APS DPB NEWS

APS Division of Physics of Beams Annual Newsletter ////////// **2018**

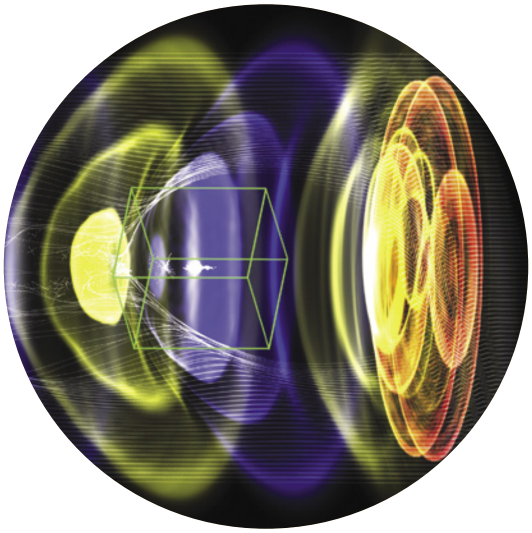

Image: Snapshot from a WarpX 3D simulation of a laser-driven plasma accelerator. See page 16 for details.
Photo Credit: Maxence Thévenet

In this Issue:

Dear Readers,

After the decidedly international flair of the 2017 newsletter, this year's edition of the APS DPB newsletter brings us a little closer to home. With a nod to the past, we present two historic pieces celebrating Oakridge National Lab's 75th anniversary and TRIUMF's 50th anniversary, covering not only their rich histories but also exciting plans for the future. Pioneering projects on the cusp of discovery—including IOTA and the FAST facility, Argonne's wakefield acceleration project and exascale accelerator modeling tools—update readers with the latest news in the community. Finally, we get a glimpse of what the future might bring with articles on the NAS Report on the Assessment of U.S.-Based Electron-Ion Collider Science, the U.S. DOE Magnet Development Program (15 Tesla magnets and beyond!), the APS Upgrade and a feature on using accelerators to probe matter in extreme conditions.

A feature on the Center for Bright Beams, combined with recurring articles such as our interview with the DPB Dissertation Award Recipient and the University Lab Highlight on Northern Illinois University, reflect a vibrant, diverse community in accelerator education advancing the state of the art in many areas of accelerator physics and engineering.

We are excited at the continued success of this newsletter series since it's reinstatement in 2015, with each new issue bringing improvements to the newsletter and an expanded readership, and we look forward to many more installments in the years to come. Please let us know if you would like to share your research in the next issue.

As always, if you have suggestions for an article or any comments, questions or concerns, please don't hesitate to get in touch.

Enjoy,

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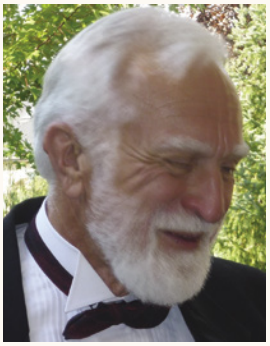

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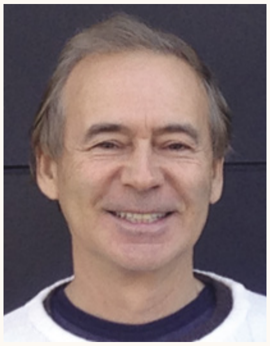

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From the Chair

Vladimir Shiltsev *Fermi National Accelerator Laboratory*

The Division of Physics of Beams worked hard this year to promote research and accomplishments in the science of beams, publish in scholarly journals, enhance education in beam science and technology, and provide a forum for communication via sponsorship of conferences. The DPB PhD Thesis Award Committee, the Fellowship Committee, and the DPB/DPF Wilson Prize Committee— chaired by Rami Kishek, Sergei Nagaitsev and Stuart Henderson, respectively—have come up with outstanding awardees. The Publications Committee, chaired by Michael Blaskiewicz, reviewed possibilities and, together with our colleagues from the EPS Accelerator Group, developed a plan to increase the impact factors of accelerator and beam science publications and journals. On this note, Physical Reviews Accelerators and Beams celebrated 20 years! We send our congratulations to its lead editor, Frank Zimmermann. Our major DPB-sponsored conference this year—IPAC'18 in Vancouver, British Columbia—was a smashing success. An exciting addition to the program this year was a set of tutorials for undergraduates, graduate students and postdoctoral fellows.

At the April APS meeting in Columbus, Ohio, we jointly organized and sponsored sessions on energy frontier colliders, nuclear physics facilities and X-ray radiation facilities with DPF, DNP and DCOMP, respectively. At the APS Annual Leadership Convocation, we informed members of Congress of the role and relevance of physics research, and specifically accelerator physics and technology. We also took part in the APS-wide discussion on various issues, from research budgets in the U.S. to the financial well-being of the American Physical Society, which receives about 70% of its income from its journals, in the oncoming era of "golden open access."

A perennial challenge is keeping DPB membership above the 2.1% threshold required to maintain division status within APS. As of July 1, 2018, we had 1210 members in DPB, about 2.17% of the APS total. The EC is working on improving this situation. We are actively recruiting new and return members, particularly our fellow beam physics colleagues and accelerator users who are members of APS but not in the DPB. Surprisingly, about 40% of APS members are not listed in any division or unit! **If you are a member, we encourage you to please check that you are in fact enrolled in the DPB (it's free to add two units).**

Our second focus is to engage organized user groups, international colleagues, and students / early career researchers, the latter of which account for only 18% of the DPB membership, half of what other divisions have. I encourage each member of DPB to make the case for membership and to encourage your colleagues, both accelerator physicists and users, to join. We welcome your suggestions on how DPB can be more effective in dealing with this issue.

Finally, I would like to use this opportunity to congratulate our newly elected members of the DPB EC - Vice-Chair Sarah Cousineau of ORNL, Council Member Stuart Henderson of JLab, Members-at-Large Mei Bai of GSI and Eric Prebys of UC Davis and Early Career Member-at-Large Martina Martinello of Fermilab – and to thank outgoing EC members Tor Raubenheimer of SLAC, Thomas Roser of BNL, Heather Andrews of LANL, Anna Grasselino of Fermilab and Alysson Gold of SLAC for their contributions!

From the Secretary Treasurer

Marion White *Argonne National Laboratory*

The Division of Physics of Beams is performing very well as an APS Division and is doing well financially. **However, membership is a serious concern; if our numbers are too low, we could cease to be an APS Division.** Please encourage your colleagues who use accelerators in their research to add the DPB to the APS Units to which they subscribe!

Over the past year, the DPB has provided funds to support the annual newsletter, the APS International Research Travel Award Program and a student support program that funded attendance to IPAC'18 and the student tutorials. Division income is mostly derived from conferences and is generally spent on these and similar activities. The executive committee met three times over the last year and have started tracking action items from our meetings. Our past secretary-treasurer, Stan Schriber, has converted his files from the past 10 years to electronic records and has been populating them into an organized filing system for use by the EC and various committees.

Voting in the 2018 election closed on November 10th, 2018. Almost 33% of DPB members voted this time, up from only 27% last year. We sincerely appreciate any suggestions as to how to increase participation in our election process.

The Ninth International Particle Accelerator Conference (IPAC 2018)

Shane Koscielniak and Tor Raubenheimer
TRIUMF and SLAC

The ninth International Particle Accelerator Conference (IPAC'18) was held in Vancouver, British Columbia, April 29-May 4,2018. Hosted by TRIUMF and jointly sponsored by the IEEE Nuclear & Plasma Sciences Society and the APS Division of Physics of Beams, the event attracted more than 1,200 delegates from 31 countries, plus 90 industry exhibitors. The scientific program included 63 invited talks and 62 contributed orals, organized in eight main classes. While it is impossible to summarize the full program in a short article, below are some highlights from IPAC'18 which demonstrate the breadth and excitement in the accelerator field at this time.

The conference opened with several plenary talks. Jonathan Bagger, director of the host laboratory TRIUMF, described the evolution of TRIUMF from its founding in 1968 by three local universities to the present-day setup with 20 member universities, users drawn from 38 countries, and an annual budget of 100 million Canadian dollars. Also in this session, Sergei Nagaitsev of Fermilab talked about the path to the Long Baseline Neutrino Facility, which includes upgrades to Fermilab proton beam accelerators (PIP-II) as well as the new detector DUNE, to be located 1300 km away. The project will engage more than 175 institutions from around the world with the aim of investigating leptonic CP violation and the mass hierarchy in the neutrino sector.

A foray into the future of accelerators by Stephen Brooks of Brookhaven National Laboratory was a walk on the wild side. The idea of a single-particle collider was presented as a possibility to achieve diffraction-limited TeV beams to bridge the potential "energy desert" between current technology and the next energy regime of interest. Relevant technological and theoretical challenges were discussed, including multiple ideas for overcoming emittance growth from synchrotron radiation, focusing beams (via gravitational lensing) and obtaining nucleus-level alignment, as was how to reduce the cost of future accelerators.

In one session devoted to photon sources and electron accelerators, Michael Spata described the Jefferson Laboratory's 12 GeV upgrade of CEBAF, which began full-power operation in April after overcoming numerous challenges, including installation and operation of a new 4 kW helium liquefier, and field emission limitations in the cryomodules. James Rosenzweig of UCLA described progress towards an all-optical "fifth-generation" light source. The scheme could lead to a compact, tunable multi-MeV gamma-ray source, and successful demonstrations have already taken place at the RUBICONICS test stand at UCLA.

Concerning novel particle sources and acceleration techniques, plasma acceleration was featured in a few talks. CERN's Marlene Turner described progress at the AWAKE experiment, which

aims to use a high-energy proton beam to generate a plasma wake that can accelerate an electron beam. The AWAKE team demonstrated self-modulation of the proton beam and measured the formation of the plasma wakefield, and the team plans to test the acceleration of an injected electron beam. Felicie Albert of Lawrence Livermore National Laboratory also described the use of laser-wakefield technology to generate betatron X rays, which could enable new measurements at X-ray free electron lasers.

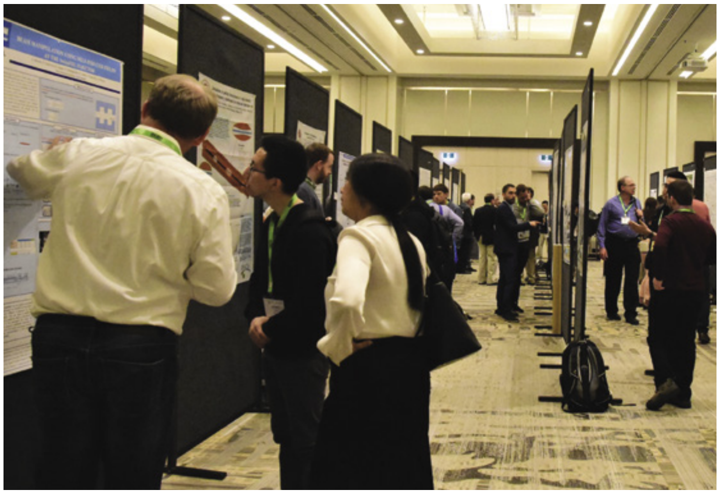
In a session devoted to beam dynamics and electromagnetic fields, Valery Telnov of the Budker Institute introduced a cautionary note about bremsstrahlung at future electron-positron colliders that will impact beam lifetimes at present-generation colliders, such as Supper KEKB, and next-generation machines, such as FCC-ee. Tessa Charles of the University of Melbourne, meanwhile, introduced the method of caustics to understand and optimize longitudinal beam-dynamics problems, such as how to minimize coherent synchrotron radiation effects in recirculation arcs.

The proton linac for the European Spallation Source (ESS) under construction in Sweden was presented by Morten Jensen during the session on accelerator technology. He outlined the variety of RF power sources used in the ESS proton linac and the development of the first-ever MW-class "inductive output tubes" for the linac's high-beta cavities. These have been tested at CERN and have reached record-setting performances of 1.2 MW output for 8.3 kW input power. Pending the development of a production series, the accelerator community may have a new RF workhorse.

As indicated, these are just a few of the many scientific highlights from IPAC'18. Industry was a major presence also. Over 70 industry exhibits were present, and a panel discussion focused on successful models for technology transfer to industry.

IPAC is committed to welcoming young researchers, offering heavily discounted fees for all students as well as 107 student grants. Almost 1,500 posters were presented by authors from 233 institutions over four days. Attendance was 24% from Asia, 41% from Europe, and 35% from the Americas, demonstrating the truly international nature of the field.

The 10th IPAC will take place in Melbourne, Australia, May 19-24, 2019.



Fermilab's Newest Accelerator Sees First Beam

Sergei Nagaitsev and Vladimir Shiltsev
Fermi National Accelerator Laboratory

On Aug. 21, 2018, a beam of 50 MeV electrons successfully circulated for the first time through the Integrable Optics Test Accelerator, a new particle accelerator at Fermilab. IOTA will serve as a precision machine with a flexible configuration, ideal for testing novel approaches towards advancing accelerator science and overcoming the limits of existing machines.

The centerpiece of the Fermilab Accelerator Science and Technology (FAST) facility, IOTA is currently circulating electrons around its 40-meter circumference, giving scientists the latitude to explore new ways of manipulating particle beams. With the expected extension to protons in 2019, it will soon be the only research accelerator capable of switching between beams of electrons and protons. Figure 1 shows a schematic of the FAST facility, comprising IOTA and its two injectors.

Fermilab scientists began planning IOTA about 10 years ago, designing and building a machine for the exploration of several different accelerator techniques with applications in numerous scientific fields in addition to high-energy physics. The facility allows scientists to explore the physics of beams composed of thousands of bunches, up to 2 nC each, as well as those consisting of single electrons. Fermilab has formed partnerships with others interested in advancing accelerator science and technology at FAST/IOTA. The most recent collaboration meeting in the summer of 2018, the sixth such meeting, attracted 29 institutional partners including European institutions, U.S. universities, national laboratories and partners from industry. We are actively seeking to grow the user community.

One of the main goals of the IOTA program is to investigate methods for addressing critical phenomena resulting from high-intensity beams such as space charge effects, beam halo formation, particle losses, beam instabilities and other inefficiencies. Key among the techniques to be tested at IOTA are integrable optics, electron lenses and optical stochastic cooling.

Beam physics innovation at IOTA

At IOTA, we have begun investigating intensity-limiting phenomena with a view to loss-free operation of extremely powerful particle beams.

One set of experiments focuses on studies of nonlinear beam dynamics with octopoles and other nonlinear magnets. This approach should keep particle beams tight and focused, reducing the halo formation observed in current machines by a factor of three to 10. The goal is to demonstrate the core principles of integrable optics, to be translated into new designs for high-power accelerators. These experiments will be conducted with both electrons and protons.

Another class of experiment relates to the development of electron lenses to compensate for space charge effects, in which repelling forces cause the beam to expand. At IOTA, the goal is to develop electron lenses that will halve the effect of space charge in today's accelerators. Innovations in this area could enhance the stability of high-power beams and reduce beam losses.

In a third experiment, researchers will investigate optical stochastic cooling, building on Fermilab's existing expertise. Between 2005 and 2011, Fermilab operated the highest-energy

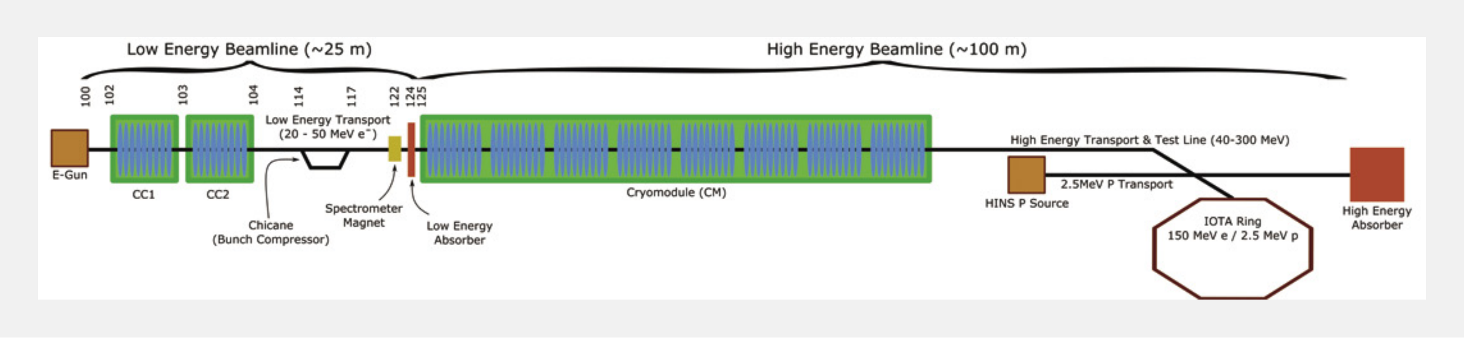


Figure 1. Layout of the FAST/IOTA facility (not to scale).

electron cooler in the world. Through optical stochastic cooling, IOTA researchers aim to increase the beam cooling rate by a factor of 1,000 to 10,000, setting the stage for electron-ion colliders in higher energy ranges.

IOTA invites research in other tantalizing topics, such as the physics of beams made of a single electron.

Promising Future Plans

Over the next year, Fermilab will install the proton RFQ injector at IOTA. Once it is in place, it will complete the trio of particle accelerators that make up the FAST facility: the proton injector, the electron injector (completed in 2017) and the IOTA ring.

IOTA is capable of circulating either protons (up to 70 MeV/c momentum) or electrons (up to 150 MeV/c) beams, and it can accommodate large-amplitude oscillations of pencil beams and large proton beams. Figure 2 schematically shows the IOTA ring.

Eight dipole magnets of nominally 0.7 Tesla connect six long straight sections and two short straight sections. Focusing is provided by 39 quadrupole magnets, and 40 additional magnets make up the correction system.

FAST electron linac

Many modern and future particle accelerators employ high-gradient superconducting RF (SRF) to generate high-energy, high-intensity and high-brightness beams for research in high-energy and nuclear physics, basic energy sciences, etc.

In 2017 the FAST/IOTA team commissioned the 1.3-GHz superconducting RF electron injector and demonstrated the highest beam accelerating gradient ever achieved in large-scale SRF accelerators. The energy gain in the eight-cavity, 1.3 GHz SRF cryomodule, CM2, exceeded 255 MeV, and the average beam accelerating gradient matched the ILC specification of 31.5 MV/m.

The FAST facility 2017 operation, with two eight-hour shifts per day, allowed us to combine active cryomodule and beamline commissioning and tuning with several beam experiments which were carried out in collaboration with external and internal research groups. These included studies of effects of the high-order modes (HOM) in SRF cavities on transverse beam emittance; tests of the advanced beam diagnostics using synchrotron radiation; experimental verification of machine learning algorithms for the optimization of the low-energy accelerator injector; investigation of the 4-D beam phase space tomography; and innovative experiments on the round-to-flat beam transformations of magnetized high intensity electron beams.

The achieved beam parameters—energy, intensity, stability and emittance—are fully adequate for the specifications of the program of accelerator R&D at the IOTA ring toward intensity frontier beams. Besides this main goal, the 300 MeV electron injector is capable of supporting a broad spectrum of advanced beam studies and experiments.

In general, FAST provides a high-fidelity site for exploring various machines comprising superconducting linacs, such as the ILC, rings and lasers, all in one facility. There are many opportunities to develop novel experiments and beam diagnostics.

Now that beams have circulated through IOTA, Fermilab invites the accelerator community to advance the science, enable projects for industry and fundamental physics, and pave the way for future discovery.

The authors would like to thank Leah Hesla (Fermilab) for her help with this article.

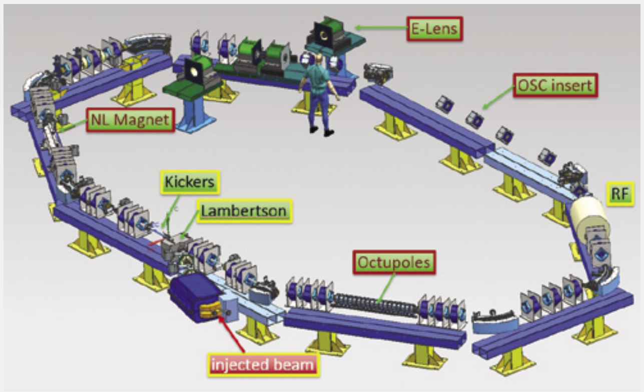
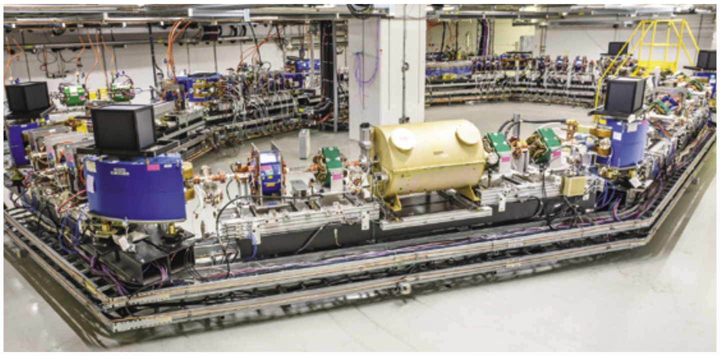


Figure 2. Schematic layout of the IOTA ring.



Fermilab's 40-meter-circumference IOTA—the Integrable Optics Test Accelerator—saw first beam on Aug. 21. **Photo Credit:** Giulio Stancari

The Advanced Photon Source Upgrade Project

Robert Hettel
Argonne National Laboratory

The world of storage ring light sources entered a fourth generation with the inception of the 3 GeV MAX-IV ring in Lund, Sweden. This machine realized an order of magnitude reduction in electron beam emittance (ε) and a corresponding increase in X-ray brightness and coherence, compared with third-generation sources. This was accomplished by successfully implementing a compact, 7-bend achromat (7BA) magnet lattice [1], realizing the multi-bend achromat (MBA) scheme for reaching low emittance that was proposed in the early 1990s [2]. The MAX-IV lattice uses precision-machined, high strength, small-aperture magnets and a small-diameter (2.2 cm) copper vacuum chamber that reaches the requisite nano-Torr vacuum pressure by virtue of the non-evaporable getter (NEG) material deposited on the chamber walls. This emittance reduction exploits the scaling of emittance with beam energy E and the number of dipoles Nd given by $\varepsilon\propto\sim E2/Nd3$ for a given lattice type [2]. MAX-Lab's bold and pioneering step initiated a new wave of fourth generation storage rings (4GSRs) – almost every storage ring light source is now studying MBA lattices that might replace the existing machine – and, in some cases, these new designs are actually being built [3-5].

High photon brightness and coherence benefit a wide range of X-ray science applications because it enables beam focusing to very small spot sizes (<10 nm). This is useful for pinpoint scattering, spectroscopy and imaging applications, and it maximizes the performance of measurement techniques that exploit brightness and coherence (Figure 1). 4GSRs increase brightness and coherence by pushing electron emittance down to values approaching the diffraction-limited photon emittance $\lambda/4\varpi$ (for photon wavelength λ) [6]. Of course, all storage rings are diffraction-limited for large enough λ, but the quest has been to reach emittances corresponding to the nanometer and angstrom wavelengths typically used at X-ray light sources. For 1 Å X-rays used to study atomic structure, the diffraction-limited emittance is 8 pm-rad, a value that is reached in the vertical plane at third generation storage ring light sources but is hundreds of times smaller than the horizontal emittance for those machines. Fourth generation emittances are pushed to the level of 100 pm-rad or, in some cases, to a few 10s of pm-rad, reaching the diffraction limit for subnanometer X-rays.

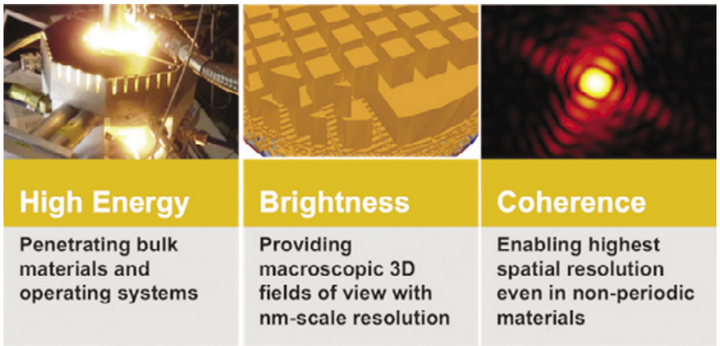


Figure 1. X-ray science enhanced by the APS-U.

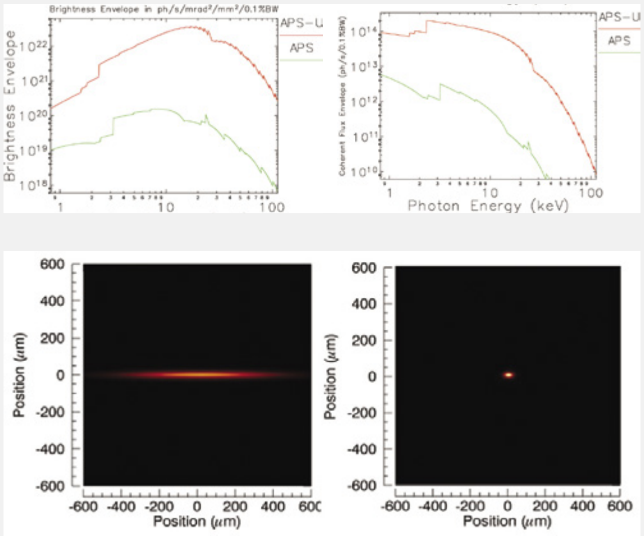


Figure 2. Comparative brightness, coherent flux and beam sizes for the APS and APS-U.

The Advanced Photon Source Upgrade (APS-U) project is the direct result of the advent of 4GSR light source technology and its embrace by the international community. In particular, with 6-GeV MBA machines being planned for the ESRF in France [3], HEPS in China [5], SPring-8-II in Japan [7] and possibly PETRA-IV in Germany[8], DOE's Basic Energy Sciences office determined that the APS-U had to be built for the United States to compete and lead in the international hard X-ray community. The APS-U will provide users of the Advanced Photon Source twice the spectral flux and two to three orders of magnitude higher spectral brightness and transverse coherence than the existing facility. The small horizontal emittance will enable the production of nearly round photon beams. These are desirable for X-ray focusing optics and many experimental techniques. With on-axis, swap-out injection [9], these also will enable the use of insertion devices having small horizontal apertures and small-diameter, round vacuum chambers. APS-U electron beam properties are summarized in Table 1.

