Title
AFRD Research Highlights 2005

Author
Chew (Ed.), Joseph

Publication Date
2005-04-27

LBNL/PUB-927
AFRD Research Highlights

In preparation for the 2005 Director's Review of the Accelerator and Fusion Research Division, each of our programs and projects prepared a brief summary of its achievements in 2004 and early 2005 as well as its plans.

In summer 2005, an improved version of this document will be made available chapter by chapter on http://www-afrd.lbl.gov, along with additional context and information and links to PDF versions of the year's top publications as chosen by the program head.

Contents

The work described in this document was supported principally by the Office of Science, U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

1. AFRD FUSION PROGRAM

Reported by Grant Logan, Fusion Program Head
and Director of the Heavy Ion Fusion Virtual National Laboratory

The Fusion Program at LBNL leads the Heavy Ion Fusion Virtual National Laboratory (HIF-VNL) a collaboration that also includes Lawrence Livermore National Laboratory and the Princeton Plasma Physics Laboratory (Figure 1-1). The HIF-VNL was formed in 2000 and operates under a Memorandum of Agreement, now being considered for a 5 year renewal for 2005 through 2010. This chapter principally concerns the Fusion Program here at LBNL, along with work at the partner laboratories that has a strong and direct connection to what we did here.

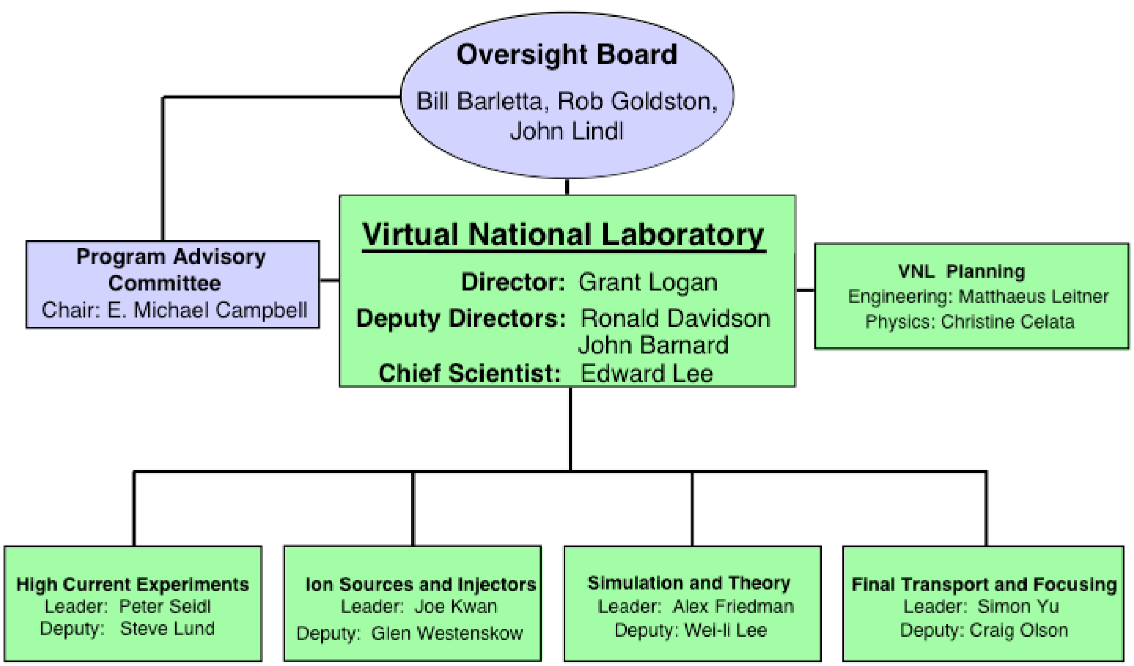


Figure 1-1. *The Heavy-Ion Fusion Virtual National Laboratory incorporates significant efforts at three laboratories—besides the AFRD fusion program whose achievements are reported here, Lawrence Livermore National Laboratory and Princeton Plasma Physics Laboratory play major roles.*

In the past year, our accomplishments included:

- Completing experiments on merging multiple beamlets for compact, high current heavy-ion injectors (work performed in the STS, a VNL facility at LLNL).
- Exploring electron cloud effects in transporting a high current beam in magnetic quadrupoles (in the HCX, a VNL facility at LBNL).
- Initiating a new heavy-ion beam experiment for longitudinal and radial compression of intense heavy ion beams in a neutralizing plasma background (in the NDCX, a new VNL facility at LBNL).

The HIF-VNL has also made progress on multi-species simulation codes to model intense heavy ion beams interacting with electron clouds and plasmas. (As you will see in this chapter, advanced simulation is a running theme in many of our efforts, and has spinoff benefits for other fields.)

We have also invented a novel accelerator, called the Traveling Wave Accelerator or TWA, that is especially suited to producing intense heavy ion beams with short (sub-microsecond) pulses. If the success promised by modeling and initial experimentation continues, the TWA could revolutionize the cost-effectiveness of accelerators that reach the parameter space we need.

The new experiments, modeling tools, and accelerator development came in response to a request that we redirect the heavy ion fusion program towards near term High Energy Density Physics (HEDP) research. The request came from the DOE Office of Science Director, the Office of Fusion Energy Science Director, and the White House Executive Office of Management and Budget.

Accordingly, have chosen a set of new experiments and research thrust areas that would enable two key achievements. Within five years, if funding is maintained, we will be able to heat targets to 1 eV. This will enable us to study the properties of warm dense matter--in particular, strongly-coupled plasmas at 0.01 to 0.1 times solid density, a frontier physics area within HEDP.

Pursuit of this five-year objective in HEDP has resulted in many innovations that will ultimately benefit heavy-ion fusion energy as well. These include neutralized beam compression and focusing, which hold the promise of greatly improving the stage between accelerator and target chamber in a fusion power plant, and the TWA, which may lead to compact, low-cost modular linac drivers.

Planned Science Campaigns

In response to constrained budgets, we are shutting down the STS facility at LLNL in mid FY05. With STS shut down, and if funding can be maintained at the FY05 level ($10M/yr for the VNL), we can support two integrated science campaigns with experiments and modeling.

1. Neutralized beam compression and focusing: Determine limits to neutralized beam longitudinal compression to short pulses and focusing in neutralizing background plasma. Carried out in a series of NDCX experiments (1A, 1B, 1C) at LBNL.
2. High brightness beam transport: Develop predictive capability for intense beam transport, including gas and electron cloud effects. Carried out primarily on the HCX facility at LBNL.

…and also support research in several critical thrust areas:

- Development of advanced theory and simulation tools for intense beams.
- Development of innovative short pulse sources and an injector to improve HEDP experimental capabilities.
- Design of unique beam-heated targets for HEDP.

The rest of this chapter gives selected highlights in six main areas of the LBNL Fusion Program: sources and injectors; high brightness beam transport; neutralization and beam compression; the TWA; and theory and advanced simulation. A concluding section takes a look at the road ahead for our HEDP research. For further in-depth reading on various topics, a publications list is appended to the chapter, with links to full-text versions of 11 selected publications in the refereed literature.

Source / Injector Highlights

Heavy ion fusion requires ion beams that have both high current and high brightness. In today's HIF experiments using hot plate contact ionization sources, the typical ion current density at the ion source is about 7 mA/cm^2. In the STS facility at LLNL, we have developed $argon^{+1}$ plasma sources with over 100 mA/cm^2 in small beamlets of ~ 2 mm diameter.

We have recently merged 119 of these high current beamlets together into a single high current composite beam (Figure 1-2) to show how future heavy-ion injectors with such "merging beamlets" architectures can be made more compact than was previously envisioned. So far, the measured beam current agrees with WARP particle simulations showing no significant beam loss.

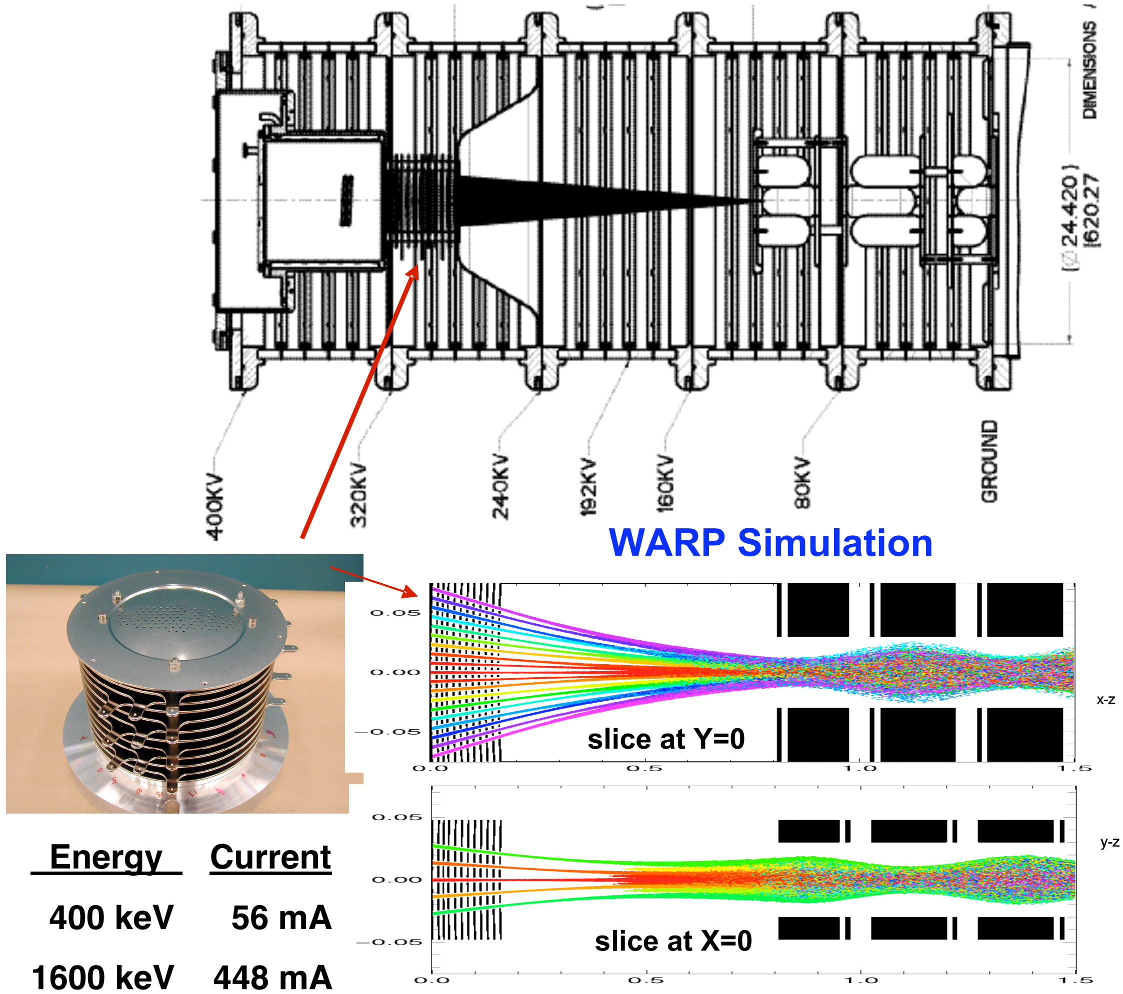


Figure 1-2. *The STS-500 has successfully merged 119 high current density beamlets into a single high-current beam. Measured beam loss agrees thus far with WARP simulations.*

High Brightness Beam Transport Highlights

The High Current Experiment or HCX (Figure 1-3) has studied high current beam transport in both electric and magnetic quadrupoles. In particular, negligible emittance growth has been observed in electrostatic transport where the beam filled 80% of the aperture (which is the maximum excursion of the beam envelope).

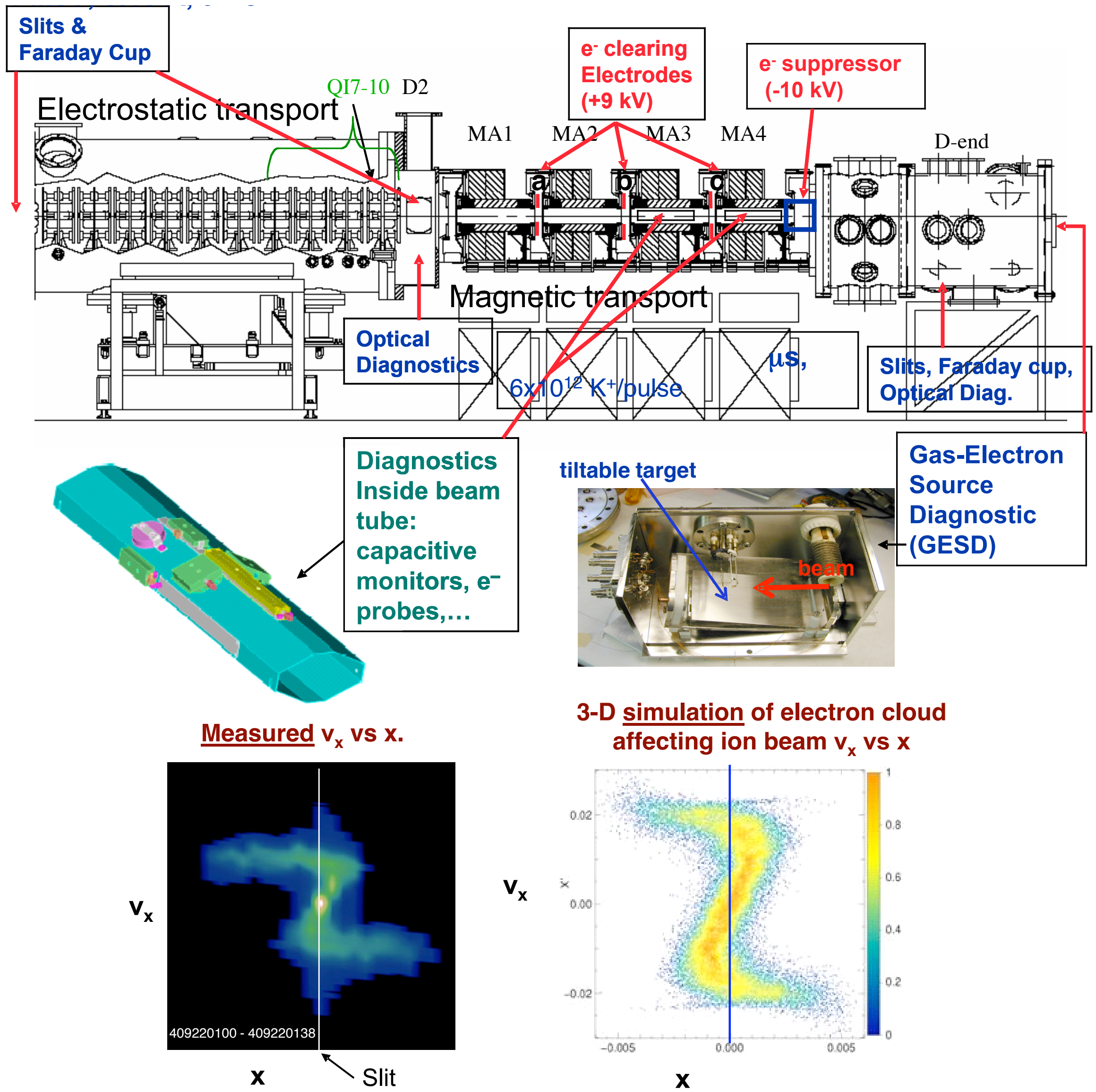


Figure 1-3. Layout of the HCX (elevation view). Some of the 15 diagnostic systems are indicated. There are electron clearing electrodes between each of the four magnetic quadrupoles, and an electron suppressor electrode at the end, to provide experimental control of electron cloud density levels. Diagnostics in the bore of the last two magnetic quadrupoles are sensitive to secondary electrons and ions that may perturb the beam distribution. Simulations (bottom of figure) *successfully model beam phase space distortions in the beam after traversing the four magnetic quadrupoles.*

Experiments involving transport through four pulsed quadrupole magnets (Figure 1-3) began in May 2003, especially to study gas and electron effects. Simulations using both envelope and discrete-particle WARP models are guiding the experiments, which require matching into a magnetic quadrupole lattice that has a half-period significantly different from that of the upstream electrostatic transport line.

Work in progress includes use of electron clearing electrodes, a variety of new diagnostics, in particular, use of optical imaging of the whole beam cross-section using fast scintillators. When the electron clearing and suppression voltages are turned off, so that electrons can stream into the magnetic quadrupoles from the end, 3-D WARP simulations with a novel large timestep electron mover successfully model the Z-shaped distortions of the exiting ion beam Vx-x phase space (bottom of Figure 1-3). *This world-leading multi-species modeling capability is key to a predictive capability for electron cloud effects in any high intensity accelerato*r.

Neutralization and Beam Compression Highlights

The first phase (1A) of the new HIF-VNL experimental facility, called the Neutralized Drift Compression eXperiment (NDCX-1A), began operation in December 2004. This facility (Figure 1-4) will be used to study the physics limits of longitudinal compression of intense heavy ion beams that are neutralized with a pre-formed background plasma. (The purpose of the background plasma is to eliminate the strong beam space charge forces that would otherwise resist compression.) This new experiment, the first of a series of NDCX experiments, was motivated by the DOE request to develop new capabilities for HEDP within five years.

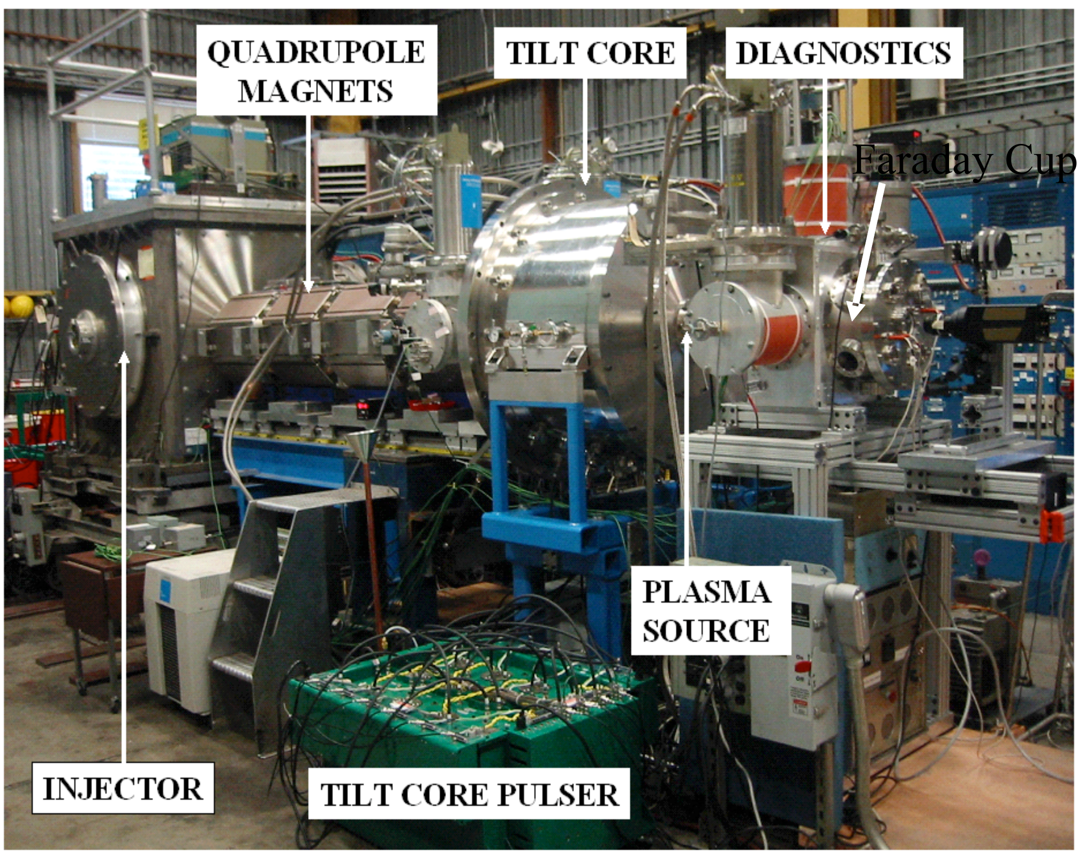


Figure 1-4. *The new NDCX-1A facility began operation in December 2005. The facility utilizes the 25-mA, 255 keV beam from the previous NTX experiment, together with an induction "tilt" core, to induce a velocity ramp to compress the beam. There is also a longer plasma-filled drift tube between the tilt core and the end diagnostics, compared to NTX.*

One year ago, we calculated that heavy-ion-heated HEDP targets of a few microns' thickness (equal to the range of our MeV ion beams) would hydro-expand in a few ns at 1 eV temperature. Therefore we needed a way to get short pulses (a few ns instead of the few μs we had previously). Simulations using the LSP particle-in-cell code showed that we could get ns pulses by adding a velocity ramp to a beam so it longitudinally drift-compresses in a neutralizing plasma background. Theory and simulations also showed that beam plasma instabilities should not limit on the achievable beam pulse compressions.

These new ideas and simulations led to the construction of NDCX-1A in FY04 by adding an existing induction acceleration module and a longer neutralizing plasma drift tube to the end of the former Neutralized Transport Experiment (NTX). The induction tilt core adds a velocity ramp from the head to the tail of a selected 250 to 500 ns portion of the 25 mA , 250 kV NTX beam. The ramp is applied with a specially-shaped induction drive pulse of 100 kV amplitude. The rear of the selected beam section catches up with the head particles in a 1 meter drift distance that is pre-filled with a background plasma confined in a weak solenoid magnetic field.

Figure 1-5 shows a series of progressively shorter pulse widths achieved in NDCX 1A over the last few months of initial operation. Such rapid and dramatic progress shows what we are looking for in these experiments. For *neutralized ion beams, velocity tilt may revolutionize high peak power accelerators* in a manner analogous to the role frequency chirp played in CPA lasers.

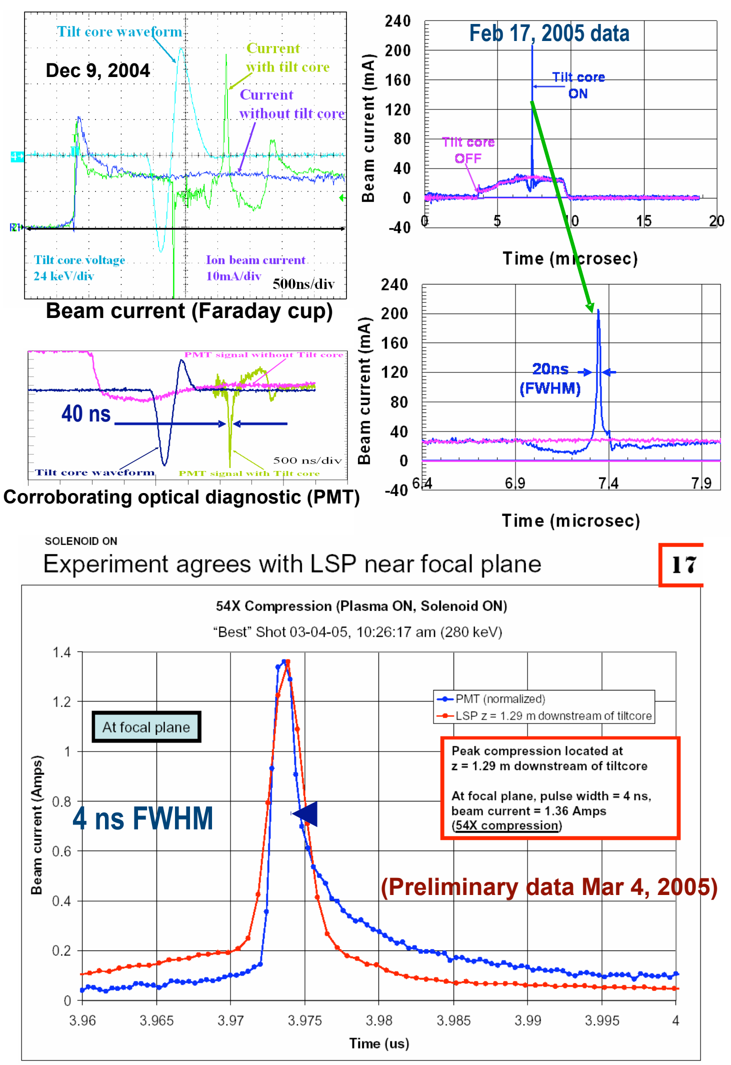
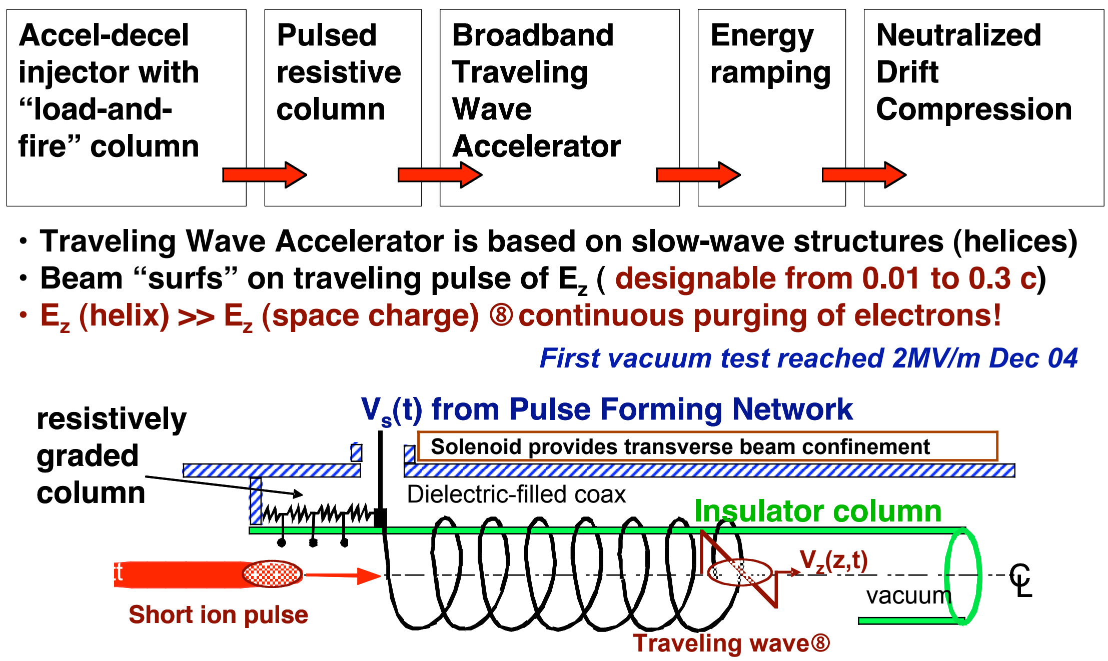


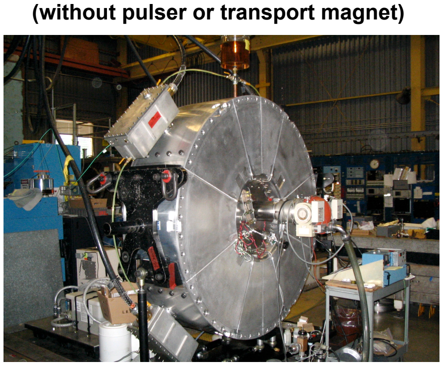
Figure 1-5. *Preliminary results on longitudinal drift compression in the NDCX 1A: over a period of three months of initial operation, minimum compressed pulse widths, starting with a 200 ns selected portion of a 255 kV beam, progress from 40 ns to 4 ns minimum pulse widths.*

A NEW ACCELERATOR INVENTED FOR ION-DRIVEN HEDP

In October 2004, LBNL hosted an HIF-VNL Workshop on Accelerator-Driven HEDP attended by accelerator specialists from LBNL, SLAC, ANL, and FNAL. They explored different ways to meet a common HEDP requirement: accelerate 10^{13} Ne^{+1} ions to 20 MeV and deliver them to a 1 mm focus on an HEDP target within 1 ns pulse width. Multi-beam induction, drift tube, and RF linacs with and without an accumulator/ stacker ring were considered, along with one totally new concept (Figure 1-6): a traveling wave helical-pulse line concept that we call the TWA for short.



Induction Module for the Dual-Axis Radiographic Hydrotest Facility (DARHT:
0.4 V·s (200kVx2μs)
~10,000 kg, 1 M$
(without pulser or transport magnet)



Traveling Wave Helix Accelerator No-beam test module (LBNL, Dec 04)
0.4 V·s (2MVx0.2μs)
~40 kg, 10 K$
(without pulser or transport magnet)

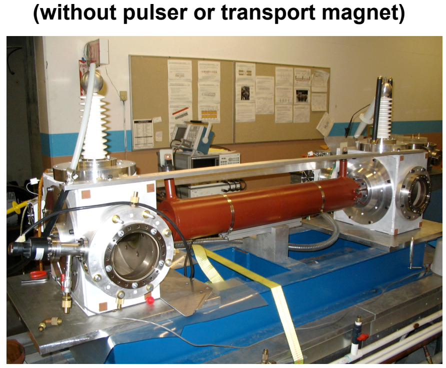


***Figure 1-6**. Top: Schematic of the TWA concept. Bottom: Comparison of two devices to couple pulsed power into a high current beam: the DARHT induction module (bottom left), and a 1 m long TWA test module that gives the same total volt-second product for beam acceleration. The TWA may ultimately prove to have a cost per volt as little as 1% that of a conventional induction linac (itself a relatively inexpensive type of accelerator), with obvious benefits for the cost-effectiveness of both HEDP experiments and heavy-ion fusion energy.*

Advanced Theory and Simulation Tools

Most of our simulation and theory work has already been mentioned as an integral part of the science campaigns discussed above. Here, we describe research aimed at the development of computational and theoretical tools in preparation for known upcoming needs, along with studies in anticipation of future science campaigns.

Electron Effects

One of the key issues is the electron-cloud effect. An initial comparison of simulation with experiment was the final FY04 milestone for the High Brightness campaign, as described in the report submitted to the Office of Fusion Energy Sciences at that time. Then we completed development of an "interpolated" drift-kinetic algorithm in WARP3D for magnetized electron motion that reverts to a direct orbit calculation in regions of weak magnetic field, and this algorithm went into production use; this was the FY05 first-quarter milestone.

Most elements of the roadmap for self-consistent modeling of electron effects were implemented during FY04 and early FY05 (see Figure 1-7).

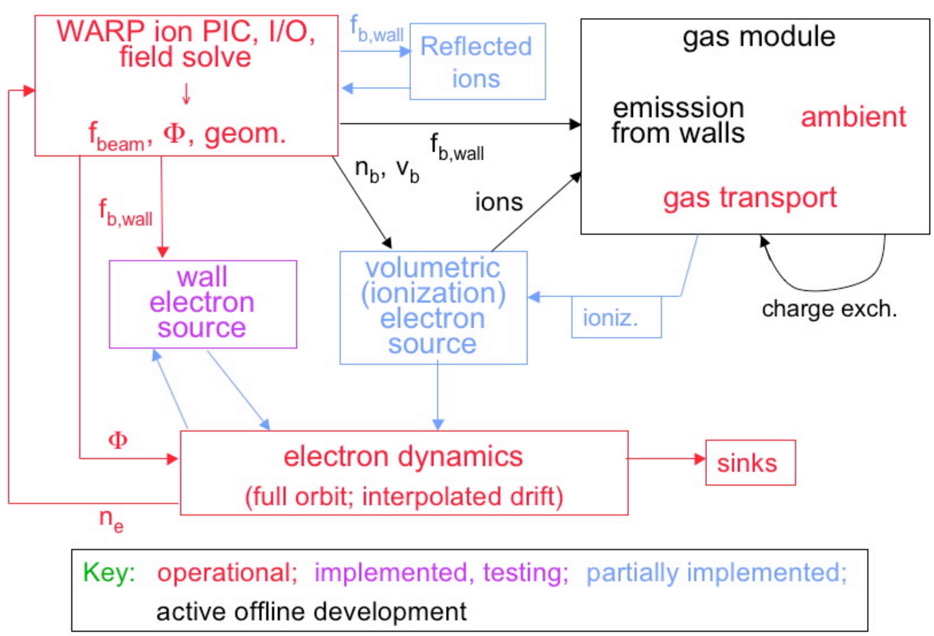


Figure 1-7. Roadmap for developing self-consistent modeling of electron and gas cloud effects in high intensity ion accelerators. This work has been published, was presented as an invited talk at the 2004 American Physical Society-Division of Physics of Plasma meeting, and will be presented as an invited talk at the 2005 Particle Accelerator Conference.

Our novel integration of Adaptive Mesh Refinement (AMR), a technique that concentrates grid resolution where it is most needed, into WARP has proved critical to the injector modeling effort. Agreement with experiment is excellent, and it is likely that this technique will be useful and essential in other such calculations, especially in injectors, in many types of accelerators. Papers on the AMR technique and its use have been published.

Our modeling of integrated experiments incorporating acceleration, compression, and focusing has shifted to nearer-term HEDP systems. Final WARP3D studies of an Integrated Beam Experiment (IBX) modeled after an IFE driver were carried out in FY04. A side benefit from this work is a clearer understanding of how a diode can launch a "matched" beam head, even though the transverse space charge force there is much less than in the body of the beam.

Our capabilities for analysis of beam phase space data, and synthesis of particle distributions from experimental data for use as the initial conditions of particle simulations, as described in last year's Field Work Proposal, were further refined and exercised. We extended the synthesis technique to the case of the optical-slit diagnostic, and carried out simulations using the initial conditions so obtained.

We carried out simulations of the modular solenoid approach to an ion driver, using the LSP code. Considerable analysis was carried out of final-focus scaling, gas effects, and other aspects of this novel concept. A report on key aspects of solenoids fields is in preparation, covering such topics as cross talk among parallel channels, tilted magnets, magnetic field in acceleration gaps and induction cores, periodic lattices, and global return flux of a system.

Plans for High Energy Density Physics

Assuming the NDCX experiments validate the possibility of compressing intense ion beams to 1 ns and focusing them, Figure 1-8 shows a unique approach we plan to take to contribute to high energy density physics within the next five years: uniform isochoric heating of thin targets using ~ 1 MeV/amu ions at the Bragg peak in dE/dx.

LBNL is supporting this work through the Laboratory-Directed Research and Development program to assess potential ion-driven HEDP targets and develop appropriate fast diagnostics.

Because of severe budget constraints and competition with lasers for HEDP studies, we need to build an accelerator capable of driving HEDP experiments in about five years for roughly the price of a table-top CPA laser. Of all the concepts we have studied so far, the TWA looks to be the most promising and affordable.

Figure 1-9 depicts an upgrade of the NDCX, called NDCX-II, that would cost about $5M in incremental hardware if based on the TWA. We plan a series of tests of the TWA concept as part of the current NDCX program. A decision to upgrade to NDCX-II could be made at the end of FY07, if the NDCX pulse compression experiments and the TWA tests are successful, and if current funding levels are maintained.

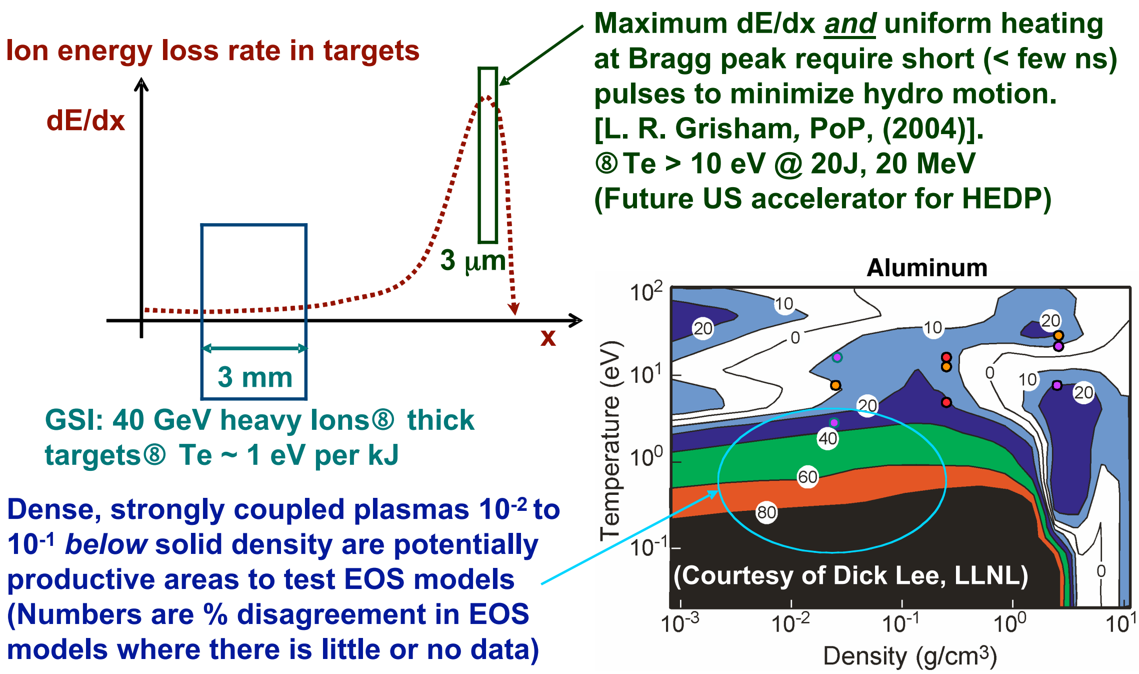


Figure 1-8. *The energy deposition of fast ions as a function of distance into the target (dE/dx) exhibits a sharp rise called the Bragg peak that typically occurs where the ion speed matches the orbital velocity of bound electrons. We propose to use ions with energy just above the Bragg peak so that both deposition and uniformity can be maximized.* Above, lower right corner*: We plan to apply this technique to thin targets at one to ten percent of solid density, a regime of HEDP where there is little or no data, and where we can best discriminate among the predictions of various equation-of-state models.*

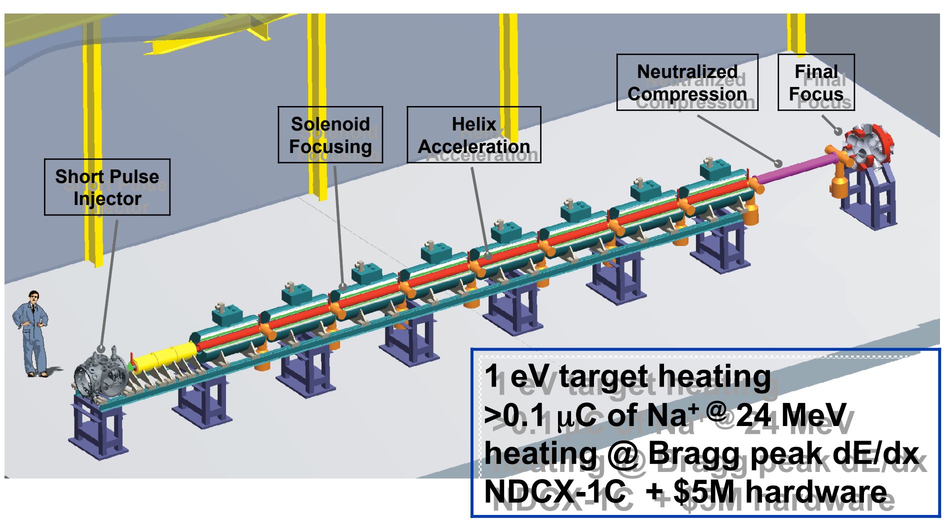


Figure 1-9. *A conceptual design for NDCX-II, an upgrade of NDCX-1C adding a 20 MeV TWA accelerator section. NDCX-II would provide proof-of-principle for accelerator-driven HEDP with a capability of heating single targets to 1 eV. Further upgrades for higher pulse rates, a beam switchyard with multiple experimental chambers, and laser driven HEDP diagnostics would be required to constitute an LBNL HEDP user facility.*

Featured Publications

These papers were chosen as exemplary descriptions of important aspects of our work. All were all published, or are under consideration, by refereed journals. The links take you to full text in the best version available to us.

