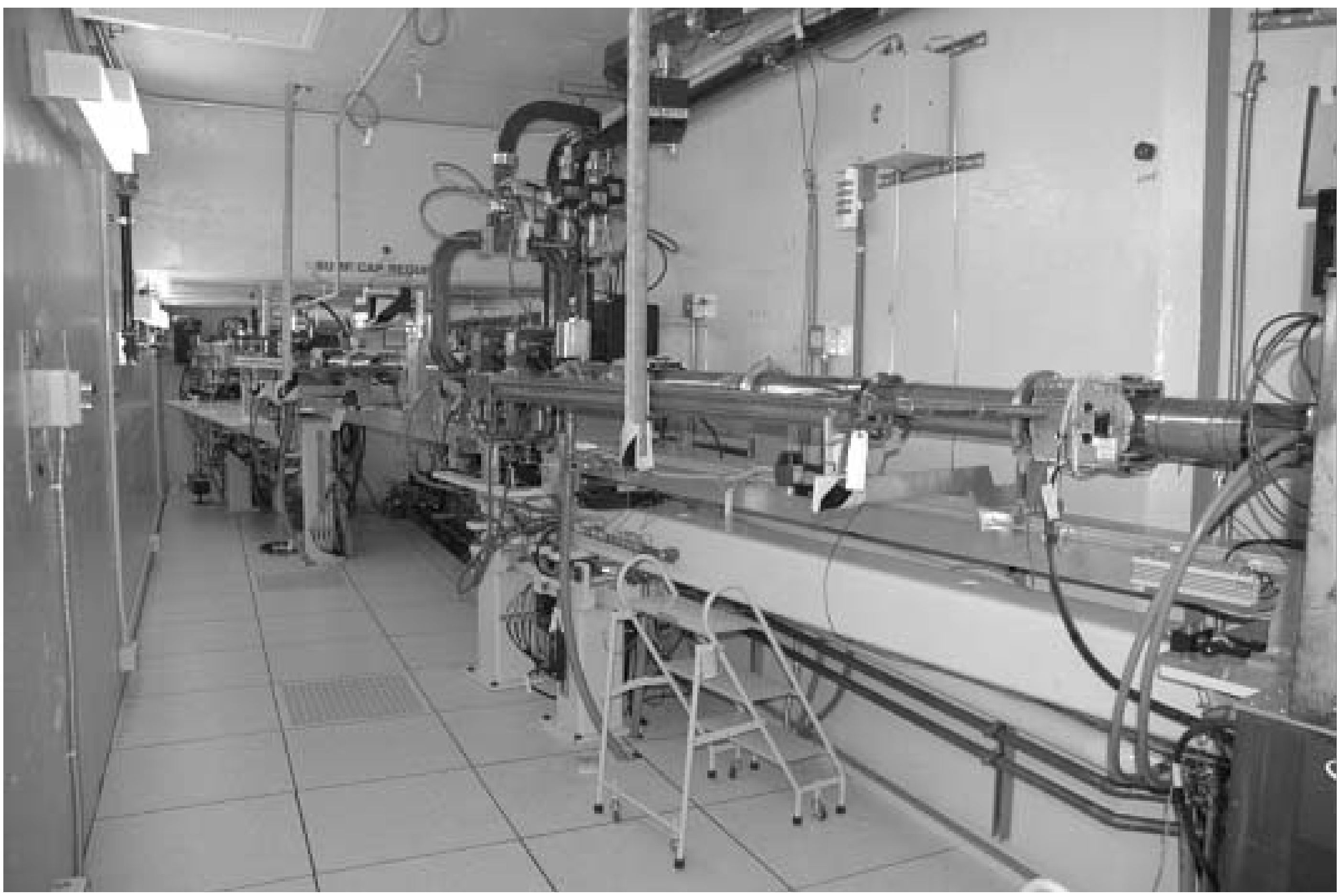

Photograph of the new *LCLS* injector installed 35-degrees off axis in an existing housing at the 2-km point in the SLAC linac. The RF gun is outside the frame of the photo to the right.