APS-U Lattice Design

The design of MBA lattices for 4GSRs has evolved since MAX-IV, including the introduction of the hybrid MBA to reduce sextupole strengths for high-energy rings [3], longitudinal gradient dipoles (L-bends) [3, 10], and "reverse bends" in the achromat. This last an idea was derived from earlier work on linear collider damping rings [11] but leveraged as an additional way to reduce MBA emittance [12]. The latter two developments enable a reduction in the integrated product of dispersion and horizontal beta functions along the dipole, reducing emittance. The APS-U lattice [13] employs all three of these developments—hybrid 7BA, L-bends and reverse bends—to reach an emittance of 42 pm-rad with a ring circumference of about 1.1 km, a beam energy of 6 GeV and 200 mA of a stored beam current.

Many beam physics challenges arise with a ring like the APS-U that is being pushed to such small emittance. The strong lattice-focusing requires strong sextupoles for correcting chromatic aberration. This leads to strong nonlinearities in the lattice optics that reduce dynamic acceptance. Extensive, sophisticated tracking and lattice parameter optimization studies using multi-objective genetic algorithms (MOGA) [14] were conducted to maximize dynamic acceptance, momentum acceptance and beam lifetime to reach viable operation conditions. Collective effects have also been extensively studied [e.g. 15], and steps have been taken to reach acceptable single- and multi-bunch instability thresholds by reduced vacuum chamber impedance. A longitudinal (and possibly transverse) multi-bunch feedback system, for example, provides temperature control of the 12 main RF cavities that can be used to avoid harmful cavity HOMs from affecting the stored beam, and implementing a superconducting fourth harmonic (1.408 GHz) bunch-lengthening cavity (Figure 3) [16]. This passive harmonic cavity will enable a 4.6 h mean Touschek lifetime in 48-bunch, 200 mA timing mode and a 23.8 h mean lifetime in 324-bunch, 200 mA high-brightness mode. The bunch-lengthening cavity introduces a spread in synchrotron frequency, but it lowers the average frequency to <1 kHz, within the bandwidth of the orbit feedback system. To operate the longitudinal feedback system together with the bunch lengthening cavity and decouple it from the orbit feedback system, the longitudinal system will feedback on bunch energy as sensed with a BPM in a high dispersion location.

The optimized dynamic acceptance for the aggressive APS-U lattice is only ± a couple of millimeters—large compared to the <15-μm horizontal and <8-μm vertical beam sizes, but too small for conventional off-axis injection and accumulation. Thus, APS-U is adopting the on-axis, swap-out injection scheme [9], where an individual stored bunch in the ring is kicked out and replaced with a full-charge fresh bunch on each injection cycle, avoiding the several-millimeter transverse oscillations of the off-axis injected beam. This mode implies that the beam injector system must be capable of reliably supplying a roughly 16 nC bunch on each injection cycle for 48-bunch, 200 mA operation. The injection kicker system must be fast enough to kick only a single stored bunch, whose upstream and downstream neighbors are only 11.4 ns away. Work is ongoing to improve the APS injector performance to meet the high-charge objective, and technology is on-hand to produce the ±18 kV, <20 ns kicker pulses [17]. One added complication is that due to a path length change in the new ring, the ring and booster will operate with two different RF frequencies separated by about 142 kHz, necessitating a new injection timing and synchronization system.

The aggressive APS-U lattice poses a challenge for commissioning which is being addressed with simulations that include errors in magnet alignment, tilt and strength, BPM errors and other factors. Tools are being created to correct first-turn orbit, coupling and optics [18].

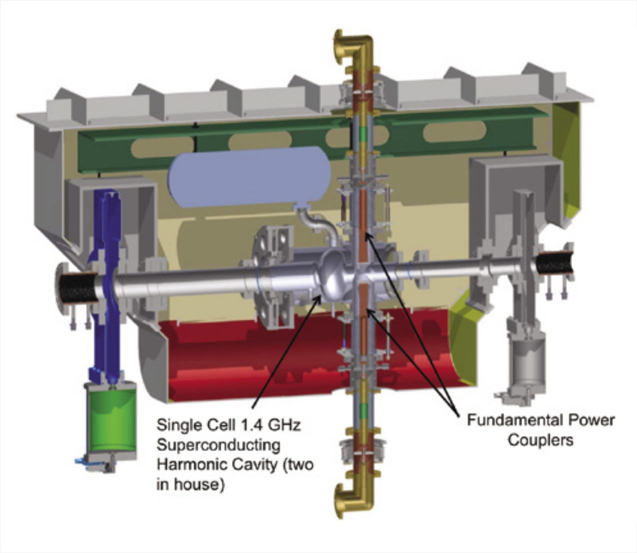


Figure 3. Superconducting fourth harmonic bunch lengthening cavity for the APS-U.

APS-U Project Scope and Implementation

The scope for the APS-U Project includes [19]:

- One new 1.1 km, 6 GeV storage ring with 40 7BA sectors
- Advanced beam diagnostics and feedback systems
- A superconducting, fourth-harmonic, bunch-lengthening cavity
- Upgrades to the injector complex and components supporting swap-out injection
- Modification of the ring's main 352 MHz RF waveguide distribution system
- New and refurbished insertion devices, including superconducting undulators (SCUs)
- Nine new high-performance X-ray beamlines that exploit high brightness and coherence
- Enhancements to 15 existing beamlines to improve their performance
- New or upgraded front ends for all beamlines to accommodate the beam's new properties

Some of the systems needed for the APS-U have been described in the previous section. Others are briefly described below.

One of 40 7BA lattice sectors for the APS-U, includes 33 magnets [Figure 4]. Magnets M3 and M4 are offset curved quadrupoles that serve as gradient dipoles. Several of the precision-machined, solid-core magnets have vanadium permendur pole tips to avoid saturation of their high pole-tip magnet fields. The six reverse bends are also offset quadrupoles (indicated by arrows). Eight-pole laminated magnets serve as fast, horizontal/vertical orbit correctors, and skew quadrupole correctors (and potentially octupoles if they prove to be beneficial to future operations). The magnets are supported by three concrete plinths and two bridge units which will be pre-assembled before installation. Except for the M1 and M2 L-bend series-wired strings, all magnets will have independent power supplies. Also, 10 ppm current stability is specified for all magnets except the fast correctors (10 kHz power supply bandwidth) and trim winding supplies, which have 100 ppm stability.

Quantity	APS	APS-U
Beam Energy (GeV)	**7**	**6**
Beam Current (mA)	**100**	**200**
Number of Bunches	**24**	**48**
Bunch Duration (ps rms)	**34**	**104**
Energy Spread (% rms)	**0.095**	**0.135**
Bunch Spacing (ns)	**153**	**77**
Emittance Ratio	**0.013**	**1**
Horizontal Emittance (pm-rad)	**3100**	**31.9**
Horizontal Beam Size (μm rms)	**275**	**12.6**
Horizontal Divergence (μrad rms)	**11**	**2.5**
Vertical Emittance (pm-rad)	**40**	**3**
Vertical Beam Size (μm rms)	**10**	**7.7**
Vertical Divergence (μrad rms)	**3.5**	**4.1**

Table 1. Parameters for the APS and APS-U storage rings (with IBS). 324-bunch mode not shown.

The vacuum chambers in the achromat arcs have a nominal diameter of 2.2 cm (Figure 5). The vacuum system consists of a combination of NEG-coated round copper chambers and aluminum extrusions with antechambers to channel synchrotron radiation to beamline exit ports and photon absorbers. About 50% of the ring chambers are NEG-coated. These act in concert with ion pumps in larger aperture chambers to reach an average pressure of around 1 nTorr and reduce peak gas pressures. Otherwise, pressure would exacerbate ion instabilities and bremsstrahlung radiation. Short, high-resistivity, copper-coated Inconel chamber sections in each sector at the fast corrector sites enable >1 kHz orbit correction. There are 560 compact, RF-shielded BPM/bellows modules with standard and non-standard cross-section designs (Figure 6). The insertion device (ID) straight section vacuum chambers for conventional IDs are aluminum extrusions having 6.3 mm internal vertical aperture 5 m long with antechambers containing NEG cartridges. The vertical aperture chambers for superconducting undulators (SCUs) are cryo-pumped. The designs of the myriad chamber components, shadow masks, transitions and the order of 1800 gapless flange joints minimize impedance seen by the stored beam.

Two added requirements for the vacuum chamber system are collimators to protect permanent magnet IDs from scattered particles and a dedicated beam dump for the swapped-out bunch. To prevent the high-power density of the kicked-out bunch from damaging the dump, the bunch first receives a small amplitude kick that causes its transverse size to increase over ensuing revolutions in the ring, thereby reducing its power density, before receiving the full swap-out kick. Another full beam dump, comprising curved aluminum absorbers in high-dispersion sections within five consecutive sectors, intercept the beam tangentially as it spirals inward following an RF trip. The high-power-density electron beam will damage these beam dump surfaces. A vertical shift, however, will present fresh, undamaged surfaces for the next full beam dump, eventually to be completely replaced.

Forty-nine planar, hybrid permanent magnet undulators (HPMUs) will be removed from the existing APS, and 23 of them will be rebuilt with new period lengths to optimally match the APS-U 6 GeV operation energy. Nineteen others will receive minor modifications, and all 42 will be reinstalled in the APS-U.

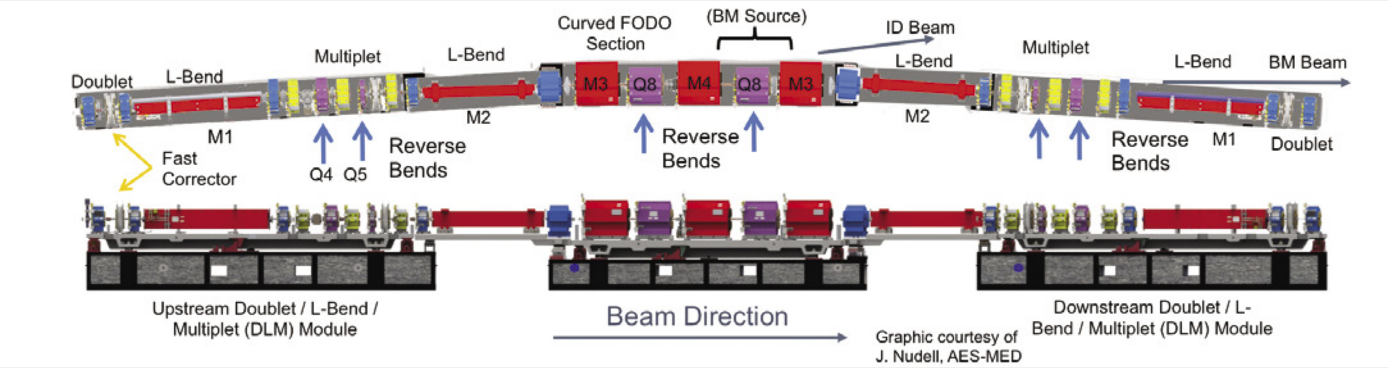


Figure 4. One of 40 7BA sectors for the APS-U.

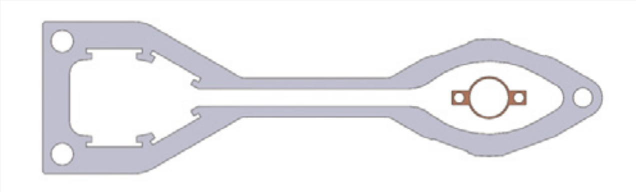


Figure 5. Existing APS vacuum chamber compared with 2.2-cm APS-U chamber.

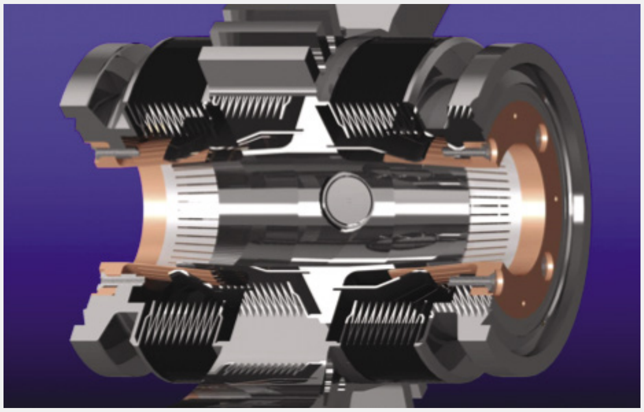


Figure 6. 2-shielded bellows BPM module.

Eight new and one refurbished 2-headed revolver undulators will be installed along with nine SCUs [20] and one electromagnetic, variably polarizing undulator. All insertion device beamlines will receive new front ends, many designed for high heat load [21]. Not included in the project, but planned to be carried out by APS Operations after, is the installation of a superconducting arbitrarily polarizing emitter (SCAPE), delta-style undulator having a 6 mm diameter, 4 m long, cryo-pumped vacuum chamber [22]. The small, horizontal aperture SCAPE device is made possible by the very small beam size and on-axis injection. Examples of APS-U IDs are shown in Figure 7.

The project includes nine new "feature" X-ray beamlines intended to exploit the brightness and coherence of the new source [19]. They enable state-of-the-art performance using techniques that include in-situ, high-energy coherent scattering; magnetic spectroscopy; coherent diffraction imaging (CDI); small- and wide-angle X-ray photon correlation spectroscopy (XPCS); ptychography and spectromicroscopy; coherent, grazing incidence small angle scattering (GiSAXS) and diffraction microscopy. Two of these beamlines will be very long (180 m and 220 m), extending beyond the present APS building into end stations housed in a new building. These new beamlines will be equipped with newly

Figure 7. Some insertion devices for the APS-U (left to right): 2-headed revolver, planar SCU and SCAPE.

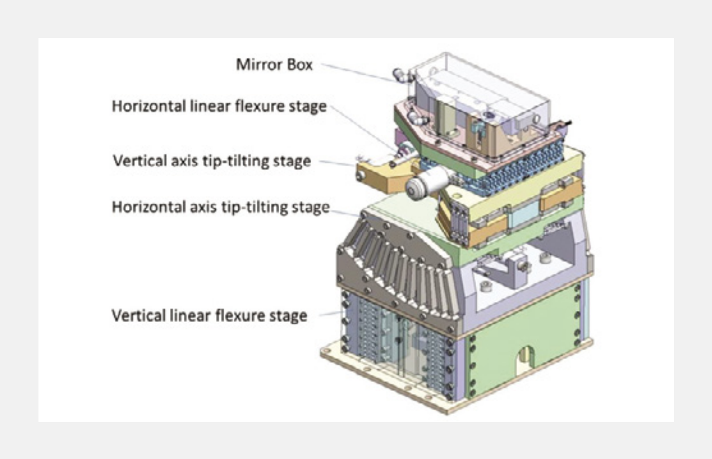


Figure 8. Multidimensional flexure stage for <50-nm hard X-ray focusing [23].

designed instruments that use state-of-the art technology to realize their functions (e.g., Figure 8). In addition, 15 of the approximately 60 existing beamlines will be upgraded with new X-ray optics (mirrors, monochromators, focusing elements, etc.) and detectors to enhance their performance. Dozens of other beamlines will receive minor improvements to assure equal or better performance than at present. The emerging challenge for beamlines channeling highly coherent X-rays, for 4GSRs and X-ray free electron lasers, is to preserve coherent wavefronts propagating through optical components. This challenge has led to an effort to develop simulation tools that model the beams and components to establish optics quality and stability requirements and, in some cases, to determine actions that can be taken to preserve coherence using photon wavefront sensors and corrective optics [24].

Adequate beam stability in position, angle, size and energy is required to avoid degrading photon beam quality for users. The traditional stability requirement is ≤10% of the particle beam dimension—which is the nominal goal for the APS-U—but it is known that actual stability requirements depend on the technique and components used in a particular beamline and could be more stringent. The most stringent 10% orbit stability goal is <0.3 µm RMS for vertical beam position in ID straight sections in a 0.01-1 kHz bandwidth. Active orbit feedback with 1 kHz bandwidth [25], multi-bunch longitudinal and possibly transverse feedback and optical component feedback will be needed in addition to an extensive design and implementation effort to eliminate sources of vibration, ground motion, temperature instability, power supply and RF power ripple and instability, EMI, sensitive detector noise, etc. The orbit feedback system will include input from X-ray BPMs [26] and eventually could be coupled with feedback systems operating within the beamlines. Other feedback and feedforward, and perhaps machine learning algorithms, will be needed to stabilize beam size in an environment with constantly changing ID field strengths.

Conclusion and Acknowledgments

The APS-U facility is in an advanced stage of design and employs the latest developments in lattice and X-ray beamline design technology to reach very high photon spectral brightness and coherence that will keep the United States at the forefront of the emerging international 4GSR, hard X-ray source world. The project team is pushing the state-of-the-art in storage ring light source design, making the APS-U Project extremely challenging but very exciting.

The author thanks the APS-U Project team, the APS Operations staff, and the APS and ANL directors for their input and support. Special thanks go to Michael Borland, Glenn Decker, Dean Haeffner and Mohan Ramanathan who greatly helped with editing this article.

References

1 M. Eriksson et al., Proc. IPAC 2011, 3026-3028 (1991).
2 D. Einfeld et al., Proc. SPIE, 2013, 201-212 (1993).
3 L. Farvacque et al., Proc. IPAC 2013, 79 (2013).
4 A.R.D Rodrigues et al., Proc. IPAC 2015, 1403-1406 (2015).
5 G. Xu et al., Proc. IPAC 2018, 1375-1378 (2018).
6 K-J Kim, Optical Engineering 34(2), 342-352 (Feb 1995).
7 H. Tanaka et al., Proc. IPAC 2016, 2867 (2016).
8 C. Schroer et al., Journal of Synchrotron Radiation Vol.25, Part 5, 1277-1290 (2018).
9 L. Emery et al., Proc. PAC 2003, 256-258 (2003).
10 R. Nagaoka, A. Wrulich, NIM A, 575, Issue 3, 292-304 (2007).
11 J. Delahaye et al., Proc. PAC 89, 1611-1613 (1989).
12 A. Streun, NIM A, 737, 148 (2014).
13 M. Borland et al., Proc. IPAC 2018, 2872-2877 (2018).
14 N. Srinivas et al., Evol. Computation 2, 221-248 (1995).
15 R. Lindberg, Proc. IPAC 2015, 1822-1824 (2015).
16 M. Kelly et al., Proc. IPAC 2015, 3267-3269 (2015).
17 C. Yao et al., Proc. NAPAC16, 1231-1233 (2017).
18 V. Sajaev et al., Proc. IPAC 2015, 553-555 (2015).
19 APS-U Preliminary Design Report, APSU-2.01-RPT-002 (2017).
20 Y. Ivanyushenkov et al., Proc. IPAC 2017, 2499-2501 (2017).
21 Y. Jaski et al., AIP Conf. Proc. 1741, 020037 (2016).
22 Y. Ivanyushenkov et al., Proc. IPAC 2017, 1596-1598 (2017).
23 D. Shu et al., AIP Conf. Proc. 1741, 030012 (2016).
24 X. Shi et al., Proc. SPIE 10388 (23 Aug 2017).
25 P. Kallakuri et al., Proc. IBIC 2017, 196-198 (2017).
26 S.H. Lee et al., AIP Conf. Proc. 1741, 020031 (2016).

Lasers for Plasma Accelerators

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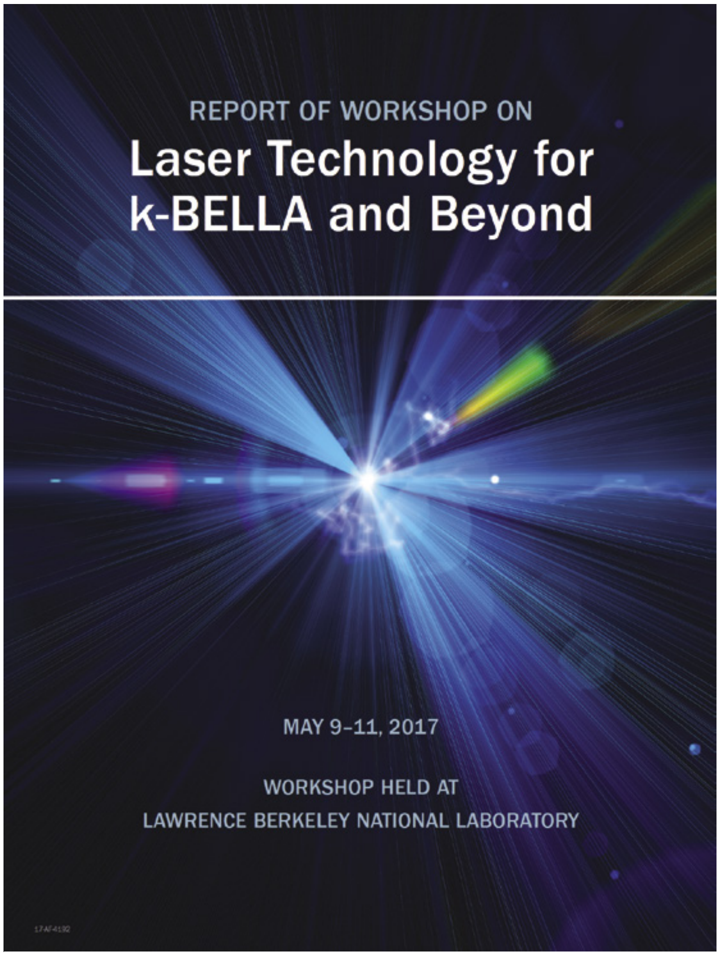
Over the last two decades, there have been significant advances in laser plasma accelerators (LPAs). Their potential is mainly considered in terms of acceleration lengths two to three orders of magnitude shorter than those of traditional RF accelerators. Compactness could revolutionize practical applications of accelerators as well as their long-term use in future high-energy colliders.

The development of laser-plasma accelerator science and technology is closely linked to progress in high-intensity ultrashort pulse laser drivers. Indeed, the very emergence of this new type of acceleration was enabled by the invention in the ‘80s and further development in the ‘90s of high-intensity chirped pulse amplification (CPA) technology. Recognized by the 2018 Nobel Prize in Physics, CPA made it possible to reach multi-terawatt and petawatt peak powers with compact laser systems, power levels previously attainable only in very large-scale facilities (e.g., the NOVA laser system in Livermore). Proliferation of these laboratory-scale systems led to the development of the entirely new scientific field of high-intensity laser-matter interactions; enabled new types of secondary-radiation sources (e.g., high-brightness x-ray, gamma ray, neutron, positron, etc.); and resulted in multiple practical and scientific applications in industry, medicine, biology, chemistry and condensed matter physics.



REPORT OF WORKSHOP ON
Laser Technology for
k-BELLA and Beyond

MAY 9–11, 2017

WORKSHOP HELD AT
LAWRENCE BERKELEY NATIONAL LABORATORY

The resulting report may be downloaded at:
https://atap.lbl.gov/ataps-vision-and-mission/#k-BELLA.

The challenge for the next generation of LPA drivers is to develop new laser technologies capable of producing not only multi-terawatt and petawatt peak powers, but also very high average powers, ranging from approximately a kilowatt to hundreds of kilowatts, which is orders of magnitude above the average power range for typical high-intensity laser systems at present. The impact of these new laser technologies will go far beyond just LPAs, benefitting the majority of practical and scientific applications of high-intensity lasers and further advancing the science of high-intensity laser-matter interactions. The range of applications that these high-average-power laser drivers will enable is exceptionally broad. They include colliders to accelerate electron and positron beams to TeV energies; compact, near-monoenergetic 1–10 MeV photon sources based on Thomson scattering; hard-x-ray FELs; plasma-based, soft x-ray lasers; and ion and proton acceleration for high-energy-density materials science as well as medical applications.

To address this power-scaling challenge and to discuss technological solutions towards ultrafast lasers that could operate in the multi-kilowatt to hundred-kilowatt average power range, Lawrence Berkeley National Laboratory hosted a workshop May 9–11, 2017, gathering 34 world-leading laser scientists, laser users and industry representatives. The workshop first assessed the current laser needs for diverse high-intensity laser-matter interaction applications. Then it examined the technical readiness of today’s laser technologies, identifying what technologies currently are or will be available in the future to dramatically increase the average power of ultrafast lasers; exploring the anticipated challenges; and estimating the resources that will be needed to address these challenges.

Based on a survey of the current state of the art and emerging technological trends and innovations, six technical solutions were proposed. They represent different levels of maturity, and vary significantly in their suitability for addressing short- and long-term challenges of power scaling.

Three approaches involve different power scaling strategies for titanium-doped sapphire (Ti:S) lasers with output wavelengths around 800 nm. One approach for power scaling is based on a Tm:YLF gain medium operating at 2 µm and will exploit technologies developed for fusion-energy lasers. Two other approaches propose different innovative architectures for coherently combining the output of fiber laser arrays operating at about 1 µm, but are also applicable to other wavelengths—2 µm, for example.

Ti:S lasers are the backbone of today's LPAs, and typically are pumped at green optical wavelengths around 530 nm, operate at average powers of a few to a few tens of watts, and produce multi-joule pulse energies, about 30 fs pulse durations, and the high pre-pulse contrast required for LPAs. The main challenges for near-term power scaling of these systems are associated with producing multi-kilowatt pump powers at green wavelengths, and the thermal management of the Ti:S crystals at these pump powers. The three proposed Ti:S laser approaches differ primarily in pump-laser strategies, as well as in the details of laser crystal geometries and heat removal configurations, but they all rely on cryogenic cooling to mitigate the thermal effects. Ti:S crystals, when cooled to 77 K, exhibit 30 times higher thermal conductivity, seven times smaller change of the refractive index and ~15 times smaller thermal expansion coefficient, which cumulatively could lead to approximately 200 times higher power, compared to room-temperature operation. The approach proposed by MIT-LL and University of Rochester relies on incoherently combined fiber lasers, which, after frequency doubling, serve as a power-scalable pump source for a single, cryo-cooled Ti:S crystal. The other two approaches, one presented by Colorado State University and another by ELI ALPS, rely on frequency-doubled multi-kilowatt and multibeam cryo-cooled Yb:YAG thick-disc pulsed amplifiers as the pump source, and differ in Ti:S crystal geometries for heat removal.

Due to their technological maturity, Ti:S lasers are attractive for reaching near-term power scaling goals into the few-kW range. However, the prospects of achieving longer-term goals of tens to hundreds of kW of average power are hindered by the inefficiency of indirect Ti:S pumping, as well as by the serious challenges of thermal management at these power levels.

The fourth approach, presented by LLNL, is based on big-aperture thulium (BAT) crystals. Tm:YLF crystals can be directly pumped by laser diodes, operate at approximately 2 µm signal wavelength and have sufficient bandwidth to support ultrashort pulses of 40–100 femtoseconds. Tm:YLF pulse lasers have been demonstrated but with relatively low energies of only tens to hundreds of millijoules. Continuous-wave operation of these crystals in the slab geometry also has been demonstrated, with average powers exceeding 200 W. Although the parameters needed for driving laser plasma accelerators have not been yet demonstrated with this technology, it is predicted that with further development it can be scaled to much higher energies, and has the potential of reaching tens to hundreds of kW of average power. Direct diode pumping is an important characteristic of this approach and holds the promise of a sufficiently high wall-plug efficiency. For laser-wakefield accelerators, the longer laser wavelengths would require more acceleration stages but lower peak powers, a tradeoff that will need to be assessed from the system point of view.