Logan, G.; Bieniosek, F.; Celata, C.; Henestroza, E.; Kwan, J.; Lee, E.P.; Leitner, M.: Roy, P.; Seidl, P.A.; Eylon, S.; Vay, J-L.; Waldron, W.; Yu, S.; Barnard, J.; Callahan, D.; Cohen, R.; Friedman, A.; Grote, D.; Kireeff Covo, M.; Meier, W. R.; Molvik, A.; Lund, S.; Davidson, R.; Efthimion, P.; Gilson, E.; Grisham, L.; Kaganovich, I.; Qin, H.; Startsev, E.; Rose, D.; Welch, D.; Olson, C.; Kishek, R.; O'Shea, P.; Haber, I.; and Prost, L., "Overview of US heavy ion fusion research," in *Proceedings* of the 20th International Atomic Energy Agency Fusion Energy Conference, Nuclear Fusion **45**, 2 (2005); LBNL-55963. http://www.iop.org/EJ/article/0029-5515/45/2/006/nf5_2_006.pdf

Roy; P.K.; S.S. Yu; S. Eylon; E. Henestroza; A. Anders; F.M. Bieniosek; W.G. Greenway; B.G. Logan; W.L. Waldron; D.L. Vanecek; D.R. Welch; D.V. Rose; R.C. Davidson; P.C. Efthimion; E.P. Gilson; A.B. Sefkow; and W.M. Sharp, "Results on intense beam focusing and neutralization from the neutralized beam experiment," presented at the American Physical Society, Division of Plasma Physics meeting (Albuquerque, NM, October 2003), Physics of Plasmas **11**, 2890-2898 (2004); LBNL-53572.

Welch, D.R.; Rose, D.V.; Yu, S.S.; Barnard, J.J., and Olson, C.L., "Simulations of neutralized final focus," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004); LBNL-56921.

Molvik, A.W.; Cohen, R.H.; Friedman, A.; Kireeff Covo, M.; Lund, S.M.; Westenskow, G.; Bieniosek, F.M.; Eylon, S.; Faltens, A.; Henestroza, E.; Kwan, J.W., Prost, L.; Roy, P.K. Seidl, P.A.; Vay, J-L; and Yu, S., "Experimental studies of electrons in a heavy-ion beam," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004); LBNL-55237.

Cohen, R. H.; Friedman, A.; Kireeff Covo, M.; Lund, S.M.; Molvik, A.W.; Bieniosek, F.M.; Seidl, P.A.; Vay, J-L.; Stoltz, P.; and Veitzer, S., "Simulating electron clouds in heavy-ion accelerators," Phys. Plasmas, in press (May 2005), LBNL-57320.

Kwan, J.W.; Grote; D.P.; and Westenskow, G.A., "High current density beamlets from an rf argon source for heavy ion fusion applications," Rev. Sci. Instrum. 75, 1838-1840 (2004), LBNL-53647.

Vay, J-L; Colella, P.; McCorquodale, P.; Serafini, D.; Van Straalen, B.; Friedman, A.; Grote, D.P.; Adam, J-C.; and H'eron, A.H., "Application of adaptive mesh refinement to particle-in-cell simulations of plasmas and beams," presented at the American Physical Society, Division of Plasma Physics meeting (Albuquerque, NM, October 2003); Phys. Plasmas **11**, 2928-2934 (2004), LBNL-53551.

Lee, E.P., "Solenoid transport for heavy ion fusion," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004); LBNL-55965.

Roy, P.K.; Yu, S.S.; Henestroza, E.; Eylon, S.; Shuman, D.B.; Ludvig, J.; Bieniosek, F.M.; Waldron, W.L.; Greenway, W.G.; Vanecek, D. L.; Hannink, R.; and Amezcua, M., "Electron beam diagnostic for space charge measurement of an ion beam," Rev. Sci. Instrum. **76**, 023301 (2005), LBNL-56392.
http://scitation.aip.org/getpdf/servlet/GetPDFServlet?filetype=pdf&id=RSINAK000076000002023301000001&idtype=cvips

Grisham, L.R.; Hahto, S.K.; Hahto, S.T.; Kwan, J.W.; and Leung, K.-N., "Experimental evaluation of a negative ion source for a heavy ion fusion negative driver," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004); LBNL-56914.

Qin, H.; Davidson, R.C.; Barnard, J.J.; and Lee, E.P., "Drift compression and final focus for intense heavy ion beams with non-periodic, time-dependent lattice," Physical Review Special Topics: Accelerators and Beams **7,** 10, p. 4201 (2004), LBNL-56917.
http://prst-ab.aps.org/pdf/PRSTAB/v7/i10/e104201?qid=3ffd642ed0761cb3&qseq=2&show=10

Full Publications List

A listing, in alphabetical order by first author, of papers published by the LBNL Fusion Program in fiscal 2004 through early calendar 2005. Asterisks designate papers associated with invited talks at major conferences.

Refereed Literature

* Barnard, J.J.; Bangerter, R.O.; Henestroza, E. Kaganovich, I.D.; Lee, E.P.; Logan, B.G.; Meier, W.; Rose, D.; Santhanam, P.; Sharp, W.; Welch, D.R.; and Yu, S.S., "A final focus model for heavy ion fusion driver system codes," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-55228.

Bieniosek, F.M.; Faltens, A.; Prost, L.; Roy, P.K.; Seidl, P.A.; Eylon, S.; Henestroza, E.; Waldron, W.; and Yu, S.S., "Experimental study of space-charge waves in intense heavy ion beams," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-55241.

Bieniosek, F.M.; Celata, C.M.; Henestroza, E.; Kwan, J.W.; Prost, L; Seidl, P.A.; Friedman, A.; Grote, D.P.; Lund, S.M.; and Haber, I., "2-MV electrostatic quadrupole injector for heavy-ion fusion," Physical Review Special Topics: Accelerators and Beams **8**, 010101 (2005). http://prst-ab.aps.org/pdf/PRSTAB/v8/i1/e010101, LBNL-56618.

*Bieniosek, F.M.; Faltens, A.; Prost, L.; Roy, P.K.; Seidl, P.A.; Eylon, S.; Henestroza, E.; Waldron, W.; and Yu, S.S., "Diagnostics for intense heavy ion beams," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-55969.

*Celata, C.M, "Scientific issues in future accelerators for heavy ion fusion," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-54472.

Celata, C.M; E.P. Lee; M. Leitner; B.G. Logan; J-L. Vay; W.L. Waldron; S.S. Yu; J.J, Barnard; R.H. Cohen; A. Friedman; D.P. Grote; A.M. Molvik; W.M. Sharp; D.V, Rose; D.R. Welch; R.C. Davidson; I.D. Kaganovich; H. Qin; and E.A. Startsev, "The Integrated Beam Experiment - A next step experiment for heavy ion fusion," in *Proceedings* of the Third International Conference on Inertial Fusion Science and Applications (Monterey, CA, September 2003), American Nuclear Society publication ISBN 089448-686-1 (2004), pp. 698 - 701), LBNL-52409.

Chung, M.; Gilson, E.P.; Davidson, R.C.; Efthimion, P.C.; Majeski, R.; and Startsev, E.A., "Laser-Induced fluorescence diagnostic of barium ions plasmas in the Paul trap simulator experiment," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004).

*Cohen, R.H.; Friedman, A.; Molvik, A.W.; Azevedo, A.; Furman, M.A.; Vay, J-L.; and Stoltz, P.; "Simulating Electron cloud effects in heavy-ion accelerators," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-56056.

*Cohen, R. H., Friedman, A., Lund, S. M., Molvik, A.W., Lee, E. P., Azevedo, T., Vay, J-L., Stoltz, P., and Veitzer, S., "Electron-cloud simulation and theory for high-current heavy-ion beams," Physical Review Special Topics: Accelerators and Beams **7**, 12, p. 4201 (2004), http://prst-ab.aps.org/abstract/PRSTAB/v7/i12/e124201, UCRL-JRNL-205555.

*Cohen, R. H., Friedman, A., Kireeff Covo, M., Lund, S. M., Molvik, A.W., Bieniosek, F. M., Seidl, P. A., Vay, J-L., Stoltz, P. and Veitzer, S., "Simulating electron clouds in heavy-ion accelerators," Phys. Plasmas, to be published (May 2005).

* Davidson, R.C., Kaganovich, I., Qin, H., Startsev, E.A., Welch, D.R., Rose, D.V., and Uhm, H.S., "Survey of collective instabilities and beam-plasma interactions for heavy ion beams," Physical Review Special Topics: Accelerators and Beams **7**, 11, p. 4801, http://prst-ab.aps.org/abstract/PRSTAB/v7/i11/e114801 (2004).

Davidson, R.C., "Korteweg-deVries equation for longitudinal disturbances in coasting charged particle beams,"Physical Review Special Topics: Accelerators and Beams **7**, 5, p. 4402 (2004), http://prst-ab.aps.org/abstract/PRSTAB/v7/i5/e054402.

Davidson, R.C., and E. A. Startsev, "Self-consistent Vlasov-Maxwell description of the longitudinal dynamics of intense charged particle beams," Physical Review Special Topics: Accelerators and Beams **7**, 2, p. 4401 (2004), http://prst-ab.aps.org/abstract/PRSTAB/v7/i2/e024401.

Debonnel, C.S.; Yu, S.S.; Peterson, P.F., "Progress towards a detailed TSUNAMI modeling of the heavy ion fusion modular point design," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-54599.

Efthimion, P.C.; Gilson, E.P.; Grisham, L.; Davidson, R. C. Davidson; Yu, S.S.; and Logan, B.G., "Development of a one-meter plasma source for heavy ion beam charge neutralization," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-56913.

Eylon, S.; Henestroza, E.; Roy, P.K.; and Yu, S.S., "Electron effects in the Neutralized Transport Experiment (NTX)," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-55156.

*Friedman, A., "Simulation of intense beams for heavy ion fusion," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-55964.

Friedman, A.; J.J. Barnard; F.M. Bieniosek; C.M. Celata; R.H. Cohen; R.C. Davidson; D.P. Grote; I. Haber; E. Henestroza; E.P. Lee; S.M. Lund; H. Qin; W.M. Sharp; E. Startsev; and J-L. Vay, "New capabilities for modeling intense beams in heavy ion fusion drivers," in Proceedings of the Third International Conference on Inertial Fusion Science and Applications (Monterey, CA, September 2003), American Nuclear Society publication ISBN 089448-686-1 (2004), pp. 689 – 693, LBNL-53933.

*E. P. Gilson, M. Chung, R. C. Davidson, P. C. Efthimion, R. Majeski, and E. A. Startsev "Simulation of long-distance beam propagation in the Paul trap simulator

experiment," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004).

Genoni, T.C.; Rose, D.V.; Welch, D.R.; and Lee, E.P., "Two-stream stability for a focusing charged particle beam," Physics of Plasmas **11**, 11 (November 2004), LBNL-56999.

Gilson, E.P.; Davidson, R.C.; Efthimion, P.C.; Majeski, R., "Paul trap simulator experiment to simulate intense beam propagation in alternating gradient transport systems," Phys. Rev. Lett. **92,** 155002 (2004).

Grisham, L.R.; Hahto, S.K.; Hahto, S.T.; Kwan, J.W.; and Leung, K.-N., "Experimental evaluation of a negative ion source for a heavy ion fusion negative driver," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-56914.

Grote, D.P., "Simulation of Integrated Beam Experiment design," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-55967.

Haber, I.; Bernal, S.; Kishek, R.A.; O'Shea, P.G.; Reiser, M.; Zou, Y.; Friedman, A.; Grote, D.P.; and Vay, J-L., "Measurement and simulation of the UMER beam in the source region," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-55967.

Hasegawa, J.; Yoshida, M.; Ogawa, M.; Oguri, Y.; Nakajima, M.; Horioka, K.; and Kwan, J.; "Influence of grid control on beam quality in laser ion source generating high current low-charged copper ions," in *Proceedings* of the Third International Conference on Inertial Fusion Science and Applications (Monterey, CA, September 2003), American Nuclear Society publication ISBN 089448-686-1 (2004), pp. 689 – 693, LBNL-54724.

Hahto, S.K.; Hahto, S.T.; Grisham, L.R.; Kwan, J.W.; Leung, K.-N.; and Saadatmand, K., "Negative ions for heavy ion fusion and semiconductor manufacturing applications," Review of Scientific Instruments **75**, 1799 (2004); LBNL-54804.

Henestroza, E.; Kwan, J.W.; Lee, E.P.; Yu, S.S.; Briggs, R.J., "Extraction and Acceleration of High Line Charge Density Beams," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-55153.

Henestroza, E; Eylon, S; Roy, PK; Yu, SS; Anders, A.; Bieniosek, F.M.; Greenway, W.G.; Logan, B.G.; MacGill, R.A.; Shuman, D.B.; Vanecek, D.L.; Waldron, W.L.; Sharp, W.M.; Houck, T.L.; Davidson, R.C.; Efthimion, P.C.; Gilson. E.P.; Sefkow, A.B.; Welch, D.R.; Rose, D.V.; and Olson, C.L., "Design and characterization of a neutralized-transport experiment for heavy-ion fusion," Physical Review Special Topics: Accelerators and Beams **7**, 8, p. 3501, (2004), http://prst-ab.aps.org/abstract/PRSTAB/v7/i8/e083501, LBNL-53928.

Hudson, S.R; Qin, H.; Davidson, R.C., "Chaotic particle trajectories in high-intensity finite-length charge bunches," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004).

*Kaganovich, I.D.; Startsev, E.A.; Davidson, R.C.; Kecskemiti, S.R; Bin-Nun, A.; Mueller, D.; Grisham, L.; Watson, R.L.; Horvat, V.; Zaharakis, K.E.; Peng, Y., "Ionization cross sections

for ion-atom collisions in high energy ion beams," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004).

Kaganovich, I.D; E. A. Startsev, R. C. Davidson and D. R. Welch, "Theory of ion beam pulse neutralization in a background plasma in a solenoidal magnetic field," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004).

Lee, W.W.; Davidson, R.C.; Startsev, E.A.; and Qin, H., "The electromagnetic Darwin model for intense charged particle beams," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004).

Leitner, M.A.; Celata, C.M.; Lee, E.P.; Logan, B.G.; Waldron, W.L.; and Barnard, J.J., "Options for an Integrated Beam Experiment," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-54596.

Lifschitz, A.F.; Maynard, G.; and Vay, J-V., "Dynamics of neutralized electrons and the focusability of intense ion beams in HIF accelerating structures," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-56915.

Logan, B. G.; Bieniosek, F.; Celata, C.M.; Henestroza, E.; Kwan, J.W.; Lee, E.P.; Leitner, M.; Roy, P. Seidl, P.A.; Eylon, S.; Vay, J-L.; Waldron, W.; Yu, S.S.; Barnard, J.J.; Callahan, D.; Cohen, R.C.; Friedman, A.; Grote, D.P.; Kireeff Covo, M.; Meier, W.R.; Molvik, A.; Lund, S.M.; Davidson, R.C.; Efthimion, P.; Gilson, E.; Grisham, L.; Kaganovich, I.; Qui, H.; Startsev, E.; Rose, D.; Welch, D.; Olson, C.L.; Kishek, R. A.; O'Shea, P.G; Haber, I.; and Prost, L., "Overview of US heavy-ion fusion progress and plans," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-56185.

Lund, S.M.; Grote, D.P.; Lee, E. P.; and Davidson, R.C., "Simulations of beam emittance growth from the collective relaxation of space-charge non-uniformities," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-55962.

Lund, S.M.; and Bukh, B, "Influence of conducting plate boundary conditions on the transverse envelope equations describing intense ion beam transport," Physical Review Special Topics: Accelerators and Beams **7**, 6, p. 4201 (2004), http://prst-ab.aps.org/abstract/PRSTAB/v7/i6/e064201, LBNL-53470.

Lund, S.M.; Bukh, B, "Stability properties of the transverse envelope equations describing intense ion beam transport," Physical Review Special Topics: Accelerators and Beams **7**, 2, p. 4801 (2004), http://prst-ab.aps.org/abstract/PRSTAB/v7/i2/e024801, LBNL-53469.

McCorquodale, P.; P. Colella; D.P. Grote; and J.-L. Vay, "A node-centered local refinement algorithum for Poisson's equation in complex geometries," J. Comput. Phys. **201,** 34-60 (2004).

Meier, W. R.; Logan, B.G., "Systems Analysis for Modular Versus Multi-Beam HIF Drivers," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-56916.

*Molvik, A.W.; Cohen, R.H.; Friedman, A.; Kireeff Covo, M.; Lund, S.M.; Westenskow, G.; Bieniosek, F.M.; Eylon, S.; Faltens, A.; Henestroza, E.; Kwan, J.W., Prost, L.; Roy, P.K. Seidl, P.A.; Vay, J-L; and Yu, S., "Experimental Studies of electrons in a heavy-ion beam," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-55237.

Molvik, A.W.; Kireeff Covo, M.; Bieniosek, F.M.; Prost, L.; Seidl, P.A.; Baca, D.; A. Coorey, A.; Sakumi, A. "Gas desorption and electron emission from 1 MeV potassium ion bombardment of stainless steel," Physical Review Special Topics - Accelerators and Beams **7**, 9, p. 3202 (2004), http://prst-ab.aps.org/abstract/PRSTAB/v7/i9/e093202; LLNL-UCRL-JRNL-203366, LBNL-55045.

Prost, L.R.; Bieniosek, F.M.; Celata, C.M.; Dugan, C.C.; Faltens, A.; Seidl. P.A.; Waldron, W.L.; Cohen, R.; Friedman, A.; Kireeff Covo, M.; Lund, S.M.; Molvik, A.W.; Haber, I., "Experimental Study of the Transport Limits of Intense Heavy Ion Beams in the HCX," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-55961.

*Qin, H.; Davidson, R.C.; Barnard, J.J.; Lee, E.P., "Drift Compression and Final Focus Options for Heavy Ion Fusion," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004).

Qin, H.; Davidson, R.C.; Barnard, J.J.; Lee, E.P., "Drift Compression and Final Focus for Intense Heavy Ion Beams with Non-periodic, Time-Dependent Lattice," Physical Review Special Topics on Accelerators and Beams **7,** 10, p. 4201 (2004), http://prst-ab.aps.org/abstract/PRSTAB/v7/i10/e104201, LBNL-56917.

Roy, P.K.; Yu, S.S.; Henestroza, E.; Eylon, S.; Shuman, D.B.; Ludvig, J.; Bieniosek, F.M.; Waldron, W.L.; Greenway, W.G.; Vanecek, D. L.; Hannink, R.; Amezcua, M., "Electron beam diagnostic for space charge measurement of an ion beam," Review of Scientific Instruments **76**, 023301 (2005), LBNL-56392.

Roy, P.K.; Yu, S.S.; Eylon, S.; Henestroza, E.; Anders, A.; Bieniosek, F.M.; Greenway, W.G.; Logan, B.G.; Waldron, W.L.; Shuman, D.B.; Vanecek, D.L.; Welch, D.R.; Rose, D.V.; Davidson, R.C.; Efthimion, P.C.; Gilson, E.P.; Sefkow, A.B.; Sharp, W.M., "Neutralized Transport Experiment," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-55157.

Roy, P.K.; Yu, S.S.; Eylon, S.; Henestroza, E.; Ludvig, J. Shuman, D.B.; Greenway, W.G.; Vanecek, D.L., "Study of a Non Intercepting Ion Beam Diagnostic for Beam Density Profile," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-55232.

Roy; P.K.; S. S. Yu; S. Eylon; E. Henestroza; A. Anders; F. M. Bieniosek; W. G. Greenway; B. G. Logan; W. L. Waldron; D. L. Vanecek; D.R. Welch; D. V. Rose; R. C. Davidson; P. C. Efthimion; E. P. Gilson; A.B. Sefkow; and W. M. Sharp, "Results on intense beam focusing and neutralization from the neutralized beam experiment," Phys. Plasmas, **11**, 2890-2898, (2004), LBNL-53572.

Sabbi, G.; Faltens, A.; Lietzke, A.; Seidl, P.A.; Lund, S.; Martovetsky, N.; Gung, C.; Minervini, J.; Schultz, J.; Meinke, R., "Development of Superconduction Magnet Systems for HIF," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-5691**8.**

Seidl. P.A.; Baca, D.; Ritchie, G.; Sabbi, G.; Shuman, D.; Kireeff Covo, M.; and Molvik, A.W., "Magnetic field measurements of quadrupoles in the High Current Experiment," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-56919.

Sharp, W.M.; Barnard, J.J.; Grote, D.P.; Celata, C.M.; Yu, S.S.; Rose, D.V.; Welch, D.R., "Simulation of drift-compression for heavy-ion-fusion," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004),, LBNL-54474.

Sharp, W.M.; D. A. Callahan, M. Tabak, S. S. Yu, P.F. Petersen, D.V. Rose, D.R. Welch, "Chamber-transport simulation results for heavy-ion fusion", Nucl. Fusion 44, S221-S227, (2004).

Sharp, W.M.; Callahan, D.A.; Tabak, M.; Yu, S.S.; Petersen, P.F.; Rose, D.V.; Welch, D.R., "Chamber-transport simulation results for heavy-ion fusion," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), pp. 684 -688 (2004).

Sonnendrucker, E.; Filbet, F.; Friedman, A.; Outdet, E.; Vay, J-L., "Vlasov simulations of beams with a moving grid," Comput. Phys. Commun., in press, (2004), LBNL-53926.

*Startsev, E.A.; Davidson, R.C.; Qin, H., "Three- dimensional simulation studies of temperature anisotropy instability in intense charged particle beams," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004).

Startsev, E. A.; Davidson, R.C., "Analytical solutions for the nonlinear drift compression (expansion) of intense charged particle beams," New Journal of Physics **6,** 141 (2004).

Stoltz, P.H.; Veitzer, S.A.; Cohen, R.; Molvik, A.; Vay J-L., "Electron effects due to grazing collisions between heavy ions and walls," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-56920.

Stoltz, P.; Veitzer, S.A; Cohen, R.; Molvik, A. W.; Vay, J-L., "Simulation of heavy-ion induced electron yield at grazing incidence," Physical Review Special Topics - Accelerators and Beams **7**, 10, pp. 3201-1 (2004), http://prst-ab.aps.org/abstract/PRSTAB/v7/i10/e103201; UCRL-JRNL-207387

Thoma, C.; Welch, D.R.; Yu, S.S.; Henestroza, E.; Roy, P.K.; Eylon, S.; Gilson, E.P., "Comparison of experimental data and 3D simulations of ion beam neutralization from the Neutralized Transport Experiment," Submitted to Physics of Plasmas, 9/30/2004, LBNL-56401.

H. S. Uhm and R. C Davidson, "Effects of electron collisions on the resistive hose instability in intense charged particle beams propagating through background plasma," Physical Review Special Topics on Accelerators and Beams **6,** 3, p. 4204 (2003),
http://prst-ab.aps.org/abstract/PRSTAB/v6/i3/e034204.

Vay, J-L.; Colella, P; Kwan, J.W.; McCorqudale, P; Serafini, D.; Friedman, A.; Grote, D.P; Westenskow, G.; Adam, J-C.; Heron, A.; Haber, I., "Application of adaptive mesh refinement to PIC simulations in inertial fusion," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-54486.

Vay, J-L; Colella, P.; McCorquodale, P.; Serafini, D.; Van Straalen, B.; Friedman, A.; Grote, D.P.; Adam, J-C.; H'eron, A.H. "Application of adaptive mesh refinement to particle-in-cell simulations of plasmas and beams," Phys. Plasmas **11**, 2928-2934, (2004), LBNL-53551.

Vay, J-L.; Colella, P.; Friedman, A.; Grote, D.P.; McCorquodale, P.; and Serafini, D.B. "Implementations of mesh refinement schemes for particle-in-cell plasma simulations," Comput. Phys. Commun., in press, (2004), LBNL-54046.

Welch, D.R.; Rose, D.V.; Yu, S.S.; Barnard, J.J., Olson, C.L., "Simulations of neutralized final focus," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-56921.

Westenskow, G.A.; Grote, D.P.; Halaxa, E.; Kwan, J.W.; Kapica, J.; Waldron, W.L., "RF Plasma source for heavy ion fusion," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-54769.

Westenskow, G.A.; Grote, D.P.; Kwan, J.W.; Hall, R.; Kapica, J.; Waldron, W., "High Current Ion Source Development for Heavy Ion Fusion," Inertial Fusion Science and Applications 2003 Proceedings, p, 702-705 (2004), LBNL-52385.

*Yu, S.S.; Abbott, R.P.; Bangerter, R.O.; Barnard, J.J.; Briggs, R.J.; Callahan, D.; Celata, C.M.; Davidson, R.; Debonnel, C.S.; Faltens, A.; Friedman, A.; Grote, D.P.; Henestroza, E.; Kaganovich, I.; Kwan, J.W.; Heitzenroeder, P.; Latkowski, J.F.; Peterson, P.F.; Rose, D.; Sabbi, G-L.; Seidl, P.A.; Sharp, W.M.; Welch, D.R., "Heavy ion fusion driver point designs," in *Proceedings* of the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004), Nucl. Instrum. Meth. A, in press (2004), LBNL-55238.

Yu, S.S.; Barnard, J.J.; Briggs, R.J.; Callahan, D.; Celata, C.M.; Davidson, R.; Debonnel, C.S.; Friedman, A.; Henestroza, E.; Kaganovich, I.; Kwan, J.W.; Lee, E.P.; Leitner, M.; Logan, B.G.; Meier, W.; Peterson, P.F.; Reginato, L.; Rose, D.; Sabbi, G-L; Waldron, W.; Welch, D.R., "The modular approach to heavy ion fusion," 16th ANS Topical Meeting on the Technology of Fusion Energy (Madison, WI, September 14-16, 2004(, LBNL-56262 Abs.

Unrefereed Publications, Conference Proceedings, and LBNL Reports

Anderson, O., "Oscillations of mismatched beams in quadrupole channels," in *Proceedings* of the European Particle Accelerator Conference (Lucerne, Switzerland, July 5-9, 2004), LBNL-55528; see also "Mismatch oscillations in high-current accelerators" at http://accelconf.web.cern.ch/accelconf/e04/PAPERS/WEPLT146.PDF

Barnard, J.J., and Lund, S.M., "Intense beam physics: space charge, halos, and related topics," course taught at the US Particle Accelerator School (Williamsburg VA, Jan. 18-30, 2004), LBNL-54926.

Bhatt, R.; Chen, C.; Henestroza, E.; and Zhou, J., "The path to ideal high-intensity beams in alternating-gradient focusing systems," presented at the 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004); LBNL-55240.

*Celata, C.M., "Heavy ion fusion-using heavy ions to make electricity," in *Proceedings* of the 20th Winter Workshop on Nuclear Dynamics (Trelawny Beach, Jamaica, March 15-20, 2004), LBNL-55145.

Logan, B.G., "Heavy-Ion Fusion Virtual National Laboratory (HIF-VNL)," HIF-VNL Program Advisory Committee Review (LBNL, Berkeley, CA, August 4, 2004); published as internal technical note only.

Logan, B.G.; Bangerter, R.O.; Callahan, D.A.; Tabak, M.; Roth, M.; Perkins, L.J.; and Caporaso, G., "Assessment of potential for ion driven fast ignition," Fusion Energy Sciences Advisory Committee Meeting (Germantown, MD, Dec. 12-14, 2004), LBNL-57122.

Logan, B.G., "Heavy-Ion Fusion Virtual National Laboratory (HIF-VNL) co-coordinated heavy-ion research by LBNL, LLNL, PPPL," Director's Review of AFRD (LBNL, Berkeley CA, May 6, 2004); published as internal technical note only.

*Molvik, A. W.; Bieniosek, F.M.; Cohen, R.H.; Eylon, S.; Faltens, A.; Friedman, A.; Henestroza, E.; Kireeff Covo, M.; Kwan, J.W.; Lund, S.M.; Prost, L.; Roy, P.K.; Seidl, P.A.; Vay, J-L.; Westenskow, G.; and Yu, S., "Experimental studies of electron and gas sources in a heavy-ion beam," 31st International Committee on Future Accelerators (ICFA) Advanced Beam Dynamics Workshop on Electron- Cloud Effects (Napa, CA, April 19-22, 2004), LBNL-55046, UCRL-PRES-203920, and UCRL-CONF-207208.

Seidl, P.A.; Molvik, A.W.; Bieniosek, F.M.; Cohen, R.H.; Faltens, A.; Friedman, A.; Kireeff Covo, M.; Lund, S.M.; Prost, L.; and Vay, J-L., "Intense ion beam transport in magnetic quadrupoles: experiments on electron and gas effects," ICFA-HB2004, 33rd International Committee on Future Accelerators (ICFA) Advanced Beam Dynamics Workshop on High Intensity and High Brightness Hadron Beams (Bensheim, Germany, October 18-22, 2004), LBNL-56242.

Sharp, W.M.; Callahan, D.A.; Grote, D.P.; Tabak, M.; Celata, C.M.: Yu, S.S.; Rose, D.V.; and Welch, D.R., "Simulation of beam compression for heavy-ion fusion," poster presentation, 31st IEEE International Conference on Plasma Science (Baltimore, MD, June 28 - July 1, 2004), LBNL-55142 Abs.

Sonnendrucker, E.; Filbert, F.; Friedman, A.; Outdet, E.; and Vay, J-L., "Vlasov simulations of beams with a moving grid," 18th International Conference on the Numerical Simulation of Plasma (Cape Cod, MA) LBNL-53926.

H. S. Uhm and R. C. Davidson, "Effects of transverse conductivity on transverse instabilities in high-intensity ion beams," IEEE Transactions on Plasma Science **32,** 440 (2004).

Abstracts Without Accompanying Papers

Barnard, J.J.; Briggs, R.J.; Callahan, D.A.; Davidson, R.C.; Friedman, A.; Grisham, L.; Lee, E. P.; Lee, R.W.; Logan, B.G.; Marx, J.N.; Rose, D.V.; Sessler, A.M.; Staples, J.W.; Tabak, M.; Welch, D.R.; Wurtele, J.S.; and Yu, S.S., "Accelerators for studies of warm dense matter," presented at the 46th annual meeting, American Physical Society, Division of Plasma Physics Meeting (Savannah, GA, November 15-19, 2004).

Celata, C.M.; Bell, B.J.; Bieniosek, F.M.; Prost, L.; Seidl, P.A.; Friedman, A.; Grote, D.P., "Simulation results in support of the High Current Experiment," presented at the 46th annual meeting, American Physical Society, Division of Plasma Physics Meeting (Savannah, GA, November 15-19, 2004), LBNL-55947.

*Celata, C.M., "Using heavy ion beams to drive inertial fusion," presented at the 2004 spring meeting of the American Physical Society (Denver, CO, May 2, 2004), Bull. AM. Phys. Soc. **49**, 2, p. 100 (2004), LBNL-55143.

*Celata, C.M., "Accelerators to make electricity--an overview of heavy-ion fusion," presented to the Amer. Assoc. of Physics Teachers (Sacramento CA, July 30, 2004) LBNL-54792 Abs.

Kireeff Covo, M.; Molvik, A. W.; Cohen, R.; Friedman, A.; Lund, S. M.; Bieniosek, F.P. Seidl, P.; Vay, J-L.; Stoltz, P.; Veitzer, S., "Comparison of simulations with experiments on electron generation and accumulation in positively charged beams," Bull. Am. Phys. Soc. **49**, 93 (Nov. 2004).

Kwan, J.W.; Bieniosek, F.M.; Waldron, W.L.; Westenskow, G.A.; Grote, D.P.; and Halaxa, E., "A multi-beamlet high current injector for heavy ion fusion," " presented at the 46th annual meeting, American Physical Society, Division of Plasma Physics Meeting (Savannah, GA, November 15-19, 2004), LBNL-55946.

Leitner, M.A.; Anders, A.; Bieniosek, F.M.; Eylon, S.; Greenway, W. G.; Henestroza, E.; Logan, B.G.; Roy, P.K.; Shuman, D.B,; Vanecek, D.L.; Waldron, W.L.; Yu, S.S.; Rose, D.V.; Thoma, C.; Welch, D.R.; Davidson, R.C.; Efthimion, P.C.; Gilson, E.P.; Kaganovich, I.; Sefkow, A.B.; Barnard, J.J.; and Sharp. W.M., "The Neutralized Drift Compression Experiment," " presented at the 46th annual meeting, American Physical Society, Division of Plasma Physics Meeting (Savannah, GA, November 15-19, 2004), LBNL-55943 Abs.

Logan, B.G., "New physics directions for heavy-ion-driven high energy density physics and fusion energy," " presented at the 46th annual meeting, American Physical Society, Division of Plasma Physics Meeting (Savannah, GA, November 15-19, 2004), LBNL-56208.

Molvik, A.W.; Kireeff Covo, M.; Cohen, R.; Bieniosek, F.; and Seidl, P., "Measurements of electron generation and accumulation in positively charged heavy-ion beams," Bull. Am. Phys. Soc. **49**, 93 (Nov. 2004), UCRL-POST-207931.

Molvik, A.W.; Cohen, R.; Friedman, A.; Kireeff Covo, M.; Lund, S.M.; Bieniosek, F.; Seidl, P.; Vay, J-L., "Electrons and gas versus high brightness ion beams," presented at the 25th International Workshop on Physics of High Energy Density in Matter (Hirschegg, Austria, 2004), UCRL-PRES-209447.

Sharp, W.M.; Barnard, J.J.; Friedman, A.; Grote, D.P.; Celata, C.M.; Yu, S.S., "Modeling drift-compression for heavy-ion fusion," 46th Annual Meeting of the Division of Plasma Physics (APS-DPP'04), Savannah, GA, November, 15-19th, 2004, LBNL-56669 Abs.

Sharp, W.M.; Callahan, D.A.; Grote, D.P.; Tabak, M.; Celata, C.M.; Yu, S.S.; Rose, D.V.; and Welch, D.R., "Simulation of beam compression for heavy-ion fusion," poster presented at the 31st IEEE International Conference on Plasma Science (Baltimore, MD, June 28-July 1, 2004), LBNL-55142.

2. ALS ACCELERATOR PHYSICS

Reported by David Robin, Group Leader

Late in 1997 the Advanced Light Source, a major user facility that had been designed, built, and operated under the leadership of AFRD, became a division of the Laboratory in its own right. AFRD maintains an extensive and formally defined relationship with the ALS, providing it with accelerator physics both for day-to-day running and for enhancements. Development of user systems such as beamlines, the management and enhancement of the scientific program, support of the users, and (as of 1999) operation of the machine are among the responsibilities of the ALS.

The mission of the ALS is to support the users in doing outstanding science in a safe environment. To achieve the goals of this mission, the ALS Accelerator Physics Group plays several important roles. The first is to make certain that the ALS *provides high-quality beam in a reliable manner* to users. The second is to strive to understand and continually *improve the performance* of the facility, keeping it at the forefront of synchrotron radiation sources. The third role is to *ensure that machine upgrades are implemented smoothly* with minimal adverse impact to users. The fourth is to *study potential upgrades* to the facility that will enhance the capabilities and capacities of the ALS. Finally, the accelerator physics group *supports other accelerator projects* both inside and out of the laboratory as well as non-accelerator projects at the ALS. The group is committed to ensuring that it works in a safe environment.

Recent Machine Upgrades

With regard to our first role—providing high-quality beam in a reliable manner to users— the ALS realized several improvements in operation as compared with the previous year. We improved vertical beam size stability by better understanding the effects of the elliptically polarized undulators; increased the brightness (by as much as 40% as seen by users of the longer undulators) with a change in vertical tune; and observed great reductions in vertical beam noise thanks to the fast orbit feedback system, which completed its first full year of operation. Additionally, two new insertion devices came into operation and a third is being installed.

Vertical Beam Size Stability

An important improvement in operation came from understanding and minimizing the variation in the vertical beam size resulting from motion of the Elliptically Polarizing Undulators (EPUs). As the gap and the shift parameter and phase settings of the EPUs are changed, the beam size varies because of a skew quadrupole field in the EPUs. This is the normal way that EPU users change polarization, and some do it quite often, but the resulting beam size variation was unacceptable for some experiments at the other beamlines.

To reduce the beam size variations, grooves were machined in the EPU vacuum chambers and skew quadrupole trim coils were installed. These coils were then energized to compensate the skew quadrupole field using a feed-forward algorithm. The feed-forward tables were generated using beam-based measurements, particularly orbit response matrix analysis.

Ultimately, through a combination of modeling and extensive measurements (beam-based mechanical, and magnetic), the cause of the beam size variations was tracked down. The cause was a small but correlated tilt of the modules on which the magnetic blocks of the EPU are mounted. Changing the EPU phase caused about three microns of differential block motion. This problem will be corrected in future EPUs.

Higher Brightness

This year we increased the photon beam brightness seen by users when we began operating with smaller vertical beta functions in the insertion device straights. This was accomplished by increasing the vertical tune from 8.2 to 9.2, thus reducing the beta function from 3.65 m to 2.25 m in the straights. This increased brightness as much as 40% for some users (depending on the length of the insertion devices). In addition, to maximize the performance of individual beamlines and therefore the photon brightness delivered, three days at the end of our annual shutdown were dedicated to beam line alignment. During this time diagnostic orbit bumps were put in to determine the relative alignments of the storage ring and the beam lines.

Orbit Stability

This was the first year of routine operation with the fast orbit feedback system. The system is able to operate with an update rate of about 1.1 kHz. It complements the existing slow orbit feedback system. With an update rate of about 1 Hz, the older system alone was only capable of suppressing noise below 0.05 Hz, and the integrated steady state closed-orbit motion in the insertion-device straights, in the frequency range between 0.05 and 500 Hz, was below 2 microns in the vertical plane and about 4 microns in the horizontal plane.

Now, the rms orbit motion in the same frequency range has been reduced to less than 2 microns horizontally and less than 1 micron vertically. Furthermore, the suppression of residual transient orbit distortions caused by insertion device motion is significantly larger than the reduction in steady state orbit noise.

The fast orbit system has been extremely reliable, with availability significantly greater than 99%; it has caused a total accelerator downtime of only a couple of hours during its first year of operation.

New Insertion Devices

This past year three new insertion devices were installed in the storage ring. The first was the W11 wiggler, replacing W16. The new device is simultaneously used as a wiggler for protein crystallography and as a modulator for the femtosecond slicing experiment. The W16 wiggler was removed because its parameters did not allow optimized, simultaneous operation of these two experiments. An improved carbon filter assembly was designed and installed on the wiggler beamline, significantly reducing outgassing and thus the scrubbing time needed after vacuum work, as well as eliminating the need for annual carbon filter replacements.

The second insertion device installed in the storage ring was an elliptically polarizing undulator with 5 cm period. This EPU will be used for photoemission electron microscopy.

The third new insertion device of the year will be a first for the ALS. It is an in-vacuum undulator--the first in-vacuum device installed in the storage ring—and will serve as the radiator for the femtoslicing experiment. It is being installed as of this writing during a scheduled shutdown.

The minimum vacuum gap is about 5.2 mm. This is significantly smaller than the present minimum gap of 8.9 mm, and there was concern about impact upon the ring's performance--primarily beam lifetime and injection efficiency. The effect of the smaller gap on the performance of the ALS has been extensively modeled, and measurements have been performed using vertical scrapers to simulate the effect of the gaps. We found that with the vertical dispersion wave that we implemented some two years ago, the effect on the smaller gaps would be insignificant down to vertical apertures of about 5 mm. This would not have been the case in earlier years, when the beam size was controlled by linear coupling; then the lifetime was already being impacted by vertical gap sizes of about 9 mm.

Future Upgrades

The highest priority in the near term is the upgrade of the ALS operation to continuous ("Top-off") injection. Top-off will increase the time-averaged current (in our case, by approximately 100%), and beam stability should be much improved because the heat load on the accelerator vacuum chamber and (even more important) on beamline optics will remain constant instead of ramping with the beam current.

The scope of the Top-off project is to increase the energy of the injector for full energy injection; upgrade the radiation safety systems to allow for injection with the safety shutters open; and reduce the disturbance of the injection process on the storage ring beam. Over the past year, the Top-off project's cost, scope and schedule were fully developed, reviewed and approved, and funding was secured. The plan is to upgrade to full-energy injection in a mid 2006 shutdown. After the shutdown the ALS would slowly (over a year) transition to Top-off operation.