(Continued from page 9)
ceeding specifications. Temporal and spatial laser shaping have been greatly improved for 2008 and are now close to design levels. The quantum efficiency of the copper cathode was initially about 10-times below expectations, but with continued run-time and an intervening laser cleaning effort the full 1-nC of bunch charge has been well established. A systematic checkout of all components has demonstrated the accuracy and reliability of the transverse phase space diagnostics, including many OTR (optical transition radiation) screens and wire scanners located both before and after the first bunch compressor chicane. The checkout was followed by a gradual tuning effort, such as orbit optimization, gun-solenoid tuning, RF phasing, and beta function and dispersion correction, eventually resulting in very repeatable normalized emittance measurements in the range of 0.8 to 1.2 microns, depending on the bunch charge (0.2 to 1 nC). The time-sliced emittance has also been measured in the injector, using a transverse RF deflecting cavity, with results between 0.6 and 0.9 microns. At a bunch charge of 1 nC, the transverse normalized rms emittance of 1.2 microns in the injector (both before and after the first bunch compressor) now appears to meet the design brightness requirements for the *LCLS* and may set a new record for electron beam brightness.

Phase-II of commissioning is presently focused on operation of the second bunch compressor, precise linac RF phase control, and demonstration of emittance preservation through the full linac with a compressed bunch. In nominal operations at 1 nC, the final bunch length must be compressed to 20 microns rms (70 fs). The bunch charge is presently kept low, at 0.25 nC, while the new systems are commissioned, but a second, more powerful transverse RF deflector at 5 GeV has already been used to measure bunch lengths as short at 6 microns (20 fs) as the linac RF phase is varied. Preliminary indications show both bunch compressors are functioning as designed, after modification of the first chicane bends in fall of 2007 to correct some field quality errors.

One major surprise has been the performance of the OTR screens downstream of the first injector bend magnets. It now appears that a significant component of the OTR light from these screens is coherent at the visible-light wavelengths of the camera's sensitivity. The coherence is presumably due to temporal micro-bunching of a small fraction of the beam charge which develops through the accelerator, enhanced by the first bend magnets after the injector. Consequently the imaged OTR light is not simply proportional to charge density, and contributes errors to the spot size and emittance measurement. The source of the micro-bunching is not clear yet, but it is too high in frequency for the laser to produce, and could be the Shot noise in the beam. Simulations of the *LCLS* beam performed several years ago [4] showed a potential micro-bunching effect, which will be Landau damped using a laser heater [5] (inverse FEL) in the injector. This laser heater system has not yet been installed, since it was presumed necessary only for FEL operations. In fact, it now appears that the laser heater will also be needed in order to suppress the coherent OTR from these screens, which otherwise has a detrimental bias on emittance measurements. For the present, wire-scanners are used to measure the emittance after the first bends of the injector, and the OTR screens beyond this point are only qualitative in their image reproduction.

Phase-II of commissioning is well under way and will continue until early August 2008 when another 3-month installation period will begin. This installation phase will include the new 340-m long electron transport line from linac to undulator (LTU), the 130-m long high-precision planar FEL undulator, and the 70-m long electron dumpline. Concurrently, the x-ray front-end transport and diagnostics systems will be installed just downstream of the electron dump. Commissioning of the LTU, undulator, and dump will begin in November 2008, and FEL commissioning with the new full suite of x-ray diagnostics will commence in May of 2009. Meanwhile, the x-ray transport systems will be extended into the Near Experimental Hall, and the first *LCLS* x-ray experimental instrument will be installed. FEL light is expected in summer of 2009, and initial x-ray experiments will immediately begin to make use of this revolutionary new light source.

During late 2009 and early 2010 the x-ray transport systems will be extended through a 200-m transport hall and will reach the Far Experimental Hall. The Near and Far Halls are designed to contain 6 major x-ray instruments, optimized for a wide range of FEL science. The instruments will be installed over the next several years, with full capability in about 2012. The *LCLS* will be operated as a general user facility by the US DOE, with access starting in late 2009 through peer-reviewed proposals. This new machine will introduce a unique new tool for x-ray studies, with unprecedented peak brightness, 1-Angstrom spatial resolution, and femtosecond-scale temporal resolution for a wide variety of scientific applications.

The undulator service building (left) and the new Near Experimental Hall (center) under construction on the SLAC site (facing east). Stanford University's Hoover Tower is seen in the background.