The fifth and sixth approaches, one presented by the team from the University of Michigan, LBNL and LLNL, and the other by the Fraunhofer Institute in Jena, Germany, rely on coherent combining of pulses from arrays of diode-pumped fiber lasers. Fiber lasers have potentially the highest wall-plug efficiency and could offer compact and cost-effective systems with tens to hundreds of kW of average power in the mid- to long term. The challenge, however, is that individual fiber lasers have a relatively low pulsed energy capacity, thus the innovative approach of coherent beam combining of multiple fiber laser apertures to achieve the required multi-joule pulse energies. The two fiber laser approaches differ significantly in how this fiber laser array architecture will be implemented.

The approach proposed by the University of Michigan-LBNL-LLNL team relies on time-domain coherent pulse combining (in addition to the spatial beam combining) to extend the CPA technique by at least two orders of magnitude. Thus, it reduces the size of the fiber laser array by a similar factor. It also intends to use integrated fiber laser modules to achieve distributed heat dissipation from the parallel laser channels, giving the overall laser driver system a compact footprint as well as high robustness. The approach proposed by the Jena group relies on multicore fiber submodules to reduce the footprint of the fiber laser array and of the complete laser driver system. Since ultrashort-pulse, fiber-laser coherent combining is an emerging technology, it is at a lower readiness level compared to the other approaches. It requires significant R&D on continuing increase in pulse energies and average powers, further scaling of the number of apertures, and demonstrating sufficient pre-pulse contrast, as well as further development of suitable control systems and optical subsystems for coherent combining. However, this technology has the highest potential for effectively scaling to long-term average-power goals.

The Workshop on Laser Technology for k-BELLA and Beyond (May 9–11, 2017) brought together 34 world-leading laser scientists, laser users and industry representatives. The workshop identified near-term, medium-term, and long-term goals and six possible laser technology paths.

The workshop identified near-term, medium-term and long-term goals for possible laser technology paths:

- Near term (5 years): 3 kW average power, relevant to radiation sources and assessment of collider control and average heat loading and to light source experiments.
  - **a.** 3 J at 1 kHz, 30 fs (referred to here as the k-BELLA laser) to drive a 1 GeV LPA
  - **b.** 30 J at 100 Hz, 30–100 fs (e.g., for laser-driven ion acceleration at a high repetition rate) with high temporal contrast
  - **c.** 30 mJ at 100 kHz, <30 fs (e.g., for pump-probe experiments at light sources)
- Medium term (5–15 years): 30 kW average power, relevant to radiation sources and a prototype collider module
  - **a.** 3 J at 10 kHz, 30–100 fs, 30 J at 1 kHz, 30 mJ at 1 MHz
- Long term (10–20 years): 300 kW average power collider module drivers and high-flux radiation sources
  - **a.** 100 fs pulses of 3 J at 100 kHz, 6 J/30 J at 50/10 kHz

In the near term, laser drivers of few-kW power will be necessary to advance laser-driven acceleration science, as well as other applications. A consensus among the attendees was that, based on the current state of the art, 1–5 kW laser systems with the required performance characteristics are now achievable. Indeed, the Colorado State University group already had demonstrated Yb:YAG laser systems suitable for pumping Ti:S lasers, which are producing joule energy pulses at kW average powers. Furthermore, on the fiber-laser front, the Jena group had already demonstrated beam combining of several fs-pulse fiber laser channels, producing average powers in the 1–2 kW range and multi-mJ combined pulse energies. The Michigan-LBNL-LLNL team had also demonstrated time-domain coherent combining, producing up to 10 mJ of combined and compressed fs pulse energy from a single fiber laser channel.

To realize this near-term goal, R&D is necessary to mature each concept, including: demonstrating Ti:S power-scaling to and beyond the kW level with the proposed approaches; demonstrating the suitability of Tm:YLF for high energy and power generation; and validating the scalability of fiber-laser systems to the high energies needed and achieving the required pre-pulse contrast.

For the medium and long term, significant R&D and industrial capacity development will be needed to demonstrate and develop lasers, optical materials and optical components capable of generating and sustaining tens to hundreds of kilowatts of average power in high-intensity ultrashort pulses. These technologies will have to be deployed as high-power test facilities for further advancing laser acceleration science and technology.

Modeling Future Accelerators on the Eve of Exascale Computing

Jean-Luc Vay
Lawrence Berkeley National Laboratory

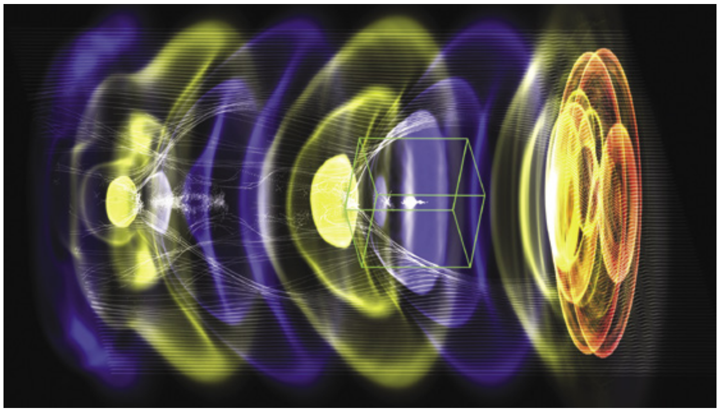


Figure 1. Snapshot from a WarpX 3D simulation of a laser-driven plasma accelerator. The laser (red) propagates from left to right and creates a plasma wake (yellow and blue) that accelerates a small electron beam (white) to high energy. A mesh refinement patch (green box) is used to increase the resolution and accuracy around the electron beam.

Particle accelerators are a vital part of the infrastructure of discovery science. It is widely recognized that the importance of accelerators to society, and the high cost of new accelerator facilities, demand that the most advanced computing tools be brought to bear on accelerator science and technology.

Simulation helps us design and understand all types of accelerators and all parts of the system-of-systems that is a modern accelerator facility, from injectors to transfer lines and storage rings. Novel technologies, such as laser-plasma accelerators, and devices with accelerator-adjacent physics, such as ion traps, also benefit.

Plasma-based advanced accelerator concepts, in particular, involve complex multiscale physics phenomena that demand the most advanced computing tools—both software and hardware—to allow high-fidelity, high-speed modeling. In fact, high-resolution simulations of a single, multi-GeV stage can take days or weeks with existing codes and supercomputers, which is far too long.

Indeed, recent reports from workshops held to establish roadmaps toward high-energy colliders based on plasma-accelerator technology[1,2] have examined the long-term goal design of e+/e−/gamma colliders with 1–50 TeV energies in the center of mass. Such colliders would require chaining a hundred to thousands of 10 GeV plasma-accelerator stages, which would be impractical to model with existing tools. Simulations need to be orders of magnitude faster.

With sustained support of simulation efforts, further hardware and software progress is expected to reduce the timeframe for detailed simulations of a single collider stage from weeks to hours—possibly minutes—on future exascale- and post-exascale supercomputers. These developments will provide powerful, high-fidelity tools for the design and optimization of future accelerators. High-resolution simulations with full physics packages enabled could even become fast enough (say, giving feedback to the operator in less than one hour) to be useful, predictive tools in accelerator control.

As part of the U.S. Department of Energy's Exascale Computing Project (ECP)[3], Lawrence Berkeley National Laboratory, in collaboration with SLAC National Accelerator Laboratory and Lawrence Livermore National Laboratory, is developing a powerful, open-source, plasma accelerator simulation tool called WarpX. The ECP is a collaborative effort of two DOE organizations: the Office of Science (SC) and the National Nuclear Security Administration (NNSA). The endeavor is focused on accelerating the delivery of a capable exascale computing ecosystem that delivers 50 times more computational science and data analytic application power than is possible with DOE high performance computing systems. WarpX is one of 25 ECP application projects (the only one in accelerator physics) selected over the entire DOE portfolio.

The workhorse algorithm for modeling plasma-based accelerators is the particle-in-cell (PIC) methodology, in which beams and plasmas follow a Lagrangian representation with electrically charged macroparticles while the electromagnetic fields follow an Eulerian representation on (usually Cartesian) grids. Exchanges between macroparticles and field quantities involve interpolation at specified orders. The standard "full PIC" implementation is often too computationally demanding because of the large disparities of space and time scales between the driver beams, which are either laser or particle beams, and the plasma columns. Speed-up is provided by either performing the simulation in a Lorentz-boosted frame of reference, which lowers the range of space and time scales, or using a quasi-static approximation to decouple fast and slow time scales. Additional approximations such as hybrid PIC-fluid, quasi-3D or laser envelope models enable additional savings at the cost of a reduction of the domain of applicability.

Fully three-dimensional simulations at high resolution using the full PIC model are ultimately needed to capture potential hosing, misalignments, tilts and other key effects of laser evolution, beam trapping and beam dynamics. Ensemble runs of simulations on large-parameter space are required to estimate tolerance to those effects as well as to study various designs.

Doing so for hundreds or thousands of chained plasma stages requires, in addition to porting the codes to the next generation of massively parallel supercomputers, pursuing the development of better algorithms that improve the accuracy and speed of existing plasma physics models. Hence, beyond the common PIC method (a second-order, finite-difference, leapfrog Maxwell solver on a uniform Cartesian grid), WarpX implements three cutting-edge algorithms: optimal Lorentz-boosted frame, mesh refinement, and a pseudo-spectral FFT-based Maxwell solver with optional Galilean transformation for control of the numerical Cherenkov instability.

WarpX involves three packages—AMReX[4], PICSAR[5] and, optionally, Warp[6]—that are combined with new source code. The PICSAR library, developed in collaboration with CEA Saclay, France, provides highly optimized elemental PIC operations. The AMReX library provides adaptive mesh refinement, which is essential for resolving small features efficiently (e.g., small electron beam or sharp plasma gradients). It also handles parallel communications and dynamic balancing of the computational load across processors. Warp already exists as a PIC code, used by the community for modeling of both conventional accelerators and advanced concepts, that provides optional physics and diagnostic modules.

In order to utilize efficiently future exascale supercomputers, it will be essential to develop effective multilevel parallelism and optimization for various processors (manycore CPU, GPU or other novel architectures that might arise). Doing so with a PIC code that includes adaptive mesh refinement and other advanced algorithms will depend critically on cutting-edge dynamic load balancing strategies that can effectively distribute the work within and across the computer nodes. Interoperability of codes on the various expected computer architectures will also be essential to reduce the cost and complexity of code development and maintenance.

All these requirements require robust and sustained team efforts in which the application scientists collaborate with computer scientists and applied mathematicians. Indeed, by partnering with the AMReX team, "the WarpX accelerator modeling team can focus on highly innovative algorithms for accelerator modeling without worrying about developing and maintaining the hybrid parallelism provided by AMReX."[7]

The first exascale supercomputers are expected to be operational in the first half of the 2020s. And if there is a great deal of continuing development, WarpX can be at a production level when the machines are ready. The code is currently running on existing manycore-CPU supercomputers such as the Cray Systems Cori at NERSC[8] and Theta at ALCF[9], where it is being tested on the very first 3D simulations of plasma-based accelerators with mesh refinement (see Figure 1). In parallel, to augment the code's functionalities and improve performance, the ongoing next step is to port the code to GPU-based systems such as Summit at OLCF[10], the world fastest supercomputer as of this writing.[11]

In addition to the detailed PIC-based models such as those employed in WarpX, it will be important to develop fast tools that require far less computational resources and can be used to guide large parameter scans. The models used in these tools can be guided by theory and fitting to the PIC-based simulations and experimental results. For the latter, machine learning may be useful to develop very fast models that can be used to guide large-scale parameter scans, based on accumulated data from simulations and experiments, fed to advanced (ML) software.

While WarpX is not yet ready for production, it is already accessible to the community for testing on computer clusters and supercomputers, and even desktops and laptops. Upon maturation, the new software will harness the power of future exascale supercomputers for the exploration of outstanding questions in the physics of acceleration and transport of particle beams in chains of plasma channels. This will benefit the ultimate plasma-accelerator goal of compact and affordable high-energy physics colliders, as well as the many spinoff applications along the way.

References

1 B. Cros and P. Muggli, "ALEGRO input for the 2020 update of the European Strategy for Particle Physics: comprehensive overview," 2018, http://www.lpgp.u-psud.fr/icfaana/alegro/documents

2 Advanced Accelerator Concepts Research Roadmap Workshop Report, 2016, https://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Advanced_Accelerator_Development_Strategy_Report.pdf

3 Exascale Computing Project, https://www.exascaleproject.org/

4 AMReX, https://amrex-codes.github.io/

5 "P-I-C-S-A-R – Particle-In-Cell Scalable Application Resource," https://picsar.net/

6 Warp, http://blast.lbl.gov/BLASTcodes_Warp.html

7 "AMRex Co-Design Center Helps Five Application Projects Reach Performance Goals - Exascale Computing Project," https://www.exascaleproject.org/amrex-co-design-center-helps-five-application-projects-reach-performance-goals/

8 National Energy Research Scientific Computing Center," http://www.nersc.gov/

9 Argonne Leadership Computing Facility, https://www.alcf.anl.gov/

10 Oak Ridge Leadership Computing Facility, https://www.olcf.ornl.gov/

11 TOP500 Supercomputer Sites, https://www.top500.org/

Fourth Generation Light Sources: Probing Matter Under Extreme Conditions

Emma McBride
SLAC National Accelerator Laboratory

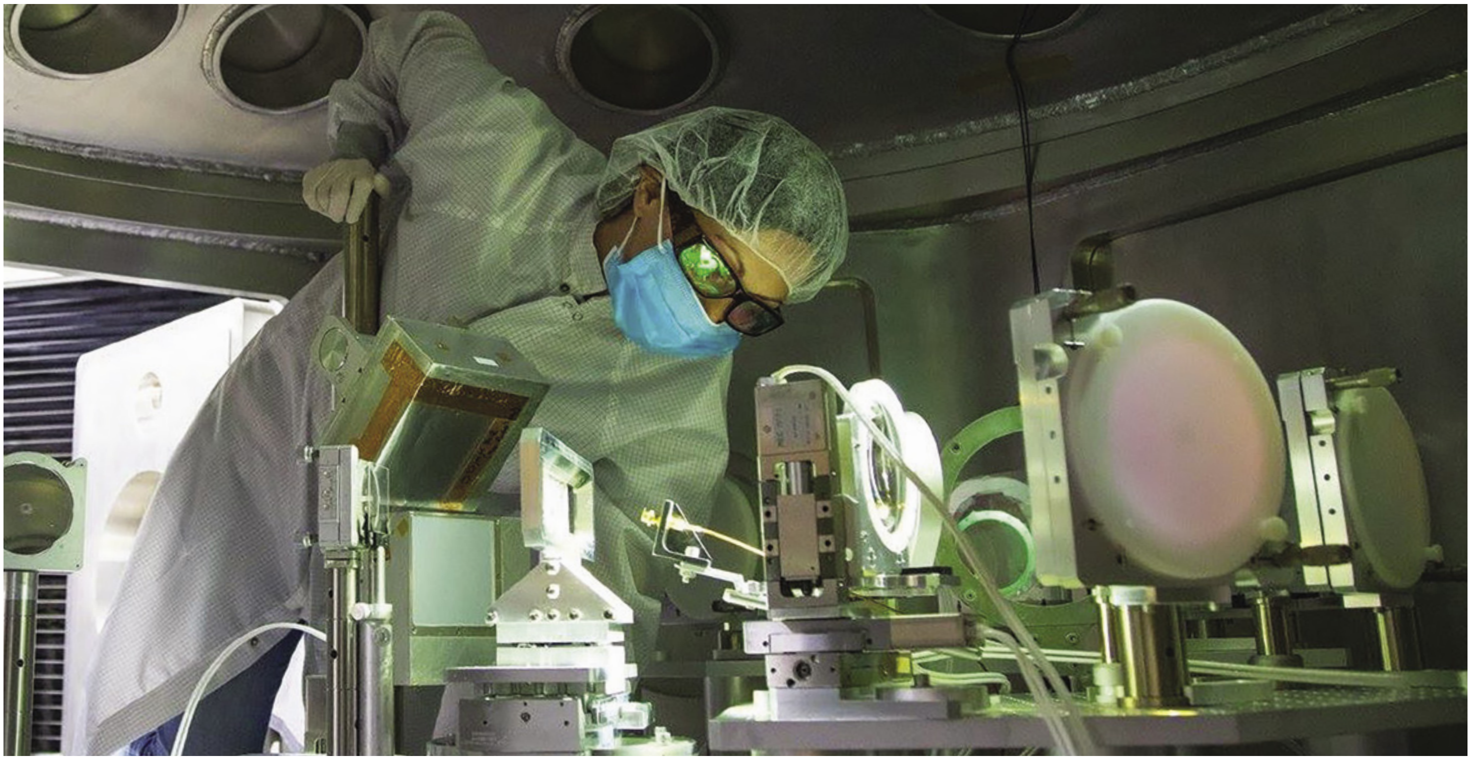


Figure 1. The MEC end station at LCLS. Photo Credit: Matt Beardsley/SLAC National Accelerator Laboratory.

Understanding the structure and behavior of matter at extreme pressures and temperatures is of critical importance to many fundamental physics applications. These include geophysics, planetary science and astrophysics, shock and plasma physics, and the search for novel phases of materials and non-equilibrium thermodynamics. Of particular interest is the area of pressure-temperature space that defines warm dense matter; an intriguing state of matter found in the cores of large planets, stellar accretion disks, and in large impact events such as meteor impacts.

Due to its abundance in nature, understanding warm dense matter is vital for planetary evolution models. Yet this fascinating state is too hot, (and hence too highly-ionized) to be described by condensed matter theories, and too strongly coupled and correlated for classical plasma physics to provide an accurate description. Direct measurements of this exotic state are necessary.

Typically, such states are generated in the laboratory through interaction of matter with high-intensity lasers which can generate the state of interest for picoseconds to nanoseconds. The subsequent abundance of free electrons in such highly-ionized matter means that typical optical diagnostics are unable to penetrate and probe these short-lived states. Femtosecond duration hard X-rays (5–12+ keV) generated by fourth generation light sources such as the LCLS free electron laser (FEL) in the United States and the European XFEL, Germany, are revolutionizing our understanding of such systems.

Structure and Kinetics of Matter at Extremes

The structure of a material is a fundamental property and understanding it is essential to understanding the high-pressure behavior of matter. High-intensity laser drivers have been used for decades to generate shock waves in matter, which generate a simultaneous increase in both pressure and density on nanosecond timescales. Using X-ray diffraction techniques, researchers probe the lattice level response of materials and determine its structure at extreme conditions.

Such studies have provided unprecedented insight into how matter behaves at extreme conditions. A recent study revealed that at pressure and temperature conditions found in the interior of hydrocarbon-rich Neptune and Neptune-like exoplanets, (currently expected to be the most abundant type of exoplanet) polystyrene (C_8H_8)n destabilizes and phase-separates into carbon and hydrogen.[1] At these hot, dense conditions, the most stable form of carbon is diamond, and on nanosecond timescales the formation of tiny, nanocrystalline diamonds are observed. As diamond is denser than the other components in this system, it is expected to fall under gravity towards the center of the planet. This "diamond rain" had long been postulated, and it was not until the combination of high-power lasers with hard X-ray FELs that such observations were possible.

This experimental configuration has proved a popular way to perform such measurements at the Matter in Extreme Conditions (MEC) end-station at the LCLS. Investigations of the crystallization timescales of quartz, with relevance to planetary impact events; probing whether strange and exotic crystal structures, like incommensurate host guest structures, can form on nanosecond timescales; and analyzing the strength and failure of materials, such as tantalum, when subjected to significant shear, have all to produced exciting and unexpected results.

These hard X-ray FEL sources, however, provide an X-ray beam that is not only extremely bright, but also collimated and can be microfocussed. As such, it is possible to perform these shock experiments perpendicular to the shock propagation direction for the first time, allowing an increased sensitivity to the onset of both solid-solid and solid-liquid phase transformations, vital when one wishes to examine the kinetics of such phase transformations. Recent work on silicon has even demonstrated that on the nanosecond timescales of laser-shock compression, phase transition boundaries can be lowered compared with static ones, contrary to the belief that under such conditions boundaries would be raised due to kinetic hinderance.[5]

Though currently very popular, X-ray diffraction is not the only technique available to researchers interested in investigating matter at extreme pressure and densities." to "Though currently very popular, X-ray diffraction is not the only technique available to researchers interested in investigating matter at extreme pressures and densities.. A significant effort has been made developing diagnostics, like small angle X-ray scattering,[6] phase contrast imaging,[7,8] including performing simultaneous phase contrast imaging with the fundamental beam and X-ray diffraction by making use of the 3rd harmonic of LCLS, viewing both the microscopic and lattice level response to shock compression.[9]

Although they are inherently weaker scattering processes than their elastic scattering counterparts, a significant effort has been made to develop inelastic X-ray scattering techniques to resolve collective electron and ion oscillations in the warm dense matter regime. This allows researchers to constrain properties such as ionization state and electron temperature.[10,11] Such measurements are only possible due to accelerator developments. The narrow energy transfer range of plasmons, for example, means that to resolve features in the eV energy transfer range, the LCLS had to be operated in the seeded mode, providing a significantly narrower X-ray bandwidth (about 0.5 eV) when compared with the typically used self-amplified spontaneous emission (SASE) mode (about 20 eV). [12,13]

Rapid Heating with X-rays

While laser-driven shock compression is a useful technique and has provided a wealth of information about matter at extreme densities, there remains a lot of phase space inaccessible with this technique due to shocked matter following a particular material-dependent path in pressure-density-temperature space. Other avenues to create warm dense matter include the rapid heating to eV temperatures (1 eV, approximately 11605 K) at solid-density. Typical pumping methods used to perform such experiments include femtosecond optical lasers,[14] and picosecond energetic ion beams,[15] but neither optical-laser nor ion-heating are ideal due to the short penetration depth of the former, and the relatively long timescales of the latter. X-ray free electron lasers with their 10s of femtosecond, extremely bright (10^{12} photons/pulse at LCLS) and large penetration depth (10s of μm for hard X-rays) are the ideal pump source for creating extremely hot matter at solid densities.

Pioneering work at FLASH (soft X-ray range) and LCLS (hard X-rays) has generated electron temperatures of 10s of eV, and

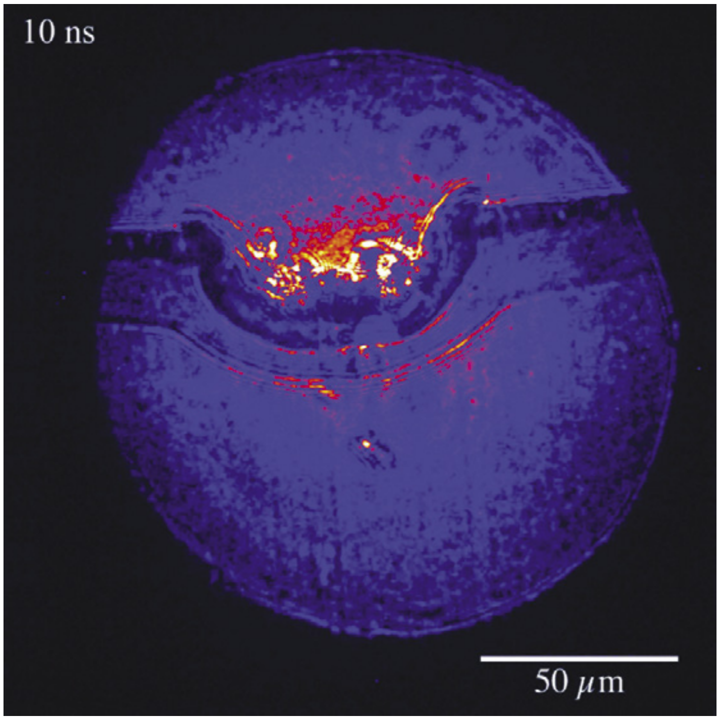


Figure 2. Phase-contrast image of shock propagating through an aluminium sample.[22]

allowed investigation of exotic physics properties. Of course, the problem remains that using the accelerator-produced X-rays as a pump source, one must rely on emission spectroscopy or optical laser diagnostics to probe the state produced.[16-18] Of particular interest would be a way to combine a hard (or soft) X-ray pump with an X-ray probe.

Tabletop Hard X-ray Accelerators

X-ray generation is not unique to FELs, and although they are cropping up in several locations around the world, demand for access continues to greatly outstrip supply. In recent years, there has been a huge effort to develop more compact accelerators with a focus on shrinking the accelerator from the kilometer length scale down to that of a lab bench. Such technology would not just revolutionize investigation of matter at extreme conditions by providing significantly more sources to perform experiments, but has the potential to revolutionize applications in medicine and industry.

A laser-wakefield accelerator is a promising table-top accelerator that uses laser-driven plasma to accelerate electrons, and a high-intensity femtosecond laser pulse is used to generate an electron plasma wave. The oscillating electrons in the plasma wave emit betatron X-rays with properties very similar to those produced at synchrotron light source, i.e., they are emitted over a broad continuous X-ray range, in a forward-directed cone. In fact, betatron sources even offer distinct advantages over X-ray FELs for some purposes. For instance, in the case of X-ray absorption spectroscopy such as XANES and EXAFS, it is extremely challenging for the FEL to span the required hundreds of eV energy range necessary. While some seminal work has been performed on iron near Earth-core conditions, these measurements would greatly benefit from the 10s of femtosecond, broadband X-rays that betatron sources provide.[19,20]

One should also note that the high-intensity, short-pulse lasers used in laser-wakefield acceleration are often used as drivers to perform warm dense matter experiments. The MEC end-station at LCLS, BL2 in Japan and the High Energy Density (HED) instrument at European XFEL all have, or will soon have, high-intensity short-pulse lasers opening up the possibility of combining the hard X-ray FEL pump with a broadband betatron X-ray probe.[20]

Looking to the future

A recent and exciting development at the LCLS has the potential to revolutionize the way in which these experiments—laser-driven shock compression techniques, spanning several nanoseconds—are done. Although the repetition rate of the LCLS is 120 Hz, a method was developed to produce two pulses with a 350 ps pulse separation, or integers of this separation, by combining two laser systems.[21] Such a time structure would be perfectly suited to the timescale of laser shock-and-release and would allow multiple measurements to be made on the same sample under identical laser conditions, providing an avenue to capture transient short-lived states under highly dynamic conditions. Such a pulse structure could also be used to perform X-ray pump X-ray probe experiments.