Also among the near-term plans is a quasiperiod long-period elliptically polarizing undulator for inelastic scattering experiments. This undulator will present more challenges than previous EPUs because it will will have stronger fields and could cause stronger perturbations of the beam dynamics. This year our tracking codes have been modified to include elliptically polarizing undulators, and the impact is being studied.

Longer-Term Upgrade Prospects

This past year the ALS went through an extensive strategic-planning exercise to find ways to stay on the cutting edge of synchrotron light sources over the next two decades. This of course includes further upgrades. One interesting possibility is a picosecond source, based on the concept put forward by A. Zholents of the Center for Beam Physics, and further explored in cooperation with our group.

By inserting crab cavities in two adjacent straight sections, we could trade increased vertical beam height for shorter pulses on the bend-magnet beamline located halfway between them. The result would be an exceedingly powerful source of (roughly) 1-ps pulses, creating opportunities for high-repetition-rate, ultrafast timing experiments. This next year we will study the feasibility of such a source and work with potential users to build the scientific case.

Non-ALS Accelerator Projects

In its final role, our group was effective in supporting non-ALS accelerator physics projects at the Laboratory. We continue to be involved in the electron optics design of an aberration-corrected photoemission microscope (PEEM-III) being built at the ALS. Members of the group also helped with the understanding and optimization of the PEP-II storage ring optics at the Stanford Linear Accelerator Center.

LDRD for a Cold Electron Source

Collaborating with the ALS and Engineering divisions and colleagues elsewhere in AFRD, we were involved in a feasibility study for of a source of electrons with a very small energy spread. The project was supported by the Laboratory-Directed Research and Development (LDRD) program; its goal is design and construction of a prototype. We anticipate a high brightness electron source in the 10 to 100 eV energy range with an effective source temperature (i.e., energy spread) of about 10 ueV, compared to the ~100 meV previously available. Such a "cold" beam will have a great impact on several applications, such as scanning electron microscopes, inverse photoemission spectroscopy, and electron interference experiments.

The key to this orders-of-magnitude improvement is a new technology: controlled ionization of cesium atoms in a way that carefully minimizes the effects of the Coulomb interaction, the main phenomenon behind the growth of emittance and energy spread. Presently, well into the first of the anticipated two years of the project, the overall design has been completed, the main components are already in house, and the experimental activity is about to begin producing ions.

Featured Publications

To give a fuller perspective on our activities, we chose the publications that best represent our accomplishments from the past year in support of the ALS. Clicking the link will bring up a copy in PDF format or take you to a Web site where it may be found.

J. Feng, E. Forest, A.A. MacDowell, M. Marcus, H. Padmore, S. Raoux, D. Robin, A. Scholl, R. Schlueter, P. Schmid, J. Stohr, W. Wan, D.H. Wei and Y. Wu, "An x-ray photoemission electron microscope using an electron mirror aberration corrector for the study of complex materials," Journal of Physics: Condensed Matter **17**, 16 (April 27, 2005) S1339-S1350; LBNL-55268.
http://www-library.lbl.gov/docs/LBNL/552/68/PDF/LBNL-55268.pdf
http://www.iop.org/EJ/abstract/-search=8809073.1/0953-8984/17/16/005

D. Robin, J. Krupnick, R. Schlueter, C. Steier, S. Marks, B. Wang, J. Zbasnik, R. Benjergerdes, A. Biocca, P. Bish, W. Brown, W. Byrne, J. Chen, W. Decking, J. DeVries, W.R. DeMarco, M. Fahmie, A. Geyer, J. Harkins, T. Henderson, J. Hinkson, E. Hoyer, D. Hull, S. Jacobson, J. McDonald, P. Molinari, R. Mueller, L. Nadolski, H. Nishimura, K. Nishimura, F. Ottens, J.A. Paterson, P. Pipersky, G. Portmann, A. Ritchie, S. Rossi, B. Salvant, T. Scarvie, A. Schmidt, J. Spring, C. Taylor, W. Thur, C. Timossi, and A Wandesforde, "Superbend upgrade of the Advanced Light Source," Nucl. Instrum. Meth. A **538**, 1-3 (11 February 2005), pp. 65-92; LBNL-52637 Journal.

Peter Schmid, Jun Feng, Howard Padmore, David Robin, Harald Rose, Ross Schlueter, and Weishi Wan, "Correction and alignment strategies for the beam separator of the photoemission electron microscope 3 (PEEM3)," Rev. Sci. Instrum. **76**, 023302 (February 2005); LBNL-55699.
http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=RSINAK000076000002023302000001&idtype=cvips&gifs=Yes

Hiroshi Nishimura, Glen Lambertson, Juris G. Kalnins, and Harvey Gould, "Feasibility of a synchrotron storage ring for neutral polar molecules," *Rev. Sci. Instrum.* **74**, 7 (2003), pp. 3271-8.

G. Portmann, J. Corbett, and A. Terebilo, "An accelerator control middle layer using MATLAB," in *Proceedings* of PCaPAC 2005, the 5th International Workshop On Personal Computers And Particle Accelerator Controls (22-25 March 2005, Hayama, Japan).

J. Safranek (SLAC) et al., "SPEAR3 commissioning" (*invited oral*), in *Proceedings* of the Third Asian Particle Accelerator Conference (Gyeongju, Korea, 22-26 March 2005).

F. Sannibale, M. Abo-Bakr, J. M. Byrd, J. Feikes, K. Holldack, H.-W. Hubers, P. Kuske, A. Loftsdottir, M. Venturini, R. Warnock, and G. Wustefeld, "A model describing stable coherent synchrotron radiation in storage rings," Phys. Rev. Lett. **93**, 9 (27 August 2004) 94801; Virtual J. Ultrafast Sci. **3**, 99 (September 2004); LBNL/PUB-890; SLAC-PUB 10827.
http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=PRLTAO000093000009094801000001&idtype=cvips&gifs=Yes

C. Steier, D. Robin, and B. Feinberg, *Conceptual Design Report of the Top-Off Upgrade of the Advanced Light Source at Lawrence Berkeley National Laborator*y, LBNL/PUB-5506, Dec. 2004.

The following items are in accepted-abstract stage with the 2005 Particle Accelerator Conference (May 12-16), so fullfledged papers are not yet available. Additional searches for abstracts may be performed at http://snsapp1.sns.ornl.gov/pls/pac05/search.html

David Robin, Barry Bailey, Kenneth Michael Baptiste, Walter Barry, Alan Biocca, Warren Byrne, Richard Donahue, Robert M. Duarte, Michael Fahmie, William Gath, James Julian, Jin-Young Jung, Slawomir Kwiatkowski, Robert Mueller, Hiroshi Nishimura, Jim Oneill, Soren Prestemon, Steven Rossi, Fernando Sannibale, Ross Schlueter, Derek Shuman, Christoph Steier, Gregory D. Stover, Chris Timossi, and Tony Warwick, "Status and plans for the ALS top-off upgrade."

Max Zolotorev, Peter Denes, Zahid Hussain, Gennadi Lebedev, Steven M. Lidia, David Robin, Fernando Sannibale, Robert W. Schoenlein, and Robert Vogel (LBNL), and Eugene Commins (UC-Berkeley), "A source for non-relativistic electrons approaching the brightness quantum limit."

David Robin, John Byrd, Slawomir Kwiatkowski, Derun Li, Fernando Sannibale, Christoph Steier, Weishi Wan, and Alexander Zholents, "Generation of picosecond x-ray pulses in the ALS using rf orbit deflection."

Christoph Steier (LBNL/AFRD); Winfried Decking (DESY, Hamburg); Y. K. Wu (Duke University FEL, Durham, North Carolina); Jacques Laskar (IMCCE, Paris); David Robin (LBNL/ALS); and Laurent Stanislas Nadolski (SOLEIL, Gif-sur-Yvette), "Measuring and understanding the momentum aperture in a storage ring" (*invited oral*).

Full Publications List

Publications since very late fiscal 2003 (a timeframe that sets our recent activities in a fuller context than the past year alone) are listed here, organized by level of scholarly review.

Refereed Literature

Y. K. Wu, E. Forest, and D. S. Robin, "Explicit symplectic integrator for s-dependent static magnetic field," Physical Review *E* **68**, 4 (2003), p. 6502.

T. Houck and S. Lidia, "Beam dynamics experiments to study the suppression of transverse instabilities," Physical Review Special Topics: Accelerators and Beams **03**0101 (2003). http://prst-ab.aps.org/pdf/PRSTAB/v6/i3/e030101

Hiroshi Nishimura, Glen Lambertson, Juris G. Kalnins, and Harvey Gould, "Feasibility of a synchrotron storage ring for neutral polar molecules," *Rev. Sci. Instrum.* **74**, 7 (2003), pp. 3271-8.

H. Rose (LBNL), "Five-dimensional Hamiltonian-Jacobi approach to relativistic quantum mechanics," in P. Hawkes, ed., *Advances In Imaging And Electron Physics* ***132***, pp. 247-85 (Academic Press, ISBN: 0-12-014774-2); LBNL-54190.
http://www-library.lbl.gov/docs/LBNL/541/90/PDF/LBNL-54190.pdf

W. Wan, J. Feng, H. A. Padmore and D. S. Robin, "Simulation of a mirror corrector for PEEM3," in *Proceedings* of the Sixth International Conference on Charged Particle Optics **(**Greenbelt, MD, October 21-25, 2002), Nucl. Instrum Meth. A **519**, 1-2 (21 February 2004), pp. 222-9; LBNL-53232.

Y.K. Wu, D.S. Robin, E. Forest, R. Schlueter, S. Andres, J. Feng, H.A. Padmore, and D.H. Wei, "Design and analysis of beam separator magnets for 3rd generation aberration compensated PEEMs," in *Proceedings* of the Sixth International Conference on Charged Particle Optics **(**Greenbelt, MD, October 21-25, 2002), Nucl. Instrum Meth. A **519**, 1-2 (21 February 2004), pp. 230-241; LBNL-55267.

J. M. Byrd, M. C. Martin, W. R. McKinney, D. V. Munson, H. Nishimura, D. S. Robin , F.Sannibale, R.D. Schlueter, W. G. Thur, J. Y. Jung, and W. Wan, "CIRCE: a ring-based source of coherent synchrotron radiation," in *Proceedings* of the Eighth International Conference on Synchrotron Radiation Instrumentation (San Francisco, CA, August 25-29, 2003), American Institute of Physics Conf. Proc. **705**:137-140.

Byrd, J.M., M.C. Martin, W.R. McKinney, D.V. Munson, H. Nishimura, D.S. Robin, F. Sannibale, R.D. Schlueter, W.G. Thur, J.Y. Jung, and W. Wan, "CIRCE: a dedicated storage ring for coherent THz synchrotron radiation," in *Proceedings* of the International Workshop on Infrared Microscopy and Spectroscopy with Accelerator-Based Sources (Lake Tahoe, CA, July 8-11, 2003), Infrared Physics and Technology **45** (5-6), 325-330 (2004); LBNL-53699.
http://www-library.lbl.gov/docs/LBNL/536/99/PDF/LBNL-53699.pdf

J. Feng, E. Forest, A.A. MacDowell, M. Marcus, H. Padmore, S. Raoux, D. Robin, A. Scholl, R. Schlueter, P. Schmid, J. Stohr, W. Wan, D.H. Wei and Y. Wu, "An x-ray photoemission electron microscope using an electron mirror aberration corrector for the study of complex materials," Journal of Physics: Condensed Matter **17**, 16 (April 27, 2005) S1339-S1350; LBNL-55268
http://www-library.lbl.gov/docs/LBNL/552/68/PDF/LBNL-55268.pdf
http://www.iop.org/EJ/abstract/-search=8809073.1/0953-8984/17/16/005

J. Feng, A.A. MacDowell, R. Duarte, A. Doran, N. Kelez, M. Marcus, D. Munson, H. Padmore, K. Petermann, S. Raoux, D. Robin, A. Scholl, R. Schlueter, P. Schmid, J. Stöhr, W. Wan (LBNL), D.H. Wei (SRRC), Y. Wu (Duke), and E. Forest (KEK), "An aberration corrected photoemission electron microscope at the Advanced Light Source," in *Proceedings* of the Eighth International Conference on Synchrotron Radiation Instrumentation (San Francisco, CA, August 25-29, 2003), American Institute of Physics Conf. Proc. **705**:1070-1073; LBNL-53195.

H. Nishimura, G. Lambertson, J.G. Kalnins, and H. Gould, "Feasibility of a storage ring for polar molecules in strong-field-seeking states," European Physical Journal D **31**, pp. 359-364, DOI: 10.1140/epjd/e2004-00153-8.
http://www.edpsciences.org/articles/epjd/abs/2004/11/d04233/d04233.html

D. Robin et al., “Superbend upgrade on the Advanced Light Source,” Nucl. Instrum. Meth. A **538**, 1-3 (11 February 2005), pp. 65-92; LBNL-52637 Journal.

F. Sannibale, J. M. Byrd, A. Loftsdottir, M. C. Martin, M. Venturini, “Fundamentals of coherent synchrotron radiation in storage rings,” in *Proceedings* of the Eighth International Conference on Synchrotron Radiation Instrumentation (San Francisco, CA, August 25-29, 2003), American Institute of Physics Conf. Proc. **705**:141-144.

F. Sannibale, M. Abo-Bakr, J. M. Byrd, J. Feikes, K. Holldack, H.-W. Hubers, P. Kuske, A. Loftsdottir, M. Venturini, R. Warnock, and G. Wustefeld, “A model describing stable coherent synchrotron radiation in storage rings,” Phys. Rev. Lett. **93**, 9 (27 August 2004) 94801; Virtual J. Ultrafast Sci. **3**, 99 (September 2004); LBNL/PUB-890; SLAC-PUB 10827. http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=PRLTAO000093000009094801000001&idtype=cvips&gifs=Yes

T. Scarvie et al., “Noise reduction efforts for the ALS infrared beamlines,” in Proceedings of the International Workshop on Infrared Microscopy and Spectroscopy with Accelerator-Based Sources (Lake Tahoe, CA, July 8-11, 2003), Infrared Physics and Technology **45** (5-6), pp. 403-8; LBNL-53724. http://www-library.lbl.gov/docs/LBNL/537/24/PDF/LBNL-53724.pdf

Peter Schmid, Jun Feng, Howard Padmore, David Robin, Harald Rose, Ross Schlueter, and Weishi Wan, “Correction and alignment strategies for the beam separator of the photoemission electron microscope 3 (PEEM3),” Rev. Sci. Instrum. **76**, 023302 (February 2005); LBNL-55699. http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=RSINAK000076000002023302000001&idtype=cvips&gifs=Yes

Unrefereed Conference Proceedings

Abstracts for the 2005 Particle Accelerator Conference

The following abstracts from AFRD's ALS Accelerator Physics Group and its collaborators have been accepted by the 2005 Particle Accelerator Conference (May 16-20, 2005, Knoxville, TN) and are expected to result in papers in its Proceedings; some will also be developed into contributions to the refereed literature. An asterisk indicates a paper in the oral program. Abstracts may be viewed at http://snsapp1.sns.ornl.gov/pls/pac05/search.html

John Byrd, Zhao Hao, Michael C. Martin, David Robin, Fernando Sannibale, Robert W. Schoenlein, Alexander Zholents, and Max Zolotorev, “Terahertz coherent synchrotron radiation from femtosecond laser modulation of the electron beam at the Advanced Light Source.”

Hiroshi Nishimura and Warren Byrne, “Simulation and automation of the EEBI test at ALS.”

Hiroshi Nishimura and Tom Scarvie, “Estimation of the effective magnet misalignments of the ALS storage ring.”

Hiroshi Nishimura, David Robin, and Christoph Steier, “Beam loss simulation studies for ALS top-off operation.”

G. Portmann, J. Corbett, and A. Terebilo, “Flexible bunch frequency for synchrotron light sources.”

G. Portmann, J. Corbett, and A. Terebilo, "An accelerator control middle layer using Matlab."

David Robin, Barry Bailey, Kenneth Michael Baptiste, Walter Barry, Alan Biocca, Warren Byrne, Richard Donahue, Robert M. Duarte, Michael Fahmie, William Gath, James Julian, Jin-Young Jung, Slawomir Kwiatkowski, Robert Mueller, Hiroshi Nishimura, Jim Oneill, Soren Prestemon, Steven Rossi, Fernando Sannibale, Ross Schlueter, Derek Shuman, Christoph Steier, Gregory D. Stover, Chris Timossi, and Tony Warwick, "Status and plans for the ALS top-off upgrade."

David Robin, John Byrd, Slawomir Kwiatkowski, Derun Li, Fernando Sannibale, Christoph Steier, Weishi Wan, and Alexander Zholents, "Generation of picosecond x-ray pulses in the ALS using rf orbit deflection."

David Robin, Richard Donahue, Robert Mueller, Hiroshi Nishimura, and Christoph Steier, "Radiation safety studies for top-off operation of the Advanced Light Source."

* Fernando Sannibale, Alan Biocca, Nicholas Kelez, Michael C. Martin, Toshiro Nishimura, Tom Scarvie, Eric Williams, and Gregory James Portmann, "Beam measurements and upgrade at BL 7.2, the second diagnostics beamline of the Advanced Light Source."

Tom Scarvie, Walter Barry, Warren Byrne, Michael Chin, Robert M. Duarte, Jim O'Neill, Fernando Sannibale, and Chris Timossi, "Diagnostics plan for the Advanced Light Source top-off upgrade."

Derek Shuman, Ross Schlueter, Christoph Steier, and Gregory D. Stover, "Stray field reduction in eddy current septum magnets."

* Christoph Steier (LBNL/AFRD); Winfried Decking (DESY, Hamburg); Y. K. Wu (Duke University FEL, Durham, North Carolina); Jacques Laskar (IMCCE, Paris); David Robin (LBNL/ALS); and Laurent Stanislas Nadolski (SOLEIL, Gif-sur-Yvette), "Measuring and understanding the momentum aperture in a storage ring" (*invited*).

Christoph Steier, Alexander Zholents, David Robin, Weishi Wan, and Walter Wittmer, "The new undulator based fs-slicing beamline at the ALS."

Gregory D. Stover, Kenneth Michael Baptiste, Walter Barry, William Gath, James Julian, Slawomir Kwiatkowski, Soren Prestemon, Ross Schlueter, Derek Shuman, and Christoph Steier, "Investigations, experiments, and implications for using existing pulse magnets for "topoff" operation at the Advanced Light Source."

Weishi Wan and Christoph Steier, "Simulation of the effect of an in-vacuum undulator on the beam dynamics of the ALS."

Weishi Wan, Jun Feng, and Howard A Padmore, "Design study on a new separator for PEEM3."

Weishi Wan, Gregory James Portmann, Warren Byrne, Hiroshi Nishimura, David Robin, Fernando Sannibale, and Alexander Zholents, "Commissioning of a locally isochronous lattice at the ALS ."

Fuhua Wang, Dan Cheever, Manouchehr Farkhondeh, Wilbur Franklin, William Graves, Ernie Ihloff, Richard Milner, Chris Tschalaer, Jan Van der Laan, Defa Wang, Dong Wang, and Townsend Zwart (MIT); Larry Carr, Boris Podobedov (BNL/NSLS, Upton, Long Island, New York); and Fernando Sannibale (LBNL), "Terahertz coherent synchrotron radiation in the MIT-Bates south hall ring."

Max Zolotorev, Peter Denes, Zahid Hussain, Gennadi Lebedev, Steven M. Lidia, David Robin, Fernando Sannibale, Robert W. Schoenlein, and Robert Vogel (LBNL), and Eugene Commins (UC-Berkeley), "A source for non-relativistic electrons approaching the brightness quantum limit."

EPAC 2004 Papers

The following papers by AFRD's ALS Accelerator Physics Group and its collaborators appear in the Proceedings of the 9th European Particle Accelerator Conference (July 5-9, 2004, Lucerne, Switzerland). For further information, see http://accelconf.web.cern.ch/accelconf/e04/

J. Byrd, S. De Santis, J.-Y. Jung, D. Li, M.C. Martin, W. McKinney, D. Munson, H. Nishimura, D. Robin, F. Sannibale, R. Schlueter, M. Venturini, W. Wan, and M. Zolotorev, "CIRCE, the Coherent InfraRed CEnter at the ALS"; LBNL-55603. http://accelconf.web.cern.ch/accelconf/e04/PAPERS/THPKF073.PDF

J. Byrd, Z. Hao, M.C. Martin, D.S. Robin, F. Sannibale, R.W. Schoenlein, M. Venturini, A.A. Zholents, and M.S. Zolotorev, "Coherent infrared radiation from the ALS generated via femtosecond laser modulation of the electron beam"; LBNL-55688. http://accelconf.web.cern.ch/accelconf/e04/PAPERS/THPKF078.PDF

W. Corbett, G. Portmann , A. Terebilo, and J. Safranek, "SPEAR 3 commissioning software." http://accelconf.web.cern.ch/accelconf/e04/PAPERS/MOPLT147.PDF

H. Nishimura, D. Robin, F. Sannibale, and W. Wan, "Lattice studies for CIRCE (Coherent InfraRed CEnter) at the ALS"; LBNL-55647. http://accelconf.web.cern.ch/accelconf/e04/PAPERS/WEPLT147.PDF

*Penn, G., J.N. Corlett, W. Fawley, M. Reinsch, W. Wan, J.S. Wurtele, and A.A. Zholents, "Harmonic cascade FEL designs for LUX." http://accelconf.web.cern.ch/accelconf/e04/PAPERS/MOPKF074.PDF

D. Robin, B. Bailey, K. Baptiste, W. Barry, W. Byrne, R. Donahue, J. Jung, S. Kwiatkowski, R. Mueller, H. Nishimura, S. Prestemon, S. Rossi, F. Sannibale, R. Schlueter, D. Shuman, C. Steier, G. Stover, and T. Warwick, "Plan to upgrade the Advanced Light Source to top-off injection operation." http://accelconf.web.cern.ch/accelconf/e04/PAPERS/THPKF076.PDF

* J. Safranek, {…} J. Byrd, D. Robin, T. Scarvie, C. Steier {…} et al., "SPEAR-3 commissioning." http://accelconf.web.cern.ch/accelconf/e04/PAPERS/THOACH01.PDF

F. Sannibale, D. Baum, A. Biocca, N. Kelez, T. Nishimura, T. Scarvie, E. Williams, and K. Holldack, "Commissioning of BL 7.2, the new diagnostic beam line at the ALS"; LBNL-55605. http://accelconf.web.cern.ch/accelconf/e04/PAPERS/THPLT140.PDF

J. Seeman, M. Browne, Y. Cai, W. Colocho, F.-J. Decker, M. Donald, S. Ecklund, R. Erickson, A. Fisher, J. Fox, S. Heifets, R. Iverson, A. Kulikov, A. Novokhatski, M. Pivi, M. Ross, P. Schuh, T. Smith, K. Sonnad, M. Stanek, M. Sullivan, P. Tenenbaum, D. Teytelman, J. Turner, D. Van Winkle, U. Wienands, M. Woodley, Y. Yan, G. Yocky, W. Kozanecki, G. Wormser, M. Biagini, J. Corlett, C. Steier, A. Wolski, and M. Zisman, "Results and plans of the PEP-II B-factory." http://accelconf.web.cern.ch/accelconf/e04/PAPERS/MOPLT143.PDF

C. Steier, E. Domning, T. Scarvie, and E. Williams, "Operational experience integrating slow and fast orbit feedbacks at the ALS." http://accelconf.web.cern.ch/accelconf/e04/PAPERS/THPLT141.PDF

C. Steier, S. Marks, S. Prestemon, D. Robin, R. Schlueter, and A. Wolski, "Study of row phase dependent skew quadrupole fields in Apple-II type EPUs at the ALS." http://accelconf.web.cern.ch/accelconf/e04/PAPERS/MOPKF071.PDF

C. Steier, A. Wolski, S. Ecklund, J. Safranek, P. Tenenbaum, A. Terebilo, J. Turner, and G. Yocky, "Orbit response matrix analysis applied at PEP-II." http://accelconf.web.cern.ch/accelconf/e04/PAPERS/TUPLT153.PDF

*Wan, W., J.N. Corlett, W. Fawley, and A. Zholents, "Design study of the bending sections between harmonic cascade FEL stages," http://accelconf.web.cern.ch/accelconf/e04/PAPERS/MOPKF073.PDF

PAC 2003 Papers

The following papers by AFRD's ALS Accelerator Physics Group and its collaborators appear in the Proceedings of the 2003 Particle Accelerator Conference (May 12-16, 2003, Portland, OR). An asterisk indicates a paper in the oral program. For further information, see http://accelconf.web.cern.ch/accelconf/p03/

* J. Corlett, W.A. Barletta, S. De Santis, L. Doolittle, W. Fawley, M.A. Green, P. Heimann, S. Leone, D. Li, S.M. Lidia, A. Ratti, K. Robinson, R. Schoenlein, J. Staples, W. Wan, R.P. Wells, A. Wolski, and A. Zholents (LBNL); M. Placidi (CERN); W. Pirkl (consultant); S.-H. Wang (Indiana University); F. Parmigiani (Sincrotrone Trieste); and R.A. Rimmer (Thomas Jefferson National Accelerator Facility), "A recirculating linac-based facility for ultrafast x-ray science"; LBNL-52605. http://accelconf.web.cern.ch/accelconf/p03/PAPERS/TOAC003.PDF

* A. Jackson and H. Nishimura, "Single-particle beam dynamics in BOOMERANG"; LBNL-52586. http://accelconf.web.cern.ch/accelconf/p03/PAPERS/TOPA009.PDF

S.M. Lidia, "Emittance compensation studies of photoinjector beams with angular momentum"; LBNL-51827 Abs. http://accelconf.web.cern.ch/accelconf/p03/PAPERS/WPAB022.PDF

S.M. Lidia, J. Corlett, J. Pusina, J. Staples, and A. Zholents, "An injector for the proposed Berkeley ultrafast x-ray light source"; LBNL-52931. http://accelconf.web.cern.ch/accelconf/p03/PAPERS/WPAB021.PDF

S.M. Lidia (LBNL); K. Floettmann (DESY); and P. Piot (FNAL), "Recent improvements to the ASTRA particle tracking code,"; LBNL-52933.
http://accelconf.web.cern.ch/accelconf/p03/PAPERS/FPAG015.PDF

H. Nishimura, C. Timossi and J. L. McDonald, "Cross platform SCA component using C++ Builder and Kylix"; LBNL-52599.
http://accelconf.web.cern.ch/accelconf/p03/PAPERS/WPPE028.PDF

H. Nishimura, H. Gould, J. Kalnins, and G. Lambertson, "Lattices for milli-eV neutral molecules."
http://accelconf.web.cern.ch/accelconf/p03/PAPERS/TPPG014.PDF

*D. Robin, "Superbend upgrade at the Advanced Light Source" (*invited*); see also Nucl. Instrum. Meth. A **538**, 1-3 (11 February 2005), pp. 65-92; LBNL-52637 Journal.
http://accelconf.web.cern.ch/accelconf/p03/PAPERS/TOPA002.PDF

D. Robin, C. Steier, W. Wan, and A. Wolski, "Impact of narrow gap undulators on the Advanced Light Source."
http://accelconf.web.cern.ch/accelconf/p03/PAPERS/WPAB086.PDF

F. Sannibale, J. M. Byrd, A. Loftsdottir, M. C. Martin, and M. Venturini, "A model for producing stable, broadband terahertz coherent synchrotron radiation in storage rings"; LBNL-53639.
http://accelconf.web.cern.ch/accelconf/p03/PAPERS/MPPB016.PDF

Tom Scarvie, Nord Andresen, Ken Baptiste, John Byrd, and Mike Chin, "Noise reduction efforts for the infrared beamline at the Advanced Light Source"; LBNL-53724.
http://accelconf.web.cern.ch/accelconf/p03/PAPERS/MPPB018.PDF

J. Staples, S.M. Lidia, and S. Virostek (LBNL), and R.A. Rimmer (Thomas Jefferson National Accelerator Facility), "The LBNL femtosource 10 kHz photoinjector."
http://accelconf.web.cern.ch/accelconf/p03/PAPERS/WPAB023.PDF

C. Steier , A. Biocca, E. Domning, S. Jacobson, G. Portmann, T. Scarvie, and E. Williams, "Commissioning results of the fast orbit feedback at the ALS."
http://accelconf.web.cern.ch/accelconf/p03/PAPERS/FPAB037.PDF

C. Steier, D. Robin, and A. Wolski, "Coupling correction and beam dynamics at ultralow vertical emittance in the ALS."
http://accelconf.web.cern.ch/accelconf/p03/PAPERS/RPPG018.PDF

* C. Steier, L. Nadolski, H. Nishimura, D. Robin, W. Wan, and A. Zholents, "Accelerator physics challenges of the fs-slicing upgrade at the ALS."
http://accelconf.web.cern.ch/accelconf/p03/PAPERS/WOAB006.PDF

Y. Sun, K.-J. Kim (University of Chicago); K. Desler, D. Edwards, H. Edwards, M. Hüening, P. Piot, and J. Santucci (FNAL); S.-H. Wang (Indiana University); S.M. Lidia (LBNL); N. Barov and D. Mihalcea (Northern Illinois University); and R. Tikhoplav (University of Rochester), "Angular momentum measurement of the FNPL electron beam."
http://accelconf.web.cern.ch/AccelConf/p03/PAPERS/WPPG039.PDF

Weishi Wan, Hiroshi Nishimura, David Robin, and Christoph Steier (LBNL); and Ying Wu (Duke), "ID modeling at the ALS." http://accelconf.web.cern.ch/accelconf/p03/PAPERS/WPAB087.PDF

S.-H. Wang (Indiana University); J. Corlett, S.M. Lidia, J. Staples, and A. Zholents (LBNL), "Flat beam production in low energy injectors." http://accelconf.web.cern.ch/accelconf/p03/PAPERS/RPPG011.PDF

Miscellaneous Unrefereed Publications

F. Sannibale, J. M. Byrd, A. Loftsdottir, M. Venturini, M. Abo-Bakr, J. Feikes, K. Holldack, P. Kuske, G. Wustefeld, H.-W. Hubers, and R. Warnock, "Stable CSR in storage rings: a model," International Committee for Future Accelerators *Beam Dynamics Newsletter* 35, p. 27 (2004); LBNL-56777; SLAC-PUB 11013. http://www-bd.fnal.gov/icfabd/Newsletter35.pdf

J.M. Byrd, S. De Santis, Z. Hao, M. C. Martin, D.V. Munson, D. Li, H. Nishimura, D.S. Robin, F. Sannibale, R.D. Schlueter, R. Shoenlein, J.Y. Jung, M. Venturini, W. Wan, A.A. Zholents, and M. Zolotorev, "Optimizing ring-based CSR sources," International Committee for Future Accelerators *Beam Dynamics Newsletter* 35, p. 70 (2004). http://www-bd.fnal.gov/icfabd/Newsletter35.pdf

C. Biscari, M. Castellano, A. Gallo, A. Ghigo, A. Marcelli, F. Marcellini, G. Mazzitelli, C. Milardi, M.A. Preger, P. Raimondi, M. Serio, M. Zobov, J.M. Byrd, F. Sannibale, P. Morini, and D. Sali, "Terahertz coherent synchrotron radiation at DAFNE," International Committee for Future Accelerators *Beam Dynamics Newsletter* 35, p. 107 (2004). http://www-bd.fnal.gov/icfabd/Newsletter35.pdf

C. Steier, D. Robin, and B. Feinberg, *Conceptual design report of the top-off upgrade of the Advanced Light Source at Lawrence Berkeley National Laboratory*, LBNL/Pub-5506, December 2004.

3. CENTER FOR BEAM PHYSICS

Reported by John Corlett, Program Head

The Center for Beam Physics (CBP) is a cornerstone program of the Accelerator and Fusion Research Division. The Center is vigorously engaged in a highly productive and tightly knit program of both theoretical studies and experimental research. We bring to bear expertise in accelerator physics and theory, accelerator modeling using high performance computing, beam electrodynamics and instrumentation, and laser-plasma acceleration that is targeted at the critical needs of the accelerator-based scientific community.

Our activities range from support of presently operating accelerator facilities such as the Tevatron and PEP-II to the development of new initiatives and advanced accelerator concepts. We provide leadership for – and make significant contributions to – major High Energy Physics initiatives such as LHC, ILC, and muon accelerators, together with a leading-edge research effort in laser-driven, advanced accelerators. In a different arena, Center for Beam Physics staff are also making strong scientific leadership and technical contributions to new concepts for future light sources, developing critical accelerator physics and technologies necessary for next generation synchrotron radiation sources.

The Center is organized into five main groups (Figure 3-1): *Accelerator Theory, Accelerator Modeling and Advanced Computing (AMAC), Beam Electrodynamics, Collider Physics,* and *l'OASIS*. The Center's work is supported by state-of-the-art experimental facilities including a 100 TW, 10 Hz laser system in the l'OASIS Laboratory, as well as rf and beam instrumentation equipment at the Lambertson Beam Electrodynamics Laboratory.

The advanced simulations work is performed primarily under the auspices of DOE's highly successful Scientific Discovery through Advanced Computing (SciDAC) program, and it benefits greatly from strong collaboration with colleagues elsewhere in LBNL—notably, mathematicians and computer scientists in the Computing Research Division and the outstanding staff at NERSC. Each of these five main efforts is further described in this chapter. Additional information about the Center can be found on our web site: http://bc1.lbl.gov/CBP_pages/CBP

Scope and Results of CBP Efforts

The Center has a total FY05 budget of ~$8.2M and a staff of approximately 50 full- or part-time members, including scientists, engineers, technical, and administrative support staff, and students.

Training of postdoctoral fellows and students is an important part of the Center's mission; there are presently 4 postdocs (with 2 more expected shortly), 4 PhD students, and 2 undergraduates in the Center. We typically host several national and international scientists and scholars each year. We benefit considerably from our proximity to the UC Berkeley campus and have one senior CBP staff scientist as a joint appointment with UC Berkeley Physics Department, in addition to several working relationships with faculty members and students.

The Center has maintained an exceptional record for productivity, which is reflected by the large number of its high quality publications. The work done by Center staff since January 2003 has been reported in approximately 150 publications, with a large fraction, about one third, of these appearing in refereed journals. A complete bibliography is provided at the end of this chapter, along with PDF files of the publications we judged most significant

The staff at the Center also contribute extensively to the national and international accelerator communities through a variety of service and leadership roles. These include participation on program and organizing committees of major accelerator conferences and workshops, participation on machine advisory committees and various facility and program review committees, as journal referees, and through service to the International Committee on Future Accelerators, the American Physical Society, and various executive and technical boards.

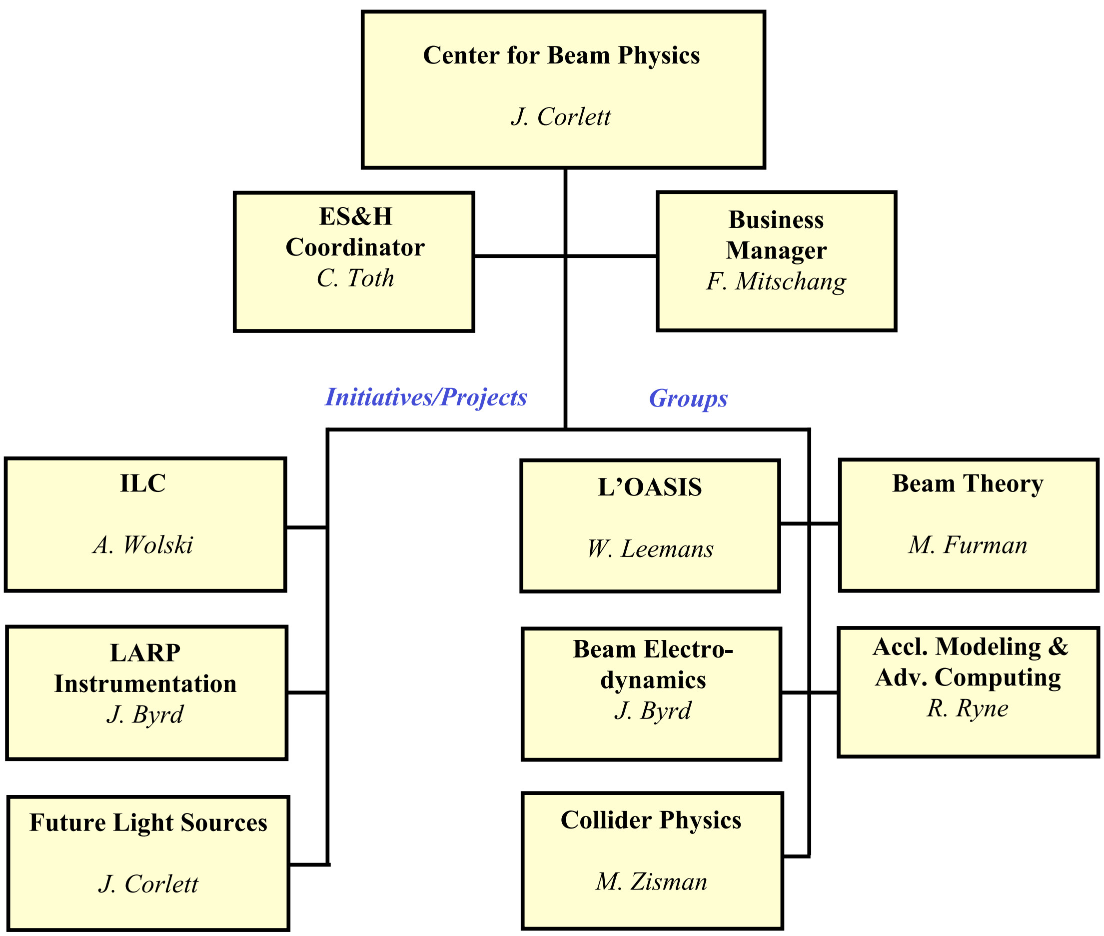


Figure 3-1. CBP comprises five standing groups and, according to need, a number of project/initiative teams.

Strategic View and Technical Progress

Historically, the Center for Beam Physics has been an incubator of new accelerator concepts that support, sustain and enable forefront science. As a strategic planning model, we work to continue this tradition. To do so, we maintain and build upon our ability to conceptualize, construct, commission and upgrade advanced accelerators. We apply these skills in a manner consistent with support of ongoing and future national needs as defined by the scientific community and the DOE/Office of Science *Strategic Plan* and *Facilities for the Future of Science* roadmaps. (It should be noted that 60% of the prioritized initiatives in the Strategic Plan involve accelerator-based science.) This approach is evident in each facet of the Center's activities, as summarized below.

This year an additional section highlights the work of the Accelerator Modeling and Advanced Computing Group, home of numerous activities of cross-cutting benefit to the Center and to others.

Laser –Based Accelerators: The l'OASIS Group

Reported by Wim Leemans, Group Leader

The Center's work on laser-driven accelerators, carried out by the *l'OASIS Group* (Laser Optics & Accelerator Systems Integrated Studies), is focused on the development of laser-based physics and technology for advanced accelerators and fundamental laser-matter interaction physics. Research into all-optical electron production and acceleration (Figures 3-2 and 3-3) at the l'OASIS Laboratory offers hope for small footprint accelerators and ultrafast radiation sources in the future.

Ground-breaking results from the l'OASIS group recently included production of ultrashort bunches of tens of femtoseconds' duration, produced in a plasma channel a few millimeters long, with approximately 500 pC of charge, at energies around 100 MeV, an energy spread of ± 2%, and normalized emittance below 1-2 mm-mrad. Research with capillary plasma channel technology is underway to allow future development of 10 cm-scale accelerating sections, each of which may result in GeV energies of the accelerated electrons.