References

1. J. Arthur *et al.*, SLAC-R-593, April 2002.
2. L. Xiao, *et al.*, "Dual Feed RF Gun Design for the LCLS," Proceedings of the 2005 Particle Accelerator Conference, Knoxville, TN, pp. 3432-3434 (2005).
3. R. Akre, *et al.*, to appear in Phys. Rev. ST Accel. Beams in March 2008.
4. M. Borland, et al., Nucl. Instrum. Methods Phys. Res., Sect. A **483**, 268 (2002).
5. Z. Huang, *et al.*, Phys. Rev. ST Accel. Beams 7, 074401 (2004).

The New Generation of FFAG Accelerators

C. Johnstone (Fermilab) and S. Koscielniak (TRIUMF)

Mail to: cjj@fnal.gov

Introduction

Fueled by recent advances, electron, proton and heavy ion accelerators are playing increasingly important roles in science, technology, and medicine including accelerator-driven subcritical reactors, industrial irradiation, material science, neutrino production, and cancer therapy. The drive for higher beam power, high duty cycle, high reliability and precisely controlled beams at reasonable cost has generated worldwide interest in Fixed-field Alternating Gradient accelerators (FFAGs). FFAGs are unique in their high repetition rates, and large acceptances characteristic of cyclotrons, yet they also embody the advantages of the synchrotron: focusing is predominately 'strong', with low injection and extraction losses. By breaking the magnet into sectors to provide edge and strong focusing, and abandoning isochronism in favor of synchrocyclotron-like operation, FFAGs are capable of multi-GeV accelerated energies. Combining, gradient, edge and weak focusing, the FFAG variants represent, in principle, the most general fixed-field accelerator.

The 'so-called' scaling versions of the FFAG were proposed independently in Japan, the USSR, and the US[1]. Both radial- and spiral-sector electron models[2] were built in the 1950s by the Midwestern Universities Research Association, but competition for the "energy frontier" prevented further development. In recent years, with the improvements in magnet and rf technology coupled with the strong interest in fast, acceleration of intense muon beams for high-energy physics, FFAGs have become the focus of international attention and collaboration. Relaxation and even elimination of the restrictive 'scaling' law have resulted in an explosion of new FFAG approaches, which have been documented and explored via a series of international workshops[3].

The scaling principle[4] was adopted to avoid potentially disastrous resonance crossing by keeping the optics constant as a function of momentum. This is achieved by deliberate addition of radial nonlinear field profiles and reversed B fields, in the radial-sector designs; or nonlinear field profiles and logarithmic spiral edges on the magnet in the spiral-sector designs. Reversed fields increase the circumference, so in compact applications, the spiral sector design is preferred. Further innovations by Y. Mori's group at KEK involved the application of a 'triplet' DFD quadrupole lattice and two proton scaling FFAGs have been constructed and operated, successfully demonstrating the anticipated high repetition rate. Table 1[4] lists these two machines (1 MeV[5] and 150 MeV [6], Figure 1) along with several others under development. In addition to these machines and those slated for physics research, at least another 20 more are presently under design or various stages of development for various applications, which range from electron irradiation to proton and ion cancer therapy[4].

In 1997, in a study of FFAGs for muon acceleration and neutrino production, it was noted that the rapid acceleration required to avoid beam loss from muon decay also allowed scaling to be essentially abandoned as betatron resonances had no time to develop[7]. A nonscaling approach[8] that employs only linear-field elements ushered in a new regime in fixed-field accelerator design and dynamics. The linear-field FFAG has the ability to compact an unprecedented range in momenta within a small component aperture. With a tune variation, which results from the natural chromaticity, the beam crosses many strong, uncorrectable, betatron resonances during acceleration, yet is relatively unsusceptible for the tens of acceleration turns timescale for muon acceleration. Further, relativistic particles in this machine exhibit a quasi-parabolic time-of-flight (Figure 2) that cannot be addressed with a fixed-frequency rf system. This leads to a new concept of bucketless acceleration within a rotation manifold[9] and Figure 3. A few-MeV electron model (EMMA) is underway at Daresbury Laboratory to demonstrate the feasibility of these untested acceleration features and to investigate them at length under a wide range of operating conditions[10].