Another exciting prospect for performing X-ray pump X-ray probe experiments to create and diagnose warm dense matter comes with the construction of the LCLS-II upgrade. Here, the copper linac will operate alongside a superconducting MHz linac. The upgraded design includes two undulators, a hard X-ray undulator and a soft X-ray undulator, opening up the exciting prospect of combining both the soft and hard X-rays at one end-station, allowing for a soft X-ray pump hard X-ray probe experiment.

References

1 Kraus et al., Nat. Ast. 1 606 (2017)
2 Gleason et al., Nat. Comms. 6, 8191 (2015)
3 Briggs et al., Phys. Rev. Lett. 118, 25501 (2017)
4 Wehrenberg et al., Nature, 550, 496 (2017)
5 McBride et al., Nat. Phys. AOP (2018)
6 Kluge et al., Phys. Plasmas 24, 102709 (2017)
7 Schropp et al., Sci. Rep. 5, (2015)
8 Nagler et al., Rev. Sci. Instrum. 87, 103701 (2016)
9 Seiboth et al., Appl. Phys. Lett. 112, 221907 (2018)
10 Fletcher et al., Rev. Sci. Inst. 87, 11 (2016)
11 McBride et al., Rev. Sci. Inst. 89, 10F104 (2018)
12 Fletcher et al., Nat. Photonics,
13 Amann et al. Nat. Photonics, 6 693 (2012)
14 Cho et al., Phys. Rev. Lett, 106, 167601 (2011)
15 Patel et al., Phys. Rev. Lett., 91, 125004 (2003)
16 Nagler et al., Nat. Phys. 5, 693 (2009)
17 Vinko et al., Nature, 482, 59 (2012)
18 Levy et al., Physics of Plasmas 22, 030703 (2015)
19 Harmand et al., Phys. Rev. B 92, 024108
20 Albert et al., Plasma Phys. Control. Fusion 56 084015 (2014)
21 Decker et al., Proceedings of FEL2015, 634 (2015)
22 Nagler et al., J. Synchrotron Radiat. 22, 520 (2015)

Advanced Acceleration Concepts at the Argonne Wakefield Accelerator Facility

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Scientists at the U.S. Department of Energy's Argonne National Laboratory are working to develop advanced acceleration concepts (AAC) at the laboratory's Argonne Wakefield Accelerator (AWA) facility [1]. In addition to the in-house AAC program carried out by the AWA group, the facility hosts more than 20 collaborators from around the world who come to use its state-of-the-art facility dedicated to the development of technology for future accelerator facilities. AWA's resourceful group of six staff, two postdoctoral fellows and several graduate students (sent by collaborators) carry out its productive AAC R&D program.

As part of Argonne's AAC studies, the laboratory seeks to explore and develop advanced acceleration techniques that are capable of operating at higher gradients and lower costs than today's operating accelerator facilities. To pioneer these AAC techniques, Argonne researchers develop a host of AAC-supporting technologies including beam diagnostics, beam sources and beam dynamics, along with theory and simulations. By successfully developing these AAC technologies, Argonne hopes to lay the foundation for the next generation of large-scale accelerator facilities, such as a multi-TeV electron-positron collider or a fifth-generation light source. In addition, these breakthroughs could yield spin-off technologies for compact accelerator applications, such as medical and industrial accelerators.

The AWA R&D program focuses specifically on the development of an AAC technique known as electron beam-driven wakefield acceleration. This technique can be further subdivided into structure wakefield acceleration (SWFA) and plasma wakefield acceleration (PWFA), where the acceleration takes place in solid-state (dielectric and metallic) structures or plasma media, respectively. In SWFAs, a charged-particle bunch (the "drive" bunch) excites electromagnetic wakefields in a structure. The structures are designed to support a strong, axial electric field (0.1-1 GV/m) to accelerate a trailing "main" bunch. There are two SWFA configurations: collinear-wakefield acceleration (CWA) and two-beam acceleration (TBA). The advantage of CWA over TBA is that it requires only one beamline, but the disadvantage is the need to stably transport both beams (with very different energy and charge) through the same beamline lattice. An important advantage of SWFA for the linear collider community is its indifference to particle species, so that an electron drive bunch will excite the acceleration wakefields for both e+ and e- main bunches. Most of the AWA R&D program has been focused on SFWA, but its PWFA program has recently become more active.

The AWA Facility

The AWA facility upgrade (Figure 1) was completed in 2015 and is now operating as a highly productive electron-beam-driven wakefield acceleration test facility. The facility houses two independent, 1.3 GHz, Cs2Te photoinjector linac and an easily reconfigurable experimental switchyard. The 70 MeV drive photoinjector produces single-bunch charges that can be varied

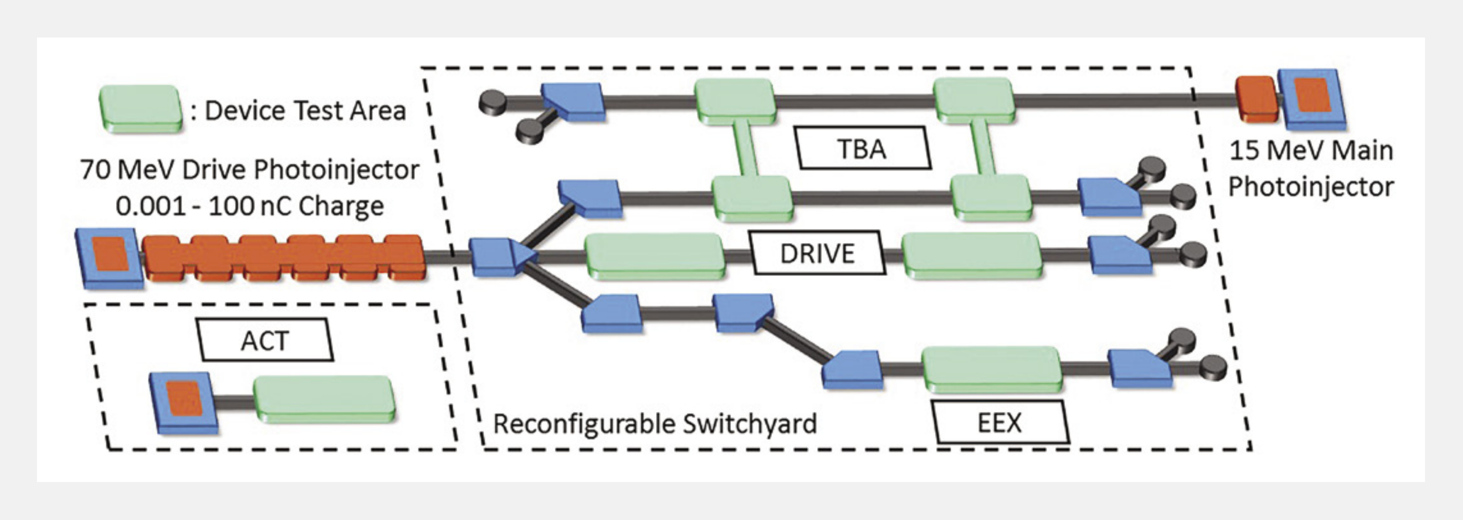

Figure 1. Schematic of the AWA beamlines, showing the two independent photoinjectors, the experimental switchyard and a standalone injector test stand, marked here as ACT.

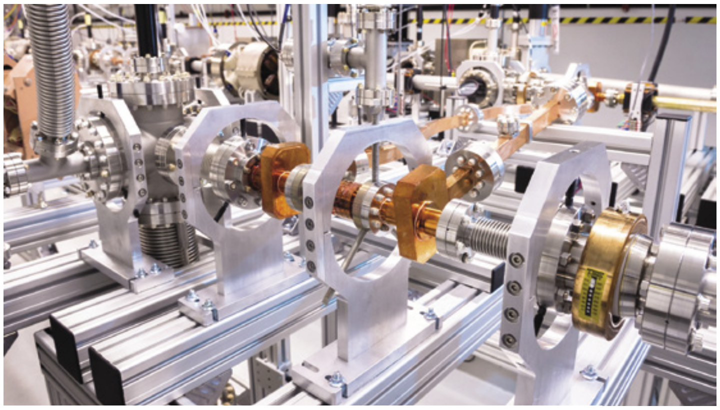

Figure 2. 11.7 GHz metallic TBA module installed at the AWA facility.

from 0.001-100 nC by changing the energy of the laser pulse incident on the photocathode. In addition, a sequence of laser pulses separated in time by one RF period can be used to generate an electron bunch train up to 650 nC with a duration of 4-25 nsec. The 15 MeV main beam photoinjector is an independent but synchronized linac capable of producing single bunches with charge up to 60 nC, but it is typically used to create low-emittance (approximately 1 nC) main bunches for TBA measurements. The experimental switchyard of the facility contains multiple, easily reconfigurable beamlines. The configuration in Figure 1 shows a typical arrangement that includes three beamlines: the world's only operating emittance exchange (EEX) beamline, a TBA beamline, and a straight-ahead drive beamline for general wakefield testing (e.g., CWA). In addition, the facility has a standalone injector test stand, the Argonne Cathode Test-stand (ACT), for cathode testing and RF breakdown studies.

Recent progress

AWA researchers have recently demonstrated high-gradient acceleration in a series of TBA experiments, in collaboration with Euclid Techlabs and conducted on the TBA beamline. To achieve high-gradient acceleration, researchers accelerated the main bunch at a gradient of 150 MV/m and RF power of 300 MW in a single TBA module (Figure 2) fabricated by collaborators at Tsinghua University in Beijing. To generate the wakefield, the researchers passed a drive bunch train of eight 45 nC bunches through an iris-loaded metallic decelerating structure (decelerator) operating at 11.7 GHz, and coupled the RF pulse through a waveguide into an iris-loaded accelerating structure (accelerator). This experiment demonstrated synchronized acceleration without degradation or main bunch particle losses. A closely related series of experiments demonstrated a gradient of 70 MV/m via TBA staging—with two TBA modules staged one after another. Two independent drive bunch trains on the TBA beamline accelerated the main bunch.

High efficiency, in either the TBA or CWA configuration, relies on advanced bunch shaping technology. In TBA, shaping the main bunch to allow for increased beam loading increases efficiency, while increasing the efficiency in CWA requires shaping of the drive bunch in order to increase the transformer ratio (TR).

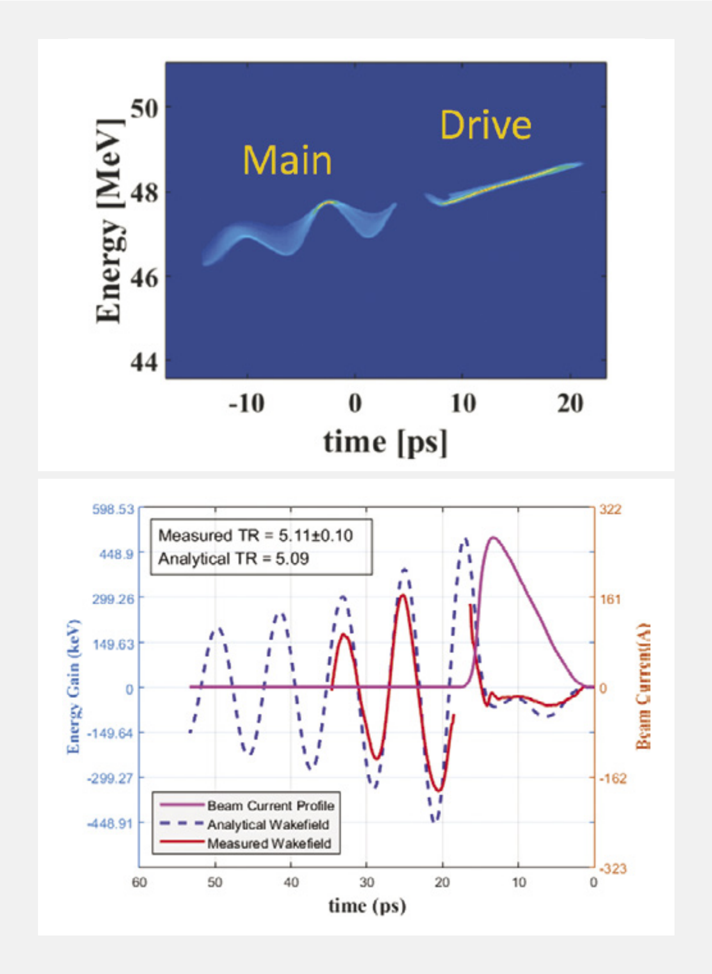

Figure 3. High Transformer Ratio. TR=5; **Top:** Longitudinal phase space of drive and main bunch, **Bottom:** Wakefield measurement compared to theoretical values.

AWA researchers recently demonstrated a high TR using the EEX beamline (Figure 1) to generate the shaped drive bunch. By doing so, they experimentally demonstrated TR≈5 in a dielectric wakefield accelerator installed in the green region of the EEX beamline. A newly developed single-shot wakefield measurement system recorded the TR. It measured the longitudinal phase space (LPS) of the drive and main beam (Figure 3, top). The wakefield and the value of TR=5 was extracted from the LPS and is shown in Figure 3, bottom.

Longitudinal bunch shaping and phase-space manipulation methods are being developed at the AWA facility and are potentially enabling technologies for many future accelerator applications. The longitudinal bunch shape determines the temporal properties of electromagnetic fields generated by the bunch itself and thus can be used to improve the efficiency of wakefield acceleration; improve the beam quality by suppressing space-charge or coherent synchrotron radiation effects; and

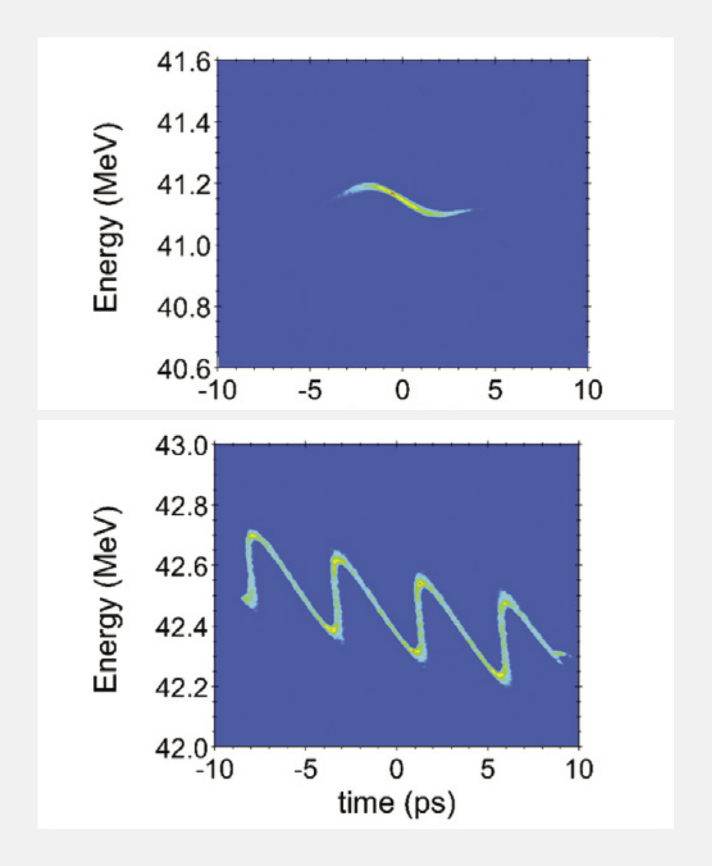

Figure 4. Longitudinal phase space of the beam. **Top:** without any manipulation; **Bottom:** after a transverse undulator, followed by emittance exchange beamline.

control the intensity, frequency, bandwidth and coherence of the radiation needed for light sources (Figure 4). AWA scientists recently used the EEX beamline to demonstrate arbitrary longitudinal bunch shaping at the AWA, and they are currently extending their longitudinal shaping methods to control the complete 6-dimensional phase space of the bunch by combing the flat beam transform with EEX. This may enable the replacement of large sections of operational accelerators (e.g., damping rings) with compact phase-space manipulation beamlines and enable scalable R&D in small facilities, as well.

Collaboration Program

Collaborators from around the world come to the AWA to test advanced acceleration concepts such as SWFA, PWFA, phase-space manipulation and novel diagnostics. Many collaborators send their graduate students to work full-time at Argonne to perform their doctoral research. Working at a small accelerator provides an excellent opportunity for graduate students to get hands-on experience, and more than ten graduate students have done their doctoral research at the AWA in the last three years. A few recent collaborator experiments are listed below.

SWFA utilizes structures with various materials, geometries and frequencies, but all must provide high-efficiency and high-gradient operation while controlling the beam breakup instability. A few of the more exotic SWFA tests conducted on the drive beamline include: the characterization of the longitudinal and transverse wakefields of an X-band photonic band-gap (PBG) structure, fabricated at Los Alamos National Laboratory; a photonic topological insulator fabricated at Cornell; and a metamaterial accelerating structure fabricated at Massachusetts Institute of Technology (MIT), which was used to generate 80 MW of RF power with plans to go to 1 GW in the next round of testing. Supporting simulation efforts for the beamline optimization on these experiments were done in collaboration with Paul Scherrer Institute in Switzerland. On the home front, collaborators from the Advanced Photon Source (APS) at Argonne are performing wakefield studies on a high-repetition rate SWFA concept based on a 220 GHz CWA for a future XFEL facility.

UCLA has helped to launch a new thrust area at the AWA on PWFA. The UCLA collaborators will use the AWA EEX beamline for a PWFA experiment to realize a simultaneous gradient of 120 MV/m and TR=6. Beam physics collaborations include: several ongoing phase space manipulation studies lead by Northern Illinois University including EEX and flat-beam generation; novel cathode studies with LANL and Illinois Institute of Technology (IIT) and flat beam studies with Hiroshima University, Japan.

The ACT beamline is used to conduct field emission studies and RF breakdown research as well as advanced photocathode and field emission cathode studies. Collaborators from Euclid, IIT, Tsinghua, Shanghui Jiaotong University, Michigan State University, and LANL have all recently used the ACT beamline.

Looking ahead

The AWA is one of the most productive AAC test facilities in the world. Its capabilities for developing electron-beam driven wakefield acceleration schemes (SFWA and PWFA), phase-space manipulation and advanced diagnostics have attracted collaborators from around the world. While the AWA is only in its third year of operation, it has already made important advances in the AAC field, such as the demonstration of staging in SWFA, 150 MV/m and 300 MW in TBA, arbitrary longitudinal bunch shaping and high TR with the EEX beamline, the testing of exotic structures based on PBG, metamaterials, and PTI, and the development of novel diagnostics. The facility looks to continue this progress on AAC technology for the next generation of accelerators through the continued efforts of the AWA group and its collaborators, postdoctoral fellows and graduate students.

References

1 https://www.anl.gov/awa

The US Magnet Development Program

Soren Prestemon and Gueorgui Velev

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The 2015 Particle Physics Project Prioritization Panel (P5) recognized the need for transformational high field magnet R&D for future collider applications. This need was further supported by the HEPAP Accelerator R&D subpanel report, which provided a suite of recommendations urging a focused, national approach in this arena. In response, the Department of Energy Office of High Energy Physics (HEP) initiated an ambitious program, the U.S. Magnet Development Program (MDP), coordinated by LBNL in close collaboration with FNAL and with the Applied Superconductivity Center of the National High Magnetic Field Laboratory, to develop superconducting accelerator magnet technology with a focus on exploring fundamental limits of superconducting materials and minimizing magnet training.

The MDP[1] is focused on transformational magnet technologies; grounded in the strong magnet-program histories of each of its members and augmented with a renewed focus on science-based technology development. To serve the HEP mission, the program has identified four key goals:

1 Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training

2 Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid low- and high-temperature-superconductor (LTS/HTS) magnet for fields beyond 16 T

3 Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction

4 Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

The multi-laboratory collaboration is organized to align with the key goals and to fully leverage the expertise and facilities available. Here we outline the priorities of each focus area and highlight examples of progress towards the program goals.

Exploring high-field Nb_3Sn accelerator magnets

The low-temperature superconductor (LTS) Nb_3Sn has a critical field exceeding 25 T—well beyond the ~11 T limit of the traditional LTS superconductor NbTi—thereby, in principle, enabling dipole magnets operating at significantly higher field than the 8-9 T used in colliders thus far. The U.S. has led in the development of Nb_3Sn accelerator magnet technology over the last couple of decades, culminating most importantly in the LHC Accelerator Research Program (LARP) and ultimately enabling the luminosity upgrade (now in progress) of the LHC. Through the U.S. HL-LHC Accelerator Upgrade Program, the U.S. is providing half of the Nb_3Sn-based quadrupoles for the interaction region.

Dipoles are another major area of R&D. In recent decades, DOE laboratories have produced magnets based on a variety of design concepts, including "Cos(θ)", "Block" and "common coil" configurations.[2,3] A key to all high field accelerator magnet concepts is the need to properly support the windings under the tremendous magnetic forces that arise during operation. This is particularly critical with Nb_3Sn material, which (in contrast to the ductile NbTi) becomes strain-sensitive and brittle after the processing that makes it superconductive. The MDP builds on this broad experience base while focusing on the critical goals outlined above.

In order to focus efforts on the best use of finite resources while maintaining a diverse program, the MDP is currently pursuing a two-pronged approach towards Nb_3Sn accelerator magnet development: a "baseline" magnet design based on a 4-layer Cos(θ) magnet, led by FNAL,[4] and a "high-risk high-reward" magnet design based on the Canted Cos(θ) concept, led by LBNL.

The Cos(θ) magnet is designed with the capability of reaching 15 T. It leverages significant advances in modern Nb_3Sn conductors as well as lessons learned from magnet support structures over the last two decades. All operating collider dipoles to date are variants of the Cos(θ) design. Fabrication of this magnet is well underway, with coil fabrication (Figure 1) and mechanical structure testing complete. The magnet is ready for assembly and then testing. The Cos(θ) magnet is highly relevant to the CERN-led Future Circular Collider (FCC) effort, since in many respects it serves as an example of the baseline magnet design used by the FCC for its design study; in fact, many of the coil parts for the FNAL Cos(θ) magnet were provided by CERN. Testing of the magnet is currently scheduled for early 2019.

The Canted Cos(θ) or CCT concept, originally proposed as an option for the Tevatron dipoles,[5] has seen renewed interest for collider dipoles due to improvements in 3-D analysis techniques,

Figure 1. Image of the outer layer of the Cos(θ) magnet. The windings, end spacers and pole are visible, as are the voltage tap and strain gauge diagnostics. Signals from the diagnostics are routed to the magnet ends on a special "trace," composed of lithography-processed copper on a kapton sheet, that is overlaid on the magnet and vacuum impregnated with the coil.

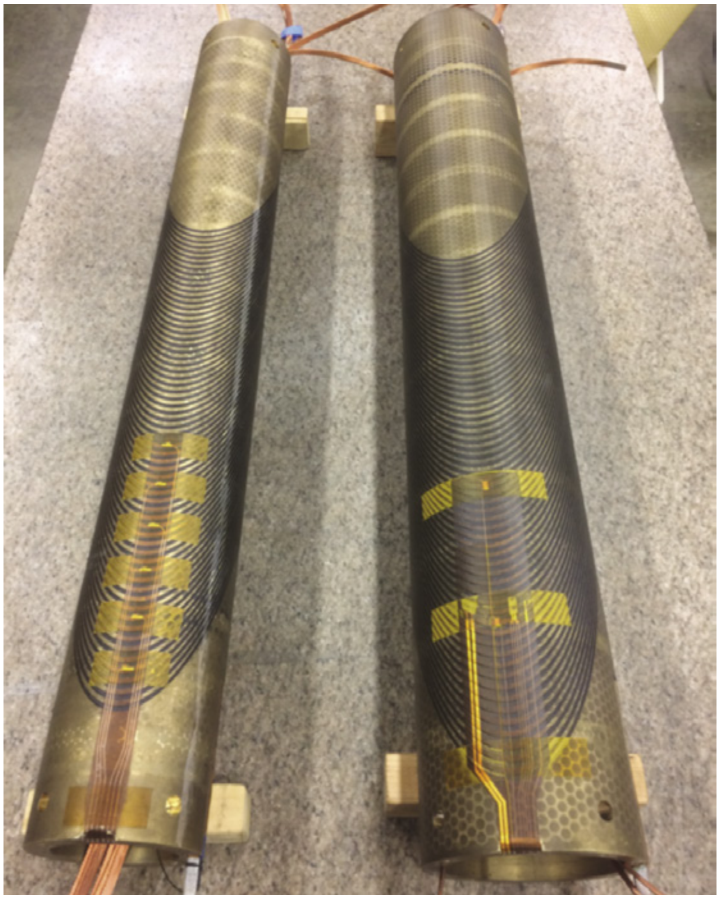


Figure 2. The two coils for the CCT5 magnet prior to assembly into the final magnet structure.

advances in CNC machining and the importance of stress management in high field accelerator magnets.[6] This effort within the MDP is led by LBNL and has focused to date on 2-layer models, at first using NbTi, which is easier to work with, to facilitate process development, and recently using Nb_3Sn. The latest magnet, CCT4, produced a peak bore field of 9.1 T in a 90 mm bore, but with significant "training." (Training is a break-in process of quenches at successively higher fields and minimizing it is important.) Feedback from the CCT4 test has led to several design modifications in the next magnet, CCT5, that should improve training performance. As of this writing in Fall 2018, the magnet is ready for testing (Figure 2); results are anticipated very soon. If successful, the CCT technology enables a natural route towards higher field: using more layers.

Magnet technology utilizing high temperature superconductors

In parallel with the Nb_3Sn magnet technology, the MDP is developing magnet technology utilizing commercially available high temperature superconductors, in particular $Bi_2Sr_2CaCu_2O_{8-x}$ (Bi2212) and $(RE)Ba_2Ca_3O_7{-}x$ (REBCO) superconductors. Here RE refers to rare-earth elements, typically yttrium. Bi2212[7] has the advantage of being produced as a round, isotropic, ductile wire that can be handled similarly to traditional LTS conductors such as NbTi. For example, the conductor can be made into a Rutherford cable, the standard profile used in accelerator magnets to enable high-current cables that lower magnet inductance and facilitate magnet protection. The Bi2212 conductor requires, however, a high temperature (about 900 degrees C) reaction in an oxygen environment which impacts fabrication processes and tooling. A significant advance in transport current has recently been achieved through "over-pressure processing."[8] The high temperature reaction is performed in a 20-50 bar atmosphere with 1-bar O_2 partial pressure, the remainder being argon. A series of racetrack coils have been produced, enabling the development of processes and tooling compatible with Bi2212 magnet fabrication. The racetrack program has demonstrated that Bi2212 magnets have very reliable performance and do not exhibit training. Work is ongoing now to develop Bi2212 coils in the CCT geometry to enable hybrid LTS-HTS magnet configurations, a key development for future high field accelerator magnet technology beyond the approximate 16 T range.