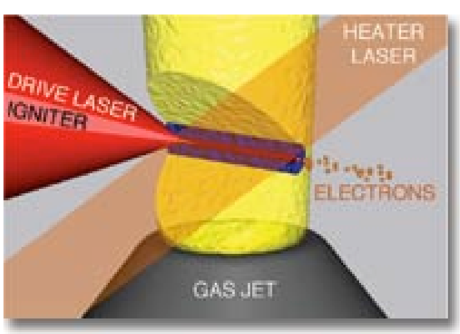


Figure 3-2. *Our laser-plasma accelerator technology uses three pulses from a multi-terawatt, multi-beam titanium:sapphire laser. They are fired in sequence into a plasma of tailored characteristics. First an igniter pulse forms a tiny plasma channel in hydrogen gas. Then a heater pulse expands the channel (also causing a density gradient, low on axis and and high toward the edges). After 500 picoseconds, with the density gradient mature and ions out of the way, an intense drive pulse sets up a wakefield upon which trapped electrons can "surf" to high energies.*

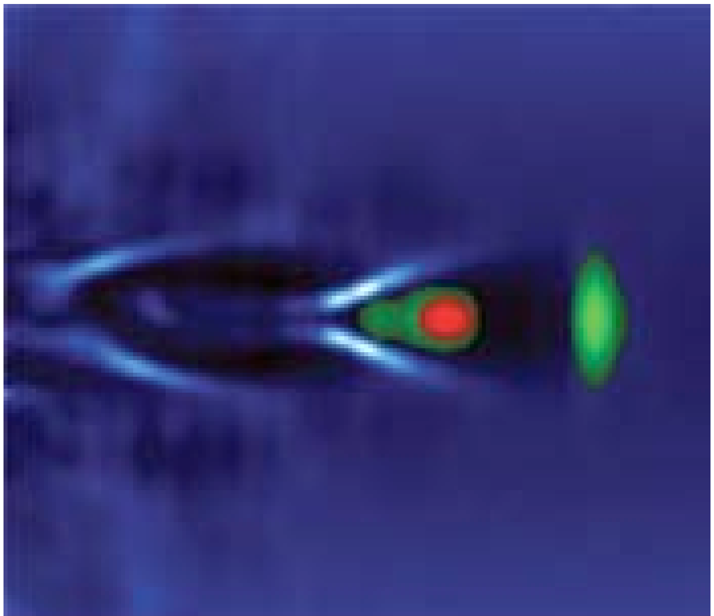


Figure 3-3. *As with many of the Center's activities, high-performance computing helps us understand and improve our laser-plasma accelerators. This simulation came from the code VORPAL, created by Tech-X Corp. and the University of Colorado-Boulder and run at LBNL's National Energy Research Supercomputing Center. A laser pulse (green) travels from left to right, leaving behind a density modulation (blue and white) in the plasma. This wake can trap a bunch of electrons (red) that "surf" the modulation to high energies. A plasma density gradient set up by a "heater" laser pulse—denoted in this simulation by a slight variation of color from the beam axis to the edges—guides the laser and improves electron-beam quality. For more information see http://oemagazine.com/fromTheMagazine/mar05/feature.html and the scholarly papers cited at the end of this chapter, such as Nature* ***431****, 538-541 (2004).*

In addition to applications in the high-energy physics community, the high-energy, ultrafast electron bunches may also be used to radiate at x-ray wavelengths in conventional undulators, producing femtosecond intense x-ray pulses. An additional use is for isotope production. The l'OASIS laboratory systems also find applications directly to high energy density physics studies.

Throughout the next decade, we plan to continue development of laser-driven electron accelerators as well as compact, high-gradient ion accelerators based on laser interaction with solid targets. The laser based ion accelerator will be explored for its potential as a compact source for isochoric heating of targets for high energy density physics (see also Chapter 1).

We will also explore its potential use in the front-ends of conventional ion accelerators, where it might alleviate the need for low phase velocity structures and thus improve ion beam quality. It may find further application as an economical and efficient source of radioactive beams for nuclear science, or as a future x-ray source.

These efforts will initially be centered around the existing l'Oasis Laboratory. It houses a multi-million dollar state-of-the-art Ti:sapphire based laser system that is unique in the US. It is equipped with up to 6 beam lines, shielded target areas with currently two target chambers, and a remote control room.

We see the second phase as a dedicated user-style facility that could support several external users simultaneously, providing laser beam time as do existing "Large Scale European Facilities" such as at the VULCAN laser at Rutherford Appleton Laboratory (UK) and the LULI2000 laser at the Ecole Polytechnique (France). LBNL would be a node in a national network of such facilities, as proposed in the SAUUL report.[1]

Future Colliders for High-Energy Physics

Involvement with conventional accelerators and colliders are important in the Center's strategy. We participate extensively in the development of future accelerator facilities that will be needed by the worldwide HEP community such as the Large Hadron Collider, the International Linear Collider, and the Super Neutrino Beam. Our roles include leadership and significant contributions to design, construction and commissioning. We also provide a modest level of support for ongoing HEP facilities such as the Tevatron and PEP-II.

Meeting Near-Term Needs through LARP

The Beam Electrodynamics, Accelerator Theory, Collider Physics, and Accelerator Modeling and Advanced Computing Groups

In support of near-term HEP objectives, we are part of the US LHC Accelerator Research Program (LARP) in which our involvement is expected to grow over the next few years. This DOE-supported activity follows on directly from our contribution to construction of the Large Hadron Collider, now nearing successful completion at CERN. Our principal activity in LARP, carried out by the *Beam Electrodynamics Group,* is the development of beam instrumentation needed to support LHC commissioning. A bunch-by-bunch luminosity monitor has already been designed and is being tested.

CBP contributions to the LARP program are also under way in the *Accelerator Theory* and *the Accelerator Modeling* and *Advanced Computing Groups*. Working together, these groups have developed a comprehensive parallel 3-D beam-beam code and used it to perform the first ever million-turn, million-macroparticle, strong-strong LHC simulation. Theory and simulations of electron cloud effects in the LHC have also combined into a key component of our LARP activities. An important goal for us is to couple these efforts to subsequent participation in LHC commissioning.

The Collider Physics group is participating in LHC commissioning planning for LARP. This group anticipates providing one or more accelerator physicists for the commissioning task at CERN, and is planning to gain experience via work at Fermilab in Tevatron Run II.

HEP in the Medium-term Future

Linear-Collider Damping Rings and the Accelerator Theory Group

In support of medium-term HEP objectives, the Center has developed a leadership role in R&D for damping rings for a future linear collider. In previous years, the Center had responsibility for design studies of the damping rings for the proposed Next Linear Collider, which would have been based on normal-conducting rf technology. In 2004, the

[1] *The Science and Applications of Ultrafast, Ultraintense Lasers: Opportunities in Science and Technology Using the Brightest Light Known to Man* ("Report on the SAUUL Workshop"), July 2002. Available at http://www.sc.doe.gov/production/bes/chm/Publications/SAUUL_report_final.pdf

global community made a decision to focus effort on an International Linear Collider with superconducting rf technology in the main linac.

The expertise we developed for the NLC damping rings is very relevant to the rather different ILC damping rings, and in the short time since the technology decision, we have made a significant contribution to the new machine. The goal of our effort is for LBNL to be given responsibility for the accelerator physics, engineering design, construction, and commissioning of these extraordinarily challenging rings. At this stage, this work is carried out in the Center's *Accelerator Theory Group* and the *Beam Electrodynamics Group*.

One major damping-ring design challenge is achieving the necessary acceptance for the large positron beam produced from the source. The average injected beam power into the damping rings is around 225 kW; loss of even a small fraction of the beam on injection will quickly cause radiation damage to important components. A significant accomplishment this past year has been the design of a lattice that meets the key parameters for damping rates and equilibrium beam sizes, while keeping nonlinear effects small enough that particle trajectories are dynamically stable even at large distances from the nominal orbit and despite the large energy errors expected for individual particles in the injected beam.

The damping rings differ significantly from existing electron storage rings (for example, those in synchrotron light sources) in the length of wiggler magnets required to provide rapid radiation damping. Techniques developed in previous years for modeling nonlinear effects from the wigglers on particle trajectories are now being applied to the ILC damping rings, and will lead to an optimized design for the wigglers. The AMAC group is providing advanced simulation tools for parallel particle tracking, and these tools have been modified in collaboration with AMAC to study space charge effects.

There are more effects that threaten the beam quality in the damping rings than in the rest of the machine. Many of these effects—for example, coherent synchrotron radiation in the dipoles and instabilities driven by vacuum chamber impedance— are relevant for accelerators used in a variety of other applications, notably synchrotron light sources. The specifications for beam stability in the ILC damping rings are extremely challenging, and meeting these goals will require advanced techniques that will be of benefit in a wide range of accelerator applications.

The scale of the damping rings is indicated by estimates for the hardware costs, which are of order $300M. Construction of a linear collider would therefore provide the opportunity for a substantial contribution from LBNL for developing, delivering and commissioning the damping rings. The Center for Beam Physics is playing a leading role in coordinating the work effectively among different institutions across several time zones. As our work progresses, we build on the existing skills and leadership role of the Center, and strengthen our ability to contribute to other accelerator projects.

Laying Groundwork for the Long-Term Future of HEP
Muon Colliders and the Collider Physics Group

In support of long-term HEP objectives, the Center continues its leadership role in R&D for muon colliders, primarily through our *Collider Physics Group*. This work evaluates feasibility of technical approaches that will be needed to build an advanced muon storage ring to support research in neutrino science. A high-intensity muon storage ring is generally viewed as the ideal source of such neutrinos.

LBNL is the lead laboratory in the Neutrino Factory and Muon Collider Collaboration, and is among the sponsoring laboratories along with BNL and FNAL. The Center is extensively represented on all key technical and executive boards associated with both the

Muon Collaboration and the Muon Ionization Cooling Experiment (MICE). If a muon-based accelerator were built in the US, LBNL would desire and expect to play a major role, and would plan to take responsibility for a major subsystem, such as the Front End (including Decay Channel, Phase Rotation, Bunching, and Cooling) or perhaps the storage ring.

LBNL plans to have a substantial role in MICE. We have responsibility for engineering design of the spectrometer solenoid for Phase 1 of MICE, and are to provide the RF-Coupling Coil (RFCC) modules for MICE Phase 2. Staff from the *Beam Electrodynamics* and the *Collider Physics Groups* conduct R&D in support of this effort, and considerable progress has been made this year. An LBNL-built 805 MHz cavity was tested at Lab G at Fermilab, and we have now nearly completed the fabrication of a 201-MHz cavity suitable for the cooling channel specifications of a neutrino factory. A 5-T solenoid that we designed continues to be used to support the rf cavity test program at Fermilab. Both the 5 T solenoid and the 805 MHz cavity have been relocated to the new MUCOOL test area (MTA) at Fermilab. The 201 MHz cavity will likewise be tested at the MTA starting this year.

Crosscutting Collaborations in Theory and Modeling

The AMAC, l'OASIS, and Theory Groups

Other distinguishing capabilities within the Center include our expertise in theory and modeling; these activities are carried out primarily in the *Accelerator Theory, l'OASIS*, and *Accelerator Modeling and Advanced Computing (AMAC) Groups*, This overarching expertise is essential to the success of our mission and is applied interactively throughout the activities of the Center.

AMAC operates at the interface between computational science and accelerator science. It works closely with the Computational Research Division and the National Energy Research Supercomputing Center and with other CBP groups, as well as other parts of AFRD, LBNL, and other institutions. Collaborations are key to its success. Its goal is to be a world leader in developing terascale accelerator modeling tools and applying those tools to solving the most important and challenging problems in accelerator science and technology.

Significant advances have been made by the *Accelerator Theory Group* in understanding the electron cloud effect and its impact on many existing and planned accelerators. The Group continues further detailed calibrations of the electron cloud simulations against measurements obtained at the CERN Super Proton Synchrotron in collaboration with CERN personnel during last year's run, progressing toward its goal of fully self-consistent terascale beam simulations of accelerators like PSR and the LHC. These simulations, which include impedances and electron-cloud effects, will help with commissioning and upgrade planning for machines like the Spallation Neutron Source and LHC.

Since October 2002, the Theory Group has participated with the Fusion Energy Program (see Chapter 1) in the integrated study of the electron-cloud effect. This activity, coordinated with Lawrence Livermore National Laboratory, is centered around the HCX driver accelerator located at LBNL, and it encompasses simulations, experimental measurements, and diagnostics developments.

The simulation tool being developed and compared with experimental results is a 3D self-consistent code that has very recently yielded a first-ever simulation of a realistic FODO cell of the arcs in the LHC. This tool is arguably the state of the art in the field, and the model it encompasses will continue to be augmented for ever more realistic and accurate simulations with a goal of a validated predictive tool.

Future Light Sources

Another important element of the Center's strategy relates to our activities in the development of accelerator science and technologies with application in future light sources. National facilities based on advanced accelerator technologies have been identified as highly attractive future "4th Generation" light sources (LBNL's Advanced Light Source being an exemplar of the third generation); see for example the report of the BESAC Subcommittee Workshop on 20-Year Basic Energy Sciences Facilities Roadmap, February 22-24, 2003. A future x-ray science facility at LBNL would enhance the existing substantial scientific activity at LBNL, provide a world-class resource in x-rays, and support the development of scientific and engineering infrastructure at Berkeley Lab.

Using the integrated resources available within the Center for Beam Physics, we have developed the conceptual designs for accelerator based facilities and related technologies for future generation light sources. This effort combines the analytical, computational, and experimental approaches from the *Theory, AMAC,* and *Beam Electrodynamics Groups*.

The critical areas we address are:

- Design of rf photocathode guns for production of high-brightness and high power (high repetition rate) electron beams.
- Development of integrated concepts for production of tailored electron beams by controlled use of laser systems in the rf photocathode gun.
- Design and demonstration of ultra-stable timing and synchronization techniques for accelerator facilities.
- Accelerator physics studies of systems for manipulation and control of the electron beam 6-D emittance.
- Physics studies of optical manipulation of electron beams to enhance radiation production.
- Physics studies of the production of wide-band and tunable temporally and spatially coherent radiation in free-electron lasers (FELs).

Using these technologies, we have developed facility concepts that offer significant advantages. These advantages include a broad wavelength range from extreme ultraviolet to hard x-rays; tunability by using seed lasers and undulator tuning; synchronization between seed laser and sample pump laser; flexibility in pulse duration and in pulse repetition rate; and large flux per pulse using FEL sources.

We have developed concepts for ultra-short-pulse soft x-ray production by cascaded harmonic generation (as in LUX; see http://lux.lbl.gov/), current-enhanced self-amplified spontaneous emission (ESASE), and other free electron laser techniques designed to produce attosecond pulses of x-rays. These schemes provide enhanced performance and capabilities over existing methods for x-ray production.

We conceived and developed ESASE techniques that generate extremely high peak current (~1-10 kA) micro-bunches within an electron beam bunch, with only limited beam quality degradation due to collective effects. This technique has particularly attractive features for the LCLS project being built at SLAC, where the much shorter gain length results in more rapid saturation of the radiation field, easing requirements on the LCLS electron beam quality or reducing the undulator length needed.

Synchronization between the interrogating x-ray pulse and a sample pump laser pulse will be critical for high-resolution pump-probe experiments with ultra-short x-ray pulses on future light sources. Addressing this issue, we have designed and built a fiber-optic based system involving a master laser and stabilized optical distribution for providing precision timing signals and frequency references over ~100 m distance. Timing errors in 100-m fiber have already been reduced from several picoseconds to 200 femtoseconds, and we are actively incorporating a set of optical techniques to reduce these timing errors to tens of femtoseconds and lower. A concept to enable locking of remote lasers has been developed, transmitting low-power cw signals over the stabilized fiber link, and experiments are to begin in spring 2005.

To produce high brightness electron bunches at the high repetition-rate commensurate with laser pump-probe studies, we have conceived and developed the engineering design for an rf photocathode electron gun designed to operate at 10 kHz bunch repetition rate. In conjunction with rf cavity design work and beam dynamics studies, we have developed a phototcathode laser concept to produce tailored, high-brightness electron bunches through precise control over the spatial and temporal intensity profiles of laser pulses.

In addition to forefront research and leadership in accelerator physics and technology studies for future light sources, CBP staff are pursuing leadership roles and responsibilities in support of the LCLS hard x-ray FEL facility, and in the FERMI @ Elettra VUV-soft x-ray FEL facility proposed by Sincrotrone Trieste.

In Summary…

The Center for Beam Physics serves as a national resource supporting the accelerator-based scientific community. It is maintaining its historical role of leadership and contributions to the field and has a strategic approach to carry this tradition into the future.

The next section gives details of the recent accomplishments of the Accelerator Modeling and Advanced Computing group (AMAC), which we highlight this year because their activities have numerous cross-cutting benefits to other work in CBP and elsewhere.

The final two sections of this chapter list our featured publications—those papers that we thought representative of our best recent achievements. PDFs of the featured publications are included on this CD; just click the links to read those you find interesting. The last section gives a full bibliography.

Accelerator Modeling and Advanced Computing

The mission of the Accelerator Modeling and Advanced Computing (AMAC) group is to support the needs of the Department of Energy's Office of Science, especially its high-energy and nuclear physics programs, with regard to accelerator simulation, design, and analysis. Our core capability is *Computational Accelerator Science*, which involves the fusion of several fields, including, among others, accelerator physics, scientific computing, computer science, and applied mathematics. Our primary focus is computational beam dynamics. We develop codes such as IMPACT, MARYLIE/IMPACT, and BEAMBEAM3D, all of which run on high-end computing platforms (i.e., parallel computers), to solve some of the most demanding computational problems in accelerator science and technology.

AMAC's success has benefited greatly from strong collaboration with organizations within LBNL and elsewhere. Within CBP, we collaborate with the Theory Group, the l'OASIS Laboratory, the Beam Electrodynamics Group, and the ILC program. We also collaborate with beam physicists elsewhere in AFRD, notably in the Heavy Ion Fusion Virtual National Laboratory.

Our work also extends to the ALS Division, the Computational Research Division, and NERSC. Outside of LBNL, we have many collaborators, several of whom participate in the Accelerator Science and Technology project of the Scientific Discovery through Advanced Computing (SciDAC) program. These include SLAC, Fermilab, BNL, LANL, UCLA, USC, the University of Maryland, and Tech-X corporation. We also collaborate with international institutions such as KEK, RAL, GSI, and CERN.

AMAC's activities fall mainly into four categories: software development, algorithm development, software application, and community interaction. Here we take the opportunity to provide some additional detail in two of these areas: software development and algorithm development.

Software Development

AMAC develops and maintains state-of-the art, fully 3-D particle-simulation codes for modeling beams in a wide range of accelerator systems, including electron and ion machines, be they linacs, rings, or colliders. We use particle-in-cell (PIC) techniques to compute space-charge effects by depositing charge on a computational grid, solving Poisson's equation on that grid, and interpolating the fields back to the particle positions.

The use of PIC methods for modeling what are essentially collisionless systems is well established in computational beam physics, plasma physics, and astrophysics, and it is orders of magnitude more efficient than direct particle-particle methods. Even so, the need to deposit particles on a 3D grid leads to a large number of simulation particles (about a million for *low* resolution simulations). This in turn makes parallel computing essential for reasonable turnaround times and the ability to perform parameter scans.

AMAC currently develops and maintains three code packages: IMPACT (for modeling beams with space charge in accelerator components, beam transport systems, and linacs), MARYLIE/IMPACT (primarily for modeling beams in circular accelerators), and BEAMBEAM3D (for modeling beam-beam effects in colliders).

Impact

IMPACT[2] was originally developed by R. Ryne and others at Los Alamos National Laboratory in the 1990s to model beams with space charge in ion linacs. Responsibility has been taken over by J. Qiang of the AMAC Group, under whose leadership the code's capabilities have been greatly expanded. As a result, it is now in use at several institutions in the US, and it is gaining interest from international institutions such as KEK, RAL, and GSI. Recent activities include:

- Development of IMPACT-T, a version that uses time as the independent variable (in contrast to IMPACT, which uses axial distance z). It being used at several locations to model photoinjectors.
- Adding an energy binning function to IMPACT so as to model beams with large energy spread, e.g., beam bunches emerging from early laser/plasma experiments.
- Adding multi-charge-state capability to IMPACT (done for the Rare Isotope Accelerator project).
- Inclusion of several new Poisson solvers, including a solver that takes geometry into account. This was developed for the RIA project to model low energy beam transport of a beam out of an ECR ion source. An example is shown in Figure 3-4.

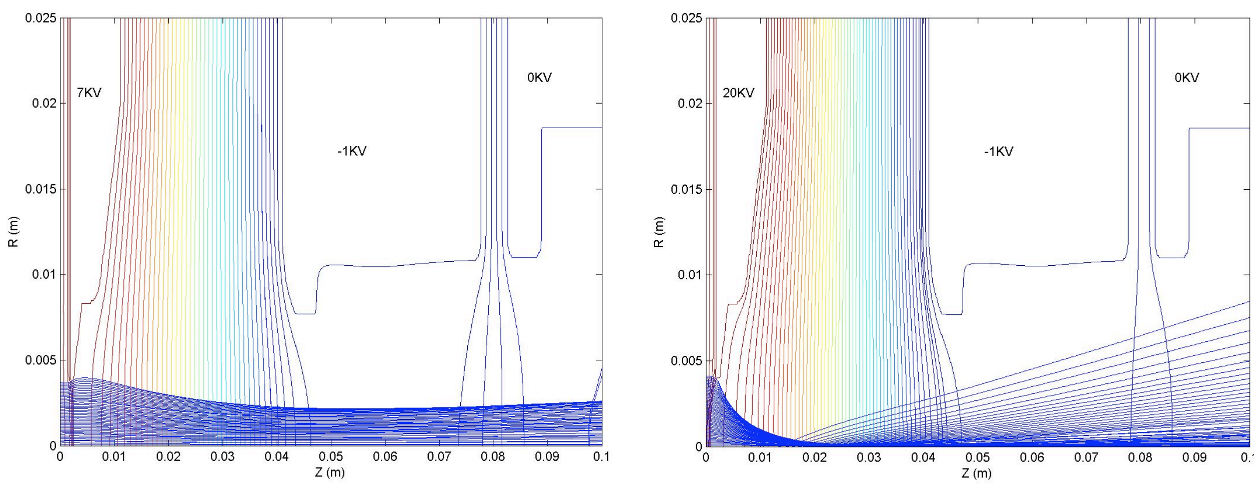


Figure 3-4. *IMPACT-T simulations of beam transport out of an ECR ion source, showing the effect of electrode voltage and the beam transport. This work was performed in collaboration with the Nuclear Sciences Division under a RIA R&D project.*

---

[2] J. Qiang, R.D. Ryne, S. Habib, and V. Decyk, "An object-oriented parallel particle-in-cell code for beam dynamics simulation in linear accelerators," *J. Comp. Phys*. **163**, 434-451 (2000).

MARYLIE/IMPACT

MARYLIE/IMPACT is a hybrid code that combines the Lie-algebraic high-order optics and tracking capabilities of MARYLIE with the 3D space-charge capability of IMPACT. It also contains IMPACT's rf cavity model, so the code can model beam with and without space charge, with and without acceleration. Recent activities include:

- Inclusion of a capability to read beamlines in the Standard Input Format (i.e. "MAD" format).
- Inclusion of an embedded 3D envelope code.
- Development of "automatic" commands that provide a simple way for the user to slice elements for space-charge calculations, make ray plots, and make lattice function plots.
- Development of a manual and a suite of examples.

BEAMBEAM3D

BEAMBEAM3D[3] is a comprehensive parallel PIC code for modeling beam-beam collisions in colliders. Developed by J. Qiang of AMAC, it provides a good example of the synergy of AMAC with the rest of CBP, as this code benefited from input by M. Furman (head of the CBP Theory Group).

BeamBeam3D has both weak-strong and strong-strong modeling capabilities, as well as the ability to model several types of collisions (head-on, crossing angle, and long-range). It has been used to model the Tevatron, PEP-II, RHIC, and the LHC. To provide a sense of the computational requirements, consider our ongoing beam-beam simulations of the LHC, which up to now have been performed on seaborg (an IBM/SP3 at NERSC) and cheetah (an IBM/SP4 at the CCS at ORNL). The largest simulations performed to date have used 2 bunches, using 2 million simulation particles per bunch, modeled for a total of 2 million machine turns, and assuming one interaction region (IR). A single simulation on 128 processors required more than 50 hours on cheetah and more than 100 hours on seaborg. We are currently pursuing the possibility of using a Cray X-1 at ORNL, which has the potential to be 10-15 times faster than seaborg, in order to perform multi-IP simulations and to perform simulations using multiple beam bunches. Recent enhancements to BEAMBEAM3D include:

- Incorporation of new Poisson solvers for improved performance and accuracy, including one based on an Integrated Green function and one based on a nonuniform grid.
- Ability to treat energy variation during collisions.
- Ability to treat multi-bunch trains and multiple collision points.

[3] J. Qiang, M.A. Furman, R.D. Ryne, "A Parallel Particle-In-Cell Model for Beam-Beam Interactions in High Energy Ring Colliders," *J.Comp.Phys*.198:278-294 (2004).

Algorithm Development

AMAC's main algorithmic requirements are related to Poisson solvers needed in our PIC codes.[4,5,6,7] Some of these algorithms are developed by collaborators, such as members of the SciDAC Applied Partial Differential Equations Center. Other algorithms, especially those that are somewhat accelerator-specific, are developed in-house. Examples of algorithms that we have developed include those based on integrated Green's functions (which are useful for modeling high-aspect ratio conditions) and shifted Green's functions (useful for modeling long-range beam-beam collisions), as well as algorithms for beams in toroidal pipes that use the ratio of the pipe radius to the radius of curvature as an expansion parameter, and solvers based on wavelets.

Wavelet-based Solvers

Work carried out by a member of AMAC (I. Pogorelov) under an LDRD project in collaboration with Northern Illinois University has resulted in the successful implementation of a 3D wavelet-based algorithm for the fast solution of the Poisson equation subject to inhomogeneous Dirichlet boundary conditions.[8]

Several factors led us to pursue the development of a solver operating in a wavelet basis. For example, multi-resolution representations of the Laplacian provide two important advantages: (i) the operator remains sparse in a wavelet basis, and (ii) preconditioners exist that are effectively diagonal in wavelet bases. Our preconditioned conjugate gradient (PCG) Poisson solver was designed to take full advantage of this combination of circumstances. And, because Poisson's equation has to be solved at every timestep, we were able to use the potential computed in the previous timestep as a good initial approximation for the iterative solution to the current one.

The solver was first tested as a stand-alone solver on two 3D model distributions--one used in galactic dynamics, the other in charged particle beam dynamics modeling. The solver was subsequently successfully integrated into the IMPACT suite of codes for 3D beam dynamics modeling, and applied to modeling the Fermilab/NICADD photoinjector. The results produced by both the standard distribution of IMPACT and by the version incorporating the wavelet-based PCG solver were found to be in excellent agreement in terms of a standard set of diagnostics (Figure 3-5).

---

[4] J. Qiang, M. Furman, and R. Ryne, "Strong-Strong Beam-Beam Simulation Using a Green Function Approach," *Phys. Rev. ST Accel. Beams*, vol 5, 104402 (October 2002).
[5] J. Qiang and R. Gluckstern, "Three-Dimensional Poisson Solver for a Charged Beam with Large Aspect Ratio in a Conducting Pipe," submitted to *Comp. Phys. Comm* (2004).
[6] McCorquodale P, Colella P, Grote DP, Vay JL, "A node-centered local refinement algorithm for Poisson's equation in complex geometries", submitted to *J. of Comp. Phys.* (2004)
[7] J. Qiang and R. Ryne, "Parallel 3D Poisson Solver for a Charged Beam in a Conducting Pipe," *Computer Physics Communications* 138, 18 (2001).
[8] [7] B. Terzic and I.V. Pogorelov, "Wavelet-Based Poisson Solver for Use in Particle-in-Cell Simulations," *in* Nonlinear Dynamics in Astronomy and Physics, J.R. Buchler and S.T. Gottesman, Eds.: Ann. N. Y. Acad. Sci. (*accepted*); preprint: http://www.math.fsu.edu/~bterzic/Research/tp2005.pdf (2004).

The new solver still needs to be optimized, and detailed comparisons of algorithm performance and accuracy still need to be done. To our knowledge, this work constitutes the first application of the wavelet-based multiscale methodology to 3D computer simulations in beam dynamics.

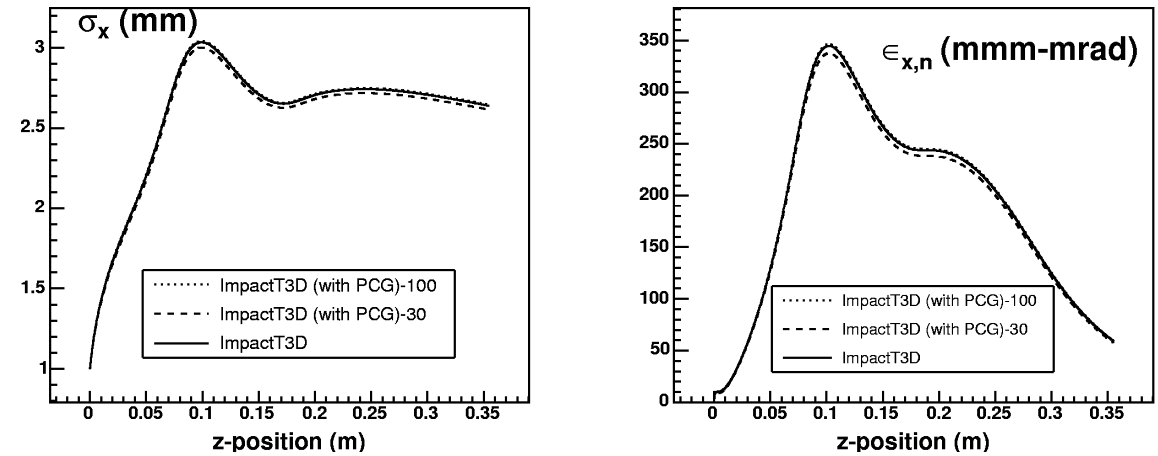


Figure 3-5. *Simulation results for the Fermilab/NICADD photoinjector done with the standard version of* IMPACT *(solid lines),* IMPACT *with preconditioned conjugate gradient (PCG) wavelet-based solver with 30x30 coefficients (dashed line), and PCG with 100x100 coefficients. Excellent agreement was found for quantities such as the rms beam size (*left*) and the rms emittance (*right*).*

High Aspect Ratio Poisson Solvers

Many beam-based systems involve high aspect ratios. Examples include flat beams, long beams in induction machines, and long beams in accumulator rings. Mathematically, some of the solvers that are now in widespread use lose accuracy unless a very large number of grid points are used in the "long" dimension, even though the beam density itself may vary slowly. The "Hockney algorithm" for treating open systems[9] represents one such algorithm that loses accuracy in high aspect ratio situations unless very many grid points are used. Work carried out by AMAC has shown that the use of an integrated Green's function (IGF) is a very promising approach to dealing with such systems.

A 2D example is shown in Figure 3-6. These plots show the error in the computed electric field, E_x, for a Gaussian charge distribution with an rms beam size of 1 mm in the x direction and 500 mm in the y direction. Notice that the vertical scale on the left hand plot (based on the Hockney algorithm using a 64x2048 grid) extends to 1, indicating errors between 10% and 100%. The vertical scale on the right-hand plot (based on the IGF method using a 64x64 grid) extends to only 0.01, indicating errors of less than 1%.

A quantitative comparison is more easily seen by comparing the results on a line through the Gaussian distribution near y=0; this is shown in Figure 3-7, using the Hockney algorithm with three grid sizes (64x2048, 64x4096, 64x8192) and the IGF method using a grid size of 64x64. In the central region the error using the Hockney method is nearly 10 times larger than the IGF method even when the grid size is 64x8192.

While the IGF approach requires more effort to set up, it is highly parallelizable. Furthermore, if the grid size is fixed, the setup time is negligible when amortized over many

[9] R.W. Hockney and J.W. Eastwood, *Computer Simulations Using Particles*, Institute of Physics Publishing, London, 1988.

thousands of time steps. In this case, neglecting the setup time, the IGF leads to *a performance increase of nearly 1000*. We have already verified (with the help of a symbolic algebra code) that the IGF approach can be extended to 3D. Such a solver is also expected to be useful in modeling certain astrophysical contexts, e.g. studying the morphology of disk galaxies, as well as galaxy mergers.

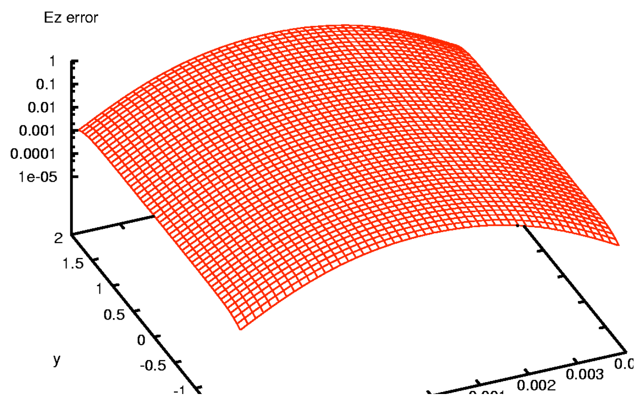
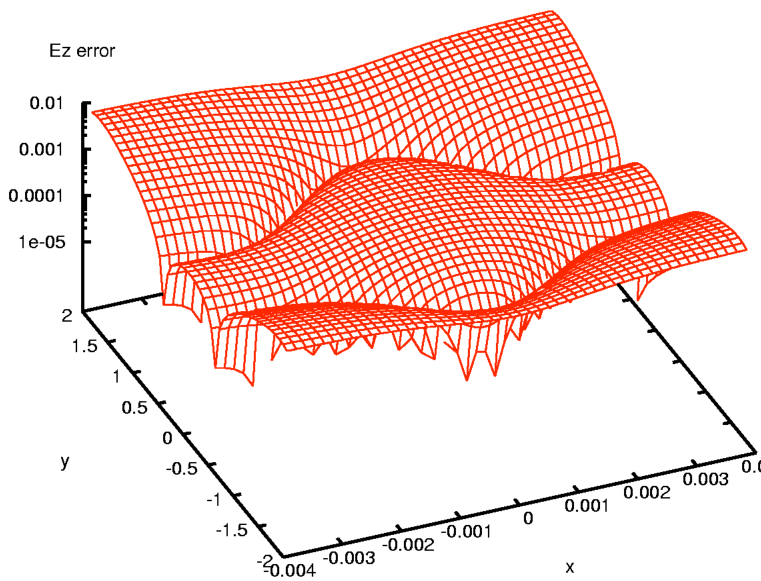


Figure 3-6. *Numerical error in the computed electric field of a Gaussian distribution of charge having rms sizes* σ_x*=1mm and* σ_y*=500mm.* Upper: *Hockney algorithm.* Lower: *integrated Green's function (IGF).*

Notice that the vertical scale in the lower (IGF) plot is 100 times smaller.



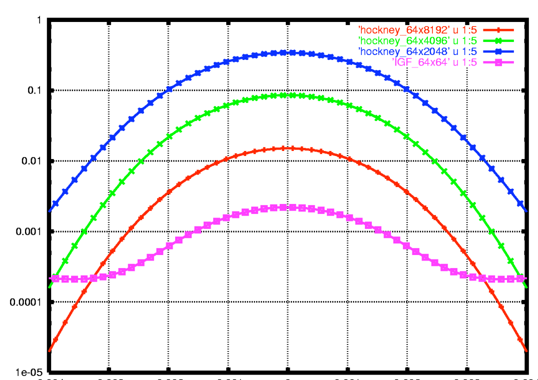


Figure 3-7*. Numerical error in the computed electric field of a Gaussian distribution of charge (*σ_x*=1mm and* σ_y*=500mm) comparing the Integrated Green Function (IGF) method with the Hockney algorithm. The plot shows the error in the x-component of electric field (vertical axis) plotted as a function of x (horizontal axis) along a line near y=0. Even using a grid size of 64x8192, the Hockney method is less accurate over most of the physical domain than the 64x64 IGF calculation.*

Featured Publications

These publications, chosen upon the advice of the Center's group leaders, best represent our accomplishments from summer 2004 (i.e., just after the last review) to the present. This list is organized by research group. The collaborative nature of many of the Center's activities causes some publications to appear under more than one heading.

Beam Electrodynamics Group

F. Sannibale, J.M. Byrd, A. Loftsdottir, M. Venturini, M. Abo-Bakr, J. Feikes, K. Holldack, P. Kuske, G. Wustefeld, H.-W. Hubers, and R. Warnock, "A model describing stable coherent synchrotron radiation in storage rings," Physical Review Letters. **93**, 9 (27 August 2004), pp. 094801/1-4; LBNL-PUB-890.

J.M. Byrd, M.C. Martin, W.R. McKinney, D.V. Munson, H. Nishimura, D.S. Robin, F. Sannibale, R.D. Schlueter, W.G. Thur, J.Y. Jung, and W. Wan, "CIRCE: a dedicated storage ring for coherent THz synchrotron radiation," Infrared Physics & Technology, **45**, 5-6 (Oct. 2004), pp. 325-30; LBNL-53699.

J.-F. Beche, J. Byrd, P. Datte, S. De Santis, M. Placidi, V. Riot, R. Schoenlein, W. Turner, and M. Zolotorev, "A laser-based longitudinal density monitor for the Large Hadron Collider," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 – 9, 2004); LBNL-55209.

J. N. Corlett, W. A. Barletta, S. DeSantis, L. Doolittle, W.M. Fawley et al., "LUX – a design study for a linac/laser-based ultrafast x-ray source," in *Proceedings* of Fourth Generation X-Ray Sources and Optics II (Denver, CO, August 2004), SPIE Proc. Vol. 5534; LBNL-57430.

Collider Physics Group

I. Reichel, M.S. Zisman, M. Placidi, K. Gollwitzer, and S. Werkema, "Aperture studies for the AP2 anti-proton line at Fermilab," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 – 9, 2004), p. 1491; LBNL-54096.

M.S. Zisman, "Neutrino factory R&D in the U.S.," in *Proceedings* of NuFact03, 5th International Workshop on Neutrino Factories & Superbeams (Columbia University, New York, NY, June 5-11, 2003); AIP Conf. Proc. 721, p. 60; LBNL-53832.

M.S. Zisman, "R&D toward neutrino factories and muon colliders," in *Proceedings* of the 2003 Particle Accelerator Conference (Portland, OR, May 2003), IEEE Cat. No. 03CH37423 (IEEE, Piscataway, NJ, 2003), p. 361; LBNL-53126.

l'OASIS Group

C.G.R. Geddes, Cs. Toth, J. van Tilborg, E.H. Esarey, C.B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W.P. Leemans, "High quality electron beams from a plasma channel guided laser wakefield accelerator," Nature **431**, 538-541 (2004); LBNL-55732.

J. van Tilborg, C.B. Schroeder, E. Esarey, and W.P. Leemans,"Pulse shape and spectrum of coherent diffraction-limited transition radiation from electron beams," Laser Particle Beams **22**, 415-422 (2004); LBNL-55868.

J. Faure, J. van Tilborg, K.A. Kaindl, and W.P. Leemans, "Modelling laser-based table-top THz sources, optical rectification, propagation and electro-optic sampling," Optical & Quantum Electronics **36**, 8 (June 2004), pp. 681-97; LBNL-57136.

W.P. Leemans, E. Esarey, J. van Tilborg, P.A. Michel, C.B. Schroeder, Cs. Toth, C.G.R. Geddes, and B.A. Shadwick, "Radiation from laser accelerated electron bunches: coherent terahertz and femtosecond x-rays," IEEE Trans. Plasma Sci., accepted (2005); LBNL-56584.

C.G.R. Geddes, Cs. Toth, J. van Tilborg, E. Esarey, C.B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W.P. Leemans. "Production of high quality electron bunches by dephasing and beam loading in channeled and un-channeled laser plasma accelerators," *invited paper*, Phys. Of Plasmas (in press); LBNL-57062.

B.A. Shadwick, G.M. Tarkenton, E. Esarey, and C.B. Schroeder, "Fluid and Vlasov models of low temperature, collisionless laser-plasma interactions," *invited paper*, Phys. Plasmas, accepted (2005); LBNL-57061.

AMAC Group

J. Qiang, R.D. Ryne, and I. Hofmann, "Space-charge driven emittance growth in a 3D mismatched anisotropic beam," Phys. Rev. Lett. **92**, 174801 (2004), LBNL-51807.