Many other variations on the nonscaling, linear-field concept are under study including FFAG systems for

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cancer therapy[11]. Historically [12], these nonscaling FFAGS, accelerate a factor of 2-3 in momentum, and execute on the order of ten turns. Slow acceleration, where beam executes hundreds to thousands of turns in the machine, greatly reduces RF requirements and expense, but requires, at a minimum, a stable tune in order to avoid resonances and associated beam blow up and loss. A hybrid design for a linear-field, nonscaling FFAG accelerator was subsequently invented[13] which uses edge and alternating-gradient focusing principles applied in a specific configuration to stabilize tunes through an acceleration cycle which extends over a factor of 6 in momentum. This design introduces a powerful new feature: essentially wedge-shaped combined function magnets with opening angles and fields chosen such that edge-focusing and dipole body-focusing assists the quadrupole-gradient focusing to minimize the variation in tune. Potential applications include the PAMELA study[14] which has been funded in the UK to research FFAGs for proton and carbon-ion therapy machines.

Finally nonlinear, nonscaling FFAGs have been designed by Rees[15] to provide more control over beta functions and dispersion – effectively making the ring isochronous and supporting longer insertions for multi-cell rf cavities, injection, scraping, and extraction systems.

Many scaling FFAGs are already in place and under construction. The exploration of nonscaling FFAGs is still in its early days with EMMA expected to come online in 2009. Effective and well-supported simulation codes remain an issue in pursuing FFAG research. Outside of individual efforts and codes, presently work is ongoing with ZGOUBI[16] and a recent initiative on the part of Michigan State University to adapt COSY INFINITY[17] for both scaling and nonscaling FFAG optimization and modeling. Only with advances in codes, can we fully explore and exploit the novel dynamics of this new generation of accelerators.

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Table 1: Operating Scaling FFAGs or scaling FFAGs under construction[4]

	Ion	*E (MeV)*	*Cells*	*Spiral Angle*	*Radius (m)*	*First Beam*	*Technical*
KEK-PoP	p	1	8	0º	0.8—1.1	2000	
KEK	p	150	12	0º	4.5—5.2	2003	100 Hz, 90% ext.
KURRI-ADSR (Figure 1)	p	2.5	8	40º	0.6—1.0	2006	Initial spec: 120 Hz, 1μA Now: 1kHz, 100μA, @200 MeV
	p	20	8	0º	1.4—1.7	2006	
	p	150	12	0º	4.5—5.1	(2007)	
NEDO-ERIT	p	11	8	0º	2.35	(2008)	70mA ionization cooling ring
PRISM study	α	0.8	6	0º	3.3	(2008)	Phase space rotator
Radiatron	e	5	12	0º	0.3—0.7	(2008)	24 kW, 10 kHz, betatron acc.

Figure 1. The three proton rings for ADSR studies at Kyoto Univ Research Reactor Institute in 2006.

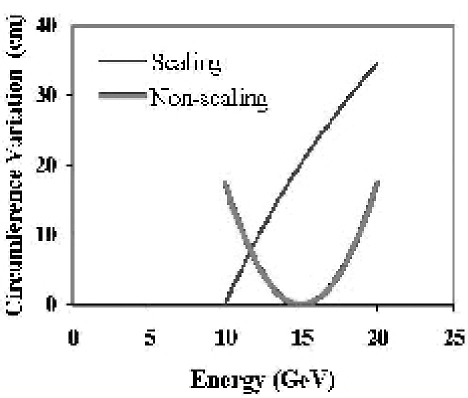

Figure 2. Circumference variation for scaling compared with nonscaling FFAGs.

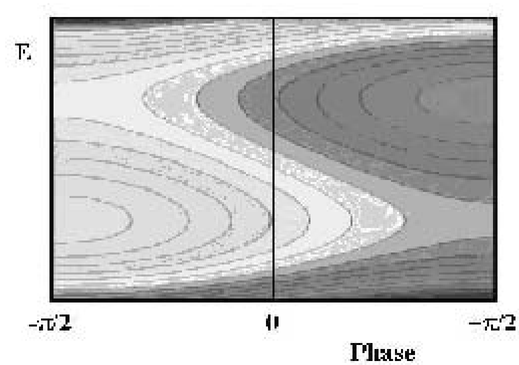

Figure 3. Acceleration (center band) path in a linear-field, nonscaling FFAG.

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