In parallel with the Bi2212 effort, the MDP is pursuing the development of REBCO-based magnet technology. REBCO is fabricated in tape form; essentially a micron-thick layer of REBCO is grown on an approximately 30–50-micron substrate (typically Hastelloy), and the conductor is then coated with copper as a stabilizer. REBCO is anisotropic, and transport-current properties depend strongly on applied field strength and angle. No conductor heat treatment is required, facilitating many aspects of magnet fabrication. A major technical issue is developing and utilizing a scalable cable architecture that provides flexibility for coil fabrication while maintaining high effective current density. The MDP is focusing on utilizing Conductor On Round Core (CORC™) cables produced by Advanced Conductor Technologies, Inc.[9] A series of advances have been made over the last couple of years within the MDP to develop relevant magnet technology, including the development of practical coil fabrication techniques and compatible materials, as well as the development of models and experiments that yield insight into the strain dependence of the material, which in turn provides critical feedback to the conductor and cable industrial partners.[10] These efforts are now focused on scaling up the designs to produce 5-T stand-alone dipole fields, ultimately to produce 5 T in a high background field in an accelerator dipole configuration.

General magnet science and technology development

An important element of the MDP is the focus on magnet science, i.e., the detailed investigation into the mechanisms that limit achievable field in accelerator magnets and the means to mitigate or eliminate them. These elements are addressed on multiple fronts, including advanced modeling (magnetic, thermal and mechanical), advanced diagnostics (voltage, acoustic and magnetic) and materials characterization.

On the modeling front, commercial finite-element analysis codes are now being applied on computer clusters, resulting in order-of-magnitude improvements on processing speed and enabling significantly more complex 3-D simulations of magnet designs throughout fabrication, cooldown and operational cycles. Custom finite elements are being developed that enable multiphysics simulations of superconducting accelerator magnets, and that capability is being incorporated into a broader suite of integrated modeling software.[11] These capabilities and others under development enable detailed analysis of, and insight into, magnet performance, in particular in the context of new paradigms such as the use of the Coupling-Loss-Induced Quench (CLIQ) system[12] to actively protect accelerator magnets.

Diagnostics and instrumentation have seen significant recent advances that enable non-invasive, independent means of identifying the location in time and space of quench onset. Perhaps the most powerful and rapidly developing method is based on acoustics (Figure 3). This idea, first applied to magnets a few decades ago, now benefits from advances from piezoelectric probes, cryogenic signal amplification and advanced timing and signal processing to provide 3-D spatial recovery of quench initiation location as well as information-laden data on precursor signals and their spatial distribution during magnet ramping.[13]

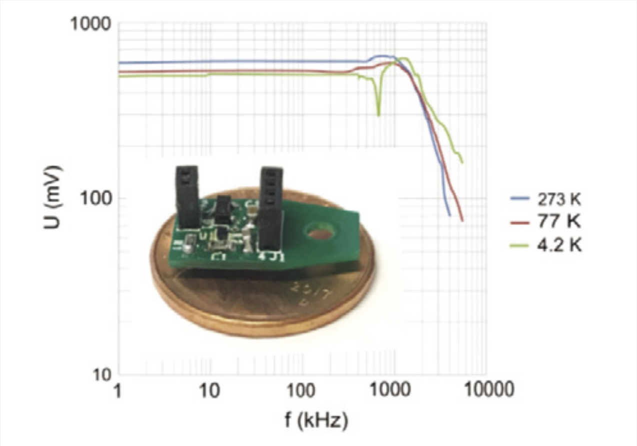


Figure 3. The latest cryogenic amplified acoustic emission sensors developed within the MDP are ultra-compact and exhibit a broad spectral bandwidth to probe the magnet disturbance spectrum (photo courtesy M. Marchevsky).

Advances in modeling and diagnostics provide feedback to magnet designers for the proper selection of materials. Studies characterizing materials in terms of strength, toughness, heat capacity, etc., at various temperatures are therefore critical to advance magnet technology and are a core part of the MDP.

Conductor research and development for high field accelerator magnets

Magnet performance is ultimately limited by the performance of the superconductors, so a dedicated element of the MDP consists of close collaboration among universities, laboratories and industry to advance properties of superconductors that will eventually be commercially available. The primary superconductors of interest to the MDP are the LTS material Nb_3Sn and the HTS materials Bi2212 and REBCO. Although Nb_3Sn is now considered a mature technology, advances in its properties continue; including very promising critical current density (J_c) results in advanced artificial-pinning-center (APC) Nb_3Sn technology,[14,15] as well as significant increase in minimum quench energy seen in trial wires, attained through the addition of high-heat-capacity dopants during conductor fabrication. This has the potential to improve magnet training.[16]

Bi2212 has benefited from well-coordinated, goal-oriented efforts to improve conductor performance. Two industrial partners have leveraged Small Business Initiative Research (SBIR) grants to develop optimized Bi2212 powders, a critical element in the conductor fabrication, and those powders have been incorporated in long wires by a highly experienced wire manufacturer. University and laboratory researchers within MDP worked closely with the industrial partners to optimize the conductor's architecture and heat treatment processing. Together these efforts have led to a more-than-tripling of the transport current over the last few years, as well as the demonstration that these improvements can be maintained through winding the wires into Rutherford cables and then fabricating magnets.[17]

To guide strategy in conductor R&D and procurements, the MDP has established a conductor advisory committee, coordinated by the ASC/NHMFL, that identifies and prioritizes potential investments in industrial conductors.

Summary

Supported by the DOE Office of High Energy Physics, the MDP is pursuing a focused program to develop superconducting magnet technology for the next generation of colliders. The program maintains a balanced effort in both traditional LTS and new HTS materials, with both benefitting from a strong technology development effort addressing the science of magnets through advanced modeling, diagnostics and materials development. Though HEP-based, the work of the MDP is highly relevant to broader DOE Office of Science interests in superconducting magnets and associated technologies. Prospects are being pursued to fully leverage opportunities for all stakeholders.

References

1 The U.S. Magnet Development Program can be found at: https://science.energy.gov/~/media/hep/pdf/Reports/MagnetDevelopmentProgramPlan.pdf

2 G. Apollinari, S. O. Prestemon, and A. V. Zlobin, "Progress with High-Field Superconducting Magnets for High-Energy Colliders," Annual Review of Nuclear and Particle Science vol. 65 (October 2015), -pp. 355-377, http://dx.doi.org/10.1146/annurev-nucl-102014-022128, Oct. 2015.

3 S. A. Gourlay, "Superconducting accelerator magnet technology in the 21st century: A new paradigm on the horizon?," Nucl. Instrum. Meth. A, vol. 893 (11 June 2018), pp. 124–137, https://doi.org/10.1016/j.nima.2018.03.004

4 I. Novitski et al, "Development of a 15 T Nb_3Sn Accelerator Dipole Demonstrator at Fermilab," IEEE Trans. Appl. Supercond., vol. 26, no. 4 (June 2016), 4001007, https://doi.org/10.1109/TASC.2016.2517024

5 D. I. Meyer and R. Flasck, "A new configuration for a dipole magnet for use in high energy physics applications," Nucl. Instrum. Meth., vol. 80, no. 2 (April 1970), pp. 339–341, https://doi.org/10.1016/0029-554X(70)90784-6

6 S. Caspi, F. Borgnolutti, L. Brouwer, D. Cheng, D. R. Dietderich, H. Felice, A. Godeke, R. Hafalia, M. Martchevskii, S. O. Prestemon, E. Rochepault, C. Swenson, and X. Wang, "Canted–Cosine–Theta Magnet (CCT)—A Concept for High Field Accelerator Magnets," IEEE Trans. Appl. Supercond, vol. 24, no. 3 (04 October 2014), pp. 1-4, https://doi.org/10.1109/TASC.2013.2284722

7 D. C. Larbalestier, J. Jiang, U. P. Trociewitz, F. Kametani, C. Scheuerlein, M. Dalban-Canassy, M. Matras, P. Chen, N. C. Craig, P. J. Lee, and E. E. Hellstrom, "Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T," Nature Materials, vol. 13, no. 4 (09 March 2014), pp. 375–381, https://doi.org/10.1038/nmat3887

8 Tengming Shen, Pei Li, and Liyang Ye, "Heat treatment control of Bi-2212 coils: I. Unravelling the complex dependence of the critical current density of Bi-2212 wires on heat treatment," Cryogenics, vol. 89 (January 2018), pp. 95–101, https://doi.org/10.1016/j.cryogenics.2017.11.006

9 J. D. Weiss, T. Mulder, H. J. ten Kate, and D. C. van der Laan, "Introduction of CORC® wires: highly flexible, round high-temperature superconducting wires for magnet and power transmission applications," Superconductor Science and Technology, vol. 30, no. 1 (January 2017), p. 014002, https://doi.org/10.1088/0953-2048/30/1/014002

10 Xiaorong Wang, Shlomo Caspi, Daniel R Dietderich, William B Ghiorso, Stephen A Gourlay, Hugh C Higley, Andy Lin, Soren O Prestemon, Danko van der Laan, and Jeremy D Weiss, "A viable dipole magnet concept with REBCO CORC wires and further development needs for high-field magnet applications," Superconductor Science and Technology, vol. 31 (6 March 2018), 045007, https://doi.org/10.1088/1361-6668/aaad8f

11 L. Brouwer, D. Arbelaez, B. Auchmann, L. Bortot, E. Stubberud, "User Defined Elements in Ansys™ for 2D Multiphysics Modeling of Superconducting Magnets," submitted to Superconducting Science and Technology.

12 M. Marchevsky, X. Wang, G. Sabbi, and S.O. Prestemon, "Acoustic detection in superconducting magnets for performance characterization and diagnostics," arXiv.org, vol. physics.acc-ph. CERN, 16-Jan-2014, https://arxiv.org/ftp/arxiv/papers/1401/1401.3950.pdf

13 E. Ravioli, "CLIQ: A new quench protection technology for superconducting magnets," doctoral dissertation, Twente University; https://ris.utwente.nl/ws/portalfiles/portal/6053232/thesis_E_Ravaioli.pdf

14 X. Xu and M.D. Sumption, "A model for the compositions of non-stoichiometric intermediate phases formed by diffusion reactions, and its application to Nb_3Sn superconductors," Scientific Reports, vol. 6, no. 1 (January 2016), p. S1127, https://doi.org/10.1038/srep19096

15 X. Xu, "A review and prospects for Nb_3Sn superconductor development," Superconductor Science and Technology vol. 30, no. 9 (3 August 2017), p. 093001, https://doi.org/10.1088/1361-6668/aa7976

16 X. Xu, P. Li, A.V. Zlobin, and X. Peng, "Improvement of stability of Nb_3Sn superconductors by introducing high specific heat substances," Superconductor Science and Technology vol. 31 (24 January 2018), 03LT02, https://doi.org/10.1088/1361-6668/aaa5de

17 Zhang, Kai; Ye, Liyang; Higley, Hugh; Gourlay, Steve; Prestemon, Soren; Shen, Tengming; Bosque, Ernesto; Lamar, Charles; Jiang, Jian; Kim, Youngjae; Lu, Jun; Trociewitz, Ulf; Hellstrom, Eric; Larbalestier, David, "Tripled critical current in racetrack coils made of Bi-2212 Rutherford cables with overpressure processing and leakage control", Superconductor Science and Technology vol. 31, no. 9 (6 September 2018), p. 105009, https://doi.org/10.1088/1361-6668/aada2f

Brighter than Yesterday: The Future of Charged Particle Beams at the Center for Bright Beams

Lipi Gupta
University of Chicago

Across the United States, over 20 graduate students, 20 professors and several postdoctoral researchers from seven universities and two national labs are working on making charged particle beams brighter. These physicists, chemists, materials scientists and others have been brought together by the National Science Foundation's Science and Technology Center: The Center for Bright Beams (CBB). Led by Cornell University, the Center also includes the University of Chicago, Arizona State University, the UCLA, the University of Florida, Brigham Young University, Clark Atlanta University, Lawrence Berkeley National Laboratory and Fermilab.

Created in 2016, CBB aims to increase the brightness of electron beams by a factor of 100 in order to open the door for many areas of research. For example, brighter beams for ultrafast electron diffraction will open access to larger, more complex molecules or the imaging of atomic motion. Compact, high-flux, hard X-ray sources from Compton backscattering will enable precision microscopy of structural materials. Coherent, continuous-wave hard X-ray sources with brighter beams will enable condensed matter physicists to study nanoscale phase separation in correlated electron systems. Brighter beams in electron microscopes could lead to better, faster imaging and to new techniques in semiconductor manufacturing and quality assurance. Linear, circular, and energy-recovered colliders with brighter beams will allow particle physicists to probe nearer the big bang, and nuclear physicists to peer deeper inside the proton.

In order to reach these goals, members of CBB work in three small, intensive teams, labeled themes. The Beam Production theme studies photoemission electron sources, focusing on developing better photocathode materials that produce electrons with near-zero momentum transverse to the beam direction. By gaining the fundamental understanding needed to improve the performance of superconducting accelerating cavities, the Beam Acceleration theme is improving the energy efficiency and increasing the accelerating gradient. Lastly, to maintain the quality of high-brightness beams, the Beam Storage and Transport theme is developing methods to transport ultra-bright beams and to minimize the impact of instabilities and non-linear resonance in storage rings. This theme also addresses transport in electron microscopes to improve aberration correction. While these themes organize the research, they are interconnected, and the Center meets regularly as a whole for seminars, smaller graduate student meetings and topical meetings at the theme intersections.

In the two short years since CBB's inception, it has already contributed insights. For example, superconducting RF cavities are the gold-standard for beam acceleration in high power accelerators, but the factors that drive their energy efficiency and accelerating gradient—their key performance parameters—are poorly understood. In 2012, Anna Grassellino of Fermilab discovered that nitrogen doping the interior surface could improve performance, but the reasons are unknown. To find the answer, Center for Bright Beams surface scientists and microscopists are

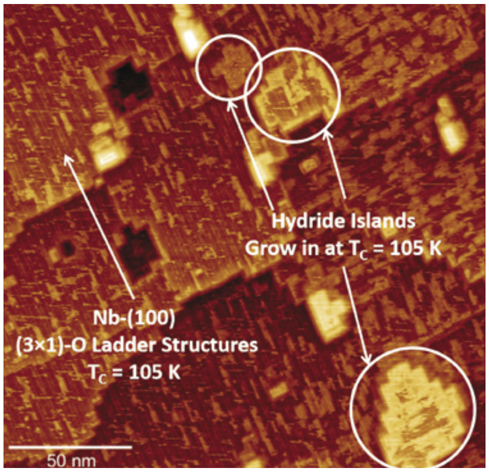


Figure 1. Hydride precipitates on a hydrogen-doped niobium surface. STM image (75x75 nm, 100 K) of the Nb-(100) after hydrogen-doping and cooling to 100 K.

Figure 2. A researcher works on superconducting RF accelerating cavity at Cornell University. The quality of the interior surface of the cavity determines performance, and the Center for Bright Beams is studying the impact of doping, impurities and trapped magnetic flux.

Figure 3. The Center for Bright Beams at its June 2018 collaboration meeting at the University of Chicago.

providing detailed information about the surface composition and structure that complements performance measurements, and condensed matter physicists are developing tools to predict the RF performance as a function of impurity doping level and profile, offering a route to optimizing the niobium surface. Already, Center for Bright Beams insights have led to an improved treatment for a cavity for the NSLS-II X-ray facility at Brookhaven National Laboratory. Efficiency has doubled.

Future accelerating cavities are likely to use compound superconductors, which have better intrinsic properties than niobium, and could operate at 4.2 K, saving millions of dollars in cooling costs (niobium cavities operate at 2 K). Liepe's group at Cornell and others have achieved promising results using Nb_3Sn, but fully capitalizing on its advantages requires better understanding of the growth properties and the impact of defects. Thanks to ab initio calculations of the growth process combined with the surface analysis of Nb_3Sn cavities grown by vapor diffusion, new growth techniques and other improvements developed by the Center for Bright Beams have halved the surface resistance, and further advances are on the horizon.

Graduate student Joshua Paul of the University of Florida finds the Center's dialogue between theory and experiment exciting and productive. "Working with experimentalists lets me refine my research to focus on what experimentalists care about," he said. "This lets me have a direct impact with my work and lets experimentalists streamline their workflow."

A combined theoretical and experimental investigation into photoemission has shown that there are many factors degrading the beam quality, including body effects, surface roughness and band structure. The investigation suggests strategies to avoid or mitigate these factors. However, when CBB started, there were no tools available for measuring such pristine beams, so CBB had to invent them. Confirmation comes from CBB's successful production of a beam whose electrons' mean energy transverse to the photocathode surface (at low current) is below 6 meV using cryogenic copper

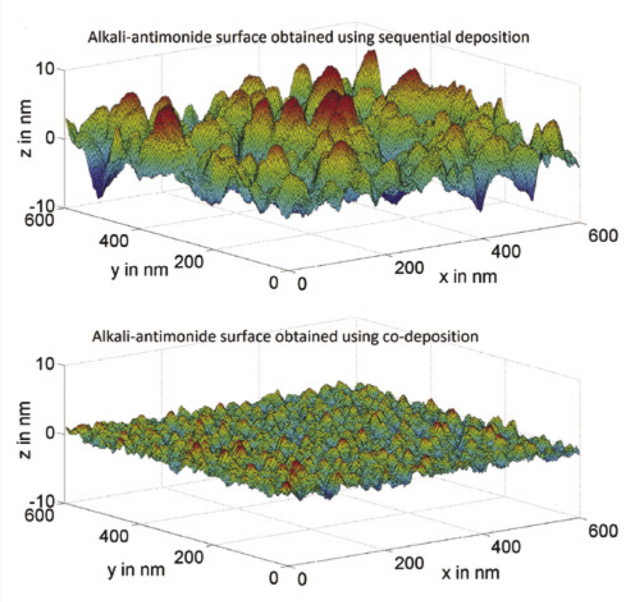


Figure 4. UHV-AFM measurements of the surfaces of alkali-antimonide photocathodes fabricated using different disposition techniques. Surface roughness generates transverse energy in the produced electron beam. (J. Feng, S. Karkare et al, J. Appl. Phys. 121, 044904 (2017).

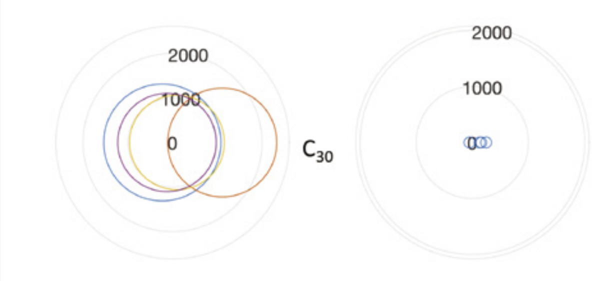


Figure 5. Measurements of C30 (third order spherical aberration) in a commercial electron microscope equipped with an aberration corrector and using standard techniques using to align the corrector (left) and an improved technique developed by CBB (right). Each colored circle indicates the precision of an individual measurement.

photocathodes. An important goal is to demonstrate record coherence-length beams for ultrafast electron diffraction.

The Beam Production team is working hand-in-hand with the Beam Storage and Transport team, whose goal is to preserve the quality of these exquisite beams as they travel to their target. A first step is to distinguish the effects of various sources of emittance dilution, and interestingly, early indications are that the electromagnetic repulsion between electrons (space charge) is important. This is well known for high-charge-density beams but was not previously known for low emittance beams at low current. This theme is also applying accelerator know-how to electron microscopes, where they have come up with a technique to rapidly calculate aberrations that could eventually lead to real-time microscope tuning. This research also looks into the source of nonlinear resonances introduced into storage rings due to nonlinear magnets such as sextupole magnets and octopule magnets.

Ritchie Patterson of Cornell and CBB's director, is pleased by the progress. "The combination of talents in the Center have led to rapid advances in understanding—far beyond what we imagined," she said.

Advancing the field of accelerator physics, however, is not enough. CBB is preparing graduate students and postdoctoral researchers for a range of careers, including accelerator science. As University of Chicago graduate student Darren Veit notes, "Working with collaborators within CBB has been an invaluable aspect of my graduate career. By working with scientists from other disciplines, I have been able to hone skills that allow me to communicate important information to people outside my field and learn how to successfully work with others on complex issues."

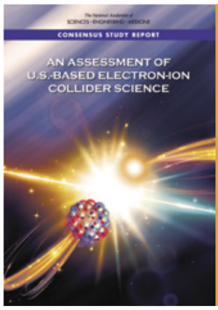
A key CBB priority is the recruitment and education of new accelerator physicists, chemists, materials scientists and engineers from diverse backgrounds. These students get the experience of working in an interdisciplinary team, opportunities for hands-on accelerator training and training in communications, entrepreneurship and other career skills.

Many CBB graduate students participate in outreach events which demonstrate simple concepts underneath the complex machinery of particle accelerators. University of Chicago graduate student Lipi Gupta attempted to simplify and present the physics of electromagnets to young girls from all over the greater Chicago area through the national Expanding Your Horizons workshop held yearly at campuses across the country. At the March 2018 workshop, each young middle-school girl got to build a small speaker out of a cup, a few magnets and some wires. They were able to plug it into their phones and use instantly to play their favorite music. Another outreach activity supported by CBB is STEP UP!, which creates "design experience" kits for use by middle-school science teachers in their classrooms. This year, CBB will take the STEP UP! kits on the road, offering training workshops for teachers in Chicago and Atlanta.

The Center for Bright Beams thanks the National Science Foundation for its generous support (NSF PHY-1549132). More information about the Center for Bright Beams is available at http://cbb.cornell.edu.

Summary of the NAS Report on the Assessment of US-Based Electron-Ion Collider Science

John Jowett and Lia Merminga
CERN and Fermi National Accelerator Laboratory



Consensus Study Report: An Assessment of U.S.-Based Electron-Ion Collider Science

Access the free PDF of the report here: https://www.nap.edu/catalog/25171/an-assessment-of-us-based-electron-ion-collider-science.

Our fellow members of the APS Division of Physics of Beams will no doubt be aware that Brookhaven National Laboratory (BNL) and Thomas Jefferson National Accelerator Facility (JLAB) have for many years been developing proposals for an electron-ion collider to serve the nuclear physics community. While there are many common lines of R&D—and intense collaboration—the two proposals differ significantly, partly because they each build upon the existing accelerator infrastructure at their respective sites. BNL already has the injector complex and hadron rings of RHIC, which could be converted into an EIC by the addition of a suitable electron accelerator and storage ring and further upgrades. JLAB, conversely, has an electron accelerator but would need to add the hadron injectors and storage ring and an electron storage ring. Both designs are complex and push the limits of present accelerator science and technology.

An important step forward in this endeavor took place when the National Academies of Science, Engineering and Medicine convened the U.S.-Based Electron Ion Collider Science Assessment Committee to assess the merits and significance of the science that could be addressed by an electron ion collider (EIC), and its importance to nuclear physics and to the physical sciences in general. The principal goals of the study were to evaluate the significance of the science that would be enabled, benefits to U.S. leadership in nuclear physics and benefits to other fields of science. The committee was not tasked with choosing a design or site.

Gordon Baym and Ani Aprahamian chaired the committee, which met four times during 2017 but continued its work for several months into 2018. Besides reviewing the physics case in depth, we received input from the many potential stakeholders from physicists to congressional staff. While mainly composed of nuclear physicists (like Aprahamian), the committee included others from related disciplines (Baym is a wide-ranging many-body theorist) and ourselves, accelerator physicists. The principal focus was on the science that could be done with an EIC, and we were not asked to compare the technical merits of either design, although we conveyed an appreciation of the technical challenges involved in constructing such a collider. Furthermore, the committee assessed the benefits of an EIC project for the progress of accelerator science in the U.S. We also compared the potential and scope of an EIC to that of other accelerator facilities, existing and proposed, worldwide. We believe that these aspects are of special interest to this newsletter's readership and encourage you to read the full report [1]. In the following we summarize our main findings. We do so quoting the report extensively, seeking not to tinker with the carefully-honed language adopted by consensus.

The committee found a compelling scientific case for such a facility. "The science questions that an EIC would answer are central to completing our understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would advance accelerator science and technology in nuclear science; it would as well benefit other fields of accelerator-based science and society, from medicine through materials science to elementary particle physics.

Our field's understanding of nucleons has advanced dramatically in recent years. We know that nucleons are made of fractionally charged quarks and antiquarks bound together by gluons, the carrier of the strong force. Three scientific issues fundamental to our understanding of matter would be addressed by an electron-ion collider. "The first is to understand in detail the mechanisms by which the mass of nucleons, and thus the mass of all the visible matter in the universe, is generated. … The second is to understand the origin of the internal angular momentum or spin of nucleons, a fundamental property that underlies many practical applications, including magnetic resonance imaging (MRI). … And third, the nature of gluons in matter—that is, their arrangements or states, and the details of how they hold matter together, is not well known."

To definitively answer these questions "requires peering into nucleons and nuclei with very-high-energy electrons, which would necessitate using the most powerful … electron microscope ever to be built. The high energy is required to achieve the needed resolution, and the only practical way of reaching the needed energies is to collide counter-rotating beams of electrons with protons or atomic nuclei (ions). To carry out the scientific investigations, such a machine must be capable of colliding a beam of 'polarized' electrons … of energies from 4 GeV up to possibly 20 GeV with a beam of polarized ions of energies from 30 GeV up to some 300 GeV at high 'luminosity.'"

The committee concluded that "an EIC would be much more capable and much more challenging to build than earlier electron or polarized proton machines. The accelerator challenges are twofold: a high degree of polarization for both beams, and high luminosity. It would be the most sophisticated and challenging accelerator currently proposed for construction in the United States and would significantly advance accelerator science and technology here and around the world."

The report continues: "Indeed, an important element of the scientific justification for a U.S. electron-ion facility is that it drives advances in accelerator science and technology, which in turn will benefit other fields of accelerator-based science and society."

Findings

The committee's conclusions were organized into a set of nine findings which are summarized here.

1. An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:
- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What is the nature of gluons in nuclei?

2. These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with sufficiently high luminosity and sufficient, and variable, center-of-mass energy.