T.P. Wangler, C.K. Allen, K.C.D. Chan, P.L. Colestock, K.R. Crandall, R.W. Garnett, J.D. Gilpatrick, W. Lysenko, J. Qiang, J.D. Schneider, M.E. Shulze, R.I. Sheffield, and H.V. Smith, "Beam-halo in mismatched proton beams," Nucl. Instrum. Meth. A **519**, 425 (2004); LBNL-56055.

J. Qiang, "Halo formation due to beam-beam interactions of beams optically mismatched at injection," Physical Review Special Topics: Accelerators and Beams **7,** 031001 (2004); LBNL-56054.

J. Qiang, M. Furman, and R. Ryne, "A parallel particle-in-cell model for beam-beam interactions in high energy ring colliders," accepted by J. Comp. Phys. (2004); LBNL-54598.

J.L. Vay, P. Colella, J.W. Kwan, P. McCorquodale, D.B. Serafini, A. Friedman, D.P. Grote, G. Westenskow, J.C. Adam, A. Héron , and I. Haber, "Application of adaptive mesh refinement to particle-in-cell simulations of plasmas and beams," Phys. of Plasmas (in press); LBNL-53551.

Theory Group

A. Wolski, G. Penn, A. Sessler and J. Wurtele, "Beam conditioning for free electron lasers: consequences and methods," Physical Review Special Topics: Accelerators and Beams **7,** 080701; LBNL-53899 (2004).

R. Cimino, I.R. Collins, M.A. Furman, M. Pivi, F. Ruggiero, G. Rumolo, and F. Zimmermann, "Can low energy electrons affect high energy physics accelerators?," Phys. Rev. Lett. **93**, 014801 (29 June 2004); CERN-AB-2004-012; LBNL-54594; SLAC-PUB-10350.

Y. Honda, A. Wolski, et al., "Achievement of ultralow emittance beam in the Accelerator Test Facility damping ring," Phys. Rev. Lett. **92**, 054802 (31 January-6 February 2004); LBNL-57214.

M. Babzien, I. Ben-Zvi, I. Pavlishin, I.V. Pogorelsky, V.E. Yakimenko, A.A., Zholents, and M. S. Zolotorev, "Optical stochastic cooling for RHIC," in T. Katayama and T. Koseki, eds., *Proceedings* of the International Workshop on Beam Cooling and Related Topics (Lake Yamanaka, Yamanashi, Japan, 2003), Nucl. Instrum. Meth. A **532**, 1-2, pp. 345-7; LBNL-57307.

A. A. Zholents and W. M. Fawley, "Proposal for intense attosecond radiation from an x-ray free-electron laser," Phys. Rev. Lett. **92**, 224801 (29 May-4 June 2004).

A.A. Zholents and W.M. Fawley, "Toward attosecond x-ray pulses from the FEL," in Sandra G. Biedron, Wolfgang Eberhardt, Tetsuya Ishikawa, Roman O. Tatchyn, editors, *Proceedings* of Fourth Generation X-Ray Sources and Optics II (Denver, August 2004), SPIE Proc. 5534 (Nov. 2004).

Corlett, John, William M. Fawley, Gregory Penn, Alexander A. Zholents , Weishi Wan, Matthias Reinsch, and Jonathan Wurtele, "Harmonic cascade FEL designs for LUX, a facility for ultrafast x-ray science," in *Proceedings* of the 2004 FEL Conference (Trieste, Italy, August 29-September 3, 2004; LBNL-55020_Conf.

Alexander A Zholents and William M. Fawley (LBNL); Paul J Emma, Zhirong Huang, and Gennady Stupakov (SLAC); and Sven Reiche (UCLA), "Current-enhanced SASE using an optical laser and its application to the LCLS," in *Proceedings* of the 2004 FEL Conference (Trieste, Italy, August 29-September 3, 2004); LBNL-54967.

Full Publications List

Publications from the last review (May 2004) to date are listed here, organized by group and then by level of scholarly review. Because of the collaborative and discipline-crossing nature of the Center, some publications are reported under more than one group.

Beam Electrodynamics Group

Refereed Publications

J. Byrd and S. De Santis, "An optical sampling technique for measuring the longitudinal beam density in a storage ring," submitted to Nucl. Instrum. Meth. A (August 2004); LBNL-56101.

F. Sannibale, J.M. Byrd, A. Loftsdotir, M, Venturini, M. Abo-Bakr, J. Feikes, K. Holldack, P. Kuske, G. Wustefeld, H.-W. Hubers, and R. Warnock, "A model describing stable coherent synchrotron radiation in storage rings," Physical Review Letters **93**, 094801 (Aug. 27, 2004), pp. 1-4; LBNL-PUB-890.

Unrefereed Conference Proceedings and Other Publications

F. Sannibale, J. M. Byrd, A. Loftsdottir, M. C. Martin, M. Venturini, "Fundamentals of coherent synchrotron radiation in storage rings," in *Proceedings* of the Eighth International Conference on Synchrotron Radiation Instrumentation (San Francisco, CA, August 25-29, 2003), American Institute of Physics Conf. Proc. **705**:141-144; LBNL-55823.

J. N. Corlett, W. A. Barletta, S. DeSantis, L. Doolittle, W.M. Fawley, et al., "LUX – a design study for a linac/laser-based ultrafast x-ray source," in Sandra G. Biedron, Wolfgang Eberhardt, Tetsuya Ishikawa, Roman O. Tatchyn, editors, *Proceedings* of Fourth Generation X-Ray Sources and Optics II (Denver, August 2004, SPIE Proc. 5534 (Nov. 2004).

J.-F. Beche, J. Byrd, P. Datte, S. De Santis, M. Placidi, V. Riot, R. Schoenlein, W. Turner, and M. Zolotorev, "A laser-based longitudinal density monitor for the Large Hadron Collider," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55209.

J.-F. Beche, J. Byrd, , S. De Santis, P. Denes, M. Placidi, W. Turner, and M. Zolotorev, "Development of an abort gap monitor for high-energy proton rings," in *Proceedings* of BIW 2004, the 11th Beam Instrumentation Workshop (Knoxville, TN, 8-11 May 2004); LBNL-56562.

J.M. Byrd, "Luminosity monitor for the Large Hadron Collider," in *Proceedings* of BIW 2004, the 11th Beam Instrumentation Workshop (Knoxville, TN, 8-11 May 2004); LBNL-55825.

J.M. Byrd, M.C. Martin, W.R. McKinney, D.V. Munson, H. Nishimura, D.S. Robin, f. Sannibale, R.D. Schlueter, W.G. Thur, J.Y. Jung, and W. Wan, "CIRCE: a ring-based

source of coherent synchrotron radiation," in *Proceedings* of the Eighth International Conference on Synchrotron Radiation Instrumentation (San Francisco, CA, August 25-29, 2003), American Institute of Physics Conf. Proc. **705**:137-140.; LBNL-55826.

J.-F. Beche, J. Byrd, S. De Santis, M. Placidi, W. Turner, and M. Zolotorev, "Development of an abort gap monitor for the Large Hadron Collider," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55208.J.-F. Beche, J. Byrd, P. Datte, S. De Santis, M. Placidi, V. Riot, R. Schoenlein, W. Turner, and M. Zolotorev, "A laser-based longitudinal density monitor for the Large Hadron Collider," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55209.

Byrd, J.M., M.C. Martin, W.R. McKinney, D.V. Munson, H. Nishimura, D.S. Robin, F. Sannibale, R.D. Schlueter, W.G. Thur, J.Y. Jung, and W. Wan, "CIRCE: a dedicated storage ring for coherent THz synchrotron radiation," in *Proceedings* of the International Workshop on Infrared Microscopy and Spectroscopy with Accelerator-Based Sources (Lake Tahoe, CA, July 8-11, 2003), Infrared Physics and Technology **45** (5-6), 325-330 (2004); LBNL-53699.

J.M. Byrd, Z. Hao, M.C. Martin, D.S. Robin, F. Sannibale, R.W. Schoenlein, M. Venturini and A.A. Zholents, "Coherent infrared radiation from the ALS generated via femtosecond laser modulation of the electron beam," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55688.

A.S. Loftsdottir, J. Byrd, and F. Sannibale, "Study of potential well distortion due to radiation impedance," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55822.

l'OASIS Group

Refereed Publications

J. Faure, J. van Tilborg, K.A. Kaindl, and W.P. Leemans, "Modelling laser-based table-top THz sources, optical rectification, propagation and electro-optic sampling," Optical & Quantum Electronics **36**, no. 8, June 2004, pp. 681-97; LBNL-57136**.**

G. Fubiani, E. Esarey, C.B. Schroeder, and W.P. Leemans, "Beat wave injection of electrons into plasma waves using two interfering laser pulses," Phys. Rev. E **70**, 016402 (2004); LBNL-53506.

C.G.R. Geddes, Cs. Toth, J. van Tilborg, E. Esarey, C.B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W.P. Leemans, "Guiding of relativistic laser pulses by preformed plasma channels," submitted to Phys. Rev. Lett., submitted (2004); LBNL-57058.

C.G.R. Geddes, Cs. Toth, J. van Tilborg, E. Esarey, C.B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W.P. Leemans. "Production of high quality electron bunches by dephasing andbeam loading in channeled and unchanneled laser plasma accelerators," invited paper, Phys. Of Plasmas (in press, 2005); LBNL-57062.

C.G.R. Geddes, Cs. Toth, J. van Tilborg, E.H. Esarey, C.B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W.P. Leemans, "High quality electron beams from a plasma channel guided laser wakefield accelerator," Nature **431**, 538-541 (2004); LBNL-55732.

W.P. Leemans, E. Esarey, J. van Tilborg, P.A. Michel, C.B. Schroeder, Cs. Toth, C.G.R. Geddes, and B.A. Shadwick, "Radiation from laser accelerated electron bunches: coherent terahertz and femtosecond x-rays," IEEE Trans. Plasma Sci. (in press, 2005); LBNL-56584.

W.P. Leemans, J. van Tilborg, J. Faure, C.G.R. Geddes, Cs. Toth, C.B. Schroeder, E. Esarey, G. Fubiani, and G. Dugan, "Terahertz radiation from laser accelerated electron bunches," *invited paper*, Phys. of Plasmas **5**, 2899-2906 (2004); LBNL-54258.

C.B. Schroeder, E. Esarey, and B.A. Shadwick, "Warm wavebreaking of nonlinear plasma waves with arbitrary phase velocities," Phys. Rev. Lett., submitted (2004); LBNL-57059.

C.B. Schroeder, E. Esarey, and W.P. Leemans,"Electron beam conditioning by Thomson scattering," Phys. Rev. Lett. **93**, 194801 (2004); LBNL-54095.

C.B. Schroeder, E. Esarey, J. van Tilborg, and W.P. Leemans, "Theory of coherent transition radiation generated at a plasma-vacuum interface," Phys. Rev. E **69**, 016501 (2004); LBNL-53228.

B.A. Shadwick, G.M. Tarkenton, and E. Esarey, "Hamiltonian description of low temperature, relativistic plasmas," Phys. Rev. Lett. **93**, 175002 (2004); LBNL-55103.

B.A. Shadwick, G.M. Tarkenton, E. Esarey, and C.B. Schroeder, "Fluid and Vlasov models of low temperature, collisionless laser-plasma interactions," *invited paper*, Phys. of Plasmas, accepted (2005); LBNL-57061.

J. van Tilborg, C.B. Schroeder, E. Esarey, and W.P. Leemans,"Pulse shape and spectrum of coherent diffraction-limited transition radiation from electron beams," Laser Particle Beams **22**, 415-422 (2004); LBNL-55868.

Cs. Toth, J. Faure, J. van Tilborg, C.G.R. Geddes, C. Schroeder, E. Esarey, and W.P. Leemans, "Tuning of laser pulse shapes in grating-based compressors for optimal electron acceleration in plasmas," Opt. Lett. **28**, 1823-1825 (2003); LBNL-52178.

R.M.G.M. Trines, L.P.J. Kamp, T.J. Schep, W.P. Leemans, E.H. Esarey, and F.W. Sluijter, "Enhancement of high-energy electron production through suppression of Raman backscattering," Europhys. Lett. **66**, pp. 492–498 (2004); LBNL-52175.

Unrefereed Conference Proceedings and Other Publications

D.L. Bruhwiler, D.A. Dimitrov, J.R. Cary, E. Esarey, and W. Leemans, "Simulation of ionization effects for high-density positron drivers in future plasma wakefield experiments," in *Proceedings* of the 2003 Particle Accelerator Conference (Portland, OR, May 2003), IEEE Cat. No. 03CH37423 (IEEE, Piscataway, NJ, 2003), pp. 734-6; LBNL-53431.

J.R. Cary, R. Giacone, C. Nieter, D. Bruhwiler, E. Esarey, G. Fubiani, and W. Leemans, "All-optical beamlet train generation," in *Proceedings* of the 2003 Particle Accelerator Conference (Portland, OR, May 2003), IEEE Cat. No. 03CH37423 (IEEE, Piscataway, NJ, 2003), pp. 719-21; LBNL-53432.

E. Esarey, S. Tochitsky, H. M. Milchberg, and C. B. Schroeder, "Summary report of working group: laser-plasma acceleration," in V. Yakimenko, ed., *Proceedings* of the 11th Advanced Accelerator Concepts Workshop (Stony Brook, NY, June 2004), AIP Conf. Proceedings **737** (New York: Amer. Inst. Phys., 2004), pp. 223-230; LBNL-56569.

D.A. Dimitrov, D. L. Bruhwiler, J. R. Cary, P. Messmer, C. Geddes, W. Leemans and E. Esarey, "Particle-in-cell simulations of intense laser pulses coupling into plasma channels," in V. Yakimenko, ed., *Proceedings* of the 11th Advanced Accelerator Concepts Workshop (Stony Brook, NY, June 2004), AIP Conf. Proceedings **737** (New York: Amer. Inst. Phys., 2004), pp. 469-477; LBNL-57057.

E. Esarey, C.B. Schroeder, and W.P. Leemans, "Plasma cathode: colliding pulse optical injection," *invited chapter* in M. Uesaka, ed., Femtosecond Beam Science (World Scientific, in press), ISBN 1-86094-343-8; LBNL-52553.

E. Esarey, C.B. Schroeder, B.A. Shadwick, J. van Tilborg, C.G.R. Geddes, Cs. Toh, and W.P. Leemans, "Radiation generation from plasma-based accelerators," in *Proceedings* of ICOPS 2004, the 31st IEEE International Conference on Plasma Science (Baltimore, MD, June 28 – July 1, 2004); LBNL-57097.

E. Esarey, B.A. Shadwick, C.B. Schroeder, and W.P. Leemans. "Nonlinear pump depletion and electron dephasing in laser wakefield accelerators," in V. Yakimenko, ed., *Proceedings* of the 11th Advanced Accelerator Concepts Workshop (Stony Brook, NY, June 2004), AIP Conf. Proceedings **737** (New York: Amer. Inst. Phys., 2004), pp. 578-584; LBNL-56568.

G. Fubiani, E. Esarey, K. Nakamura, C.B. Schroeder, and W.P. Leemans, "Electron beam generation using two-pulse colliding-pulse injection and a plasma density gradient," in V. Yakimenko, ed., *Proceedings* of the 11th Advanced Accelerator Concepts Workshop (Stony Brook, NY, June 2004), AIP Conf. Proceedings **737** (New York: Amer. Inst. Phys., 2004), pp. 887-893; LBNL-57024.

C.G.R. Geddes, Cs. Tóth, J. van Tilborg, and W.P. Leemans, "Laser guiding at > 10^{18} W/cm^2 in plasma channels formed by the ignitor heater method," in *Proceedings* of CLEO/IQEC 2004, the Conference on Lasers and Electro-Optics and International Quantum Electronics Conference (San Francisco, CA, May 16 - 21, 2004); LBNL-51833.

C.G.R. Geddes, Cs. Toth, J. Van Tilborg, E. Esarey, C.B. Schroeder, D. Bruhwiler, J. Cary, and W.P. Leemans, "Laser guiding at relativistic intensities and wakefield particle acceleration in plasma channels," in V. Yakimenko, ed., *Proceedings* of the 11th Advanced Accelerator Concepts Workshop (Stony Brook, NY, June 2004), AIP Conf. Proceedings **737** (New York: Amer. Inst. Phys., 2004), pp. 521-527; LBNL-56157.

R. Giacone, J.R. Cary, C. Nieter, E. Esarey, G. Fubiani, W.P. Leemans, and C.B. Schroeder, "Generation of single pulse particle beams in a plasma channel by laser injection in laser wakefield accelerators," in *Proceedings* of the 2003 Particle Accelerator Conference

(Portland, OR, May 2003), IEEE Cat. No. 03CH37423 (IEEE, Piscataway, NJ, 2003), pp. 1885-7; LBNL-55069.

W.P. Leemans, "Laser wakefield accelerators: status and future," in *Proceedings* of ICOPS 2004, the 31st IEEE International Conference on Plasma Science (Baltimore, MD, June 28 – July 1, 2004); LBNL-57126.

Wim Leemans, "Advances in laser driven accelerator R&D," in V. Yakimenko, ed., *Proceedings* of the 11th Advanced Accelerator Concepts Workshop (Stony Brook, NY, June 2004), AIP Conf. Proceedings **737** (New York: Amer. Inst. Phys., 2004), pp. 11-28; LBNL-56226.

W.P. Leemans, C.G.R. Geddes, J. van Tilborg, M. Dickinson, S. DiMaggio, D. Syversrud, J. Wallig, N. Ybarrolaza, and Cs. Tóth, "L'OASIS Ti:sapphire laser facility: a multi-beam, multi-terawatt system for wake-field acceleration studies," in *Proceedings* of CLEO/IQEC 2004, the Conference on Lasers and Electro-Optics and International Quantum Electronics Conference (San Francisco, CA, May 16 - 21, 2004); LBNL-57114.

P. Michel, E. Esarey, C. B. Schroeder, Cs. Tóth, W. P. Leemans, and D. Schneider, "Thomson scattering from laser wakefield accelerators," in V. Yakimenko, ed., *Proceedings* of the 11th Advanced Accelerator Concepts Workshop (Stony Brook, NY, June 2004), AIP Conf. Proceedings **737** (New York: Amer. Inst. Phys., 2004), pp. 393-399; LBNL-56572.

K. Nakamura, K., G. Fubiani, C. G. R. Geddes, P. Michel, J. van Tilborg, C. Tóth, E. Esarey, C. B. Schroeder, and W. P. Leemans, "Laser triggered injection of electrons in a laser wakefield accelerator with the colliding pulse method," in V. Yakimenko, ed., *Proceedings* of the 11th Advanced Accelerator Concepts Workshop (Stony Brook, NY, June 2004), AIP Conf. Proceedings **737** (New York: Amer. Inst. Phys., 2004), pp. 901-906; LBNL-56575.

C. B. Schroeder, E. Esarey, and W. P. Leemans, "Beam conditioning for free-electron lasers via Thomson scattering," in V. Yakimenko, ed., *Proceedings* of the 11th Advanced Accelerator Concepts Workshop (Stony Brook, NY, June 2004), AIP Conf. Proceedings **737** (New York: Amer. Inst. Phys., 2004), pp. 628-634; LBNL-56570.

C.B. Schroeder, E. Esarey, B. A. Shadwick, and W. P. Leemans, "Trapping and dark current in plasma-based accelerators," in V. Yakimenko, ed., *Proceedings* of the 11th Advanced Accelerator Concepts Workshop (Stony Brook, NY, June 2004), AIP Conf. Proceedings **737** (New York: Amer. Inst. Phys., 2004), pp. 564-570; LBNL-56571.

B.A. Shadwick, G.M. Tarkenton, and E.H. Esarey, "Thermal effects in intense laser-plasma interactions," in V. Yakimenko, ed., *Proceedings* of the 11th Advanced Accelerator Concepts Workshop (Stony Brook, NY, June 2004), AIP Conf. Proceedings **737** (New York: Amer. Inst. Phys., 2004), pp. 449-455; LBNL-56584.

J. van Tilborg, G. Fubiani, C.G.R. Geddes, Cs. Tóth, E. Esarey, C.B. Schroeder, and W.P. Leemans, "High-energy coherent THz radiation from laser wakefield accelerated ultrashort electron bunches," in *Proceedings* of CLEO/IQEC 2004, the Conference on Lasers and Electro-Optics and International Quantum Electronics Conference (San Francisco, CA, May 16 - 21, 2004); LBNL-55864.

J. van Tilborg, C. G. R. Geddes, C. Tóth, E. Esarey, C. B. Schroeder, M. C. Martin, Z. Hao, and W. P. Leemans, "coherent transition radiation from a laser wakefield accelerator as an electron bunch diagnostic," in V. Yakimenko, ed., *Proceedings* of the 11th Advanced Accelerator Concepts Workshop (Stony Brook, NY, June 2004), AIP Conf. Proceedings **737** (New York: Amer. Inst. Phys., 2004), pp. 372-378; LBNL-56573.

Cs. Tóth, C.G.R. Geddes, J. van Tilborg, and W. P. Leemans, "A multi-beam, multi-terawatt Ti: sapphire laser system for laser wake-field acceleration studies," in V. Yakimenko, ed., *Proceedings* of the 11th Advanced Accelerator Concepts Workshop (Stony Brook, NY, June 2004), AIP Conf. Proceedings **737** (New York: Amer. Inst. Phys., 2004), pp. 978-982; LBNL-57056.

Cs. Tóth, J. van Tilborg, C.G.R. Geddes, G. Fubiani, C.B. Schroeder, E. Esarey, J. Faure, G. Dugan, and W.P. Leemans, "Powerful pulsed THz radiation from laser-accelerated relativistic electron bunches," Proc. SPIE **5448**, 491-504 (2004); LBNL-57055.

Cs. Tóth, J. Faure, J. van Tilborg, C. G. R. Geddes, C. B. Schroeder, E. Esarey, W. P. Leemans, "Asymmetric pulse shapes in grating-based CPA compressors and optimal electron acceleration in plasmas," in Ferenc Krausz, Georg Korn, Paul Corkum, and Ian A. Walmsley, eds., *Ultrafast Optics IV* (Berlin, Germany: Springer, 2004), pp. 351-358; LBNL-57054.

Theory Group

Refereed Publications

M. Babzien, I. Ben-Zvi, I. Pavlishin, I. Pogorelsky, V. Yakimenko, A. Zholents, and M. Zolotorev, "Optical stochastic cooling for RHIC using optical parametric amplification," Phys. Rev. Special Topics: Accelerators and Beams **7**, 012801; LBNL-54823 (2004).

M. Babzien, I. Ben-Zvi I. Pavlishin, I.V. Pogorelsky, V.E. Yakimenko, A.A., Zholents AA., and M. S. Zolotorev, "Optical stochastic cooling for RHIC," Nucl. Instrum. Meth. A **532**, 1-2, pp. 345-7; LBNL-57307 (2004).

M. Babzien, I. Ben-Zvi, I. Pavlishin, I.V., Pogorelsky, V.E. Yakimenko VE, A.A. Zholents, and M.S. Zolotorev, "Optical stochastic cooling for RHIC using optical parametric amplification," Phys. Rev. Special Topics: Accelerators and Beams **7**, 1; LBNL-54823 (2004).

W. Cheng, Y. Avitzour, Y. Ping, S. Suckewer, N. J. Fisch, M. S. Hur, and J. S. Wurtele, "Reaching the nonlinear regime of Raman amplification of ultrashort laser pulses," Phys. Rev. Lett. **94**, 045003 LBNL-57305 (2005).

R. Cimino, I.R. Collins, M.A. Furman, M. Pivi, F. Ruggiero, G. Rumolo, and F. Zimmermann, "Can low energy electrons affect high energy physics accelerators?," Phys. Rev. Lett. **93**, 014801 (Feb. 9, 2004); CERN-AB-2004-012; LBNL-54594; SLAC-PUB-10350.

L. Friedland, F. Peinetti, W. Bertsche, J. Fajans, and J. Wurtlele, “Driven phase space holes and synchronized Bernstein, Greene, and Kruskal modes,” Phys. Plasmas **11**, 4305; LBNL-57302 (2004).

Y. Honda, A. Wolksi et al., “Achievement of ultralow emittance beam in the Accelerator Test Facility damping ring,” Phys. Rev. Lett. **92**, 054802 (2004); LBNL-57214.

M.S. Hur, G. Penn, J.S. Wurtele, and R. Lindberg, “Slowly varying envelope kinetic simulations of pulse amplification by Raman backscattering," Phys. Plasmas **11**, 5204; LBNL-57304 (2004).

E. Keil and A. M. Sessler, “Muon acceleration in FFAG rings,” Nucl. Instrum. Meth. A **538**, p. 159 (2005); LBNL-54798.

R.R. Lindberg, A.E. Charman, and J.S. Wurtele, “Robust autoresonant excitation in the plasma beat-wave accelerator: a theoretical study,” arXiv:physics/0403081 (March 2004); LBNL-57303.

R. R. Lindberg, A.E. Charman, J.S. Wurtele and L. Friedland, “Robust autoresonant excitation in plasma beat-wave accelerator," Phys. Rev. Lett. **93**, 055001; LBNL-57311 (2004).

D. Mohl and A. M. Sessler, “Beam cooling: principles and achievements,” Nucl. Instrum. Meth. A **532**, 1 (2004); LBNL-54830.

H. Okamoto, K. Okabe, Y. Yuri, D. Mohl and A. M. Sessler, “One-dimensional ordering of ultra-low density ion beams in a storage ring,” Phys. Rev. E **69**, 066504 (2004); LBNL-54827.

J. Qiang, M.A. Furman, and R.D Ryne, “A parallel particle-in-cell model for beam-beam interaction in high energy ring colliders," J. Comp. Phys. 198, 1 (20 July 2004), pp. 278-294; LBNL-54598.

M. Venturini, R. Warnock, R. Ruth, and J. A. Ellison, “Coherent synchrotron radiation and bunch stability in a compact storage ring," Phys. Rev. Special Topics: Accelerators and Beams **8**, 014202 (2005); LBNL-54866.

R. Warnock, R. Ruth, M. Venturini, and J. A. Ellison, “Impedance description of coherent synchrotron radiation with account of bunch deformation,” Phys. Rev. Special Topics: Accelerators and Beams **8**, 014402 (2005); LBNL-57213.

A. Wolski, G. Penn, A. Sessler, and J. Wurtele, “Beam conditioning for FELs: consequences and methods," Phys. Rev. Special Topics: Accelerators and Beams **7**, 80701; LBNL-53899 (2004).

A. A. Zholents and W. M. Fawley, “Proposal for intense attosecond radiation from an x-ray free-electron laser,” Phys. Rev. Lett. **92**, 224801; LBNL-54084 (2004).

A.A. Zholents and G. Penn, “Obtaining attosecond X-ray pulses using a self-amplified spontaneous emission free electron laser,” submitted to Phys. Rev. Special Topics: Accelerators and Beams (2005); LBNL-56773.

Unrefereed Conference Proceedings and Other Publications

S. Berg, E. Keil, D. Trbojevic et al., “Review of current FFAG lattice studies in North America,” in *Proceedings* of the 17th International Conference on Cyclotrons and their Applications (Tokyo, Japan, Oct. 18 – 22, 2004); LBNL-57174.

J.M. Byrd, S. De Santis, J.-Y. Jung, M.C. Martin, W.R. McKinney, D.V. Munson, H. Nishimura, D. Robin, F. Sannibale, R.D. Schlueter, M. Venturini, W. Wan, and M.S. Zolotorev, “CIRCE, the coherent infrared center at the ALS," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55603.

A.E. Charman, G.E. Penn, A. Wolski, and J. Wurtele, “Beam conditioning and harmonic generation in free electron lasers,” in *Proceedings* of Frontiers of Nonlinear Physics 2004, July 2004; LBNL-57312.

J.N. Corlett, W.A. Barletta, S. De Santis, L. Doolittle, W.M. Fawley, P. Heimann, S. Leone, S. Lidia, D. Li, G. Penn, A. Ratti, M. Reinsch, R. Schoenlein, J. Staples, G. Stover, S. Virostek, W. Wan, R. Well, R. Wilcox, A. Wolski, J. Wurtele, and A. Zholents, “LUX - a recirculating linac-based facility for ultrafast x-ray science,” in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55621.

J.N. Corlett, W.M. Fawley, G. Penn, A.A. Zholents, W. Wan, M. Reinsch, J. Wurtele, “Harmonic cascade FEL designs for LUX, a facilty for ultrafast x-ray science,” in *Proceedings* of the 2004 FEL Conference (Trieste, Italy, August 29-September 3, 2004), pp. 637-9; LBNL-55020.

W. Fawley, A.A. Zholents, P. Emma, Z. Huang, G. Stupakov and S. Reiche , “Current-Enhanced SASE using an Optical Laser and its Application to the LCLS,” in *Proceedings* of the 2004 FEL Conference (Trieste, Italy, August 29-September 3, 2004), pp. 582-585; LBNL-54967.

W. Fawley, A.H. Lumpkin, and D.W. Rule, “A concept for z-dependent microbunching measurements with coherent x-ray transition radiation in a SASE FEL,” in *Proceedings* of the 2004 FEL Conference (Trieste, Italy, August 29-September 3, 2004), pp. 515-518; LBNL-55080.

W. Fawley, “Towards attosecond X-ray pulses from the FEL,” LBNL-55689.

W. Fawley, “Design study of the bending sections between harmonic cascade FEL stages,” LBNL-56171, June 2004.

W. Fawley, “Noise and temporal coherence evolution through a multi-stage harmonic cascade,” abstract submitted to the 2004 FEL Conference (Trieste, Italy, August 29-September 3, 2004); LBNL-54968 Abs. (2004).

W. Fawley and R.J. Briggs, “Campaign to minimize the transverse impedance of the DARHT-2 induction linac cells,” LBNL-56796 (February 2005).

W. Fawley and R. Briggs, “A simple model for induction core voltage distributions,” July 2004; LBNL-55079.

M.A. Furman, “Closing remarks,” in *Proceedings* of ECLOUD04, the 31st Internaional Committee for Future Accelerators (ICFA) Advanced Beam Dynamics Workshop on Electron-Cloud Effects (Napa, CA, 19-23 April 2004); LBNL-57165.

M.A. Furman, “ECLOUD04 workshop,” Sec. 5.2.1 of ICFA Beam Dynamics Newsletter No. 33 , p. 215 (April 2004); LBNL-56110,

M.A. Furman, “Goals for the workshop," in *Proceedings* of ECLOUD04, the 31st Internaional Committee for Future Accelerators (ICFA) Advanced Beam Dynamics Workshop on Electron-Cloud Effects (Napa, CA, 19-23 April 2004); LBNL-57166.

M.A. Furman, “Electron cloud build-up in hadron machines," Sec. 5.2.1 of ICFA Beam Dynamics Newsletter No. 33, p. 70 (April 2004); LBNL-56109 (Aug. 2004).

Y. Honda, J.L. Nelson, M.C. Ross, A. Wolski, and M.D. Woodley, “Coupling correction in the KEK-ATF using orbit response matrix analysis,” LBNL-57046, March 2005.

E. Keil, A.M. Sessler, and S. Berg, “Electron models of a FFAG muon accelerator,” in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-54819.

E. Keil, A.M. Sessler, and D. Trbojevic, “A non-scaling radial-sector fixed field alternating gradient (FFAG) ring for carbon cancer therapy,” in *Proceedings* of FFAG’04, the FFAG Accelerator Workshop (KEK, Tsukuba, Japan, October 13-16, 2004); LBNL-57191 Abs.

E. Keil, A.M. Sessler, and D. Trbojevic, “Fixed field alternating gradient accelerators (FFAG) for fast hadron cancer therapy,” abstract submitted to the 2005 Particle Accelerator Conference (Knoxville, TN, May 2005); LBNL-57176 Abs.

K.-J. Kim, B. Carlsten, D. Dowell , K. Flöttmann, K. Jensen, J. Petillo, A. Sessler, and G. Stupakov, “Towards advanced electron beam brightness enhancement and conditioning,” Argonne National Laboratory Report ANL/APS/LS-305, February 2004; LBNL-57179.

X.-P. Li, H. Enokizono, H. Okamoto, and Y. Yuri, A.M. Sessler, and J. Wei., “Phonon modes and the maintenance condition of a crystalline beam,” abstract submitted to the 2005 Particle Accelerator Conference (Knoxville, TN, May 2005); LBNL-57178 Abs.

R. Macek (*presenter*) and M.A. Furman, “Summary of the ECLOUD'04 workshop," *invited talk*, ICFA-HB2004, the ICFA Advanced Beam Dynamics Workshop on High Intensity and High Brightness Hadron Beams (Bensheim, Germany, October 18-22, 2004); LA-UR-04-8606; LBNL-57160 (2004).

S. Marks, M. Venturini, W. Wan, and A. Wolski, “Frequency map analysis of nonlinear dynamics in the NLC main damping rings,” LBNL-56505, August 2004.

S. Marks, M. Venturini, and A. Wolski, “Dynamic aperture study for the NLC main damping rings,” in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55882.

J.L. Nelson, M.C. Ross, A. Wolski, and M.D. Woodley, "Analysis of KEK-ATF optics and coupling using LOCO," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55726.

J.L. Nelson, M.C. Ross, A. Wolski, and M.D. Woodley, "Beam-based alignment at the KEK-ATF damping ring," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55728; SLAC-PUB-10587.

J.L. Nelson, M.C. Ross, A. Wolski, and M.D. Wooley, "Initial studies of nonlinear dynamics in the KEK-ATF wigglers," LBNL-57047, March 2005.

G. Penn, "Staged energy cascades for the LUX FEL," LBNL-55973.

G. Penn, M. Reinsch, J. Wurtele, J.N. Corlett, W.M. Fawley, A. Zholents, W. Wan "Harmonic cascade FEL designs for LUX," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004), p. 488; LBNL-56329.

G. Penn, M. Reinsch, and J.S. Wurtele, "Analytic Model of Harmonic Generation in the Low-Gain FEL Regime," in *Proceedings* of the 2004 FEL Conference (Trieste, Italy, August 29-September 3, 2004), p. 71-74; LBNL-56177.

S.O. Prestemon, D.S. Robin, R.D. Schlueter, C.A. Steier, and A.Wolski, "Study of row phase dependent skew quadrupole fields in Apple-II Type EPUs at the ALS," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-57210.

J. Qiang, M. Furman and R. D. Ryne, W. Fischer, and K. Ohmi, "Recent advances of strong-strong beam-beam simulation," in *Proceedings* of ICAP04, the 8th International Computational Accelerator Physics Conference (St. Petersburg State University, St. Petersburg, Russia, June 28-July 2, 2004); LBNL-56360 (2004).

I. Reichel and A. Wolski, "A reduced emittance lattice for the NLC positron predamping ring," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55449.

J. Seeman, J. Browne, Y. Cai, J.N. Corlett, C. Steier, A. Wolski, M.S. Zisman, W. Kozanecki, and G. Wormser, et al., "Results and plans of the PEP-II B-factory," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004), p. 875; LBNL-57208.

C.A. Steier, P.G. Tenenbaum, A.Terebilo, J.L. Turner, A. Wolski, and G. Yocky, "Orbit response matrix analysis applied at PEP-II," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-57207.

D. Trbojevic, A. G. Ruggiero, E Keil, N. Neskovic, and A. Sessler, "Design of a non-scaling FFAG accelerator for proton therapy," in *Proceedings* of the 17th International Conference on Cyclotrons and their Applications (Tokyo, Japan, Oct. 18-22, 2004); LBNL-57177.

D. Trbojevic, S.J. Berg, M. Blaskiewicz, A.G. Ruggiero, E. Keil, C. Johnston, M. Cradock, S. Koscielniak, A. Garren, A. Sessler, and E.D. Courant, "A design principle for the non-scaling fixed field alternating gradient synchrotron," LBNL-57212.

Y. Vinokurov, G. Penn. J.Wurtele, E. Esarey, A.M. Sessler, and A. Wolski, "Beam conditioning and FEL studies using MAD and Genesis," abstract submitted to the 2005 Particle Accelerator Conference (Knoxville, TN, May 2005); LBNL-56733 Abs.

A. Wolski, "Lattice design for an ILC damping ring with 3km circumference," LBNL-56506, October 2004.

A. Wolski, "Lattices with large dynamic aperture for ILC damping rings," LBNL-57045, February 2005.

M. Venturini, "Longitudinal single-bunch instabilities in the NLC main damping rings," LBNL-55103 (2004).

M. Venturini, S. Marks, and A. Wolski, "Dynamical aperture study for the NLC main damping rings," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55882.

M. Venturini and A. Wolski, "Dynamical map for combined function magnets with solenoid, dipole and quadrupole fields," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55807.

A. Wolski and M.D. Woodley, "Normal form analysis of linear beam dynamics in a coupled storage ring," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55727, SLAC-PUB-10589

A. Wolski and F. Zimmermann, "Summary of Workshop Session F on electron-cloud instabilities," in *Proceedings* of ECLOUD04, the 31st Internaional Committee for Future Accelerators (ICFA) Advanced Beam Dynamics Workshop on Electron-Cloud Effects (Napa, CA, 19-23 April 2004); LBNL-56002; CERN-2002-001, May 2004.

A. Wolski, "A simple way to characterize linear coupling in a storage ring," LBNL-54774, March 2004.

A. Wolski and F. Zimmermann, "Closed orbit response to quadrupole strength variation," LBNL-54360, January 2004.

R.L. Warnock, G.V. Stupakov, J.A. Ellison, and M. Venturini, "Linear Vlasov analysis for stability of a bunched beam," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55806

A. Zholents, J.M. Byrd, W. Fawley, Z. Hao, M.C. Martin, D. Robin, F. Sannibale, R.W. Schoenlein, M. Venturini, M.S. Zolotorev, "Towards attosecond x-ray pulses from the FEL," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55689

A. Zholents, J.M. Byrd, Z. Hao, M.C. Martin, D. Robin, F. Sannibale, R.W. Schoenlein, M. Venturini, M.S. Zolotorev, "Coherent infrared radiation from the ALS generated via femtosecond laser modulation of the electron beam," in *Proceedings* of the 2004

European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-57301.

F. Zimmermann, E. Benedetto, F. Ruggiero, D. Schulte, M. Blaskiewicz, L. Wang, G. Bellodi , G. Rumolo, K. Ohmi, S.S. Win, M.A. Furman, Y. Cai, M. Torino, F. Pivi, V.K. Decyk, W. Mori, A.F. Ghalam, and T. Katsouleas, "Review and comparison of simulation codes modeling electron-cloud build up and instabilities," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55239.

Collider Physics Group

Refereed Publications

B. Dehning, J. Matheson, G. Mugnai, I. Reichel, R. Schmidt, F. Sonnemann, and F. Tecker, "Beam based alignment at LEP," Nucl. Instrum. Meth. A **516**, 9 (2004); LBNL-56099.

Unrefereed Conference Proceedings and Other Publications

G. Barr, E. Baynham, E. Black, T. Bradshaw, M.A.C. Cummings, M.A. Green, S. Ishimoto, Y. Ivanushenkov, W. Lau, and M. Zisman, "MICE Absorber and Focus Coil Safety Working Group design document: preliminary design and assessments," M. Zisman, ed.; LBNL-55860.

J.S. Berg, E. Keil, D. Trbojevic, and A.M. Sessler, "Review of current FFAG lattice studies in North America," in *Proceedings* of the 17th International Conference on Cyclotrons and their Applications (Tokyo, Japan, Oct. 18-22, 2004); LBNL-57174.

P. Fabbricatore, S. Farinon, U. Bravar, and M. A. Green. "The mechanical and thermal design for the MICE detector solenoid magnet system," IEEE Transactions on Applied Superconductivity **15**, No. 2 (in press); LBNL-57376 (2005).

M. A. Green, S. Q. Yang, G. Barr, U. Bravar, J. Cobb, W. Lau, R. S. Senanayake, and H. Witte, "The mechanical and thermal design for the MICE focusing solenoid magnet system," IEEE Transactions on Applied Superconductivity **15**, No. 2 (in press); LBNL-57396 (2005).

M.A. Green, G. Barr, W. Lau, R. S. Senanayake, and S. Q. Yang "The MICE focusing solenoids and their cooling system," in *Proceedings* of the International Cryogenic Engineering Conference (Beijing, China, 11-14 May 2004); LBNL-57380.

M.A. Green, S. Q Yang, and W. Lau, "Modeling free convection flow of liquid hydrogen within a cylindrical heat exchanger cooled with helium gas at 14 K," in *Proceedings* of the International Cryogenic Engineering Conference (Beijing, China, 11-14 May 2004); LBNL-57379.

M. A. Green, S. Q. Yang, and W. Lau, "Modeling the thermal mechanical behavior of a 300 K vacuum vessel that is cooled by liquid hydrogen in film boiling," in *Proceedings* of the International Cryogenic Engineering Conference (Beijing, China, 11-14 May 2004); LBNL-57378.

E. Keil, A.M. Sessler, and S.Berg, "Electron models of a FFAG muon accelerator," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-54819.

E. Keil, A.M. Sessler, and D. Trbojevic, "A non-scaling radial-sector fixed field alternating gradient (FFAG) ring for carbon cancer therapy," in *Proceedings* of the 17th International Conference on Cyclotrons and their Applications (Tokyo, Japan, Oct. 18-22, 2004); LBNL-57191.

D. Li., S. Virostek, M. Green, and M. Zisman, "Progress on rf coupling coil module design for the MICE channel," abstract submitted to the 2005 Particle Accelerator Conference (Knoxville, TN, May 2005); LBNL-56730 Abs.

M.A. Green, G. Barr, E. Baynham, J. Cobb *et al*., "Design issues for the superconducting focusing magnet that goes around the liquid hydrogen absorber for the Muon Ionization Cooling Experiment (MICE)," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004), p. 1765; LBNL-57377.

I. Reichel, M.S. Zisman, M. Placidi, K. Gollwitzer, and S. Werkema, "Aperture studies for the AP2 anti-proton line at Fermilab," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004), p. 1491; LBNL-54096.

I. Reichel and A. Wolski, "A reduced emittance lattice for the NLC positron pre-damping ring," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004); LBNL-55449.

J. Seeman, J. Browne, Y. Cai, J.N. Corlett, C. Steier, A. Wolski, M.S. Zisman, W. Kozanecki, and G. Wormser, et al., "Results and plans of the PEP-II B-Factory," in *Proceedings* of the 2004 European Particle Accelerator Conference (Lucerne, Switzerland, July 5 - 9, 2004), p. 875; LBNL-57208.

D. Trbojevic, A. G. Ruggiero, E Keil, N. Neskovic, X. Vinca and A. Sessler, "Design of a non-scaling FFAG accelerator for proton therapy," in *Proceedings* of the 17th International Conference on Cyclotrons and their Applications (Tokyo, Japan, Oct. 18-22, 2004); LBNL-57177.

M.S. Zisman, "Muon ionization cooling experiment (MICE)," in *Proceedings* of the 22nd International Linear Accelerator Conference (Lubeck, Germany, August 16-20, 2004); LBNL-56146.

AMAC Group

Refereed Publications

P. McCorquodale, P. Colella, D.P. Grote, and J.L. Vay, "A node-centered local refinement algorithm for Poisson's equation in complex geometries," submitted to J. Comp. Phys (2004).

E. Sonnendrucker, F. Filbet, A. Friedman, E. Oudet, and J.L. Vay, "Vlasov simulations of beams with a moving grid," Comp. Physics Comm. (in press).

J. Qiang, R.D. Ryne, and I. Hofmann, "Space-charge driven emittance growth in a 3D mismatched anisotropic beam," Phys. Rev. Lett. **92**, 174801 (2004); LBNL-51807.

J. Qiang, "Halo formation due to beam-beam interactions of beams optically mismatched at injection," Phys. Rev. Special Topics: Accelerators & Beams **7**, 031001 (2004); LBNL-56054.

J. Qiang, M. Furman, and R. Ryne, "A parallel particle-in-cell model for beam-beam interactions in high energy ring colliders," *J. Comp. Phys*. (2004); LBNL-54598.

J.L. Vay, P. Colella, J.W. Kwan, P. McCorquodale, D.B. Serafini, A. Friedman, D.P. Grote, G. Westenskow, J.C. Adam, A. Héron , and I. Haber, "Application of adaptive mesh refinement to particle-in-cell simulations of plasmas and beams," Phys. of Plasmas, in press (2004); LBNL-53551.

J.L. Vay, P. Colella, A. Friedman, D.P. Grote, P. McCorquodale, and D.B. Serafini, "Implementations of mesh refinement schemes for particle-in-cell plasma simulations"; Comp. Physics Comm. (in press); LBNL-54046 (2004).

J.L. Vay, J.C. Adam, and A. Héron, "Asymmetric PML for the absorption of waves. application to mesh refinement in electromagnetic particle-in-cell plasma simulations," Comp, Physics Comm. (in press); LBNL-52676 (2004).

J. Qiang and R. Gluckstern, "Three-dimensional Poisson solver for a charged beam with large aspect ratio in a conducting pipe," submitted to Comp. Phys. Comm; LBNL-54282 (2004).

J. Qiang, "Halo formation from mismatched beam-beam interactions," submitted to Phys. Rev. Special Topics: Accelerators & Beams; LBNL-54353 (2004).

Tawada, M; Cai, Y; Ohmi, K; Kamada, S; Qiang, J; and Oide, K,, "Study of the beam-beam limit in e+ e- circular colliders," in *Proceedings* of ICAP04, the 8th International Computational Accelerator Physics Conference (St. Petersburg State University, St. Petersburg, Russia, June 28-July 2, 2004), *Phys. Rev. Lett*. **92**, 214801 (2004); LBNL-55556.

K. Ohmi, M. Tawada, Y. Cai, S. Kamada, K. Oide, and J. Qiang, "Luminosity limit due to the beam-beam interactions with or without crossing angle," Phys. Rev. Special Topics: Accelerators & Beams **7**, 104401 (2004); LBNL-57267.

R. Garnett and J. Qiang, "Smooth Approximation with Acceleration in an Alternating Phase Focusing Superconducting Linac," Nucl. Instrum. Meth. A **496**, 33 (2003); LBNL-50146.

Unrefereed Conference Proceedings and Other Publications

I. Hofmann, G. Franchetti, J. Qiang, and R.D. Ryne, "Self-consistency and coherent effects in nonlinear resonances," in *Proceedings* of HALO'03, the 29th International Committee on Future Accelerators (ICFA) Advanced Beam Dynamics Workshop on Beam Halo Dynamics, Diagnostics, and Collimation (May 19-23, Montauk, NY); LBNL-54601 (2003).

M. Ikegami, T. Kato, Z. Igarashi, A. Ueno, Y. Kondo, J. Qiang, and R. Ryne, "Comparison of particle simulation with J-PARC Linac MEBT beam test results," in *Proceedings* of HALO'03, the 29th International Committee on Future Accelerators (ICFA) Advanced Beam Dynamics Workshop on Beam Halo Dynamics, Diagnostics, and Collimation (May 19-23, Montauk, NY); LBNL-54600.

J. Qiang, M. Furman, and R.D. Ryne, "Recent advances and applications of beam-beam simulation codes," in *Proceedings* of ICAP04, the 8th International Computational Accelerator Physics Conference (St. Petersburg State University, St. Petersburg, Russia, June 28-July 2, 2004); LBNL-55539a.

M. Tawada, Y. Cai, K. Ohmi, and J. Qiang, "Beam-beam simulation studies for PEP-II and KEKB," LBNL-55558.

M. Tawada Y. Cai, K. Ohmi, J. Qiang, K. Oide, and S. Kamada, "Study of beam-beam interactions with or without crossing angle," in *Proceedings* of ICAP04, the 8th International Computational Accelerator Physics Conference (St. Petersburg State University, St. Petersburg, Russia, June 28-July 2, 2004); LBNL-55557.

J. Qiang, "Strong-strong beam-beam simulation on parallel computer," LBNL-57366, July 2004.

R.H. Cohen, A. Azevedo, A. Friedman, M.A. Furman, A.W. Molvik, P.H. Stoltz, and J.-L. Vay, "Simulating electron cloud effects in heavy-ion accelerators, 15th International Symposium on Heavy Ion Inertial Fusion (Princeton, NJ, June 7-11, 2004); LBNL-56056.

A.W. Molvik, F.M. Bieniosek, R.H. Cohen, S. Eylon,A. Faltens, A. Friedman, E. Henestroza, M. Kireeff Covo, J.W. Kwan, S.M. Lund, L. Prost, P.K. Roy, P.A. Seidl, J.-L. Vay, G. Westenskow, and S. Yu, "Experimental studies of electrons in a heavy-ion beam," LBNL-55237 (July 2004).

A.W. Molvik, R.H. Cohen, A. Friedman, M. Kireeff Covo, S.M. Lund, F.M. Bieniosek, E.P. Lee, L. Prost, P.A. Seidl, J.-L. Vay, and M.A. Furman, "Progress in measuring electron cloud effects in HIF accelerators," presented at the 45th Annual Meeting of the American Physical Society Division of Plasma Physics (Albuquerque, NM, Oct. 27-31, 2003); LBNL-53550.

J. Qiang, M.A. Furman, R.D. Ryne, W. Fischer, and K. Ohmi, "Recent advances of strong-strong beam-beam simulation," in Proceedings of ICAP04, the 8th International Computational Accelerator Physics Conference (St. Petersburg State University, St. Petersburg, Russia, June 28-July 2, 2004); LBNL-56360.

J. Qiang, M. Furman, R.D. Ryne, W. Fischer, T. Sen, M. Xiao, "Parallel strong-strong/strong-weak simulations of beam-beam interactions in hadron accelerators," in *Proceedings* of HALO'03, the 29th International Committee on Future Accelerators (ICFA) Advanced Beam Dynamics Workshop on Beam Halo Dynamics, Diagnostics, and Collimation (May 19-23, Montauk, NY); LBNL-53638.

J. Qiang, R.D. Ryne, T. Sen, and M. Xiao, "Macroparticle simulations of antiproton lifetime at 150 GeV in the Tevatron," in *Proceedings* of the 2003 Particle Accelerator Conference (Portland, OR, May 2003), IEEE Cat. No. 03CH37423 (IEEE, Piscataway, NJ, 2003); LBNL-51808.

P.H. Stoltz, M.A. Furman, J.-L. Vay, A.W. Molvik, and R.H. Cohen, "Numerical simulation of the generation of secondary electrons in the High Current Experiment," Phys. Rev. Special Topics: Accelerators & Beams **6**, 5; LBNL-54710 (2004).

M. Venturini, J. Qiang, R. Ryne, and A. Wolski, "Space-charge effects in the ILC damping rings," in *Proceedings* of the 2003 Particle Accelerator Conference (Portland, OR, May 2003), IEEE Cat. No. 03CH37423 (IEEE, Piscataway, NJ, 2003); LBNL-56727 Abs.

T. P. Wangler, K.R. Crandall, R.W. Garnett, D. Gorelov, P. Ostroumov, J. Qiang, R. Ryne, R. York, "Advanced beam-dynamics simulation tools for the RIA driver linac, part I: low energy beam transport and radiofrequency quadrupole," in *Proceedings* of the RIA R&D Workshop (August 26-28, 2003, Washington, DC).

T.P. Wangler, C.K. Allen, K.C.D. Chan, P.L. Colestock, K.R. Crandall, R.W. Garnett, J.D. Gilpatrick, W. Lysenko, J. Qiang, J.D. Schneider, M.E. Shulze, R.I. Sheffield, and H.V. Smith, "Beam-halo in mismatched proton beams," Nucl. Instrum. Meth. A **519**, 425 (2004); LBNL-56055.

4. SUPERCONDUCTING MAGNETS

Reported by Stephen Gourlay, Program Head

> *Mission: Develop and establish the technologies associated with high field superconducting magnets in order to provide cost-effective options for the next-generation high-energy physics accelerators and apply our expertise towards achieving the goals of the high-energy-physics community.*

Performance requirements of modern accelerators continue to press the limits of magnet technology. Ever-higher beam energy is a constant goal in high-energy physics, so magnets must be made both stronger and more cost-effective. Advanced magnets are especially important in an upgrade scenario, where a higher-energy and/or higher-luminosity machine must fit into an existing tunnel. Our program is directed towards advancing all aspects of the technological infrastructure for high field magnet development relevant to possible future accelerators.

Our role—as not only a leading R&D group but also the administrators of the multi-institutional DOE/HEP National Conductor Development Program—is to create both evolutionary improvements and paradigm shifts in the application of accelerator magnets, providing innovative technology that enables new science. Achievement of these goals requires development and application of new materials, new magnet designs, and new techniques for magnet construction.

These innovations will find application both in dipole bending magnets for hadron machines at the energy frontier and in final-focus quadrupoles for high-luminosity interaction points. In addition, this work will benefit non-HEP applications, such as superconducting undulators in light sources.

In recent years we have passed a number of key milestones in both magnet fabrication and materials development work, culminating in the successful test of HD-1, which exceeded 16 tesla. To put this result in perspective, one might compare it with the world's other high-field programs, none of which have exceeded 11.5 T despite considerable investment and effort. The success of our program has been internationally recognized.

While much of our attention is focused upon the base of enabling technologies for future high-energy colliders, our unique capabilities can already provide essential contributions to HEP. In particular, LBNL is a key player in the US LHC Accelerator Research Program (LARP). Started in 2003 by the U.S. Department of Energy, LARP brings together the resources of four national laboratories (BNL, FNAL, LBNL, and SLAC) to develop advanced technology for future LHC upgrades. Upgrading the machine luminosity was identified by the High-Energy Physics Advisory Panel (HEPAP) as an "absolutely central" medium-term goal. A key element in this effort is the development of powerful Nb_3Sn quadrupoles to better focus the beams at the interaction points. LBNL supports this goal with a broad magnet R&D effort involving design studies, conductor R&D, mechanical models, and simple prototypes.

Much of our magnet R&D work involves close collaboration with industry, in particular on the development of advanced superconductors and improved manufacturing methods. This area of R&D includes superconducting materials with high critical current density at high field, and very fine filaments (to improve stability and reduce losses). New cable manufacturing methods and insulation materials are also required. These collaborations are carried out through the DOE/HEP National Conductor Development Program as well as the Small Business Innovation Research (SBIR) program. Each year we contribute to the SBIR program by providing technical support to the companies and advice on the DOE programmatic goals.

Figure 4-1 shows the organization of our program, with its two major groups of elements—materials and cabling, and magnets.

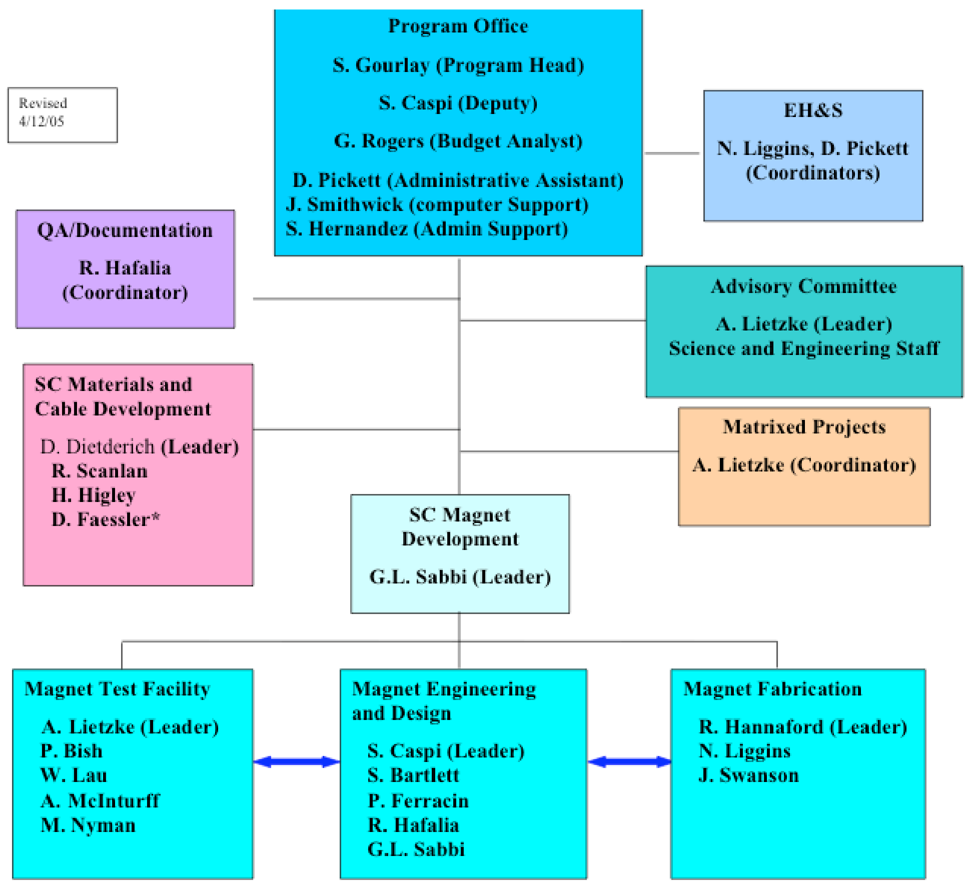


Figure 4-1. *Two major areas of endeavor—development of superconducting materials and cable, and design, fabrication, and test of magnets—make up a "complete from melt to magnet" set of capabilities.*

Conductor and Cable Development

Stronger and more-affordable magnets alike start with better materials and cable, and the goals of the National Conductor Development Program are quite demanding: a critical current density of 3000 A/mm^2 (at 4.2 K and 12 T) and a net cost of \$1.5 per kA-m. (For comparison, the NbTi superconductor for the Superconducting Super Collider in the early 1990s cost the same per kA-m at the much lower field of 6 T.) Now in the sixth year and supported at \$500k per year, the program has made impressive progress towards these goals. The J_c of Nb_3Sn conductor now exceeds 3000 A/mm^2, and we are projecting that the cost goals can be met when the manufacturing processes, now at the research stage, are properly industrialized.

With those goals achieved or in sight, the emphasis of the program is turning toward reducing filament diameter while maintaining the current density. Related studies include:

- Cabling work to reduce critical current (I_c) degradation
- Techniques for making cable out of new conductor designs such as powder-in-tube
- Heat treatment studies to optimize the residual resistivity ratio and J_c
- The effect of transverse strain on degradation and the relationship of strain degradation to the conductor substructure

Besides our work in the National Conductor Development Program *per se*, we continue to provide significant cabling support for other magnet and cable development programs.

Coil Geometries and Magnet Construction Techniques

At present, accelerator magnet technology is dominated by the use of NbTi superconductor and the magnet geometries and construction techniques suited to this ductile material. For several years, though, it has been clear that parameters in future accelerators and upgrades, such as field or gradient and large beam-induced heat loads, will require the use of materials well beyond the capabilities of NbTi. The magnets for the Large Hadron Collider (LHC), soon to be commissioned at CERN, represent the ultimate application of NbTi.

Further progress beyond 10 T requires the use of the "A15" compounds. The most practical and available of them is Nb_3Sn, which has been the focus of accelerator magnet programs in the US. In a practical geometry, magnets based on Nb_3Sn technology should be able to exceed fields of 16-17 T at 4.2 K. In a recent single test we succeeded (where others had failed) in achieving 16 T in a dipole magnet. The experiment also served as proof of principle for an approach to building high-field magnets out of this brittle material.

Higher fields (17-18 T) should be achievable at 1.8 K. The challenge however, is to support the brittle, strain-sensitive conductor against the immense Lorentz forces while keeping the stress to below 200 MPa or lower. New fabrication techniques, materials, instrumentation and design will be needed to investigate coil geometries, support structures and fabrication.

The route to these very-high field accelerator magnets is being pursued through parallel research paths. One is the use of sub-scale magnets for focused technology development. This sub-scale approach is now an integral part of our main program. Sub-sized models are a cost-efficient way to test support-structure designs, conductors and cables, quench-protection schemes, and fabrication techniques. If new materials such as MgB_2 or Bi-2212 become available in sufficient quantity and with good properties, coils of those materials will be fabricated and tested in the sub-sized models.

It is becoming increasingly apparent that sophisticated analysis is the key to building successful magnets, so we have placed more and more emphasis on this area, making significant progress. Our design team has combined a number of engineering tasks into a single streamlined process. Integrating mechanical, magnetic, structural, thermal and electrical design has now become routine. This level of integration of multiple disciplines, which appears unique to our program, is used to investigate new and more complex magnet designs. It will also help us unravel complex mechanics-related performance issues, such as the near universally observed but still incompletely understood "training" process by which a magnet reaches its full potential in a series of ramps to successively higher fields, interspersed with quenches.

Near-Term Contributions and LARP

While much of our attention is the base of enabling technologies for future high-energy colliders, we are also well positioned to provide significant contributions to HEP in the near term. In particular, LBNL is a key player in the US LHC Accelerator Research Program (LARP). Started in 2003 by the U.S. Department of Energy, LARP brings us together with Fermilab and Brookhaven to develop advanced magnet technology for future LHC upgrades. LBNL supports this program with a broad effort involving design studies, Nb_3Sn conductor R&D, mechanical models, and simple prototypes. The High-Energy Physics Advisory Panel (HEPAP) has determined that such a luminosity upgrade is "absolutely central" to the future of HEP.

In addition, we are providing support to ongoing projects (separately funded) in other areas of science, such as nuclear physics, fusion energy science, high energy density physics, light sources, and nuclear magnetic resonance.

The main component of the magnet program in FY06 will be the fabrication and test of HD2. A successful test of HD2 will represent a promising step toward an LHC energy doubler (~15 Tesla operating field); in particular, for upgrade scenarios involving a high field, single-turn injector with a limited dynamic range in the main collider ring.

The magnet design and analysis effort in FY06 will be directed towards a further increase of the dipole field. This objective will require a combination of improved material properties, better design efficiency, and a complete understanding of the behavior of the coil and structure under large forces. As an optional next step in this direction, an upgraded version of HD1 could be developed, aiming at a dipole field above 17 T. This goal may be achieved using the fabrication and testing experience from HD1, improved conductor, and a lower operating temperature.

The sub-scale program will continue with investigations into conductor and insulation development, new instrumentation, thermo-mechanical effects and quench protection studies. In addition, the fabrication and test of a sub-scale coil using the high-temperature-superconductor Bi-2212 will be pursued, in view of possible applications of high-temperature superconductor technology (which we use cryogenically) to develop coil inserts for the main dipoles.

In the near future we will also be actively pursuing expansion of our technology and techniques into other areas, such as power transmission, energy production, very high field magnetic-resonance imaging, and the International Thermonuclear Experimental Reactor (ITER) project.

The Road Further Ahead

Achieving 16 T in a dipole configuration was a major step, establishing the feasibility of Nb_3Sn for accelerator applications. But it is only the beginning of a complex, synergistic group of processes that will lead to the ultimate goal of an industrialized, multi-meter-long magnet with large aperture and accelerator-grade field quality. Getting there will require an intensive, long-term effort by both LARP and our base program to address several issues.

The medium-term goals (5 – 7 years) include increasing the field to the maximum practical limit for Nb_3Sn, which is approximately 17 T; increasing the bore size; and improving the field quality. Length issues are particularly important to understand, so within the next several years, a quadrupole 3 to 4 m long should be produced, followed a few years later with the demonstration of a practical quadrupole that meets the requirements for an LHC interaction region upgrade.

A very-high-field, accelerator-quality collider dipole that operates above 15 T under high synchrotron-radiation heat loads will take significantly longer to develop. With a vigorous, adequately funded program, this technology can be demonstrated by 2015.

Superconducting Magnet Design

Reported by Shlomo Caspi, Magnet Design Team Leader

LBNL has now tested several 1-m-long magnets, including the record-setting HD1, proving that Nb_3Sn magnet technology can be successfully used up to 16 T and can withstand an applied pre-stress of 180 Mpa. The use of keys and bladder in combination with an external aluminum shell to assemble magnets out of this brittle material has proved effective at delivering high pre-stress and taking full advantage of the thermal expansion difference between iron and aluminum.

We have achieved complete integration of computer-aided design methods for the electrical (PRO-E), magnetic (TOSCA) and structural (ANSYS) aspects of these magnets. The result is not only a greatly improved magnet design process, but also new insight into magnet training. The subscale magnet program proved to be an excellent way of testing new hypotheses about training, and with the inclusion of strain gauges into coils during impregnation, we established a new way of measuring the state of coils during assembly, cool-down, excitation and a quench.

The high field program is now at a crossroads. We are facing two important question regarding Nb_3Sn dipole magnets. First, what is the next logical field point to aim for beyond 16 tesla? Second, what will be the impact of stress from the Lorentz forces at that field? In a recent analytical study we attempted to answer both questions. The technology for pushing Nb_3Sn dipoles fields to 18 or even 20 T is quite possible today. Such magnets could be built without stress management, but the cost would be too high for the hundreds or thousands of magnets needed in accelerators, though it would be acceptable for one-of-a-kind experiments.

To reduce magnet cost, R&D will have to concentrate on reducing coil size (the larger the coil the greater the stress), reducing overall magnet size, and keeping the coils stress below 200 MPa. The study also pointed out the need for including high-T_c insert coils for fields beyond 16 T. Given successful R&D, this would be a good way to implement "grading"— adjustment of the current density between the inner and outer coils of a magnet in accordance with the difference in maximum field between these layers. Grading results in a more efficient coil because less conductor is needed to reach a given field or gradient, but has the indirect effect of increasing the coil stress.

Details of the Dipole Study

In a dipole carrying a cosine theta current distribution, the coil size W will correspond to the maximum attainable field according to the curves shown in Figure 4-2 (assuming the best conductors for both NbTi and Nb_3Sn). Replacing the NbTi LHC dipole (W=31 mm) with Nb_3Sn would bring that magnet to ~16T, an increase of ~6T from the present NbTi limit. Doubling the coil size from 31mm to 62mm would increment the field to 18.5 T (an increase of 2.5 T at a cost of more than twice the coil area).

The corresponding Lorentz stress created at high fields is given in Figure 4-3 for different bore sizes. The decrease in Lorentz stress with increased field is a result of the increase in the coil width (W) needed to generate that field. Clearly, beyond 16 T, improving the conductor current density will reduce coil size at the expense of higher stress.

The stored energy at high fields will become an additional R&D issue, as it will increase by a factor of 3-4 beyond present-day protection levels (Figure 4-4).

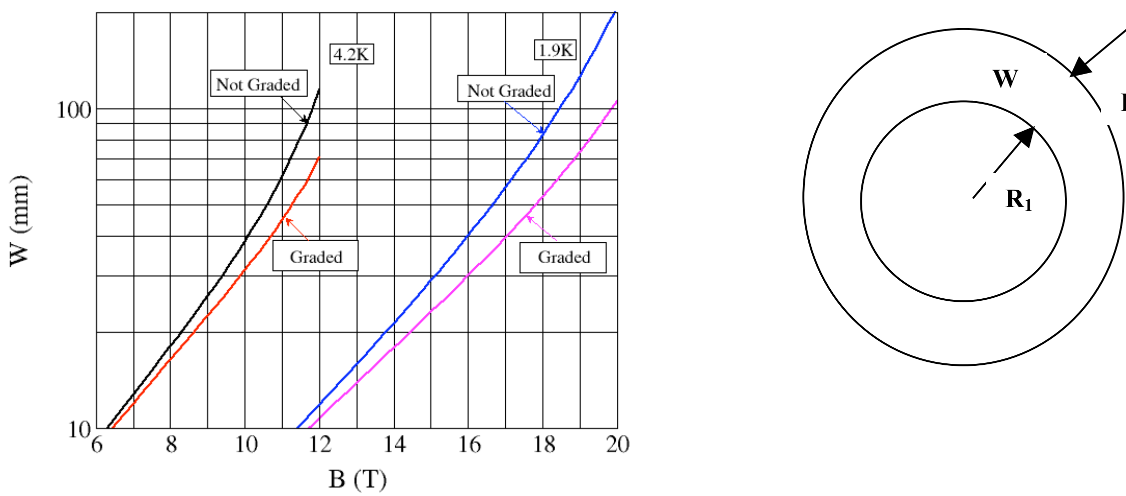


Figure 4-2. Coil size W for a maximum attainable dipole field. The assumed current densities for both NbTi and Nb_3Sn are the best available today.

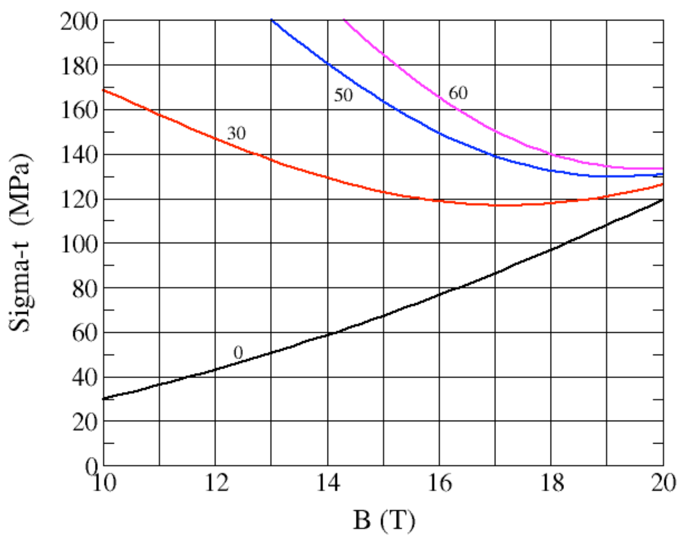


Figure 4-3. Maximum stress under Lorentz forces decreases with field due to the increase in coil size W required to generate that field. The curves correspond to several bore sizes in mm.

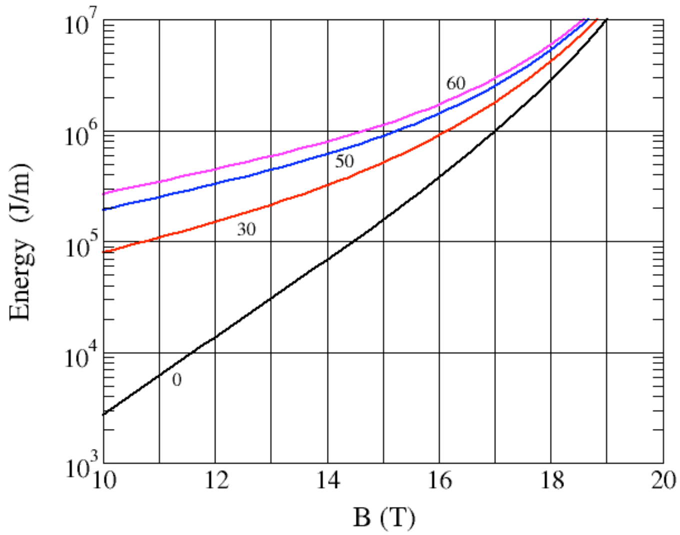


Figure 4-4. Stored energy in Nb_3Sn dipoles as a function of field. The curves correspond to several bore sizes in mm.

Very High Field Accelerator Magnets

Reported by GianLuca Sabbi, Magnet Development Team Leader

Accelerator magnet technology is dominated by the use of NbTi superconductor, with magnet geometries and construction techniques suited to this ductile material. For several years, however, it has been clear that parameters in future accelerators and upgrades, such as field or gradient and large beam-induced heat loads, will require the use of materials well beyond the capabilities of NbTi. The magnets for the Large Hadron Collider (LHC), soon to be commissioned at CERN, represent the ultimate application of NbTi.

Further progress beyond 10 T requires the use of the "A15" compounds. The most practical and available of them is Nb_3Sn, which has been the focus of accelerator magnet programs in the US. In a practical geometry, magnets based on Nb_3Sn should be able to exceed fields of 16-17 T at 4.2 K. In a recent single test we succeeded in achieving 16 T in a dipole magnet. The experiment also served as proof of principle for an approach to building high-field magnets out of this brittle material.

Higher fields (17-18 T) should be achievable at 1.8 K. The challenge however, is to support the brittle, strain-sensitive conductor against the very large Lorentz forces while keeping the stress below 200 MPa. New fabrication techniques, materials, and instrumentation will be needed in pursuing this goal, as well as design concepts involving optimized coil geometries and support structures.

In order to probe the ultimate performance limits of materials and magnets, full-scale prototypes are required. However, many technology development issues can be more effectively addressed using small models. In order to make the best use of our resources, several years ago we have started a sub-scale magnet series focused on issues such as the test of new support structures, cables, quench-protection schemes, and fabrication techniques. In the future, the sub-scale series will also be used to evaluate new conductors such as MgB_2 or Bi-2212, once they become available in sufficient quantity and with properties and cost suitable for practical magnet R&D.

It is becoming increasingly apparent that sophisticated analysis is the key to building successful magnets, so we have placed more and more emphasis on this area, making significant progress. Our design team has combined a number of engineering tasks into a single streamlined process. Integrating mechanical, magnetic, structural, thermal and electrical design has now become routine.

This level of integration of multiple disciplines, which appears to be unique to our program, is used to investigate new and more complex magnet designs. It will also help us unravel subtle mechanics-related performance issues, such as the near universally observed but still incompletely understood "training" process by which a magnet reaches its full potential in a series of ramps to successively higher fields, interspersed with quenches.

Our design and analysis capabilities, along with our parallel approach to model magnet R&D, have resulted in a very efficient use of program resources leading to successful tests of three record-setting dipoles based on three different coil configurations: cosine-theta (D20, 13.5 T); common coil (RD3b, 14.5 T); and block-coil (HD1, 16.1 T). The magnet design and analysis effort in FY06 and beyond will be directed towards a further increase of the dipole field. This objective will require a combination of improved material properties, better design efficiency, and a complete understanding of the behavior of the coil and structure under large forces.

In FY06, the main component of this program will be the fabrication and test of HD2, a 15 T dipole with 35 mm clear bore. A successful test of HD2 will represent a promising step toward an LHC energy doubler. As an additional step towards this goal, an upgraded version of HD1 may be developed, aiming at a dipole field above 17 T. This goal may be achieved using the fabrication and testing experience from HD1, improved conductor, and a lower operating temperature.

Following HD2, we will begin the design of HD3. The objectives for this magnet are a short-sample dipole field of 17 T (using graded coils with either Nb_3Sn or high-temperature superconductor inserts), a 40-50 mm aperture, and improved field quality.

The sub-scale program will continue with investigations into conductor and insulation development, new instrumentation, thermo-mechanical effects and quench protection studies. In addition, the fabrication and test of a sub-scale coil using the high-temperature superconductor Bi-2212 will be pursued, in view of possible applications of high-temperature superconductor technology (which we use cryogenically) to develop coil inserts for the main dipoles.

In the near future we will also be actively pursuing expansion of our technology and techniques into other areas of science, such as nuclear physics, fusion energy science, high energy density physics, light sources, and nuclear magnetic resonance. Examples of such (separately funded) projects are short period undulators for synchrotron light sources, advanced techniques for magnetic resonance imaging, and energy production efforts such as the International Thermonuclear Experimental Reactor (ITER).

Conductor Development: Strand and Magnet Stability

Reported by Daniel Dietderich

In recent years, magnet programs such as ours have begun experimenting with superconductor that has high critical-current density and is made from strands with large sub-elements. We have learned that the exact nature of the heat treatment that makes them superconducting—performed after they have been formed into coils—can have a large influence on the performance of these materials. (Some materials appear to be more sensitive to the details of heat treatment, others less so.) Our investigations also led us to a novel short-sample experimental method that better simulates the conditions the material will experience in actual magnet and thus predicts their behavior more accurately.

Discovering and Characterizing a New Problem

In recent years, the Superconducting Magnet Program has fabricated several high-field magnets from Nb_3Sn. Most of the magnets, both full-scale (RD-3b, RD-3c and HD-1) and sub-scale (SM-01, SM-04, and SM-05), achieved greater than 90% of the current that you would expect based on "short sample" measurements (in which a strand of the conductor is immersed in an external magnetic field rather than being formed into a magnet). However, several subscale magnets, including, NMR-1 and SM-06, each with different conductors and different magnetic fields, only achieved 40-70% of the short-sample limit. Similar behavior has been observed in magnets at Fermi National Accelerator Laboratory.

Strand and cable measurements made at Fermilab and Brookhaven National Laboratory suggest that conductor instability keeps it from reaching the critical current in an actual magnet that short-sample testing would lead us to expect. It has been postulated that flux jumps in the low-field regions of the magnets are the reason. However, the difference between what the strands *per se* can achieve and what they can do in a magnet is considerable, so we launched a major effort to understand and quantify the influence of strand performance on magnet behavior.

The SM-06 diagnostics showed that before the magnet quenched, there were voltage imbalances consistent with flux-jumping behavior in the low-field regions. The limiting coils (SC-12 and SC-13) were made with the same Modified Jellyroll strand, ORe 186. (A Modified Jellyroll strand is produced by co-wrapping a Cu sheet and an expanded sheet of Nb that had been slit around a tin rod.) Even with a short heat treatment time of 72 hours at 650^{o}C, the residual resistivity ratio (RRR), which is the ratio of the resistance at 300 K to that at 20 K, of the two coils was undesirably low, in the range of 7-12.

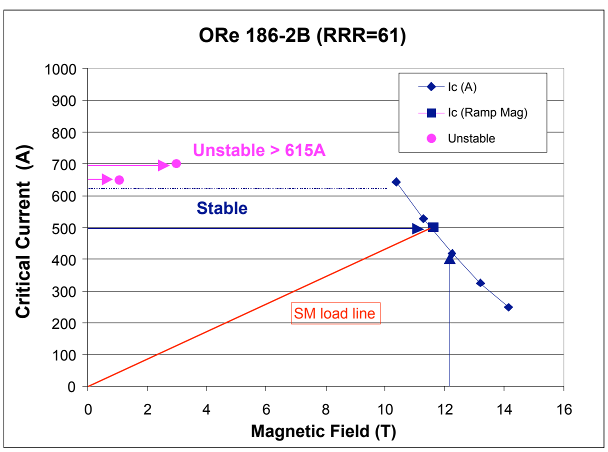
The low RRR is believed to result from a rapid conversion of the Nb barrier to Nb_3Sn, thus permitting Sn to diffuse into the Cu stabilizer. Thus we focused on controlling RRR – which can be in our bailiwick rather than the material manufacturer's, because brittle materials like Nb_3Sn have to be formed into the shape of the magnet coils and *then* heat-treated to make them superconducting.

Exploring and Controlling RRR

By heat-treating samples of ORe186 for different durations at the same temperature, we were able to make wires with similar critical currents but very different RRR values (between 4.7 and 61). To simulate magnet operation in a short-sample test, we kept the sample current steady and swept the externally applied magnetic field. With this procedure, the higher-RRR sample could sustain currents greater than 600 A (Figures 4-5 and 4-6), while the sample with the lower RRR quenched at about half that current. This seems to confirm that RRR is the culprit and heat treatment is the root cause.

The load line for SM-06 is included in Figure 4-6 and the highest quench current (338A per strand) is shown on the load line. All of the other quenches were below this, but not by more than 5%. There is a well-defined quench level, or threshold, in the magnet that is also seen in the wire. For sample currents below I_s (the stability current the sample current at which a conductor is stable during a field ramp) the field can be ramped to the short sample limit providing a V-H curve. This is shown as a solid horizontal line with an arrowhead that ends at I_c (data points denoted with square symbols).

Another Modified Jellyroll strand (ORe 143) proved much less sensitive to heat treatment conditions. It could be given a final heat treatment of 650˚ C for 180 hours and provide higher RRR values, in the range of 37-42. This strand has been used in magnets (SM-01 and SM-04) that did indeed reach nearly their short-sample performance. These magnets were assembled from coils SC-01, SC-02 and SC-08, all of which performed very well. Coils SC-01 and SC-02 formed the first sub-scale magnet, SM-01, of the racetrack design. These two coils, used in several magnet configurations since SM-01, have always performed as expected. Thus we conclude that the Ore 143 strand in these coils is stable.