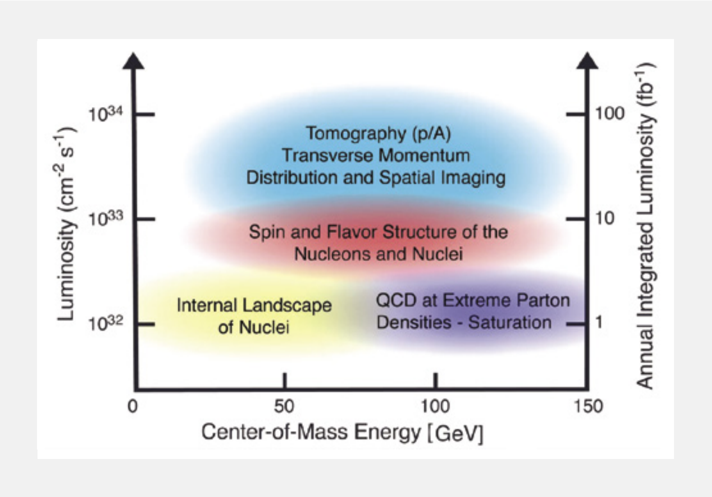


Figure 1. Energy and luminosity requirements for answering the three questions: spin, mass and gluons.

3. An EIC would be a unique facility in the world, and would maintain U.S. leadership in nuclear physics.

4. An EIC would maintain U.S. leadership in the accelerator science and technology of colliders, and help to maintain scientific leadership more broadly.

5. Taking advantage of existing accelerator infrastructure and accelerator expertise would make development of an EIC cost effective and would potentially reduce risk.

6. The current accelerator R&D program supported by the Department of Energy is crucial to addressing outstanding design challenges.

7. To realize fully the scientific opportunities an EIC would enable, a theory program will be required to predict and interpret the experimental results within the context of QCD, and further, to glean the fundamental insights into QCD that an EIC can reveal.

8. The U. S. nuclear science community has been thorough and thoughtful in its planning for the future, taking into account both science priorities and budgetary realities. Its 2015 Long Range Plan identifies the construction of a high luminosity polarized Electron Ion Collider (EIC) as the highest priority for new facility construction following the completion of the Facility for Rare Isotope Beams (FRIB) at Michigan State University.

9. The broader impacts of building an EIC in the U.S. are significant in related fields of science, including in particular the accelerator science and technology of colliders and workforce development.

EIC Conceptual Designs and Enabling Accelerator Technologies

The report reads: "The three primary areas that require significant accelerator science and technology R&D are energy, luminosity, and polarization. The extensive energy variability and elaborate interaction region of an EIC require advanced superconducting magnet designs beyond state of the art. To attain the highest luminosities demanded by the science, cooling of the hadron beam is essential. Novel beam cooling techniques are under development. Energy recovery linacs, a special type of recirculating linac, presently offer the only credible concept for electron cooling of high-energy, colliding beams. To optimize the overlap of the colliding beams at the interaction point, specialized superconducting radio-frequency (SRF) cavities rotate the beams as they collide. Polarized beams require polarized particle sources beyond the state of the art, special magnets, and a further level of mastery of beam physics to preserve the polarization through the acceleration process to the collisions.

"Two conceptual designs for an EIC facility have evolved in the United States, each of which proposes using infrastructure already available to the U.S. nuclear science community. One, eRHIC, is based on the RHIC ion complex at Brookhaven National Laboratory; and the other, Jefferson Laboratory Electron Ion Collider (JLEIC), uses the Continuous Electron Beam Acceleratory Facility at the Thomas Jefferson National Accelerator Facility as a full-energy electron injector."

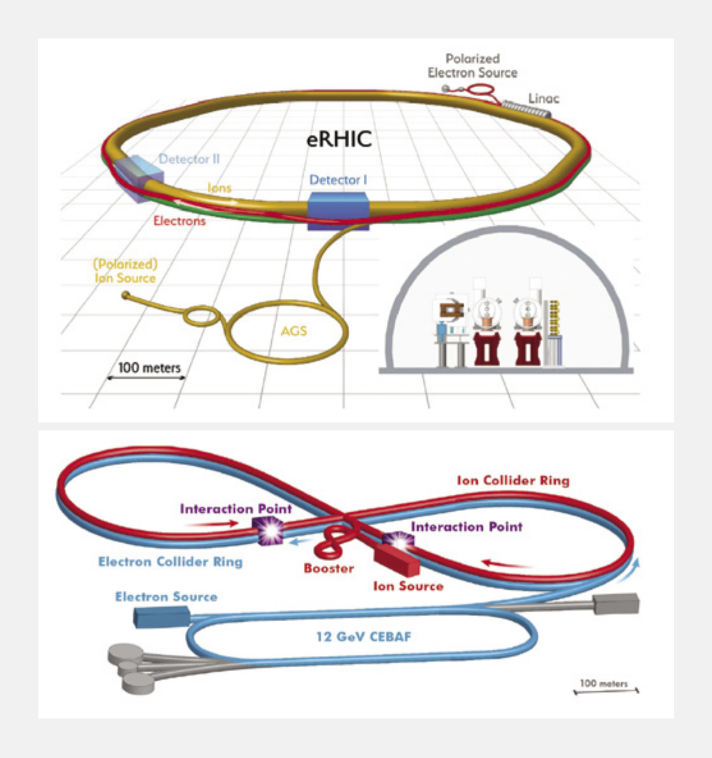


Figure 2. Schematic layout of eRHIC and JLEIC.

Furthermore, the committee reported that "to reach the performance goals of the proposed EIC conceptual designs, a number of accelerator advances are required. Several of these advances are common to all EIC designs and include the following: advanced magnet designs, strong hadron beam cooling, high-current (multiturn) ERL technology, crab cavity operation with hadron beams, the generation of polarized ^{3}He beams and development and benchmarking of simulation tools. The successful implementation of an EIC requires the successful validation of these key concepts through high fidelity-simulations and demonstration experiments."

The committee asserted that the innovations required to design, construct and support an EIC will help the United States maintain international leadership in nuclear physics, accelerator science and related fields. Building an EIC would help boost the U.S. STEM workforce by attracting outstanding graduate students and other personnel.

While discussion of design specifications as they related to achieving the scientific goals was explored, no detailed comparisons were made between the two existing designs.

In summary, the Committee on the Assessment of the Science of the Electron Ion Collider concluded that an EIC is timely and has the support of the nuclear science community. The science that it will achieve is unique and world-leading, and will ensure global U.S. leadership in nuclear science as well as in the accelerator science and collider technology. It was noted that the latter would position the U.S. for future high-energy collider projects in other fields.

References

1 National Academies of Sciences, Engineering, and Medicine. 2018. An Assessment of U.S.-Based Electron-Ion Collider Science. Washington, DC: The National Academies Press. https://doi.org/10.17226/25171.

University Spotlight: Northern Illinois University

Swapan Chattopadhyay, Bela Erdelyi, Philippe Piot, and Mike Syphers
Northern Illinois University

Northern Illinois University has a modest physics department with 23 full-time and active faculty members. While deceptively small, it punches above its weight, given its proximity to two major national laboratories—Fermi National Accelerator Laboratory (Fermilab) and Argonne National Laboratory (ANL)—and two of the nation's top research universities—the University of Chicago and Northwestern University. In addition, NIU is home to the Northern Illinois Center for Accelerator and Detector Development (NICADD), founded in 2001 with grants from the State of Illinois and the National Science Foundation (NSF) to foster the development of a new generation of accelerator and detector technologies and to provide high-tech educational and research opportunities for students. The center's three objectives are:

1. The advancement of accelerator research and development.
2. The advancement of detector research and development.
3. The provision of educational opportunities in science and technology.

Each objective broadens the research tradition established by the local national laboratories and help ensure that Northern Illinois University remains an established center of research and education.

The faculty are split into two major research areas: materials science and condensed matter physics (11 faculty members) in collaboration with ANL and Northwestern University; and particle and beam physics (11 faculty members) with associated detector, accelerator and theoretical efforts in collaboration with Fermilab, ANL, the University of Chicago and Northwestern. There is one faculty member in medical physics, with very strong ties to accelerator and particle physicists, and local and national research hospitals. The proximity to Chicago offers a highly diverse student body. Students come from diverse socio-economic, cultural, national and international backgrounds.

The accelerator research program together with laboratory astrophysics studies were initiated at NIU as part of NICADD by one of its founding members, late Courtlandt "Court" L. Bohn in 2002. Bela Erdelyi (2004) and Philippe Piot (2005) were its initial appointees. Since then, the accelerator activities at NIU have been visible in the national and international scene with growing collaboration and involvement with Fermilab, ANL, DESY, CERN, Jefferson Lab, etc. The first doctoral student in accelerator physics graduated in 2009. Since then, many doctoral students have graduated and have been placed around the world at major laboratories and universities, including DESY (Germany), CERN (Switzerland), Cornell (USA). There are four post-doctoral research assistants and more than a dozen doctoral students currently engaged in active accelerator and beam physics research at NIU in collaboration with various laboratories.

At present, there are four full-time faculty members in the accelerator cluster of research excellence, with three holding joint appointments at Fermilab and two holding visiting adjunct scientist appointments at ANL. A search committee is exploring prospects for further growth in accelerator research faculty at NIU. Two new tenure-track faculty members in physics or jointly with electrical engineering, with at least one joint appointment with Fermilab, at the assistant and associate professor levels, are currently under active search nationally and internationally.

In addition to its association with NICADD, the NIU accelerator cluster further benefits from its accelerator faculty being participating members of a joint Fermilab-NIU cooperative research and development agreement (CRADA). Collaborating senior accelerator scientists and engineers from Fermilab's accelerator and technology divisions and its technology transfer activities include Sergei Nagaitsev, Vladimir Shiltsev, Alexander Valishev, Sergey Belomestnykh and Charles V. Thangaraj.

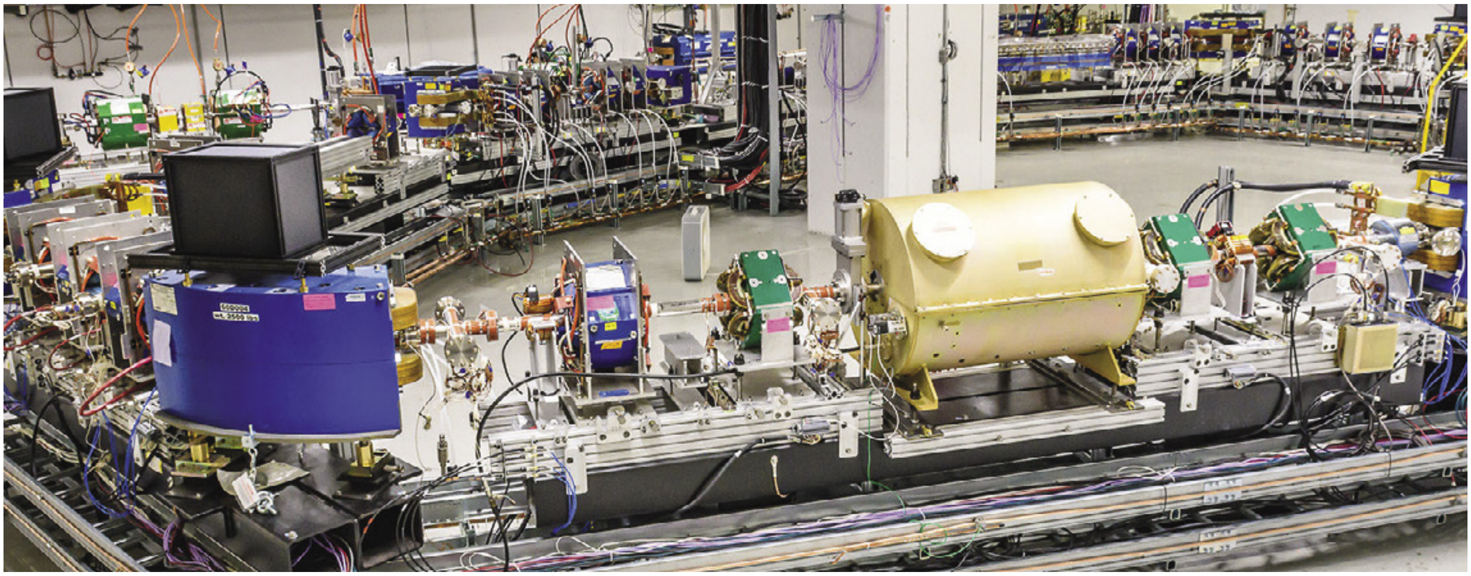
The NIU accelerator cluster has hosted the national United States Particle Accelerator School (USPAS) twice, has participated in the REU and other undergraduate programs, its faculty members being recipients of various DOE, NSF, DoD, DRDO and Fermilab Laboratory Directed Research and Development (LDRD) grants. These diverse associations and projects have also enabled significant collaboration with the NIU's College of Engineering and Engineering Technology. The cluster faculty are members of various national and international research, review, funding agency and professional society committees, panels and boards.

The major thrusts of research are: high brightness beams; advanced laser-beam techniques; theoretical and experimental nonlinear beam dynamics; particle colliders and accelerators at the energy and precision frontier; and emerging quantum sensors using beams and associated technologies. The research profiles of the four active beam physics faculty members are given below.

Faculty Research Profiles

Philippe R. G. Piot leads an experimental research group currently with many graduate research assistants and undergraduates. His personal research interests and his research group's laboratory capabilities are the production and measurement of high-brightness electron beams, advanced acceleration concepts and compact accelerator-based coherent radiation sources. Piot maintains a small laser-optics laboratory in the physics department at NIU as well as the state-of-the-art High Brightness Electron Source Laboratory (HBESL, including an associated laser laboratory) operated by NIU and located at Fermilab's Illinois Accelerator Research Center. In addition, Piot currently is the primary research user of the relativistic electron beam from the FAST photocathode and superconducting linear accelerator facility, with a significant advanced research program in laser-beam interaction for various advanced applications, such as Thomson-scattered gamma-ray source. Prof. Piot's group carries out experiments collaboratively at the Argonne Wakefield Accelerator (AWA) facility, the DESY facility in Hamburg, Germany, and the FAST/IOTA complex at Fermilab.
(see: https://www.niu.edu/physics/directory/faculty/piot.shtml)

Bela Erdelyi leads a theoretical research group currently with two post-doctoral research associates and two graduate research assistants. His research interests lie in the nonlinear dynamics of complex systems, especially charged particle beam dynamics. With the help of his students and postdocs, he develops novel theories and devises new numerical methods at the precision and intensity frontiers of beam dynamics. To this end, he studies nonlinear, completely integrable Hamiltonian systems and their applications to accelerator science. Large-scale, high-fidelity simulations on high-performance computing systems is another area where hia group expends considerable effort. Current projects include electron cooling of heavy ion beams and ultra-cold charged particle

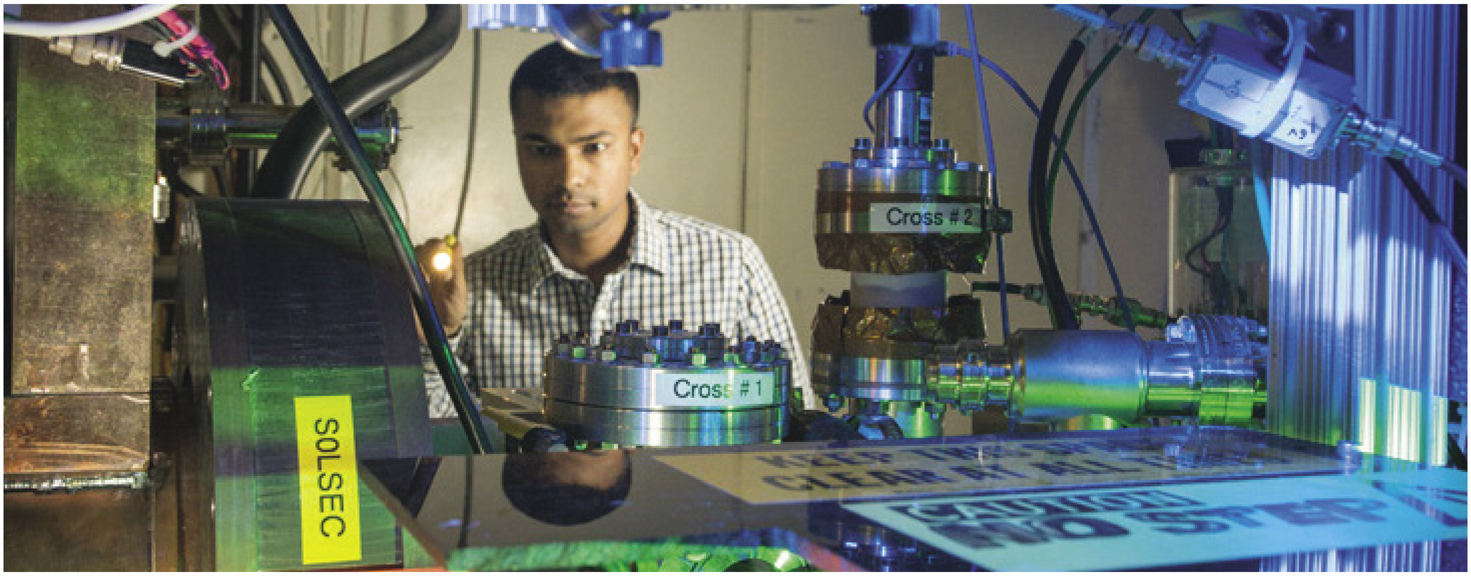


sources. He also collaborates with a wide variety of scientists, ranging from mathematicians (integrability) to computer scientists (parallel code development) and application scientists, such as attosecond science and high-power laser physicists.

Students and post-doctoral appointees take part in the full range of research performance and dissemination activities. His outreach activities include working with the Integrable Optics Test Accelerator (IOTA) in the Fermilab FAST facility, Extreme Light Infrastructure (ELI) in Hungary (Attosecond) and Czechia (Beamlines) and collaborating with scientists in the Center for Advanced Accelerators (CASA) at Jefferson Lab.
(see: https://www.niu.edu/physics/directory/faculty/erdelyi.shtml)

Michael J. Syphers leads a research group with one post-doctoral research associate, three graduate research assistants and one undergraduate student in a research experience fellowship. His research group explores particle beam dynamics and nonlinear phenomena associated with beam production, beam transport and storage for use in high energy and nuclear physics experiments that examine fundamental properties of particles and fields. Students engage in beam measurements and analyses relevant to the production of muon beams for Fermilab's Muon g-2 experiment and the diagnostic verification of the beam properties, including spin polarization; computational analyses of muon beam dynamics within the g-2 storage ring; nonlinear resonant extraction of proton beams for muon production and delivery to the Mu2e experiment; and examinations of enhancements to all the above. Also included are studies of all-electric storage rings for future electric dipole moment searches, and development of beam system concepts for future experiments such as rare eta decay searches and new-generation muon experiments with higher beam flux. Syphers has taught at the 2016, 2018, and 2019 United States Particle Accelerator School (USPAS) on fundamental accelerator physics, storage rings for precision physics, as well as at the CERN Accelerator School (CAS) in 2018 and at the Exotic Beams Summer School held at Argonne National Laboratory in 2017.
(see: https://www.niu.edu/physics/directory/faculty/syphers.shtml)

Swapan Chattopadhyay leads a research group with one post-doctoral research assistant and two graduate research assistants. His personal research interests and his research group's laboratory capabilities are general accelerator and beam physics, high energy and high-luminosity particle colliders, synchrotron radiation sources and free electron lasers, nonlinear dynamics and ultrashort electron and photon sources in the femto- and atto-second regimes. Most recently, Chattopadhyay contributed to the national dialogue in the U.S. on the emerging "quantum initiative" and the role of quantum sensors in particular, in advancing precision studies at the frontier of particle physics, astrophysics, cosmology and quantum information science. He is involved in a number of national and international scientific projects. At Fermilab, he is involved in studies of advanced space-charge dominated collective nonlinear dynamics and optical stochastic phase-space cooling in the FAST/IOTA accelerator complex, the storage ring dynamics in the Muon g-2 experiment, the accelerator physics challenges of the PIP-II accelerator complex supporting the Deep Underground Neutrino Experiment (DUNE) and the use of atomic beams falling under gravity as quantum sensors of the "dark and early universe" in the Mid-band Atomic Gradiometer Interferometric Sensor (MAGIS-100) experiment. Internationally, Chattopadhyay is involved in the Future Circular Colliders (FCC) design effort and the proton-driven plasma acceleration experiment AWAKE at CERN.
(see: https://www.niu.edu/physics/directory/faculty/Chattopadhyay.shtml)



Celebrating 75 Years: A History of Oak Ridge National Laboratory

Paul Langan
Spallation Neutron Source, Oak Ridge National Laboratory

In recognition of the 75th anniversary of Oak Ridge National Laboratory's founding as a world leader in innovative research and technology, this article looks back at some of the more notable events involving neutrons and accelerators at the lab.

1943: The Secret City

World War II is raging as some of the world's brightest minds help establish a top-secret research and development facility in eastern Tennessee, which will later be named Oak Ridge National Laboratory.

1944: Putting neutrons to work

From its origins in the Manhattan Project, including the X-10 Graphite Reactor, ORNL helps pioneer nuclear engineering and energy technologies. Ernest Wollan, Lyle Borst and others begin using neutrons produced by the reactor to demonstrate neutron diffraction and make the first observations of Bragg reflections.

1948: Building accelerators to produce neutrons

Tasked with developing an accelerator program to, initially, produce neutrons for research, Oak Ridge scientists begin acquiring or building Van de Graaff accelerators, the only known source of neutrons with precise energies. They later acquire a Cockcroft-Walton unit, an early particle accelerator named for its inventors, to test radiation effects at lower energies.

1950: First proof of neutron decay

Arthur Snell and Frances Pleasonton measure the half-life of neutrons and prove they decay into a proton, an electron and an electron antineutrino.

1951: Discovery of crystal magnetic structure

Clifford Shull, Wilbur Strauser, and Ernest Wollan use neutrons to reveal the magnetic structure of a crystal, manganese oxide, providing the first direct evidence of antiferromagnetism predicted by Louis Néel.

1963: Oak Ridge Isochronous Cyclotron

Among the first new-generation cyclotrons, ORIC begins operations to exploit the azimuthally varying field principle to achieve significantly higher energies for a wide range of particles.

1965: High Flux Isotope Reactor

ORNL's High Flux Isotope Reactor (HFIR) achieves criticality and begins producing super-heavy elements, such as californium, while researchers apply its neutron beams to materials studies.

1969: Oak Ridge Electron Linear Accelerator

ORELA begins full operation to provide neutron cross-section data that indicates the likelihood of interaction between an incident neutron and a target nucleus. It features beam energies up to 180 MeV, a neutron production rate up to 10^{14} n/sec and 50 kW of beam power.

1975: Radiopharmaceutical heart-imaging agent

Using isotopes produced at HFIR, ORNL researchers demonstrate a radioactive imaging agent that detects how much of a patient's heart muscle is still alive after a heart attack.

1979: 25 MV Tandem Electrostatic Accelerator

The tandem electrostatic accelerator is a high-voltage generator inside a 100-foot-tall, 33-foot-diameter pressure vessel. It features a folded configuration with both low- and high-energy acceleration tubes contained in the same column structure.

1980: Holifield Heavy Ion Research Facility

Consisting of the new 25 MV tandem accelerator and the modified Oak Ridge Isochronous Cyclotron, this facility uses one of the devices, or both in a coupled mode, to provide a wide range of energetic beams for experiments.

1982: Award for studying magnetism and superconductivity

Herbert A. Mook Jr. wins the Department of Energy's Outstanding Scientific Accomplishment in Solid State Physics award for using neutron diffraction to demonstrate the co-existence of magnetism and superconductivity in rare-earth rhodium borides.

1994: Nobel Prize for neutron research

Clifford Shull shares the Nobel Prize in Physics with Bertram Brockhouse. Shull wins for research he conducted while at ORNL with the late Ernest Wollan, which enabled neutron scattering techniques that led to improved materials and technologies.

1996: Holifield Radioactive Ion Beam Facility

Originally the Holifield Heavy Ion Research Facility, HRIBF opens after ORNL reconfigures its 25 MV tandem electrostatic accelerator and its isochronous cyclotron to produce high-energy radioactive ion beams for research into nuclear structures and astrophysics. HRIBF will continue operating until 2012.

~~SECRET~~ CLINTON LABORATORIES

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Date May 25, 1944

R. L. Doan Department

E. O. Wollan Department

Diffraction of neutrons

MAY 27 1944
R. L. DOAN

I would like to attempt to measure the diffraction of neutrons by single crystals. I have brought some equipment with me from Chicago, and Dr. Borst has shown me an opening in the pile at which this work could be done.

I would appreciate obtaining approval to go ahead with this experiment.

A problem assignment sheet for this work is enclosed.