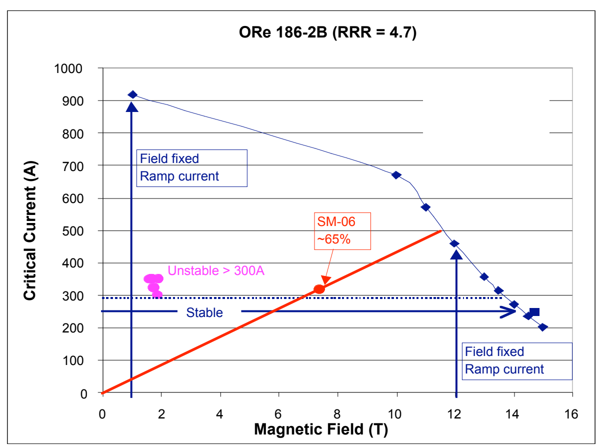


***Figure 4-5* (above left):** *A strand with an RRR of 61 exhibited a stability current (no quenches at all) of 615 A. Above this current the sample quenched during a field sweep.* ***Figure 4-6* (above right)** *shows that a strand with an RRR of 4.7 achieved only about half that performance. The horizontal dashed line in the figures represents the highest current that the sample could carry and remain stable (I_s). Our group is one of the first to explore this new issue of strand stability during a magnetic field ramp while holding the sample current fixed, which more realistically simulates a magnet environment and more closely relates to magnet performance.*

Additional studies of strand stability have been reported by Brookhaven. One of their studies also used Ore 186, although from a different section of the billet. If their data are included alongside ours in a semi-log plot of J_s vs. RRR (Figure 4-7), a yet-unexplained phenomenon becomes clear: our data have a linear fit throughout the RRR range, but the Brookhaven data, similar to ours for low RRR, diverge at higher RRR values. Further research is required in order to understand this phenomenon.

Also shown in Figure 4-7 is the quench current per strand in magnet SM-02. One coil of this magnet was made with a mixed strand cable (14 superconducting strands and 7 Cu strands). The superconducting strand EP 214, made by IGC, consisted of 19 sub-elements inside a single diffusion barrier. The diameter of the diffusion barrier (the non-Cu area) was ~ 500 microns. However, the sub-elements were internally split, so the magnetically measured effective diameter D_{eff} was ~195 microns. The strand's RRR was a high 126, but its J_s was low, which is consistent with a large D_{eff}. This was the only magnet fabricated at LBNL using this type of strand.

This work has shown that for a given wire diameter, sub-element size (D_{eff}), and Cu fraction, the RRR of the strand determines the low field instability current limit I_s. Although this effect can be inferred from the relations developed by Wilson and others, it has only appeared as a practical problem in the new high-J_c, large-sub-element strands that have been developed recently for High Energy Physics magnet programs. Since all of the filaments within a sub-element become sintered during Nb_3Sn formation, producing a large "effective filament," the only means to assure strand stability is to reduce the sub-element size from present levels.

The different sub-element designs (single barrier vs. multiple barrier) appear to affect stability. However, the results principally show the importance of retaining a high RRR, even if one must make the tradeoff of reducing J_c slightly at high fields, to insure strand and magnet stability.

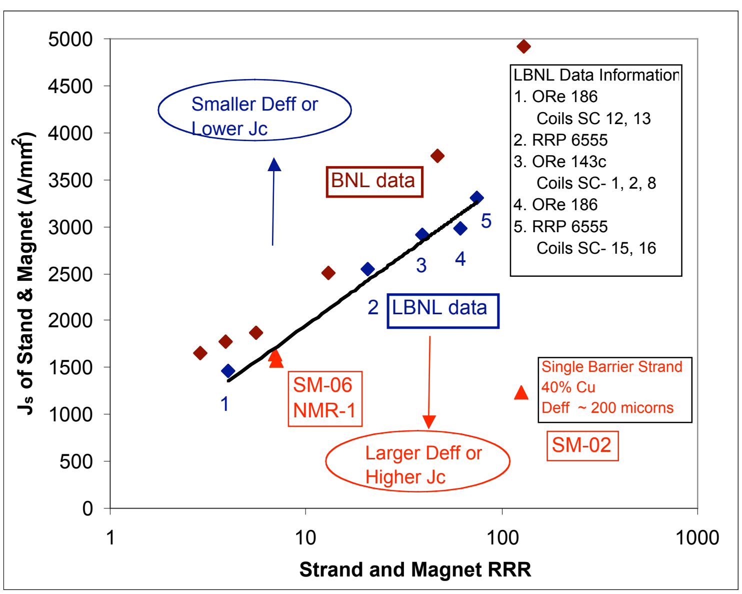


Figure 4-7. *The stability critical current density (J_s) for similar strands with a range of RRR values showed a linear trend in our work but diverged for high RRR in Brookhaven's. The performance results from two magnets—SM-06 and SM-02—are also shown.*

Cabling R&D

Reported by Daniel Dietderich

How best to make cable out of superconductor strands is another longtime area of research here at LBNL. We continue to map the cabling parameter space for Nb_3Sn strands. This includes new cables with different width, thickness, and keystone angle, as well as strands made by different processes with different internal configurations. Figures 4-8 and 4-9 illustrate the parameters of some of our new cables.

We have come to use a different approach to defining cable "compaction." Instead of using a volumetric packing factor that compares the strand area in a cable cross section to the cables cross sectional area (thickness x width), we parameterize the thickness and width compaction independently. The resulting parameter is similar to the definition of linear strain of a material (ΔL/L).

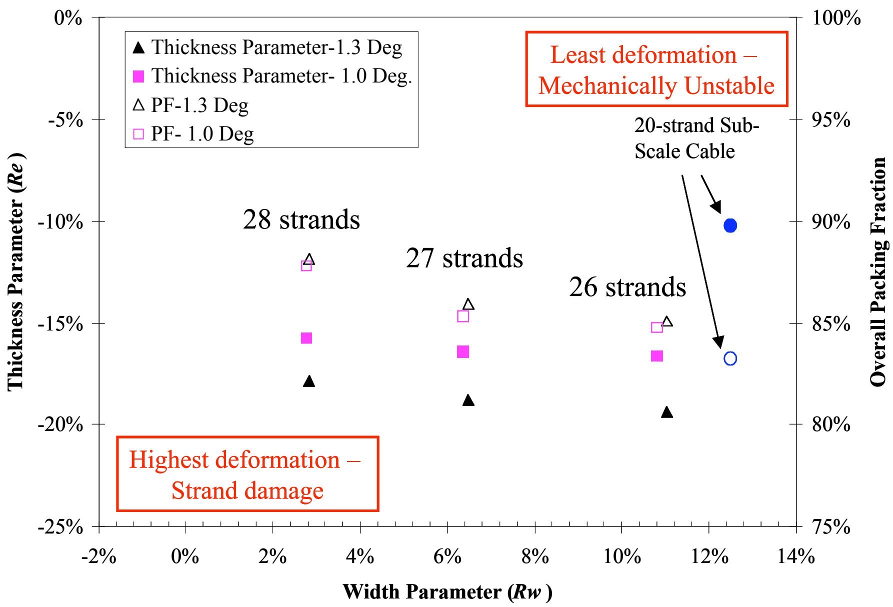
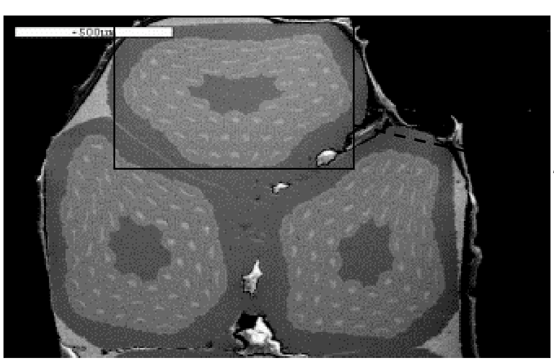


Figure 4-8. *As part of LARP (the Large Hadron Collider Accelerator Research Program), we have made six prototype cables, with 26, 27, and 28 strands and keystone angles of 1.0º and 1.3º, respectively, in search of a range of combinations that combines mechanical stability with minimal strand damage.*



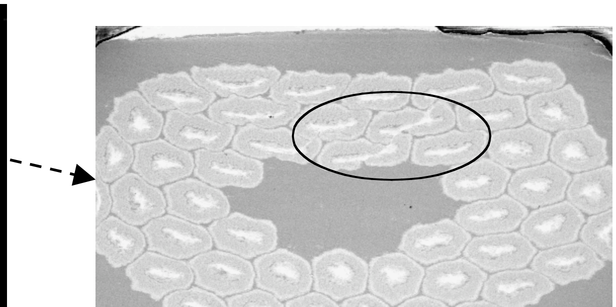


Figure 4-9*. LARP prototype cable 913R-A with 28 strands and a keystone angle of 1.0º.* Left*: Three strands at the edge of the cable.* Right*: Higher magnification of the strand at the edge of the cable showing the sheared sub-elements. These observations help to determine that 27 would be the right number of strands for the LARP cables designated TQ.*

Technology Transfer

The Superconducting Magnet Group has a history of making state of the art cable of NbTi, Nb_3Sn, and Bi-2212 for many laboratories, institutions, and companies. Figure 4-10 shows the level and distribution of cabling effort from January 2003 to January 2005. Anticipated effort for fiscal year 2005 is also included; note that the level of NbTi cabling effort for the LHC is starting to decrease while the Nb_3Sn cabling effort for LARP is starting to increase.

We continue to make cable out of state of the art $Bi_2Sr_2Ca_1C_2O_{8+x}$ (Bi-2212) strand from Showa Electric, Japan under a long term WFO agreement. This oxide superconductor, besides having a high T_c, has a very high H_{c2}, greater than 75 T at 4.2 K. This property makes it of interest to magnet designers. The critical current density of Bi-2212 conductor is lower than that of NbTi and Nb_3Sn at low fields, but at fields greater than about 16 T it is better. As the Jc of Bi-2212 is improved, the field at which the Jc vs. H curve of Nb_3Sn crosses that of Bi-2212 crossover will shift to lower fields.

This cabling effort with Showa may start to decrease in the near future as Showa begins to develop in-house cabling equipment. However, LBNL will help, and in exchange Showa will aid us in the heat treatment of Bi-2212 cable and coils that are being developed for our base program. Many materials issues must be addressed to develop coils for the wind-and-react sub-scale program due to the high temperature heat treatment (900 C peak) and the requirement that it be done in an the oxygen atmosphere.

Potentially new WFO opportunities are being explored. The SMG has been contacted by another longtime supplier and collaborator, Oxford Superconducting Technologies, to aid them in development of two cables, one made of Bi-2212 strand and the other of small diameter (0.2mm) NbTi wire.

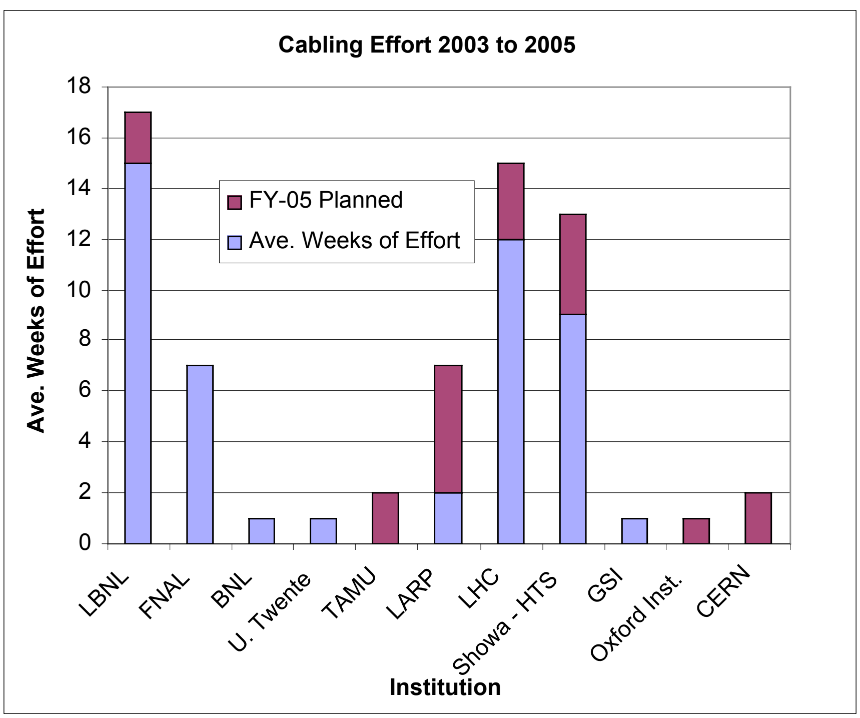


***Figure 4-10**. The average weekly cabling effort from January 2003 to January 2005, along with plans for the remaining part of fiscal 2005, show something of a changing of the guard in technologies as well as a project transition: NbTi cabling effort for the LHC is starting to decrease, while the Nb_3Sn cabling effort for LARP, a candidate material for a potential future LHC upgrade, is starting to increase.*

Featured Publications

These publications are representative of our best work published from summer 2004 (i.e., just after the last Division Review) to date. Clicking on each link will bring up the full text in Portable Document Format, or take you to a site where the article can be found.

Ferracin, P., Bartlett, S., Caspi, S., Chiesa, L., Dietderich, D.R., Gourlay, S.A., Hafalia, R.R., Hannaford, C.R., Lietzke, A.F., McInturff, A.D., Sabbi, G., Scanlan, R.M., "Mechanical design of a second generation LHC IR quadrupole," in *Proceedings* of MT-18, the 18th International Conference on Magnet Technology (October 20-24, 2003, Morioka, Japan), IEEE Trans. Appl. Supercond. **14**, 2 (June 2004), pp. 235-238; LBNL-53131.

Hafalia, A.R., Bartlett, S., Caspi, S., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hannaford, C.R., Lietzke, A.F., McInturff, A.D., Sabbi, G., Scanlan, R.M., "HD-1: design and fabrication of a 16 Tesla Nb_3Sn dipole magnet," in *Proceedings* of MT-18, the 18th International Conference on Magnet Technology (October 20-24, 2003, Morioka, Japan), IEEE Trans. Appl. Supercond. **14**, 2 (June 2004), pp. 283-286; LBNL-53132.

Ferracin, P., Bartlett, S.E., Caspi, S., Dietderich, D.R., Gourlay, S.A., Hannaford, C.R., Hafalia, A.R., Lietzke, A.F., Mattafirri, S., Nyman, M., Sabbi, G., "Mechanical analysis of the Nb3Sn dipole magnet HD1," submitted to the *Proceedings* of the 2004 Applied Superconductivity Conference (Jacksonville, FL, October 3-8, 2004), to be published in IEEE Trans. Appl. Superconductivity; LBNL-54887 Abs.

Sabbi, G.L., Bartlett, S.E., Caspi, S., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hafalia, A.R., Hannaford, C.R., Lietzke, A.F., Mattafirri, S., McInturff, A.D., "Design of HD2: a 14 tesla Nb3Sn dipole with a 35 mm bore," submitted to the *Proceedings* of the 2004 Applied Superconductivity Conference (Jacksonville, FL, October 3-8, 2004), to be published in IEEE Trans. Appl. Superconductivity; LBNL-54891 Abs.

Ferracin, P., Bartlett, S.E., Caspi, S., Dietderich, D.R., Gourlay, S.A., Hannaford, C.R., Hafalia, A.R., Lietzke, A.F., Mattafirri, S., McInturff, A.D., Nyman, M., Sabbi, G., "Development of a large aperture Nb3Sn racetrack quadrupole magnet," submitted to the *Proceedings* of the 2004 Applied Superconductivity Conference (Jacksonville, FL, October 3-8, 2004), to be published in IEEE Trans. Appl. Superconductivity; LBNL-54888 Abs.

A.R. Hafalia, S. Caspi, S.E. Bartlett, D.R. Dietderich, P. Ferracin, S.A. Gourlay, C.R. Hannaford, H. Higley, A.F. Lietzke, B. Lau, N. Liggins, S. Mattafirri, A.D. McInturff, M. Nyman, G.L. Sabbi, R.M. Scanlan, and J. Swanson, "Structure for an LHC 90mm Nb_3Sn quadrupole magnet," submitted to the *Proceedings* of the 2004 Applied Superconductivity Conference (Jacksonville, FL, October 3-8, 2004), to be published in IEEE Trans. Appl. Superconductivity.

Gourlay, S.A., "High field accelerator magnet development in the USA" (*invited talk*), in *Proceedings* of MT-18, the 18th International Conference on Magnet Technology (October 20-24, 2003, Morioka, Japan), IEEE Trans. Appl. Supercond. Vol. **14**, No. 2 (June 2004), pp. 333-338; LBNL-53128.

Caspi, S., Bartlett, S., Chiesa, L., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hafalia, R.R., Hannaford, C.R., Lietzke, A.F., Sabbi, G., Scanlan, R.M., "Thermal, electrical and mechanical response to a quench in Nb_3Sn coils," in *Proceedings* of MT-18, the 18th International Conference on Magnet Technology (October 20-24, 2003, Morioka, Japan), IEEE Trans. Appl. Supercond. Vol. **14**, No. 2 (June 2004), pp. 361-364; LBNL-53129.

Caspi, S., Bartlett, S.E., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hannaford, C.R., Hafalia, A.R., Lietzke, S., Nyman, M., Sabbi, G., "Measured strain of a Nb3Sn coil during excitation and quench," submitted to the *Proceedings* of the 2004 Applied Superconductivity Conference (Jacksonville, FL, October 3-8, 2004), to be published in IEEE Trans. Appl. Superconductivity; LBNL-54885 Abs.

Lietzke, A.F., Caspi, S., Chiesa, L., Coccoli, M., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hafalia A.R., McInturff, A.D., Sabbi, G., and Scanlan, R.M., "Test results of RD3c, a Nb_3Sn common-coil racetrack dipole magnet," in *Proceedings* of ASC02, the Fourth Applied Superconductivity Conference (Houston, TX, August 4-9, 2002), IEEE Trans. Appl. Supercond. Vol. **13**, No. 2 (June 2004), pp. 1292-1296; LBNL-49916.

Lietzke, A.F., Bartlett, S., Bish, P.A., Caspi, S., Chiesa, L., Dietderich, D.R., Ferracin, P., Goli, M., Gourlay, S.A., Hafalia, R.R., Hannaford, C.R., Higley, H., Liggins, N.L., Mattafirri, S., McInturff, A., Nyman, M., Sabbi, G., Scanlan, R.M., Swanson, J., "Test results for HD-1, a 16 tesla Nb_3Sn dipole magnet," in *Proceedings* of MT-18, the 18th International Conference on Magnet Technology (October 20-24, 2003, Morioka, Japan), IEEE Trans. Appl. Supercond. Vol. **14**, No. 2 (June 2004), pp. 345-348; LBNL-53243.

Full Publications List

Refereed

Dietderich, D.R. Marks, S., Prestemon, S.O., Schlueter, R., "NbTi and Nb_3Sn superconducting undulator designs," in *Proceedings* of the Eighth International Conference on Synchrotron Radiation Instrumentation (San Francisco, CA, August 25-29, 2003), American Institute of Physics Conf. Proc. **705**.

Scanlan, R.M., Dietderich, D.R., and Zeitlin, B.A., "Development of cost-effective Nb_3Sn conductors for the next generation hadron colliders," in *Advances in Cryogenic Engineering* ***48B*** (Plenum Press, New York), pp. 933-940.

Scanlan, R.M., Pyon, T., Gregory, E., Zeitlin, B.A., "Progress on a high current density low cost Nb_3Sn conductor scaleable to modern niobium titanium production," in *Advances in Cryogenic Engineering* ***48B*** (Plenum Press, New York), pp. 978-985.

MT-18

These papers were presented at the 18th International Conference on Magnet Technology (October 20-24, 2003, Morioka, Japan) and appear in its refereed *Proceedings*, published in IEEE Trans. Appl. Supercond. Vol. **14**, No. 2 (June 2004).

Caspi, S., Bartlett, S., Chiesa, L., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hafalia, R.R., Hannaford, C.R., Lietzke, A.F., Sabbi, G., Scanlan, R.M., "Thermal, electrical and mechanical response to a quench in Nb_3Sn coils," pp. 361-364; LBNL-53129.

Ferracin, P., Bartlett, S., Caspi, S., Chiesa, L., Dietderich, D.R., Gourlay, S.A., Hafalia, R.R., Hannaford, C.R., Lietzke, A.F., McInturff, A.D., Sabbi, G., Scanlan, R.M. "Mechanical design of a second generation LHC IR quadrupole," pp. 235-238; LBNL-53131.

Gourlay, S.A., "High field accelerator magnet development in the USA" (*invited talk*), pp. 333-338; LBNL-53128.

Hafalia, A.R., Bartlett, S., Caspi, S., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hannaford, C.R., Lietzke, A.F., McInturff, A.D., Sabbi, G., Scanlan, R.M., "HD-1: design and fabrication of a 16 Tesla Nb_3Sn dipole magnet," pp. 283-286; LBNL-53132, 6/24/2003.

Hasegawa, T., Nishioka, J., Ohtani, N., Hikichi, Y., Scanlan, R., Gupta, R., Hirano, N., and Nagaya, S., "12kA HTS Rutherford cable," pp. 1066-1069.

Lietzke, A.F., Bartlett, S., Bish, P.A., Caspi, S., Chiesa, L., Dietderich, D.R., Ferracin, P., Goli, M., Gourlay, S.A., Hafalia, R.R., Hannaford, C.R., Higley, H., Liggins, N.L., Mattafirri, S., McInturff, A., Nyman, M., Sabbi, G., Scanlan, R.M., Swanson, J., "Test results for HD-1, a 16 tesla Nb_3Sn dipole magnet," pp. 345-348; LBNL-53243.

ASC04

These presentations were given at the 2004 Applied Superconductivity Conference (Jacksonville, FL, October 3-8, 2004) and are expected to appear in its reviewed *Proceedings*, to be published in IEEE Transactions on Applied Superconductivity.

Bartlett, S.E., Caspi, S., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hannaford, C.R., Hafalia, A.R., Lietzke, A.F., Mattafirri, S., Sabbi, G., "Mechanical support and assembly of long Nb_3Sn accelerator magnets using key and bladder technology"; LBNL-54893 Abs.

Caspi, S., Bartlett, S.E., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hannaford, C.R., Hafalia, A.R., Lietzke, S., Nyman, M., Sabbi, G., "Measured strain of a Nb3Sn coil during excitation and quench"; LBNL-54885 Abs.

Devred, A., Gourlay, S.A., Yamamoto, A., "Future accelerator magnet needs"; LBNL-55059 Abs.

Dietderich, D.R., Higley, H., Scanlan, R.M., "Design and fabrication of Rutherford-type cables for high field magnets"; LBNL-54897 Abs

Dietderich, D.R., Bartlett, S., Lietzke, A.F., Mattafirri, S., Scanlan, R.M., Prestemon, S.O., Schlueter, R.D., Marks, S., Wang, B., Wahrer, B., "Design fabrication and test results of undulators made with Nb_3Sn cable; LBNL-54896 Abs.

D.R. Dietderich, S.E. Bartlett, S. Caspi, P. Ferracin, S. A. Gourlay, H. C. Higley, A. F. Lietzke, S. Mattafirri, A. D. McInturff, G.L. Sabbi, and R.M. Scanlan, "Correlation between strand stability and magnet performance"; LBNL-56328.

Ferracin, P., Bartlett, S.E., Caspi, S., Dietderich, D.R., Gourlay, S.A., Hannaford, C.R., Hafalia, A.R., Lietzke, A.F., Mattafirri, S., McInturff, A.D., Nyman, M., Sabbi, G. "Development of a large aperture Nb_3Sn racetrack quadrupole magnet"; LBNL-54888 Abs.

Ferracin, P., Bartlett, S.E., Caspi, S., Dietderich, D.R., Gourlay, S.A., Hannaford, C.R., Hafalia, A.R., Lietzke, A.F., Mattafirri, S., Nyman, M., Sabbi, G., "Mechanical analysis of the Nb_3Sn dipole magnet HD1"; LBNL-54887 Abs.

A.R. Hafalia, S. Caspi, S.E. Bartlett, D.R. Dietderich, P. Ferracin, S.A. Gourlay, C.R. Hannaford, H. Higley, A.F. Lietzke, B. Lau, N. Liggins, S. Mattafirri, A.D. McInturff, M. Nyman, G.L. Sabbi, R.M. Scanlan, and J. Swanson, "Structure for an LHC 90mm Nb_3Sn quadrupole magnet," presented at the 2004 Applied Superconductivity Conference (Jacksonville, FL, October 3-8, 2004).

Hafalia, A.R., Caspi, S., Bartlett, S.E., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hannaford, C.R., Lietzke, A.F., Mattafirri, S., Sabbi, G.L., "Structure for a 90mm Nb_3Sn cosine-2 theta IR quadrupole magnet"; LBNL-54886 Abs.

Lietzke, A.F., Bartlett, S.E., Bish, P., Caspi, S., Dietderich, D., Ferracin, P., Gourlay, S., Hannaford, C.R., Hafalia, R., Higley, H., Lau, W., Liggins, N., Mattafirri, S., Nyman, M., Sabbi, G., Swanson, J., Scanlan, R., "Test results of HD1b, an upgraded 16 tesla Nb_3Sn dipole magnet"; LBNL-54894 Abs.

Mattafirri, S., Bartlett, S.E., Bish, P.A., Caspi, S., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hannaford, C.R., Hafalia, A.R., Lau, W.G., Lietzke, A.F., McInturff, A.D., Nyman, M., Sabbi, G.L., Scanlan, R.M., "Performance analysis of HD1: a Tesla Nb_3Sn dipole magnet"; LBNL-54890.

Sabbi, G.L., Bartlett, S.E., Caspi, S., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hafalia, A.R., Hannaford, C.R., Lietzke, A.F., Mattafirri, S., Nyman, M., "Development of a prototype superconducting magnet for ex-situ NMR spectroscopy"; LBNL-54889 Abs.

Sabbi, G.L., Bartlett, S.E., Caspi, S., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hafalia, A.R., Hannaford, C.R., Lietzke, A.F., Mattafirri, S., McInturff, A.D., "Design of HD2: a 14 tesla Nb3Sn dipole with a 35 mm bore"; LBNL-54891 Abs.

Sabbi, G.L., Faltens, A., Lietzke, A.F., Mattafirri, S., Seidl, P., Martovetski, N., Gung, C., Minervini, J., Schultz, J., Meike, R., "Performance and cost optimization of superconducting focusing quadrupoles for HIF experiments"; LBNL-54898 Abs.

ASC02

These papers were presented at the Fourth Applied Superconductivity Conference (Houston, TX, August 4-9, 2002) and appear in its reviewed *Proceedings*, published in IEEE Trans. Appl. Supercond. Vol. **13**, No. 2 (June 2004).

Chiesa, L., Caspi, S., Coccoli, M., Dietderich, D., Gourlay, S., Hafalia, R., Lietzke, A., McInturff, A., Scanlan, R., "Performance comparison of Nb_3Sn magnets at LBNL," pp. 1254-1257; LBNL-49918.

Hafalia, R., Caspi, S., Chiesa, L., Coccoli, M., Dietderich, D., Gourlay, S., O'Neill, J., Sabbi, G., Scanlan, R., "An approach for faster high field magnet technology development," pp. 1258-1261; LBNL-49918.

Lietzke, A.F., Caspi, S., Chiesa, L., Coccoli, M., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hafalia A.R., McInturff, A.D., Sabbi, G., and Scanlan, R.M., "Test results of RD3c, a Nb_3Sn common-coil racetrack dipole magnet," pp. 1292-1296; LBNL-49916.

McInturff, A., Blackburn, R., Elliott, T., Henchel, W., McIntyre,P., Sattarov, A., "Construction of block-coil high-field model dipoles for future hadron colliders," pp. 1355 – 1357.

Sabbi, G., Caspi, S., Chiesa, L., Coccoli, M., Dietderich, D., Gourlay, S., Hafalia, R., Lietzke, A., McInturff, A., Scanlan, R., "Nb_3Sn magnets for the LHC IR," pp. 1262-1265; LBNL-49901.

Xue, Y., Mark, S., Shoup, S., MicroCoating Technologies, Inc., Marken, K.R., Miao, H., Maarten, M., Oxford Superconducting Technology, Gourlay, S.A., Scanlan, R., "Development of CCVD ceramic insulation for Bi-2212 superconducting wires and Rutherford cables," pp. 1796 – 1799.

Unrefereed Conference Proceedings and Other Publications and Presentations

PAC03

These papers were given at the 2003 Particle Accelerator Conference (Portland, OR, May 12-16, 2003) and published in its unrefereed *Proceedings*. Asterisks indicate oral presentations.

*Chiesa, L., Caspi, S., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hafalia, R.R, Lietzke, A.F., McInturff, A.D., Sabbi, G., Scanlan, R.M., "Magnetic field measurements of the Nb_3Sn common coil dipole RD3c," pp.170-172. http://accelconf.web.cern.ch/accelconf/p03/PAPERS/TOAB008.PDF

Ferracin, P., Caspi, S., Chiesa, L., Dietderich, D.R., Gourlay, S.A., Hafalia, R.R., Lietzke, A.F., McInturff, A., Sabbi, G., Scanlan, R.M., "Field quality analysis of the next generation IR quadrupole for the LHC," pp. 1984-1986. http://accelconf.web.cern.ch/accelconf/p03/PAPERS/WPAE021.PDF

*Gourlay, S.A., Strait, J., et al., "Towards a new LHC interaction region design for a luminosity upgrade," pp. 42-44. http://accelconf.web.cern.ch/accelconf/p03/PAPERS/MOPA006.PDF

Prestemon, S., Dietderich, D.R., Gourlay, S.A., Heimann, P., Marks, S., Scanlan, R.M., Schlueter, R., "Design and evaluation of a short period Nb_3Sn superconducting undulator prototype," pp. 1032-1034. http://accelconf.web.cern.ch/accelconf/p03/PAPERS/MPPG010.PDF

Sabbi, G.L., Faltens, A., Leitner, M., Lietzke, A., Seidl, P., Barnard, J., Lund, S., Martovetsky, N., Gung, C., Minervini, J., Radovinsky, Schultz, J., Meinke, R., "Superconducting focusing quadrupoles for heavy ion fusion experiments"; LBNL-53463. http://accelconf.web.cern.ch/accelconf/p03/PAPERS/WPAE023.PDF

CEC/ICMC 2003 Abstract

Scanlan, R.M., Dietderich, D.R., and Gourlay, S.A., "A new generation Nb_3Sn wire, and the prospects for its use in particle accelerators," presented at the Cryogenic Engineering and International Cryogenic Materials Conference (Anchorage, AK, September 22 – 26, 2003); LBNL-54374.

5. ION BEAM TECHNOLOGY

Reported by Richard A. Gough, Program Head

Creativity and innovation are hallmarks of the work carried out by the members of the Ion Beam Technology Program (IBT). We pursue a broad spectrum of scientific and technical activities related to the production and application of plasmas and ion beams. The integrating theme connecting these diverse activities is the staff's core expertise with ion sources, accelerating systems, and plasma science, as well as techniques for modification of materials to enhance their functionality even at the atomic scale. IBT's capabilities and resources position us to contribute effectively to a wide variety of national needs, including the training of students and postdocs.

Our work is organized as shown in Figure 5-1 to span a diverse set of activities that range from basic research and development in ion sources and low-beta acceleration to applications in biology and medicine, materials, microelectronics, nanofabrication, and homeland security. In addition, we have successfully provided front-end systems for several accelerator-based science facilities. The Front End Systems for the Spallation Neutron Source (SNS), which we successfully completed and delivered in 2002, continue to perform well in meeting the needs of SNS commissioning.

There are approximately 60 part- or full-time members, including scientists and engineers, technical and administrative support staff, students, and a large number of visitors associated with the activities of the IBT Program. Students form an integral part of the IBT environment: there are presently 7 graduate students whose thesis work depends primarily or completely on work done in our program, and since 1997, there have been eleven Ph.D. theses based on this work. Our activities are highly collaborative in nature, and we have many visitors from other universities and laboratories, as well as from industry.

Our activities in FY04 are supported by a projected total budget of approximately $5.7 M. Since January 2004 the work done by IBT staff has been reported in ~ 55 publications overall, over 40 of which were in refereed proceedings and journals. A complete bibliography of publications is provided at the end of this chapter that report on recent accomplishments, together with active links to selected publications that are representative of recent work.

Our choice of activities is guided by our vision of the future, for which we continuously develop and strengthen our core expertise in ways that enhance our ability to contribute to areas of national need. We have established a reputation for outstanding contributions to major projects, and are widely seen as the partner of choice for ion sources and complete front-end systems.

In particular, we position ourselves to contribute to new initiatives that will become part of the national science agenda, such as Spallation Neutron Source (SNS) upgrades, a Rare Isotope Accelerator (RIA), and advanced proton drivers. To sustain these capabilities we are engaged in R&D activities to develop improved ion sources that will be needed for a planned SNS upgrade, as well as a cargo screening system for the Department of Homeland Security based on a radio-frequency quadrupole linac (RFQ).

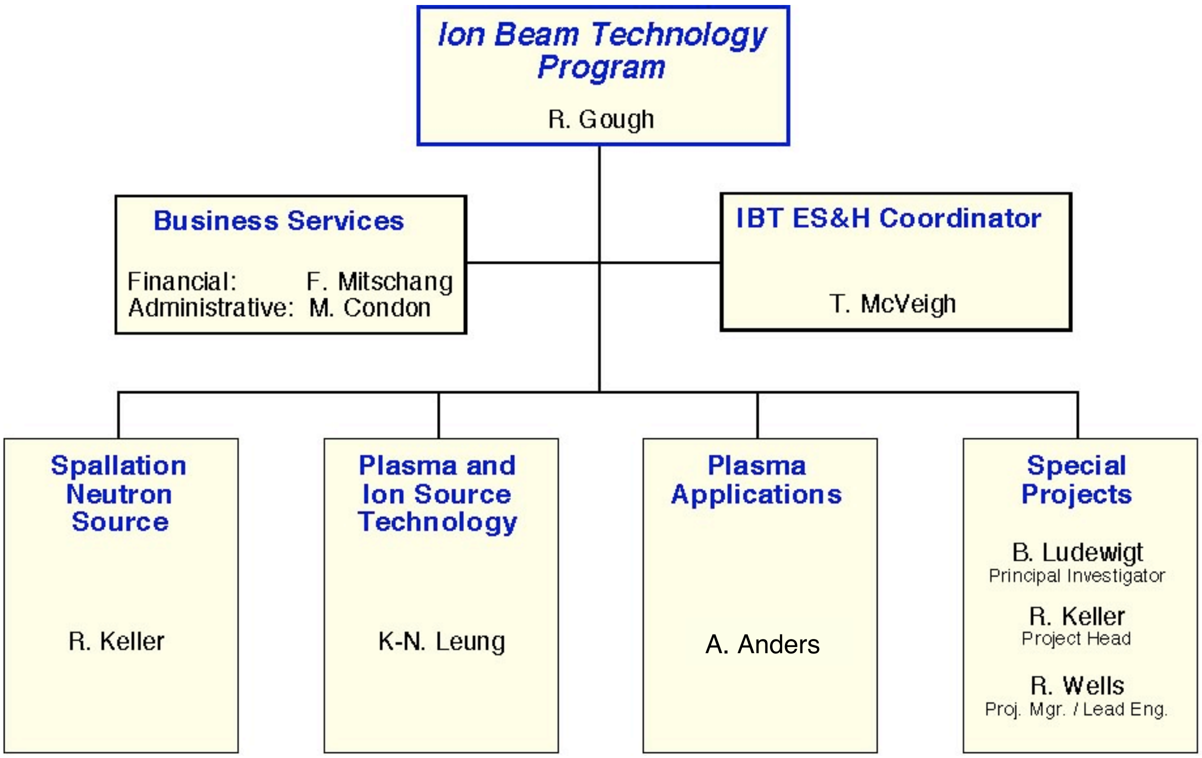


Figure 5-1. *Organization of the IBT program.*

The IBT Program has maintained its traditionally high level of productivity during the past year. In the following pages we provide a brief description of some of the recent activities and accomplishments in each of the principal programmatic areas, followed by a bibliography of publications from January 2004 to the present.

Front-End R&D

Reported by Roderich Keller

Ion-source and accelerator front-end development builds on our well-established core capabilities to deliver high-power, high-quality ion beams to support forefront research in high energy and nuclear physics and in the basic energy sciences. Ion sources for a future upgrade of the Spallation Neutron Source, early R&D toward a an eventual Rare Isotope Accelerator, and a burgeoning area of expertise in low-level rf controls for uses like the front end and linac of the SNS are among our recent highlights.

A More-Powerful Ion Source for an SNS Upgrade

The LBNL-built H^- ion source at the Spallation Neutron Source (SNS) project in Oak Ridge continues to demonstrate excellent peak performance in support of SNS linac commissioning activities. A significant overall performance improvement will be required, however, when the average SNS beam-power goal is raised to 3 MW.

Inspired by the durability demonstrated elsewhere by Electron Cyclotron-Resonance (ECR) proton sources, we are pursuing a novel development approach with the HYBRid Ion Source (HYBRIS) concept. In this approach, an electron cyclotron resonance plasma generator operating at 2.45 GHz is used as a plasma cathode, and electrons are extracted and injected at moderate energy into an SNS-type multi-cusp H^- ion source as illustrated in Figure 5-2. As a first result, electron currents up to 1.5 A were extracted, and activities now concentrate on igniting and maintaining a discharge in the H^- ion source chamber.

In parallel with these experiments, a series of beam simulations is being conducted with the goal of developing an optimized system for H^- beam formation and low-energy beam transport. In this system, the electrons accompanying the negative ions are removed from the beam at moderate energies and the ion beam is kept parallel to the system axis.

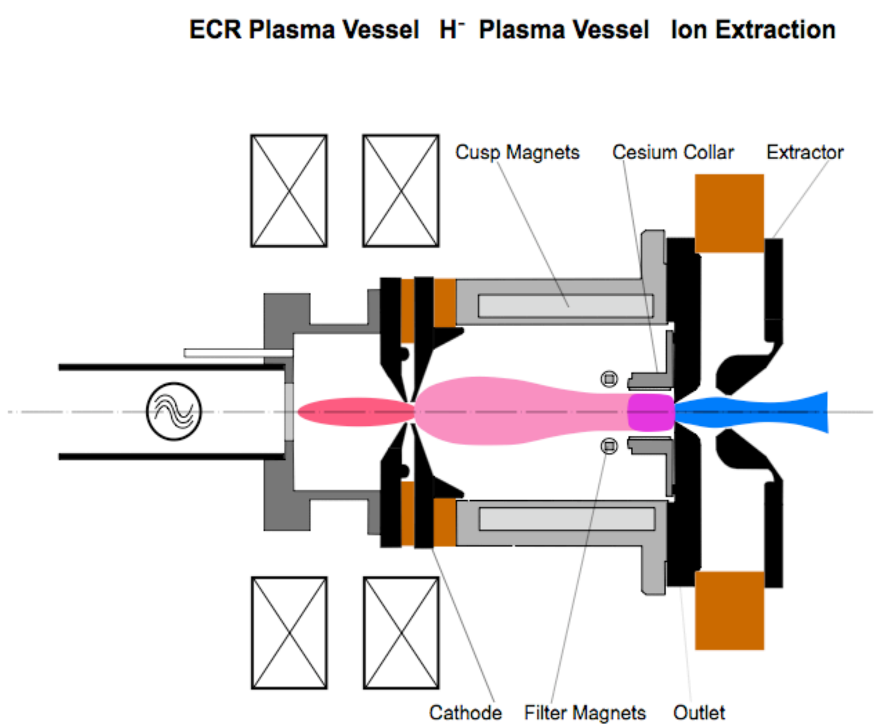


Figure 5-2. Ion source schematic illustrating the HYBRIS principle. It is a chain of two sources. An ECR plasma generato rinjects a multicusp source. That multicusp secondary source is driven by chopped dc power, rather than the rf power used in the present SNS source; but unlike conventional dc-powered H^- sources, it needs no short-lived filaments.

Another line of endeavor aimed at serving a future national need is the preparation work aimed at a future Rare Isotope Accelerator (RIA) project. This work, funded by grants from the Department of Energy and an LBNL Laboratory Directed R&D project, involves LBNL's Nuclear Physics and Engineering Divisions along with various parts of AFRD. The IBT Program coordinates these efforts, particularly in the areas of ECR ion sources; code development for and simulation of low-energy beam transport; superconducting magnet development; rf chopper development; and a cw low-level rf control system. We maintain close contacts with the two organizations, Argonne National Laboratory and Michigan State University, that are preparing to compete to lead the project and host the facility.