CLASSIFICATION CANCELLED
DATE ... 27 ...
For The Atomic Energy Commission
H. R. Carroll
Chief, Declassification Branch

E. O. Wollan

EOW/e

RECEIVED
MAY 26 1944
R. L. DOAN

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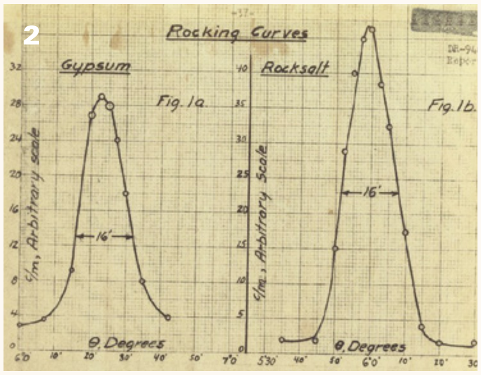

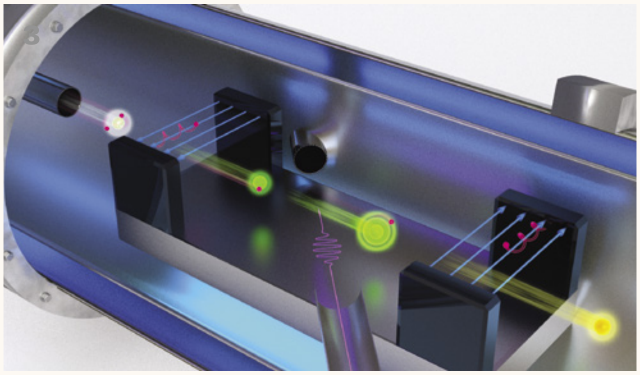

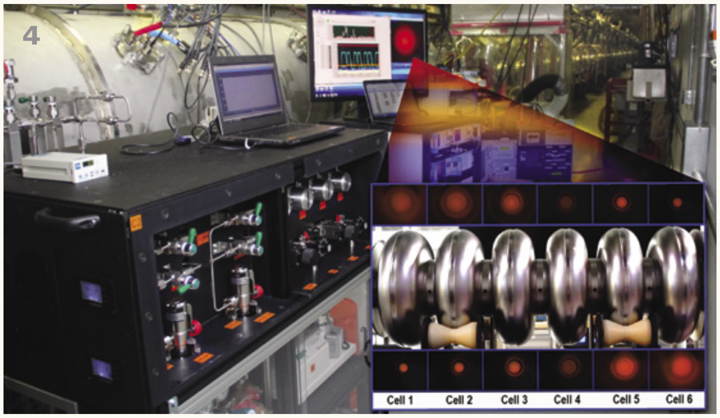

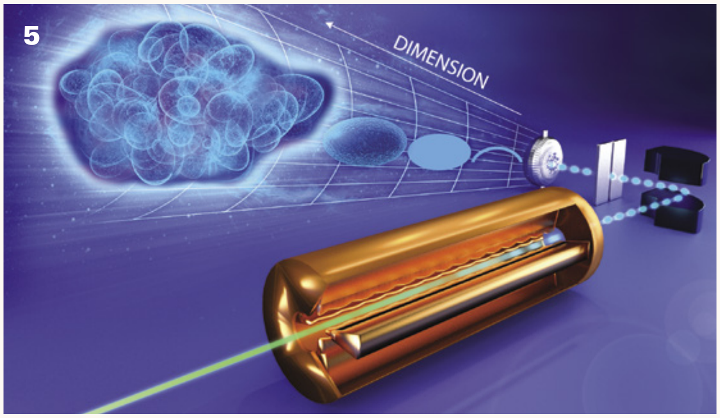

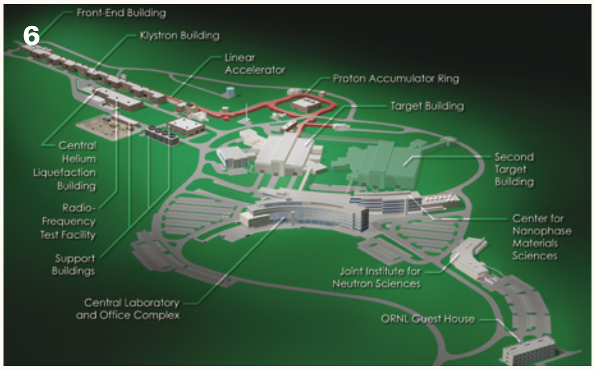

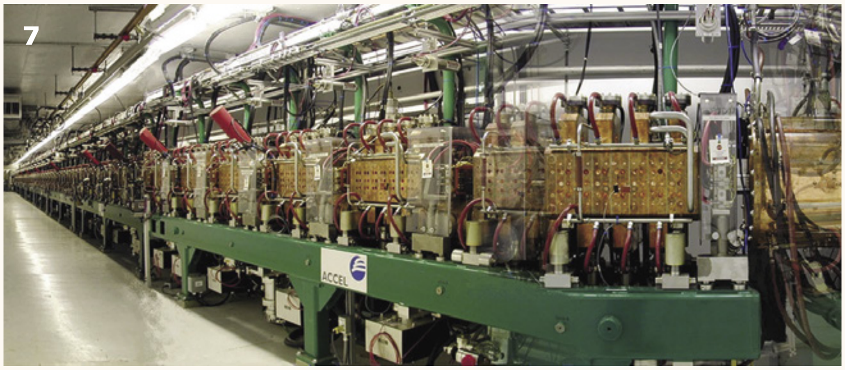

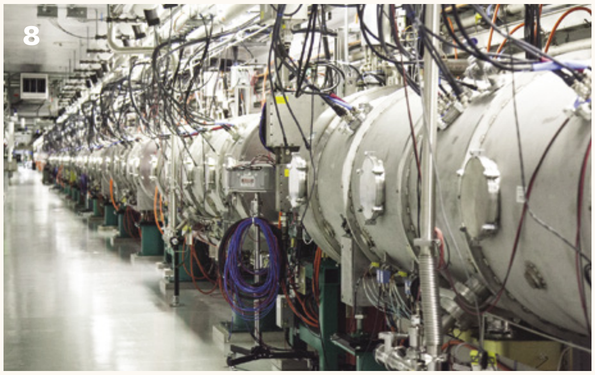

1 The original "research proposal" Ernest Wollan wrote in 1944 requesting funding for neutron experiments at the ORNL X-10 pile. // **2** Ernest Wollan's 1944 hand-drawn graph of the first observation of Bragg reflections using neutron diffraction at Oak Ridge. // **3** Conceptual image of laser electron stripping. Left to right: incoming hydrogen particle with two electrons (red); first electron is stripped in a magnetic field; excitation (purple beam) of the remaining electron by a laser (center); remaining electron is stripped by a second magnetic field; resulting proton particle (yellow). Image credit: ORNL/Jill Hemman // **4** Behind the work station, an SNS cryomodule undergoes in-situ plasma processing. Inset shows a 6-cell cavity with monitored plasma inside each cell. Image credit: Genevieve Martin/ORNL. // **5** Conceptual image of 6D beam measurement in a particle accelerator, showing that the beam's structural complexity increases when measured in progressively higher dimensions. Image credit: ORNL/Jill Hemman // **6** Planned upgrades to the Spallation Neutron Source include doubling the power through the Proton Power Upgrade and adding a new-generation neutron source, the Second Target Station. // **7** Spallation Neutron Source linac accelerator's ring-to-target beam transport tunnel. // **8** Cryomodules at the Spallation Neutron Source linac. // **9** The 1.4 MW Spallation Neutron Source at Oak Ridge National Laboratory is the world's most powerful pulsed-beam neutron source.

1999: Spallation Neutron Source construction begins

The $1.4 billion SNS is the first U.S. science facility of its scale to be constructed in more than a decade. Attending is special guest and Nobel Laureate Clifford Shull.

2006: Spallation Neutron Source begins operations

SNS begins operations, and by 2009 increases its beam power to 1.0 MW, or eight times that of the world's leading pulsed spallation source. This increase in power, when combined with advanced instrument technology developed at SNS, gives researchers a 50- to 100-fold net improvement in measured neutron beam peak intensity.

2007: Oak Ridge Electron Linear Accelerator

The American Nuclear Society recognizes the 38-year-old ORELA as a Nuclear Historic Landmark. Research at this linac has led to more than 500 published papers. The accelerator will continue operating until 2015.

2010: HFIR helps discover "tennessine" (element 117)

Berkelium is a radioactive element needed to produce element 117, and it can only be made at HFIR. After 250 days of irradiation, 22 mg of berkelium-249 are sent to the Joint Institute for Nuclear Research in Dubna, Russia, which produces the first six atoms of element 117—later named "tennessine" in honor the contributions of ORNL, Vanderbilt University and the University of Tennessee.

2015: HFIR turns 50 and achieves landmark status

Highlights of HFIR's half-century of research include the invention of neutron polarization analysis in 1969, the implementation of small-angle neutron scattering in 1978 and investigating high-temperature superconductivity in the early 1990s.

2016: SNS uses plasma cleaning on superconducting cavities

SNS staff develop in-situ plasma processing to remove contaminants, which limit operational performance, from the surface of superconducting accelerator cavities. This reduces cavity cleaning time from up to eight months to just a few weeks without removing the cavities.

2016: New state of water discovered

Neutron scattering and computational modeling reveal a unique and unexpected quantum tunneling behavior of water molecules under extreme confinement.

2017: Laser stripping process targets beam loss

Significant beam loss in the injection of the accelerator caused by the ion-stripping material interacting with the circulating-ring proton beam prompts SNS accelerator scientists to develop the first laser-assisted hydrogen ion-stripping process to aid ring injection and reduce beam loss.

2017: Neutrons peer into a running engine

Researchers use neutrons to investigate the performance of a new aluminum-cerium alloy in a gasoline-powered engine—while the engine is running.

2017: First nanoscale look at a living cell membrane

Scientists use neutrons to make the first-ever direct nanoscale examination of a living cell membrane. Researchers identify tiny groupings of lipid molecules, called lipid rafts, that are key to a cell's ability to function, resolving a longstanding debate.

2018: Complete 6D characterization of accelerator beam

SNS scientists produce the world's first six-dimensional measurement of an entire accelerator beam. To avoid monopolizing the SNS accelerator during long periods of data acquisition, researchers conduct the measurements at the ORNL Beam Test Facility, a functional copy of the SNS linac injector.

2018: Neutrons probe a metal-organic framework

Scientists at Oak Ridge use neutrons to show how an MOF exhibits a selective, fully reversible and repeatable capability to remove nitrogen dioxide gas from the atmosphere.

2018: SNS sets record for neutron production beam power

After years of innovations in mercury target design, linac improvements, and other advancements, SNS completes a full production cycle at 1.4 MW, the highest beam power ever delivered for a full cycle.

2018: Plasma processing enables 1 GeV beam energy

The plasma cleaning process developed at SNS in 2016 helps bring linac beam energy to the design goal of 1 GeV.

SNS Spotlight: The world's most powerful accelerator-based neutron source

Today, thanks in part to its superconducting radio-frequency (RF) linear accelerator, the Spallation Neutron Source remains the world's most powerful pulsed neutron beam source, operating at or near its design power of 1.4 MW. The SNS accelerator complex, stretching nearly the length of three football fields, consists of a hydrogen ion source, a 1 GeV linac and a proton accumulator ring.

The proton beam is initially accelerated through a normal conducting copper drift-tube linac and a coupled-cavity linac. Once the particle beam reaches approximately 0.4c, the superconducting section of the accelerator takes over, accelerating the beam to 0.88c. Superconducting cavities permit more rapid ion acceleration per meter than a room-temperature copper linac and provide operational flexibility.

The SNS complex can deliver up to a 1.4 MW proton beam—the highest beam power ever delivered during a neutron production run cycle—in pulses 60 times per second to a mercury target. The mercury not only provides a ready supply of available neutrons, it also circulates to help dissipate the sudden bursts of energy that are produced by the proton pulses impacting the target. Each proton hitting the nucleus of a mercury molecule in the target "spalls" off 20 to 30 high-energy neutrons, a portion of which are directed to advanced beamline instruments. Cryogenic moderators are located next to the target to lower the neutrons' energy for specific types of experiments.

Oak Ridge scientists and engineers have significantly extended the life expectancy of SNS targets by studying the performance of earlier targets and making modifications, including injecting small bubbles of helium gas into the target vessel's liquid mercury jet flow—an improvement that reduces mechanical strain and cavitation damage caused by the proton pulses.

Neutron scattering provides essential details about atomic-, meso- and nanoscale structures, forces and activities that in many cases simply cannot be obtained using any other technique. Neutrons have ideal energies for observing atoms in motion, and they are non-destructive, deeply penetrating and uniquely sensitive to magnetism and lighter elements such as hydrogen. SNS, with its 19 advanced beamline instruments, enables a wide range of science under ambient conditions, as well as in extreme and complex environments.

SNS and ORNL's other world-class neutron source, the continuous beam High Flux Isotope Reactor, together in FY 2018 provided 102,883 hours of beamtime for research, hosted 1,205 unique visiting users who conducted 1,188 user experiments that resulted in 646 published papers (457 instrument publications by users and189 other publications by ORNL's neutron science staff).

Looking to the Future

With Department of Energy approval, ORNL will move ahead with two major upgrades at SNS: implementing a Proton Power Upgrade (PPU) and building a Second Target Station (STS). The PPU will double the available proton beam power to 2.8 MW by adding more superconducting cryomodules and new RF sources in the klystron gallery including 28 klystrons, three high-voltage converter modulators and associated support equipment. Some existing RF equipment will be upgraded to accommodate the increased beam loading.

PPU will enable faster discovery and the study of smaller and more complex samples. It will also allow the SNS linac to deliver a portion of its additional proton power to the STS instrument hall—at 15 pulses per second—to power up to 22 new world-leading instruments. STS will enable breakthroughs in materials research including biological, polymer, quantum, complex and engineered materials. STS will deliver capabilities far beyond those of current U.S. sources, producing more cold (lower energy) neutrons, with a factor of four increase in range of wavelengths and a 40 times increase in pulsed brightness.

With a new suite of instruments boasting the latest advances in high-resolution optics, instrument design and neutron spin manipulation, STS will deliver instrument-specific performance gains that are 100 to 1,000 times better than existing neutron instruments. Together, these improvements will offer unprecedented neutron science capabilities vital to the US economy and research community, speed up the pace of discovery with faster data collection, and provide more opportunities to visiting scientists to complete their materials research at ORNL.

Edited by Paul Boisvert, ORNL Communications

The Research Accelerator Division at Oak Ridge National Laboratory welcomes inquiries from industry, academia and government agencies to collaborate with ORNL in accelerator science and the development of new accelerator technologies.

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Tales of TRIUMF

Stuart Shepherd, Ewart Blackmore, Jens Dilling and Kathryn Hayashi
TRIUMF

Founded 50 years ago to meet research needs that no single university could provide, Canada's premier accelerator laboratory continues to drive discoveries.

The TRIUMF laboratory's 50-year legacy is imprinted on its 13-acre campus in Vancouver. Decades-old buildings made of cinderblock and corrugated steel sit alongside new facilities housing state-of-the-art equipment. With each new facility, the lab continues its half-century journey. From a regional, tri-university meson facility, TRIUMF has become a national and international hub for science.

At the laboratory's heart is the original 520 MeV cyclotron—a negative-hydrogen-ion accelerator so well engineered when it was first built that it continues to function (albeit with updated controls and electronics). Over the past 50 years, the TRIUMF cyclotron has spurred the growth of a diverse and multidisciplinary community whose ideas continue to coax new uses from the decades-old accelerator, and these new applications serve to continuously redefine TRIUMF as an institution. A superconducting linear accelerator now complements the original cyclotron; 17 universities and counting have joined the original trio; and an expanding network of collaborators now spans the globe. TRIUMF, which began with a daring idea and a simple patch of rainforest on the University of British Columbia's (UBC) south campus, is this year reflecting on its rich past, its vibrant present and the promise of a bright future.

The tri-university meson facility

The first inklings for the tri-university meson facility were themselves products of three separate elements: first, a trio of Canadian universities; second, a novel accelerator concept; and third, an appetite for collaboration within the field of nuclear physics in the early 1960s. The researchers involved were well-positioned to develop such a proposal. John Warren, then head of the nuclear physics group at UBC, had established a team of remarkable graduate students while constructing a 3-MeV Van de Graaff accelerator. Erich Vogt had just transitioned to the UBC physics faculty from an illustrious career as a theoretical nuclear physicist at Chalk River Laboratories in Ontario. And finally, J. Reginald Richardson, a Canadian-born physicist at the UCLA, had finalised a concept for a sector-focused, spiral-ridge negative-hydrogen-ion cyclotron (many of the ideas for which came while holidaying at his cottage on Galiano Island on the west coast of British Columbia). In the years that followed, all three of them would become directors of TRIUMF.

At the time, the world was ready to dig deeper into nuclear structure and explore other hadronic mysteries using powerful meson beams. This push for "meson factories" led to LAMPF in the U.S., SIN (now PSI) in Switzerland and, eventually, TRIUMF in Vancouver.

In 1964, a young physicist named Michael Craddock (who would become a long-time CERN Courier contributor) completed his doctorate in nuclear physics at the University of Oxford in the U.K. before joining the UBC physics faculty. In June 1965, Craddock attended a meeting between UBC, the University of Victoria and Simon Fraser University, and wrote a summary of the proceedings: an agreement to develop a proposal for a tri-university meson facility based on the Richardson negative-hydrogen-ion cyclotron. Three years later, the group received $19 million Canadian dollars in federal funding, and construction began.

Warren presided as TRIUMF's first director, and many of the accelerator's build team came from his Van de Graaff graduate students. The initial organisation consisted of a university faculty member directing the engineers and consultants responsible for each of the main components of the cyclotron—ion source, radiofrequency systems, magnet and vacuum. Joop Burgerjon, the engineer for the construction of the 50 MeV negative-hydrogen-ion cyclotron at the University of Manitoba, which was itself a copy of the 50 MeV UCLA cyclotron, became TRIUMF's chief engineer.

Ewart Blackmore (one of this article's authors) was one of Warren's graduate students who came back to work on the accelerator design and construction. In 1968, while working as a postdoctoral fellow at what is now the Rutherford Appleton Laboratory in the U.K., Blackmore and another postdoctoral fellow, David Axen (also a former UBC graduate student) received a call to coordinate an experiment to measure the dissociation rate of negative hydrogen ions in a magnetic field. This is an important parameter for setting the maximum magnetic field of the cyclotron. The measurement used the proton linac at Rutherford and resulted in a higher dissociation rate than expected from earlier experiments, increasing the size of the cyclotron by 4%.

Upon his return to Vancouver, Blackmore shouldered the responsibility for the cyclotron's injection, beam diagnostics and extraction systems. All of these components and more were put to the test with a full-scale model of the cyclotron's centre core, which achieved first beam in 1972. Finally, despite a six-month delay to reshape the magnetic field produced by the 4000-tonne magnet, the TRIUMF team of about 160 physicists, engineers and technical staff coaxed a beam of protons from the cyclotron on 15 December 1974. TRIUMF's scientific programme began the following year with an initial complement of experimental beamlines: proton, neutron, pion and muon. In the end, the project was on-budget and very near the original schedule. The machine reached its designed current of 100 μA in 1977, with Blackmore coordinating the first five years of commissioning and operations. He recalls that it was a remarkable experience to witness the moment first beam was achieved from the cyclotron. "At the start of it all, most of us had little understanding of cyclotrons and related technologies, but we had the valuable experience we had gained as graduate students."

International physics hub

The story of TRIUMF quickly developed, the lab reinventing itself time and again to keep up with the fast pace at which the field was evolving. By the early 1980s, TRIUMF was a well-established accelerator laboratory that operated the world's largest cyclotron. In those days, TRIUMF utilised proton and neutron beams to drive a powerful research programme in nucleon-nucleon and nucleon-nucleus interaction studies, muon beams for muon spin rotation experiments in material sciences, pion beams for nuclear structure studies, and meson beams for precision electroweak experiments.

However, as the field advanced, new discoveries in meson science were changing the landscape. TRIUMF responded by proposing an even larger accelerator system, the 30GeV Kaons, Antiprotons, Other hadrons and Neutrinos complex. When fully complete, KAON would have allowed cutting edge high energy physics experiments at the intensity frontier. It was a bold proposal that garnered substantial national and international interest but ultimately did not find enough political support to be funded. Nevertheless, the concept itself was considered visionary. The science that TRIUMF wanted to enact was taken up decades later in modified forms at the J-PARC complex in Japan. It will also be revived at the upcoming FAIR facility in Germany (see CERN Courier, July/August 2017, p41).

The loss of KAON forced an existential crisis on TRIUMF, and the laboratory responded in two parallel efforts. First, TRIUMF expanded Canada's contributions to international physics collaborations. During the decade-long campaign to design KAON, TRIUMF had developed an impressive array of scientific and engineering talent and capabilities in the design of accelerators, production targets and detectors. This enabled the Canadian physics community—supported by TRIUMF—to contribute to CERN's Large Hadron Collider (LHC) and join the ATLAS collaboration, building components such as the warm twin-aperture quadrupoles for the LHC and the hadronic endcap calorimeter for ATLAS. This positioned TRIUMF as Canada's gateway to international subatomic physics and paved the way for Canada's contributions to other major physics collaborations, like T2K in Japan.

The laboratory's second response was the development at TRIUMF of a new scientific programme centred on rare isotopes. By the 1980s, there was burgeoning interest in the field of rare isotopes, opening new avenues of research for TRIUMF into nuclear astrophysics, fundamental nuclear physics and low-energy precision probes of subatomic symmetries. TRIUMF had recognised the worldwide shortage of isotope production facilities and understood the role it could play in rectifying the situation. The lab already possessed expertise in beam and target physics, design and engineering—not to mention a high-powered 520-MeV cyclotron that could act as a beam driver for producing exotic isotopes.

Rare-isotope beams at TRIUMF started during the KAON era with the small Test facility of Isotope Separation OnLine (TISOL) project in 1987, which used an isotope-separation concept developed at CERN's ISOLDE facility. Experience at TISOL gave its proponents confidence that a much larger rare-isotope beams facility could be built at TRIUMF. So, the Isotope Separator and Accelerator (ISAC) era was born at TRIUMF. Today, TRIUMF's ISAC boasts the highest production power of any ISOL-type facility and some of the highest rates of rare-isotope production in the world. ISAC enables TRIUMF to produce isotopes for a variety of research areas, including studies of the formation of the heavy chemical elements in the universe, exploration of phenomena beyond the Standard Model of particle physics and inquiry into the deepest secrets of the atomic nucleus. In addition, spin-polarised, beta-emitting isotopes produced at TRIUMF make possible detailed probes for surface and interface studies in complex quantum materials or novel batteries. This benefits the molecular- and materials-science communities.

TRIUMF is continuing to build on its expertise and capabilities in isotope science by adding new rare-isotope production facilities to supply the laboratory's existing experimental stations. A new project, the Advanced Rare Isotope Laboratory (ARIEL), will add two rare-isotope production stations driven by a new proton beamline from the cyclotron and a new electron beamline from a new superconducting linear accelerator (designed and built in Canada). ARIEL will triple the output of the science programme based on rare-isotope beams, creating new opportunities for innovation and allowing the lab to branch off into promising new areas, even outside of subatomic physics, materials science and nuclear astrophysics. Although ARIEL's completion date is set for 2023, the facility's multi-stage installation will allow the TRIUMF community to begin scientific operations as early as 2019.

An innovation lab

TRIUMF's history is defined not only by a drive to push the frontiers of science and discovery, but also those of innovation. The flexibility of the iconic cyclotron at the heart of TRIUMF's scientific programme has allowed the lab to venture into areas that few could have imagined at the time of its original proposal. Standing on the shoulders of its founders, TRIUMF's community now turns to the next half-century and beyond, and asks: How can TRIUMF increase its impact on people's everyday lives?

Fundamental research remains core to TRIUMF's mission. But the laboratory has long appreciated the necessity and opportunity for translating its technologies to the benefit of society. TRIUMF Innovations, the lab's commercialisation arm, actively targets and develops new opportunities for collaboration and company creation surrounding the physics-based technologies that emerge from the TRIUMF network.

Perhaps the most longstanding of these collaborations is TRIUMF's 30-plus-year partnership with the global health science company Nordion. A team of TRIUMF scientists, engineers and technicians works with Nordion to operate TRIUMF cyclotrons to produce commercial medical isotopes used in diagnosing cancer and cardiac conditions. During the course of this partnership, more than 50 million patient doses of medical isotopes produced at TRIUMF have been delivered to patients around the world.

Another outcome of TRIUMF Innovations is ARTMS Products Inc., which produces cyclotron-target technology that enables cleaner and greener manufacturing of medical isotopes within local hospitals. ARTMS has already secured venture capital funding and multiple successful installations are under way around the world. Its technology for producing the most commonly used medical isotope, technetium-99, will help stabilise the global isotope supply chain in the wake of the shutdown of the Chalk River reactor facility.

TRIUMF Innovations will play a key role in fostering industry relationships enabled by the future Institute for Advanced Medical Isotopes (IAMI), a critical piece of infrastructure that will advance nuclear medicine in Canada. Supported by TRIUMF's life sciences division, IAMI will provide infrastructure and expertise towards developing new diagnostics and radiotherapies. IAMI will also provide industry partners with facilities to study and test new isotopes and radiopharmaceuticals that promise to improve the health of patients in Canada and around the world.

Similarly, TRIUMF and TRIUMF Innovations are working to support the emerging field of targeted alpha-emitting therapeutics—radiotherapy medicines that hold new promise for patients who have been diagnosed with advanced and life-threatening metastasised cancers. Multiple new companies are developing treatments, but all are hampered by a global shortage of actinium-225 (225Ac), a hard-to-produce isotope at the core of many of these therapies. The TRIUMF cyclotron is unmatched in potential 225Ac production capacity, and the laboratory is working with researchers and industry partners to bring this production online. It is also helping speed up development of new therapies that could offer new hope to patients with cancers that are currently deemed incurable.

Beyond these developments, TRIUMF Innovations manages a portfolio of TRIUMF products and services. These range from providing irradiation services for stress testing communications and aerospace technologies to improving the efficacy and safety of mining exploration by using muon detectors to help geologists estimate the size and location of ore deposits.

In the coming years, TRIUMF Innovations will continue to advance commercialisation both within TRIUMF and through TRIUMF's networks. For example, TRIUMF is now seeking to develop a new data science hub to connect its 20 member universities and global research partners to private-sector training opportunities and new quantum computing tools. Drawing on data science acumen developed through the ATLAS collaboration, TRIUMF is building industry partnerships that train academic researchers to use their data-science skills in the private sector and connect them with new research and career opportunities.

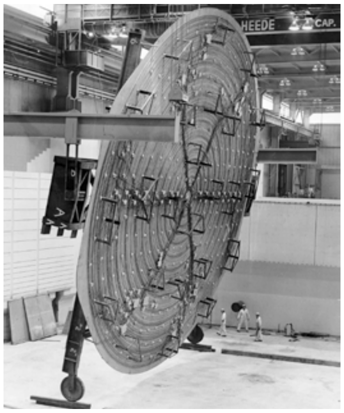
It is clear that TRIUMF's sustained focus on commercialisation and collaboration will ensure that the lab continues to bring the benefits of accelerator-based science into society and to pursue world-leading science with impact.

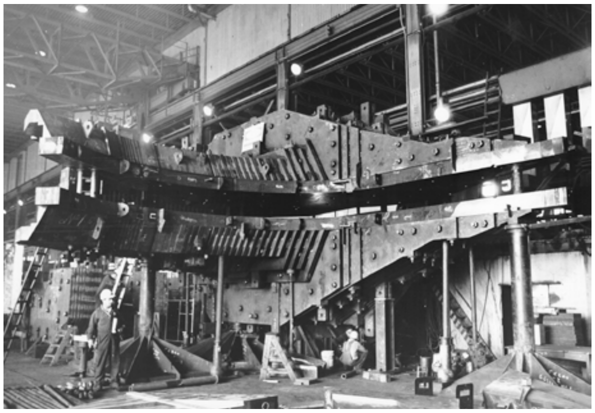
The quest continues...

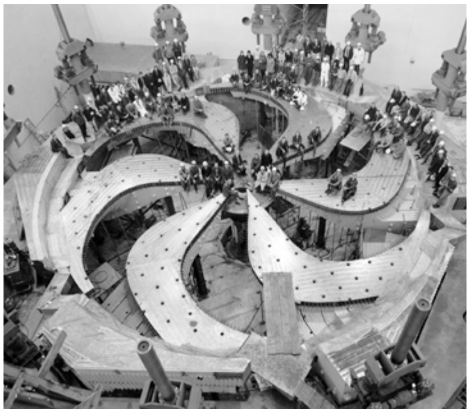
Fifty years in, TRIUMF's narrative is a continuous work in progress, a story unfolding beneath the mossy boughs of the same fir and alder trees that looked down on the first shovel strike, the first sheet of concrete, the first summer barbecue.

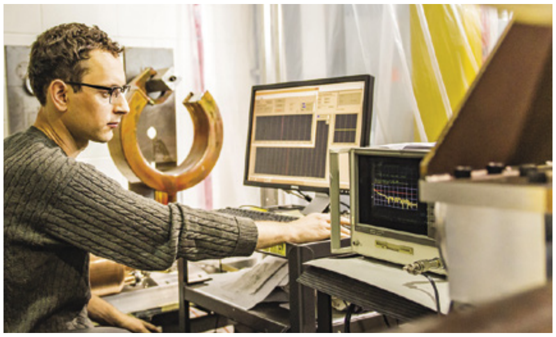
In the coming years, the lab will continue to welcome fresh faces, to upgrade and add new facilities, to broach new frontiers, and to confront new challenges. It is difficult to predict exactly where the next era of TRIUMF will lead, but if there is one thing we can be sure of, it is that TRIUMF's community of discoverers and innovators will be exploring ideas and seeking out new frontiers for years to come.

For more information, visit TRIUMF50.com









Summaries by the Student Poster Prize Winners at IPAC18

Space Charge Limitations for Bunch Compression in Synchrotrons

Yao-shuo Yuan,

Technische Universität Darmstadt and GSI

For proton or heavy-ion synchrotrons, bunch compression achieved via a fast bunch rotation in longitudinal phase space is a well-accepted scheme to generate short, intense ion bunches for various experimental applications. During bunch compression, coherent beam instabilities and incoherent single-particle resonances can occur because of increasing space charge, resulting in an important limitation for the bunch intensity.

This work focuses on an investigation of 3-D beam motion during bunch compression, using a set of coupled, transverse-longitudinal envelope equations including dispersion, compared with particle-in-cell (PIC) simulations. Furthermore, based on the 3-D coupled-envelope model and PIC simulations, an analysis of the "competition mechanism" between the coherent space-charge driven beam instability and the incoherent particle resonance phenomena during bunch compression is discussed. It is shown that during bunch compression, the 90° condition of phase advance is associated with a fourth order single particle resonance and the 120° condition with the recently discovered dispersion-induced instability, which should be avoided during bunch compression.

Studies of Horizontal Instabilities in the CERN SPS

Mario Beck,

University of Rostock and CERN

As part of the LHC Injectors Upgrade (LIU) for the High Luminosity Large Hadron Collider (HL-LHC) project at CERN, beams with double the intensity of current values will have to be accelerated by the CERN Super Proton Synchrotron (SPS) and extracted towards the Large Hadron Collider (LHC). Experience has shown, however, that coherent horizontal instabilities may develop, posing a potential intensity limitation for future high intensity operation.

To understand the mechanism of these instabilities and to check if the SPS impedance model reproduces the observations, the PyHEADTAIL code, developed for beam dynamics simulations at CERN, compares simulations with measurements. The chromaticity in the machine was accurately measured over a broad range of $\Delta P/P$ and has been used as an input in simulations. PyHEADTAIL simulations have then been employed to determine instability growth rates as a function of chromaticity for different machine models and optics, explore stabilizing techniques and benchmark the impedance model with tune-shift and growth-rate measurements.

A good accordance is found between simulations and measurements. Simulations also show that for higher intensities, a horizontal instability can develop in the SPS in chromaticity regions where it has been observed before during high-intensity operation. The studies reveal that this instability can be damped with higher chromaticity values or octupoles, and thus it is not expected to prevent future high-intensity operation.

A 2D Steady-State Space Charge Solver for Azimuthally Symmetric Problems of Arbitrary Degree

Alysson Gold,

Stanford University & SLAC National Accelerator Laboratory

In designing and optimizing accelerator and radio-frequency source components, correctly and rapidly simulating the steady-state interaction between particle beams and electromagnetic fields is crucial. The research I presented at IPAC'18 looked at new approaches to solving the self-consistent trajectories of particles in the presence of external and self-fields (i.e., the propagation of space-charge-dominated beams). I focused on two methods to map from the individual macro-particle trajectories to the continuous source terms, space charge and current density, which drive the fields in subsequent iterations of the solver.

The first method reformulates the self-field contribution as a path integral over the particle trajectory instead of as a volume integral of the space-charge density in each mesh cell. This is made possible by the assumption of steady-state, allowing for a frequency domain treatment of the source terms and fields. The second method uses the dual space of the particle trajectories, treating them as bounds on conserved current rather than as discrete particles. By applying charge conservation, we can interpolate between these bounds to obtain a continuous current density, requiring one to two orders of magnitude fewer particles to obtain similar accuracy as approaches which treat the trajectories as discrete particles. We conclude with benchmarking results that show this method is as accurate as state-of-the-art solvers for electrostatic problems, while running 80 to 120 times faster.

2018 Outstanding Doctoral Thesis Research in Beam Physics Award Recipient

An Interview with Sergey Antipov

CERN

1) Let's start with your thesis research. Can you give a brief description of what it entailed and the impact it had on the field?

In short, one has to be careful when choosing combined function dipoles for a hadron machine. The problem is the electron cloud that can accumulate in these magnets and drive an instability similar to the one observed in the Fermilab Recycler proton storage ring. The gradient of the magnetic field works like a magnetic bottle, confining the electrons within the field lines such that they stay trapped there long after the beam has passed. This trapping can lead to an increase of electron density over many beam revolutions and lets it reach densities far exceeding those of a pure dipole of the same strength.

2) How did you get into the field of accelerator physics, and your research area in particular?

My first encounter with accelerator physics happened during a summer internship at Fermilab. It then struck me how many areas of physics are combined in accelerator physics, how diverse and challenging the problems are. So after finishing my master's degree in Moscow, I came to Chicago to pursue a doctorate in this field. I tried several different areas: I started by studying the dynamics of quench in superconducting RF cavities; then transitioned to beam dynamics and worked on the design of the IOTA test ring and its experiments; and eventually ended up investigating collective stability in the Recycler.

3) What was the greatest challenge you faced during your PhD (technical or otherwise)?

I guess it was writing the thesis.

4) What advice do you have for current graduate students in accelerator physics?

Think outside the box—chances are the obvious solutions have already been tried.

5) What are you doing now? Is it a continuation of your previous research, or are you starting something new?

I am currently a postdoctoral fellow at CERN, working on coherent beam stability for Hi-Lumi LHC. My current project is a logical continuation of what I was doing for my thesis, although the focus has shifted from electron-cloud-driven instabilities to beam coupling impedance. LHC is a terrific machine to work on. It never stops puzzling us.

6) Any plans /aspirations for the future? Where do you see the future of plasma wakefield acceleration heading?

I am not an expert in plasma wakefield acceleration, although it is exciting to follow the progress in this field. For particle physics, the intensity frontier is looking quite promising. We might be coming close to finally solving the mysteries of neutrinos, for example, with DUNE. It would be interesting to see if we can push the intensities further with smart tricks like nonlinear optics or space charge compensation.

7) Tell us a fun fact about you! An interesting hobby, perhaps.

During my time in the U.S., I used to collect the states I visited. So far, I've set foot in only 26, but I hope to complete the list one day.

Upcoming Events

Date	Title	Location
Conferences & Meetings		
March 4 - 8, 2019	APS March Meeting	Boston, United States
April 13 - 16, 2019	APS April Meeting	Denver, United States
May 5 - 10, 2019	European Conference on Accelerators in Applied Research and Technology (ECAART'19)	Split, Croatia
May 19 - 24, 2019	International Particle Accelerator Conference (IPAC'19)	Melbourne, Australia
June 30 - July 5, 2019	International Conference on RF Superconductivity (SRF'19)	Dresden, Germany
August 25 - 30, 2019	International Free-Electron Laser Conference (FEL'19)	Hamburg, Germany
September 2-6, 2019	North American Particle Accelerator Conference (NA-PAC'19)	Lansing, United States
September 8 - 12, 2019	International Beam Instrumentation Conference (IBIC'19)	Malmö, Sweden
September 15 - 20, 2019	ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs (ERL'19)	Berlin, Germany
October 5 - 11, 2019	International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'19)	New York, United States
May 10 - 15, 2020	International Particle Accelerator Conference (IPAC'20)	Caen, France
August 30 - September 4, 2020	Linear Accelerator Conference (LINAC'20)	Liverpool, United Kingdom
Summer/Fall 2020	ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'20)	Chicago Area, United States
Accelerator Schools		
January 21 - February 1, 2019	U.S. Particle Accelerator School (USPAS) Winter 2019	Tennessee, United States
June 17 - 28, 2019	U.S. Particle Accelerator School (USPAS) Summer 2019	New Mexico, United States
January 7 - March 15, 2019	Joint Universities Accelerator School (JUAS)	Archamps, France
March 11 - 22, 2019	CERN Accelerator School: High Gradient Wakefield Accelerators	Sesimbra, Portugal
June 5 - 9, 2019	CERN Accelerator School: Advanced Accelerator Physics	Slangerup, Denmark
September 8-21, 2019	CERN Accelerator School: Introduction to Accelerator Physics	Vysoke-Tatry, Slovakia

In Memoriam

Burton Richter & Leon Lederman

July 19, 2018

Nobel Prize-winning Stanford physicist Burton Richter dies at 87

By Andrew Myers and Glennda Chui

Richter designed particle accelerators and carried out experiments that led to the Nobel Prize-winning discovery of the charm quark.

Burton Richter, the Paul Pigott Professor in the Physical Sciences, Emeritus, former director of the Department of Energy's SLAC National Accelerator Laboratory and winner of the 1976 Nobel Prize in physics, died July 18 in Palo Alto. He was 87.

Richter's Nobel Prize-winning discovery of the J/psi subatomic particle, shared with MIT's Samuel Ting, confirmed the existence of the charm quark. That discovery upended existing theories and forced a recalibration in theoretical physics that reverberated for years. It became known as the "November Revolution." One Nobel committee member at the time described it as "the greatest discovery ever in the field of elementary particles."

"We mourn the loss of Burton Richter as a major figure in the field of physics and as the leader of SLAC during a critical period in its history," said Stanford President Marc Tessier-Lavigne. "His co-discovery of a new subatomic particle changed physics forever, and his leadership of SLAC empowered many others to achieve transformative scientific discoveries. His many honors, including the Nobel Prize and the National Medal of Science, are testament to his lasting contributions to Stanford and to our world."

Richter was remembered as a talented physicist whose achievements laid the groundwork for many decades of discoveries.

"Burt was unique in that he was both a particle physicist and an accelerator physicist, whereas most people are one or the other," said SLAC Director Chi-Chang Kao. "This rare combination gave him the vision and also the daring to build the SPEAR Storage Ring to look for new elementary particles, which led to him winning the Nobel Prize in physics for discovery of the J/psi particle. Burt was an inspiration for us all to be bold in what we aim for."

Stanford Provost Persis Drell, who served as director of SLAC from 2007 to 2012, said Richter was farsighted in his leadership of SLAC. "Burt was a visionary director of SLAC, with a forceful personality and a tremendous drive. His fingerprints are all over many of the advances in accelerators in the 20th century, as well as in the development of the X-ray light sources enabled by electron accelerators."

Inspired by the stars

Richter was born in Brooklyn, New York, on March 22, 1931. His love of science started during the nightly blackouts during World War II, meant to foil potential air raids. Those pitch-black nights revealed an unparalleled view of the night sky and a hazy band of stars known as the Milky Way.

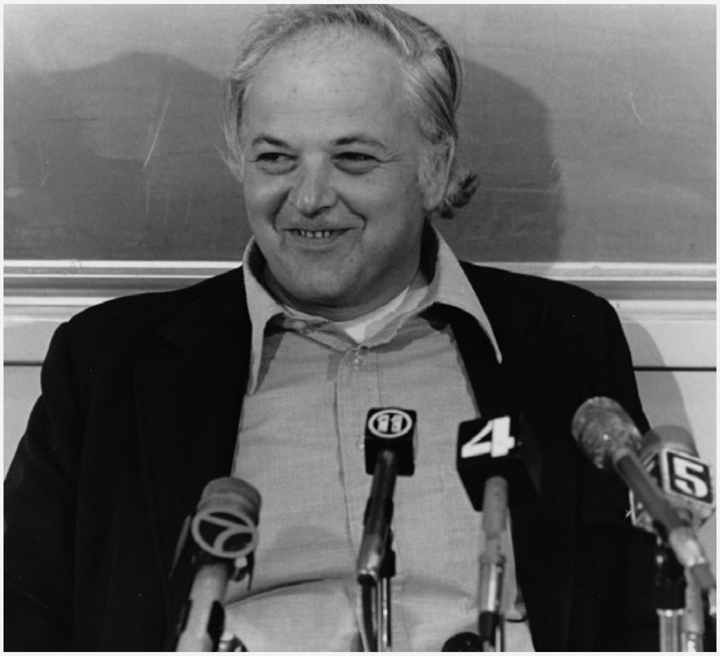
Richter received his Bachelor of Science degree in 1952 and his doctorate in physics in 1956, both at the Massachusetts Institute of Technology. While there, Richter had access to a particle accelerator, where he began working with powerful machines that that could isolate, accelerate and control beams of electrons. That work brought Richter to Stanford's High-Energy Physics Lab in 1956 as a research associate. In 1960, he became an assistant professor of physics, made associate professor in 1963 and was promoted to professor in 1967. During this time, Richter married his wife, Laurose, and had two children, Elizabeth and Matthew.

It was at SLAC (then known as Stanford Linear Accelerator Center) where, in the early 1960s, he designed SPEAR, the Stanford Positron-Electron Accelerator Ring. It included a groundbreaking type of detector that has been used in particle colliders ever since, and it would eventually produce his biggest discovery. This was the first of several accelerators Richter would design.

"Burt Richter was a superb physicist, especially because he knew about both accelerators and particles, which is rare," said SLAC Deputy Director Emeritus Greg Loew, who joined the lab in 1958 and helped design its 2-mile-long linear particle accelerator.

After Richter secured funding for SPEAR in 1970, it took him just 27 months to build the accelerator, at a cost of $6 million. Experiments commenced in 1973 and on November 10, 1974, a Sunday, Richter and team witnessed history – a new subatomic particle.

The next morning, Richter told a colleague at MIT, Samuel Ting, about the discovery. To his surprise, Ting had just discovered the same particle. Ting called his particle J. Richter dubbed his psi. In the "November Revolution," the researchers issued a joint



Burton Richter at his Nobel Prize press conference, 1976 (Image credit: Stanford News Service).

introduction of the J/psi to the world. Two years later, they would share the Nobel Prize. Richter was just 45, among the youngest Nobel recipients ever.

"It was the last step the scientific community needed to believe that charm quarks were real, and was a major step on the way to the Standard Model of particle physics that describes all the fundamental particles and forces," said Martin Breidenbach, a professor at SLAC and Stanford who began working with Richter as a postdoctoral researcher in the late 1960s.

"In my career I have met no one who has made more fundamental contributions in electron-positron and electron-electron colliders, in the precision instrumentation used in colliders and in experimental physics," Ting said. "After we received the Nobel Prize together in 1976, I met him many times and we became good friends. My wife, Susan, and I are going to miss him deeply."

Visionary leader

In 1984, Richter became director of SLAC, a job he held through 1999. During that time, Richter oversaw the construction of the Stanford Linear Collider, which produced much more energetic collisions and was the only one of its kind ever built. Other machines followed, positioning SLAC to take advantage of new frontiers in photon science.

"Perhaps his greatest contribution as director was, in the 1990s, designing a future for SLAC that would look very different from the past," said Drell. "He recognized that pursuing an X-ray free-electron laser at SLAC could be used to provide a revolutionary science opportunity to the photon science community who use X-rays as their tool for discovery. This vision became the Linac Coherent Light Source. Burt recognized that outstanding science needed to drive the future of the institution, and he did not flinch from designing that future."

When he stepped down as SLAC director, Richter focused on public policy issues in science and energy, for which he received the prestigious 2007 Philip Hauge Abelson Prize from the American Association for the Advancement of Science. In 2010, nearing 80, Richter published Beyond Smoke and Mirrors: Climate Change and Energy in the 21st Century, an apolitical layman's exploration of the real facts of climate and energy. In the book, he decried the deniers and the catastrophists alike, emerging as an unabashed advocate of nuclear energy.

"With Burt's passing, we have lost a great physicist and a great friend," said former Secretary of State George Shultz, a distinguished fellow at the Hoover Institution. "I was privileged to work with Burt at Stanford over many years, most recently in the course of our energy task force meetings at the Hoover Institution. We would discuss a wide variety of energy topics, and by the time any speaker was winding up, the group would naturally turn toward Burt's seat, knowing his name card would be up. Nothing got by Burt Richter. I will miss him, but his spirit will live on."

In addition to sharing the Nobel Prize, Richter received the nation's highest scientific honor, the National Medal of Science, in 2014; the U.S. Department of Energy's Enrico Fermi Award in 2012; and the DOE's Ernest Orlando Lawrence Award in 1976. He was a member of the National Academy of Sciences, a fellow of the American Academy of Arts and Sciences and the American Association for the Advancement of Science, and former president of the International Union of Pure and Applied Physics and the American Physical Society. Richter was also a member of JASON, an independent group of scientists that advises the U.S. government.

Richter served as a member of the DOE's Nuclear Energy Advisory Committee and chaired its fuel cycle subcommittee from 2000 to 2013, and was a member of the first PCAST Review Panel for the National Climate Change Assessment. He was also a senior fellow at Stanford's Freeman Spogli Institute for International Studies; a member of the advisory council of the Precourt Institute for Energy; and an affiliate at the Stanford Woods Institute for the Environment.

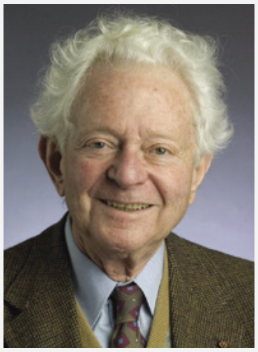
Richter is survived by his wife, Laurose; daughter Elizabeth Richter of Columbia, Maryland; and son Matthew Richter, daughter-in-law Cheryl Richter and grandchildren Allison and Jennifer Richter, all of Woodside, California. No public memorial service is planned.

October 3, 2018

Leon Lederman, Nobel laureate, former laboratory director and passionate advocate of science education, dies at age 96

By Rhianna Wisniewski, Fermi National Accelerator Laboratory

Batavia, Illinois — Leon Lederman, a trail-blazing researcher with a passion for science education who served as Fermilab's director from 1978 to 1989 and won the Nobel Prize for discovery of the muon neutrino, died peacefully on October 3 at a nursing home in Rexburg, Idaho. He was 96.



He is survived by his wife of 37 years, Ellen, and three children, Rena, Jesse and Rachel, from his first wife, Florence Gordon.

With a career that spanned more than 60 years, Lederman became one of the most important figures in the history of particle physics. He was responsible for several breakthrough discoveries, uncovering new particles that elevated our understanding of the fundamental universe. But perhaps his most critical achievements were his influence on the field and his efforts to improve science education.

"Leon Lederman provided the scientific vision that allowed Fermilab to remain on the cutting edge of technology for more than 40 years," said Nigel Lockyer, the laboratory's current director. "Leon's leadership helped to shape the field of particle physics, designing, building and operating the Tevatron and positioning the laboratory to become a world leader in accelerator and neutrino science. Today, we continue to develop and build the next generation of particle accelerators and detectors and help to advance physics globally. Leon had an immeasurable impact on the evolution of our laboratory and our commitment to future generations of scientists, and his legacy will live on in our daily work and our outreach efforts."

Through Lederman's early award-winning work, he rose to prominence as a researcher and began to influence science policy. In the early 1960s, he proposed the idea for the National Accelerator Laboratory, which eventually became Fermi National Accelerator Laboratory (Fermilab). He worked with laboratory founder Robert R. Wilson to establish a community of users, credentialed individuals from around the world who could use the facilities and join experimental collaborations.

According to Fermilab scientist Alvin Tollestrup, who worked with Lederman for more than 40 years, Lederman's success was in part due to his ability to bring people together and get them to work cohesively. "One of his greatest skills was getting good people to work with him," Tollestrup said. "He wasn't selfish about his ideas. What he accomplished came about from his ability to put together a great team."

Lederman began his tenure as Fermilab director in 1978, at a time when both the laboratory staff and the greater particle physics community were deeply divided. As a charismatic leader and a respected researcher, Lederman unified the Fermilab staff and rallied the U.S. particle physics community around the idea of building a proton-antiproton collider. Originally called the energy doubler, the particle accelerator eventually became the Tevatron, the world's highest-energy particle collider from 1983 until 2010.

"Leon gave U.S. and world physicists a step up, a unique facility, a very high-energy collider, and his successors keep working for these things," said Director Emeritus John Peoples, who worked with Lederman for more than 40 years and served as Lederman's deputy director from 1988 to 1989. "Leon made that happen. He set things in motion."

In order to begin plans for a high-energy proton-antiproton collider, Lederman convinced the greater physics community, the Department of Energy, president Reagan's science advisor and Congress.

"Leon had the ability to lead. He was unifying and convincing," Peoples said. "He had the ability to listen to people carefully and could synthesize things well. He was very persuasive. In some sense, I was manipulated at every level."

Lederman's ability to convince others stemmed in part from his charm and his sense of humor, Peoples said.

"He seemed to have an enormous storehouse of jokes," Peoples said. "He had a lighthearted personality, he could have been a stand-up comic at times."

Lederman was born on July 15, 1922, to Russian-Jewish immigrant parents in New York City. His father, who operated a hand laundry, revered learning. Lederman graduated from the City College of New York with a degree in chemistry in 1943, although by that point, he had become friends with a group of physicists and became interested in the topic. He served three years with the United States Army in World War II and then returned to Columbia University in New York to pursue his Ph.D. in particle physics, which he received in 1951. During graduate school, Lederman joined the Columbia physics department in constructing a 385-MeV synchrotron at Nevis Lab at Irvington-on-the Hudson, New York. He remained as part of that collaboration for 28 years and eventually serving as director of Nevis labs from 1961 to 1978.

In 1956, while working as part of a Columbia team at Brookhaven National Laboratory, Lederman discovered the long-lived neutral K meson. In 1962, Lederman, along with colleagues Jack Steinberger and Melvin Schwartz, produced a beam of neutrinos using a high-energy accelerator. They discovered that sometimes, instead of producing an electron, a muon is produced, showing the existence of a new type of neutrino, the muon neutrino. That discovery eventually earned them the 1988 Nobel Prize in physics.

The advancement of particle accelerators continued to spur discoveries. At Brookhaven in 1965, Lederman and his team found the first antinucleus in the form of antideuteron — an antiproton and an antineutron. In 1977, at Fermilab, Lederman led the team that discovered the bottom quark, at the time the first of a suspected new family of heavy particles.

"All of those experiments were important because they set the stage for learning that we have at least two generations of leptons and something else," Tollestrup said.

Lederman served as director of Fermilab from 1978 to 1989. During his tenure as laboratory director, Lederman had a significant impact on laboratory culture. He was responsible for establishing new amenities that set Fermilab apart from other labs, such as the first daycare facility at a Department of Energy national laboratory and an art gallery that continues to host rotating exhibits.

He also had significant impact on the next generation of scientists. It was during his years at Columbia, an institution that required students to teach, that Lederman developed a passion for science education and outreach, which became a theme throughout his career. Between 1951 and 1978 he mentored 50 Ph.D. students. He liked to joke about their success, saying that not a single one was in jail.

As director of Fermilab, Lederman established the ongoing Saturday Morning Physics program, which has attracted students from around the Chicago areas for decades to learn more about particle physics from experts, originally from Lederman, and then a long list of leading scientists. The program has inspired generations of high school students.

Recognizing the need for more focused education in science and math, Lederman focused on creating learning spaces and opportunities for students. In the early 1980s, Lederman worked with members of the Illinois state government to start the Illinois Math and Science Academy, which was founded in 1985, and worked with officials to try to adjust the science curriculum in Chicago's public schools so that students learned physics first, forming the foundation for their future scientific education. He founded and was chairman of the Teachers Academy for Mathematics and Science and was active in the professional development of primary school teachers in Chicago. He also helped to found the nonprofit Fermilab Friends for Science Education, a national leading organization in precollege science education.

In later years, Lederman continued his outreach efforts, often in memorable ways. In 2008, he set up shop on the corner of 34th Street and 8th Avenue in New York City and answered science questions from passersby.

During his career, Lederman received some of the highest national and international awards and honors given to scientists. These include the 1965 National Medal of Science, the 1972 Elliot Creeson Medal from the Franklin Institute, the Wolf Prize in 1982 and the Nobel Prize in 1988. He received the Enrico Fermi Award in 1992 for his career contributions to science, technology and medicine related to nuclear energy and the science and technology of energy, and was given the Vannevar Bush Award in 2012 for exceptional lifelong leaders in science and technology.

In addition to his appointments at Columbia, Nevis and Fermilab, Lederman also served as the Pritzker professor of science at Illinois Institute of Technology and chairman of the State of Illinois Governor's Science Advisory Committee. He also served on the Board of the Chicago Museum of Science and Industry, the Secretary of Energy Advisory Board and others.

When Lederman stepped down as Fermilab's director in 1989 and Peoples took the role, Lederman shared some sage advice. A desk nameplate, which sits on People's desk more than 25 years later, reads "I'm listening."

Leon Lederman celebrates his birthday with children from the Fermilab daycare center.

Leon Lederman stands outside Wilson Hall at Fermilab on the day he learned he was awarded the 1988 Nobel Prize.

APS DPB Awards & Fellowships

Robert R. Wilson Prize for Achievement in the Physics of Particle Accelerators, 2018

Alexander Wu Chao
SLAC National Accelerator Laboratory
Citation: "For insightful, fundamental and broad-ranging contributions to accelerator physics, including polarization, beam-beam effects, nonlinear dynamics, and collective instabilities, for tireless community leadership and for inspiring and educating generations of accelerator physicists."

Outstanding Doctoral Thesis Research in Beam Physics Award, 2018

Sergey Antipov
CERN
Citation: "For experimental studies and analysis of the electron cloud build-up and corresponding instability in accelerators with combined function magnets and for the development of an effective mitigation technique applied in the Fermilab's Recycler ring"

APS Fellow Nominations by the DPB in 2018

Jean-Luc Vay
Lawrence Berkeley National Laboratory
Citation: "For development of novel methods for simulating beams and plasmas and application of these methods to accelerator physics."

Ying Wu
Duke University
Citation: "For outstanding contributions to the Duke University storage ring Free-Electron Laser and High Intensity Gamma Source upgrades."

Anatoli Zelenski
Brookhaven National Laboratory
Citation: "For groundbreaking work in developing high-intensity high-brightness polarized ion beam sources, in particular, optically-pumped polarized sources."

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