Low-Level RF Controls for the SNS

Although nearly three years have passed since we delivered the SNS Front-End Systems and much of our SNS-related work is oriented toward eventual upgrades, we have continued making contributions to the completion of the SNS construction project in another area. Low-level RF (LLRF) controls for the front-end systems and the linac downstream of them are proving to be a valued additional contribution to the SNS and a successful new engineering competency for LBNL. After demonstrating success with two successive generations of LLRF technology, we are now building and commissioning a third-generation system. Beam tests that, for the first time, involve superconducting linac rf cavities recently began at the SNS site in Oak Ridge.

Accelerator-Driven Neutron Source

Reported by Roderich Keller

IBT is leading a project to design and build the Engineering Prototype of an Accelerator Driven Neutron Source (ADNS) for Active Screening of Shielded Special Nuclear Materials (ASNM). Our partners are Lawrence Livermore National Laboratory (LLNL) and General Electric Global Research Center (GEGRC)—a collaborative effort that takes maximum advantage of the core competencies, experience, and overall capabilities of the three organizations that have pioneered various aspects of this technology.

This engineering prototype (Figure 5-3) is being developed so the US Department of Homeland Security can test concepts for the detection of nuclear weapons, or their component parts, concealed in intermodal cargo containers. It uses active interrogation techniques with beams of neutrons and/or photons to reveal the presence of amounts of ^{239}Pu or ^{235}U that are significant but cannot be detected reliably by passive radiation sensors or active radiography systems. If any special nuclear materials (SNM) are present, the pulsed neutron beam induces fission, which leads to the production of β-delayed high-energy γ-rays, providing a unique and readily detectable signature.

The project is structured in several phases that include a general feasibility study for such a system; conceptual through final design; and the fabrication, assembly and test of a 5-MeV deuteron accelerator with 12 mA average current, consisting of ion source, low-energy beam transport, RFQ accelerator, high-energy beam transport, and neutron target. We are currently in Phase I A of this project, the feasibility study.

In parallel, we are also designing and building a high-energy beam transport system and neutron target for an ADNS Feasibility Prototype being put together by LLNL. It is based on a commercial RFQ accelerator delivering an average current of 0.1 mA deuterons at an energy of 4 MeV. This prototype will be installed in a deep pit on the LLNL test site; delivery of the Berkeley-built components is planned for May 2005.

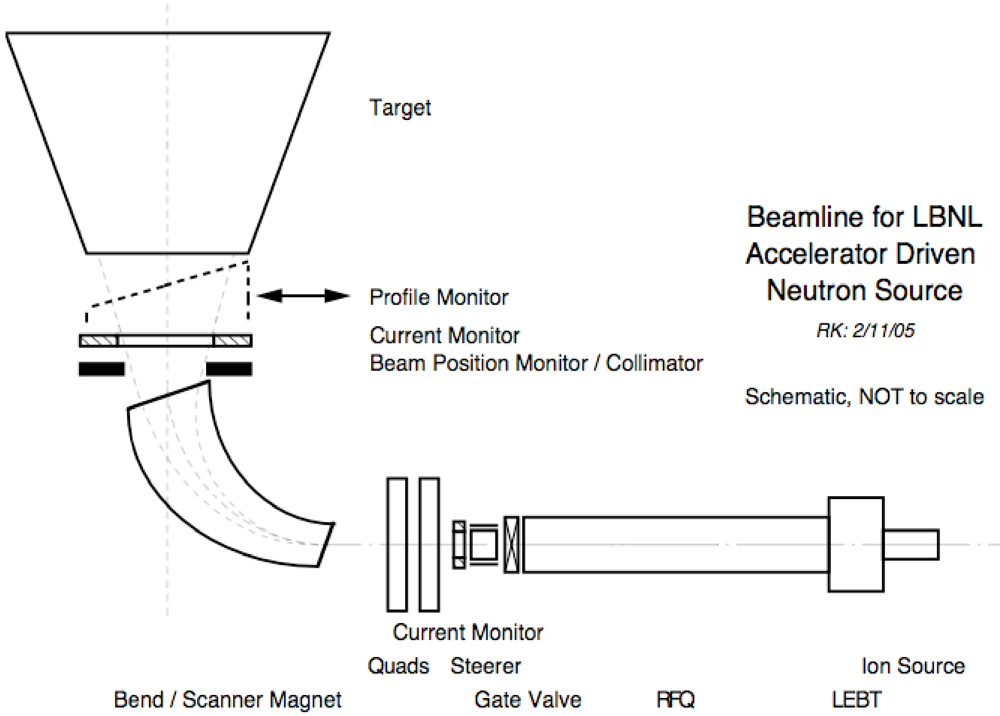


Figure 5-3. *Schematic of the Accelerator-Driven Neutron Source Engineering Prototype. The profile monitor is retracted for neutron production runs.*

Neutron Generator Development

Reported by Jani Reijonen

Three main types of neutron generators have been developed by the Plasma and Ion Source Technology Group (P&IST):

1. Axial, single beamlet;
2. Coaxial, high yield, multibeam; and
3. Point.

Their applications include special nuclear materials (SNM) detection for nuclear non-proliferation, airline cargo screening and boron neutron capture therapy (BNCT) cancer therapy studies. The status of each of these endeavors is described below.

1. Axial, Single Beamlet Neutron Generator for Special-Nuclear-Materials Detection Applications

The axial D-D neutron generator is built in sections corresponding to its three main components (Figure 5-4): an actively water-cooled, external-antenna, rf-driven ion source; a multi-stage ion beam accelerator structure; and a water-cooled, explosively bonded titanium-on-copper target.

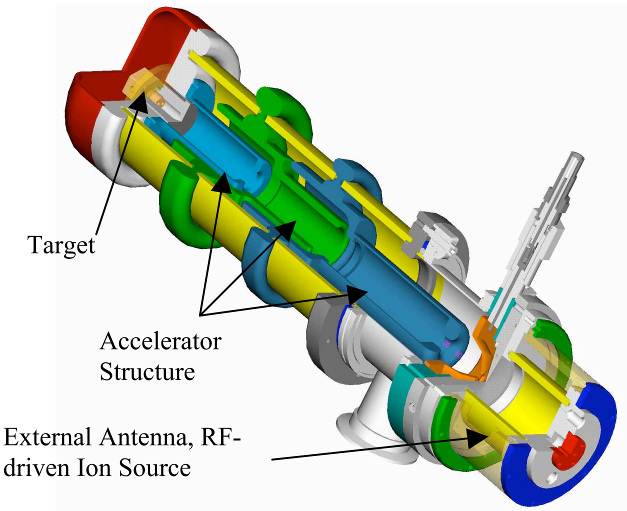


Figure 5-4*. On the* left *is a computer-aided design rendering of the axial neutron generator. On the* right *is a photograph of the generator mounted on the test stand; the source is at the bottom and the target at top.*

The ion source generates an atomic species purity >95% and >100 mA/cm^2 of current density at 3 kW of discharge power. At 2 mA of D^+ ion beam and 100 kV of acceleration voltage, the yield is 10^8 n/s.

Also under development is an axial neutron generator that has no exposed high-voltage elements (Figure 5-5). The neutron yield will be similar to that of the sectioned-accelerator axial neutron generator.

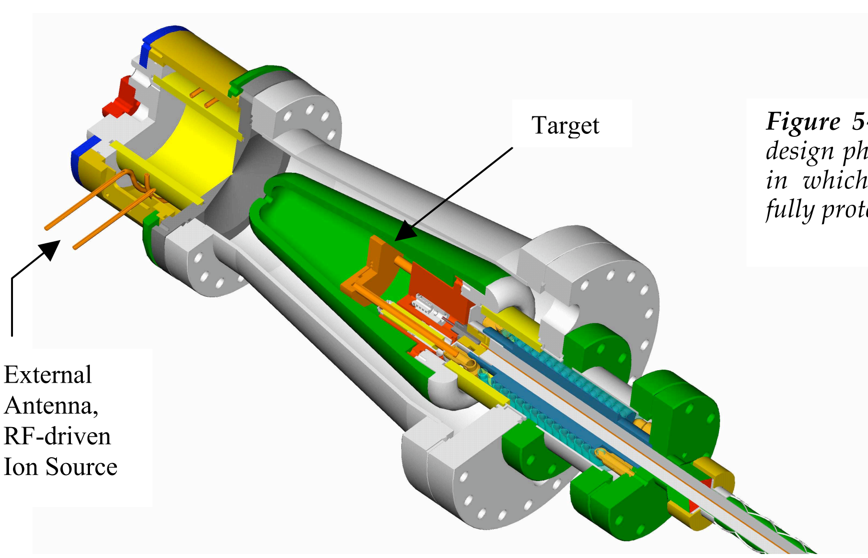


Figure 5-5. *The next step, now at the design phase, is an axial neutron generator in which the high voltage elements are fully protected.*

2. Coaxial Multi-Beamlet Neutron Generator for Boron Neutron Capture Therapy Applications

The high yield D-D neutron generator uses a unique cylindrical target geometry (Figure 5-6) to achieve large target area with compact outer dimensions. The ion source in this geometry is placed in the middle of the generator. The deuterium beam is extracted from the source toward a co-axially placed cylinder target. The latest coaxial neutron generator developed in the Plasma and Ion Source Technology Group will be able to generate 10^{11} n/s at 400 mA of beam current and 120 kV of energy. The coaxial neutron generator was delivered to a hospital/university consortium in Turin, Italy, in December 2004 and recently produced first neutrons.

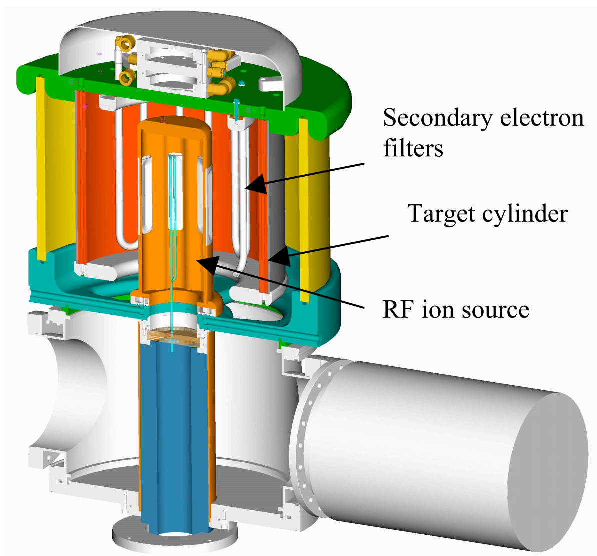


Figure 5-6: *A CAD rendering* (left) *shows the main components of the co-axial neutron generator. On the* right *the neutron generator is shown being installed on a test stand.*

3. Point Neutron Generator for Screening Airline Cargo

In partnership with Tensor Technologies Inc., the Plasma and Ion Source Technology Group is developing a cargo container screening system for LD-3 containers (a standard size and shape used by airlines). P&IST is responsible for developing the neutron generator and Tensor Technologies is responsible for the detector system.

The system is based on PFNTS (Pulsed Fast Neutron Transmission Spectroscopy), which requires a point neutron source with nanosecond beam pulsing and a broad tritium-tritium neutron energy spectrum. The ion source in this application has a toroidal shape. Beamlets are extracted toward the central axis of the neutron generator, and impinge on a small-diameter target tube. An illustration of the point neutron generator is shown in Figure 5-7. The project began in October 2004, and we are currently operating test ion sources and fabricating a prototype beam pulser system.

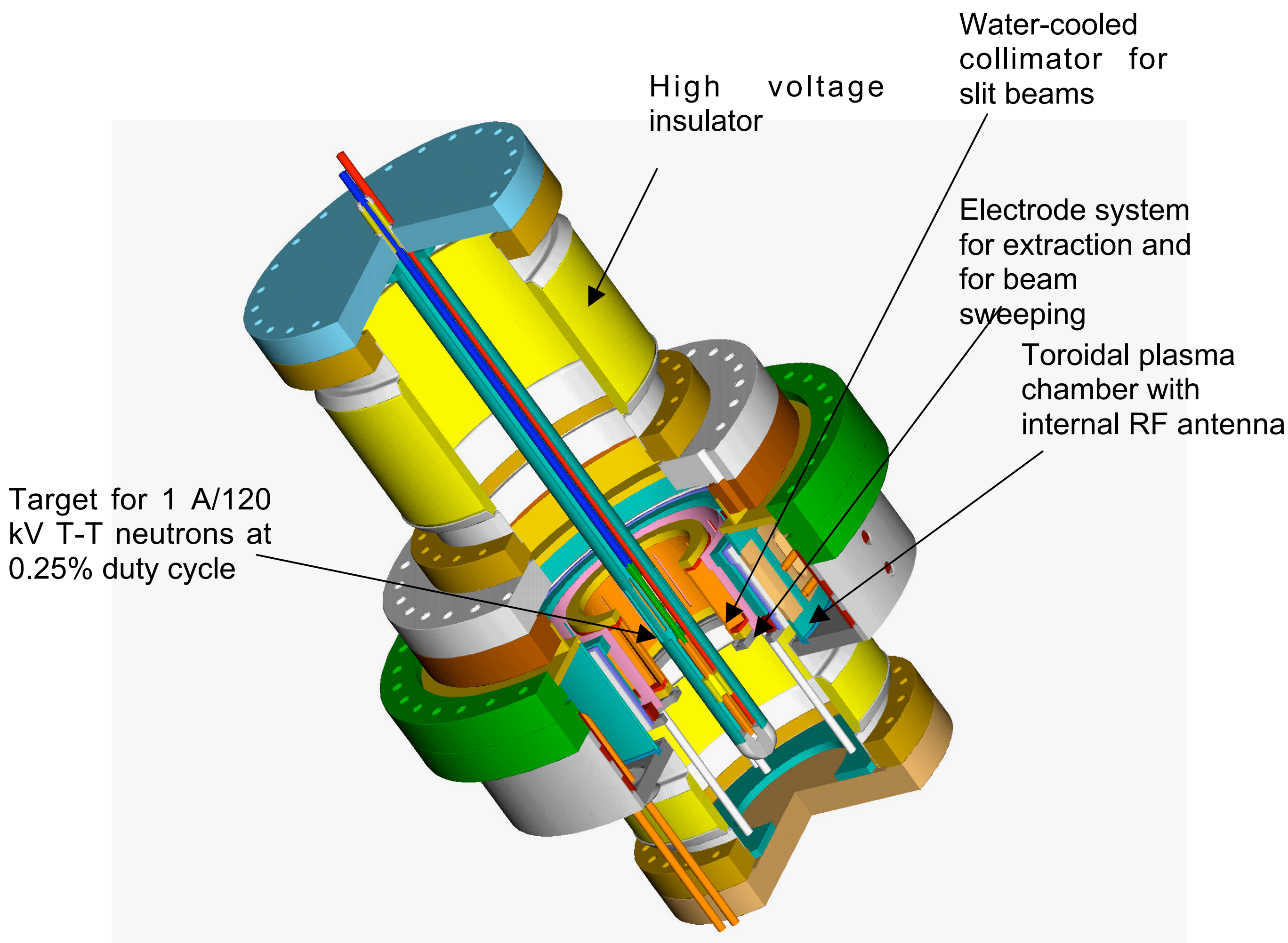


Figure 5-7. *Point neutron generator with nanosecond pulsing capability. T-T neutrons are used to achieve the broad neutron energy spectrum appropriate for the PFNTS detection scheme.*

The Quest for a Scalable Quantum Computer

Reported by Thomas Schenkel

Quantum computation offers the potential to revolutionize information technology. Currently there is an intense search for ways to implement coherent quantum control in systems that are scalable to many thousand quantum bits (qubits). Nuclear and electron spins of donor atoms in silicon are very promising qubit candidates, and our program aims at demonstrating few-qubit control in silicon transistor structures.

To achieve this goal we are developing a single ion placement technique that allows the implantation of single ions into selected locations in silicon devices. Single ion detection is achieved through the use of highly charged dopant ions (e. g., $^{31}P^{13+}$, and $^{209}Bi^{45+}$), and position accuracy is achieved by transporting ions though nanometer scale holes in scanning probe tips. We have recently succeeded in integrating an ion beam with a scanning probe for the first time.

Figure 5-8 shows a pattern formed in a thin resist layer by aligned implantation of argon ions. We have imaged single ion impact sites and expect to achieve single ion array formation in the next few months.

In parallel with the development of this crucial single atom control technique, we are developing a novel single spin readout device that is based on spin dependent transport in silicon transistors. Donor spins are promising qubits because of their long coherence times. We have performed the first studies of spin coherence of implanted donors in isotopically purified ^{28}Si samples. In collaboration with Steve Lyon's group at Princeton, we found a decoherence time of 300 μs for donor electron spins even under less than fully optimized conditions. This is the first measurement of this essential qubit metric for an engineered pre-device structure. It confirms the great potential of electron spin qubits for scalable quantum computing and it guides our development of few-qubit devices.

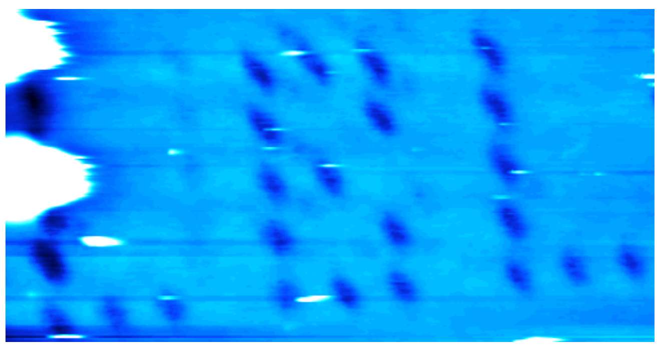


***Figure 5-8**. Pattern (500 nm dot size) formed by ion implantation with scanning probe alignment.*

Advances in Ion Beam Lithography

Reported by Qing Ji

Maskless ion beam lithography schemes have been developed at LBNL for future integrated circuit manufacturing, thin film media patterning, and micromachining. For the past year, significant results have been achieved for resolution improvement, and novel focused ion beam systems have been demonstrated that may have important benefits in the ion beam user community.

Maskless Micro-Ion-Beam Reduction Lithography Project

The Maskless Micro-Ion-Beam Reduction Lithography (MMRL) system completely eliminates the first stage of the conventional Ion Projection Lithography (IPL) system, *i.e.*, the ion beam illumination column before the stencil mask and the mask itself. During the past year, feature sizes of 50 nm (Figure 5-9) have been achieved on polymethyl methacrylate (PMMA) resist by adding limiting apertures, eliminating the dc magnetic field effect, getting rid of gas impurities etc. A pattern generator, which can individually switch ion beamlets on and off, is being fabricated in the microfabrication laboratory at UC Berkeley.

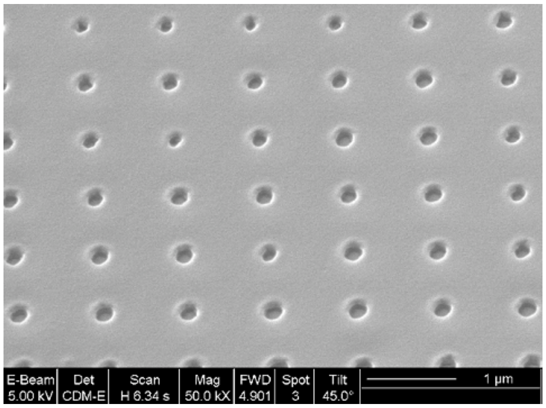


Figure 5-9. *PMMA resist exposure results using the Maskless Micro-Ion Beam Reduction Lithography System have achieved 50-nanometer feature sizes. Using a pattern generator that is now being fabricated, we expect to go beyond these test results and perform our first maskless lithography this year.*

Figure 5-10 shows a schematic diagram of the pattern generator. The heavily boron-doped silicon layer faces the plasma side. Under the conductive P^+ layer, there is a thermally grown SiO_2 insulation layer. A metal layer is then deposited under the insulation layer. The metal layer is patterned into lines and pads so that biasing voltages can be individually applied to each beam-forming aperture. With this pattern generator, we expect to demonstrate maskless lithography this year.

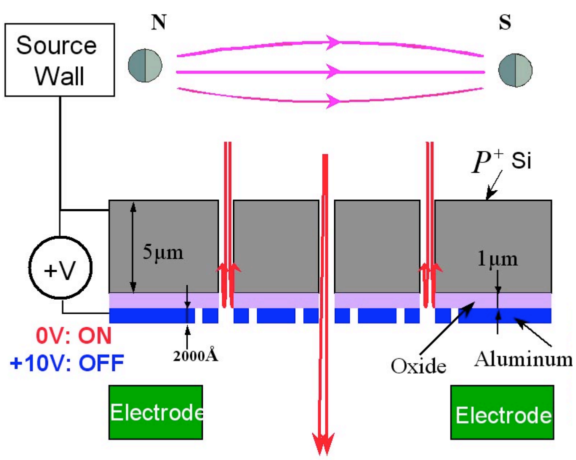


Figure 5-10. *A switchable pattern generator for the MMRL system is being fabricated at UC Berkeley.*

C_{60} Cluster-ion Beam Development

ToF-SIMS has been used to characterize numerous types of organic and bio-organic surfaces. A C_{60} cluster-ion beam is favored over the gold (Au) and Bismuth (Bi) cluster-ion beam given its increased yield of high-molecular-weight fragments while minimizing sample damage. We have developed a C_{60} plasma ion source (Figure 5-11), which is superior in ion current (at least two orders of magnitude higher) and brightness than an electron impact ionization source. Outputs of more than 400 nA of C_{60}^+ ions and 200 nA of C_{60}^- ions have been achieved.

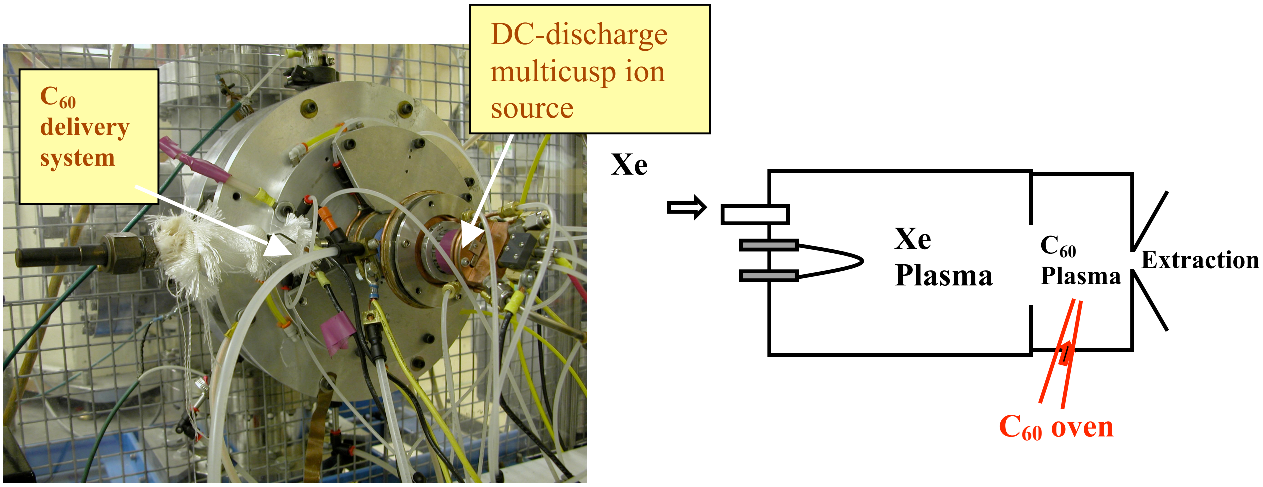


Figure 5-11. Left: *Photo of dc filament discharge, multicusp C_{60} plasma source mounted on a test stand.* Right: *A schematic drawing of the C_{60} ion source.*

Formation of Nanopore Arrays Using Plasma-Based Thin Film Deposition

The ability to fabricate arrays of apertures in membranes with diameters of only a few nanometers is important in many fields of research, including ion beam lithography, DNA sequencing, single ion implantations, and single molecule studies. We have developed a means of forming arrays of nanopores simultaneously on a thin solid-state membrane using plasma-based thin film deposition.

Depositing layers of metallic thin films can reduce the aperture sizes of a pre-fabricated membrane from a few micrometers down to tens of nanometers and even below (see Figure 5-12). This technique offers a way to reduce aperture size of a variety of substrate materials in any shape, both conducting and insulating. Such nanopore arrays can serve as membrane channels for DNA sequencing and as masks in ion beam imprinters for fabrication of quantum dots.

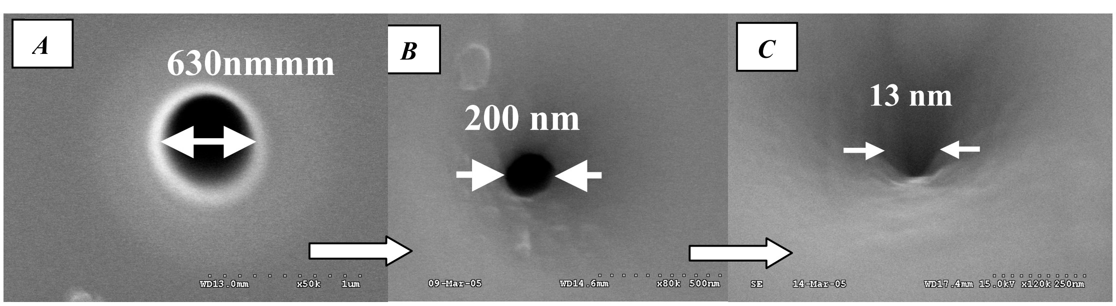


Figure 5-12. *SEM micrographs of an aperture after each subsequent copper deposition. The size of the aperture continues to reduce from (A) 630 nm, to (B) 200 nm , to (C) 13 nm.*

Applications of Advanced Coatings

Reported by Andre Anders

The Plasma Application Group (PAG) has long played a leading role in the development of advanced coatings and thin films that are used to modify and enhance the functionality of various materials. This work finds application in many areas, including accelerator components, microelectronics, in biomedicine. Many of the group's unique capabilities are made available to companies in a wide variety of fields that are developing leading applications.

One recent example is the transfer of a unique plasma deposition capability to an emerging leader in biomedical devices—a company that is developing artificial retinas and related devices to restore vision for individuals afflicted with retinitis pigmentosa, age-related macular degeneration, and other outer-retinal diseases that can lead to blindness. To meet the company's requirements, our group developed a new generation of our patented twist filter (Figure 5-13) for the deposition of transparent, super-hard and chemically inert coatings without undesired "macroparticles." This work was successfully completed in February 2005.

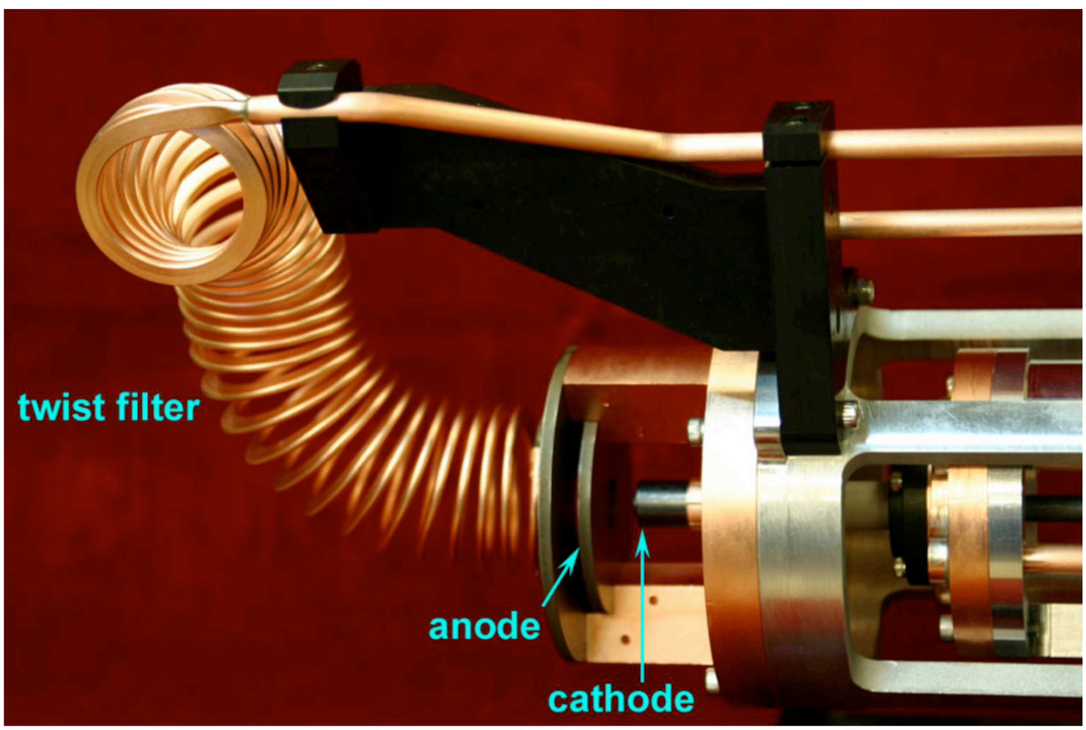


Figure 5-13. *Twist filter plasma duct with improved source-filter coupling.*

IBT Program Summary and Outlook

In summary, we have a broad set of ongoing activities that provide significant intellectual challenges. Through these activities we have the opportunity to contribute to the advancement of critical technologies that can enable forefront science. In carrying out this work, we benefit from a healthy mix of core LBNL staff, many visitors from around the world, and a large number of students. As we look to the future, we continue to direct our efforts toward new initiatives where there is a strong overlap with our core capabilities.

IBT Glossary of Acronyms

ADNS	Accelerator-Driven Neutron Source
AFRD	Accelerator and Fusion Research Division
ASNM	Active Screening of Shielded Special Nuclear Materials
BNCT	Boron Neutron Capture Therapy
CAD	Computer-aided design
DNA	Deoxyribonucleic Acid
ECR	Electron Cyclotron Resonance
GEGRC	General Electric Global Research Corporation
HYBRIS	Hybrid Ion Source
IBT	Ion Beam Technology
IPL	Ion Projection Lithography
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
LLRF	Low Level Radio Frequency
MMRL	Maskless Micro-Ion-Beam Reduction Lithography
P&IST	Plasma and Ion Source Technology (Group)
PAG	Plasma Applications Group
PFNTS	Pulsed Fast Neutron Transmission Spectroscopy
PMMA	PolyMethyl MethAcrylate (resist)
RFQ	RadioFrequency Quadrupole
RIA	Rare Isotope Accelerator
SNM	Special Nuclear Materials
SNS	Spallation Neutron Source
ToF-SIMS	Time-of-Flight Secondary Ion Mass Spectrometry

Featured Publications

These publications, chosen in consultation with Group Leaders in our program, are representative of the most significant IBT accomplishments from January 1, 2004 to the present. This list is organized alphabetically by lead author.

Clicking on the link will bring up a copy in Portable Document Format, or take you to a place where you can download a copy.

A. Anders, "Observation of self-sputtering in energetic condensation of metal ions," Appl. Phys. Lett. **85** (2004), pp. 6137-6139; LBNL-55876.

A. Anders, "Time-dependence of ion charge state distributions of vacuum arcs: an interpretation involving atoms and charge exchange collisions," IEEE Trans. Plasma Sci. **33** (2005), pp. 205-209; LBNL-56214.

A. Anders, K. Fukuda, and G. Y. Yushkov, "Ion charge state fluctuations in vacuum arcs," J. Phys. D: Appl. Phys. **38** (2005), pp. 1021-1028; LBNL-56737.

R. Keller, P. Luft, M. Regis, J. Wallig, M. Monroy, A. Ratti, and D. Syversrud, R. Welton, and D. Anderson, "A hybrid ion-source concept for a proton driver front-end," in Proceedings of the 33rd ICFA Advanced Beam Dynamics Workshop on High Intensity and High Brightness Hadron Beams (Bensheim, Germany, Oct. 2004), AIP Conf. Proceedings Series (in press); LBNL-56148.

Q. Ji, L. Ji, Y. Chen, and K.N. Leung, "Combined electron- and ion-beam imprinter and its applications," Applied Physics Letters **85**, 4618 (2004); LBNL-56384.

Park, S.J., Persaud, A., Liddle, J.A., Nilsson, J., Bokor, J., Schneider, D.H., Rangelow, I.W., and Schenkel, T., "Processing issues in top-down approaches to quantum computer development in silicon," Microelectronic Engineering **73-74**, pp. 695-700 (2004); also: cond-mat/0310195 (2004); LBNL-53004 Abs.

A. Persaud, S. J. Park, J. A. Liddle, I. W. Rangelow, J. Bokor, R. Keller, F. I. Allen, D. H. Schneider, and T. Schenkel, "Quantum computer development with single ion implantation," Special Issue: Experimental Aspects of Quantum Computing, Quantum Information Processing **3**, 1-5 (2004), pp. 233-245.

A. Persaud, T. Schenkel, I.W. Rangelow, S.J. Park, J.A. Liddle, and J. Bokor. "Single ion implantation with scanning probe alignment," in *Proceedings* of the 48th International Conference on Electron, Ion, and Photon Beam Technology And Nanofabrication (June 1-4, 2004, San Diego, CA); J. Vac. Sci. Technol. B **22** (2004), p. 2992; LBNL-54264.

R.F. Welton, M.P. Stockli, S.N. Murray, and R. Keller, "The status of the Spallation Neutron Source ion source," in *Proceedings* of the 10th International Conference on Ion Sources (JINR, Dubna, Russia, September 2003), Rev. Sci. Instrum. **75**, 5 (2004), pp. 1793-1795 (2004); LBNL-56654.

Full Publications List

Publications from January 2004 to date are listed here, organized by group and then by level of scholarly review.

Front-End R&D, Spallation Neutron Source, and Special Projects

Refereed Literature

R. Keller, P. Luft, M. Regis, J. Wallig, M. Monroy, A. Ratti, and D. Syversrud, R. Welton, and D. Anderson, "A hybrid ion-source concept for a proton driver front-end," in *Proceedings* of the 33rd ICFA Advanced Beam Dynamics Workshop on High Intensity and High Brightness Hadron Beams (Bensheim, Germany, Oct. 2004), AIP Conf. Proceedings Series (in press); LBNL-56148.

M.P. Stockli, R.F. Welton, and R. Keller, "Self-consistent, unbiased root-mean-square emittance analysis," in *Proceedings* of the 10th International Conference on Ion Sources (JINR, Dubna, Russia, September 2003), Rev. Sci. Instrum. **75**, 5 (2004), pp.1646-1649; LBNL-56079.

R.F. Welton, M.P. Stockli, S.N. Murray, and R. Keller, "The status of the Spallation Neutron Source ion source," in *Proceedings* of the 10th International Conference on Ion Sources (JINR, Dubna, Russia, September 2003), Rev. Sci. Instrum. **75**, 5 (2004), pp. 1793-1795 (2004); LBNL-56654.

R.F. Welton, M.P. Stockli, R.T. Roseberry, Y. Kang, and R. Keller, "The design of high power, external antennas for radio frequency multicusp ion sources," in *Proceedings* of the 10th International Conference on Ion Sources (JINR, Dubna, Russia, September 2003), Rev. Sci. Instrum. **75**, 5 (2004), pp.1789-1792 (2004); LBNL-55851.

Plasma Applications Group

Refereed Literature

A. Anders, "Fundamentals of pulsed plasmas for materials processing," Surf. Coat. Technol. **183** (2004), pp. 301-311; LBNL-51683.

A. Anders, "Observation of self-sputtering in energetic condensation of metal ions," Appl. Phys. Lett. **85** (2004), pp. 6137-6139; LBNL-55876.

A. Anders, "Operational and maintenance manual for pulsed cathodic arc for diamond-like carbon films," LBNL/PUB-3182.

A. Anders, "Time-dependence of ion charge state distributions of vacuum arcs: an interpretation involving atoms and charge exchange collisions," IEEE Trans. Plasma Sci. **33** (2005), pp. 205-209; LBNL-56214.

A. Anders, "Physics of arcing, and implications to sputter deposition," *Thin Solid Films*, in press (2005); LBNL-54220-Journal.

A. Anders, K. Fukuda, and G. Y. Yushkov, "Ion charge state fluctuations in vacuum arcs," J. Phys. D: Appl. Phys. **38** (2005), pp. 1021-1028; LBNL-56737.

A. Anders and R. A. MacGill, "Asymmetric injection of cathodic arc plasma into a macroparticle filter," J. Appl. Phys. **95**, 12 (2004), pp. 7602-7606; LBNL-54195.

A. Anders, E. M. Oks, and G. Yu.Yushkov, "Cathodic arcs: Fractal voltage and cohesive energy rule," submitted to Appl. Phys. Lett. (2005); LBNL-57025.

A. Anders and G. Y. Yushkov, "The kinetic energy of carbon ions in vacuum arc plasmas: a comparison of measuring techniques," J. Appl. Phys. **96**, 2 (2004), pp. 970-974, 2004, LBNL-54194.

E. Byon, J.-K. Kim, S.-C. Kwon, and A. Anders, "Effect of ion mass and charge state on transport of vacuum arc plasmas through a biased magnetic filter," IEEE Trans. Plasma Sci. **32** (2004), pp. 433-439; LBNL-53728.

S. L. Johnson, P. A. Heimann, A. G. MacPhee, A. M. Lindenberg, O. R. Monteiro, Z. Chang, R. W. Lee, and R. W. Falcone, "Bonding in liquid carbon studied by time-resolved x-ray absorption spectroscopy," Phys. Rev. Lett. **94** (2005), pp. 057407-4; LBNL-54802.

Mammana, V.P., Monteiro, O. and Fonseca, L., "The approach curve method for large anode-cathode distances," J. Vac. Sci. Technol. B **22**, 715 (2004); LBNL-53817 (2003).

E. M. Oks, A. Anders, I. G. Brown, I. A. Soloshenko, and A. I. Shcherdin, "Instability of a low-pressure hollow-cathode discharge in a magnetic field (in Russian)," *Fizika Plazmy*, in print (2005); LBNL-57306.

E. Oks, I. Brown, and A. Anders, "Some effects of magnetic field on a hollow cathode ion source," Rev. Sci. Instrum. **75**, 4 (2004), pp. 1030-1033; LBNL-53529.

J. Rosén, A. Anders, L. Hultman, and J. M. Schneider, "Charge state and time resolved plasma composition of a pulsed zirconium in a nitrogen environment," J. Appl. Phys. **96**, 9 (2004), pp. 4793-4799; LBNL-56277.

J. Rosén, A. Anders, S. Mráz, and J. M. Schneider, "Charge-state-resolved ion energy distributions of aluminum vacuum arcs in the absence and presence of a magnetic field," submitted to J. Appl. Phys. (2005); LBNL-57297.

P. K. Roy, S. S. Yu, S. Eylon, E. Henestroza, A. Anders, F. M. Bieniosek, W. G. Greenway, B. G. Logan, W. L. Waldron, D. L. Vanecek, D. R. Welch, D. V. Rose, R. C. Davidson, P. C. Efthimion, E. P. Gilson, A. B. Sefkow, and W. M. Sharp, "Results on intense beam focusing and neutralization from the neutralized beam experiment," Phys. Plasmas **11** (2004), pp. 2890-2898; LBNL-53974

S. Sangyuenyongpipat, T. Vilaithong, L. D. Yu, A. Verdaguer, I. Ratera, D. F. Ogletree, O. R. Monteiro, and I. G. Brown, "Metal ion bombardment of onion skin cell wall," Nucl. Instrum. Meth. B **227** (2005), pp. 289–298; LBNL-57309.

Unrefereed Conference Proceedings and Other Publications

A. Anders, "Physics of arcing, and implications to sputter deposition," in *Proceedings* of the 5th Int. Conf. on Coatings on Glass (Saarbrücken, Germany, July 2004), pp. 59-68; LBNL-54220-Conference.

A. Anders, "Cathodic arc spots: ignition probability as fundamental concept to describe spot types, phases, and motion," in *Proceedings* of the 21st Int. Symposium on Discharges and Electrical Insulation in Vacuum (Yalta, Ukraine, Sept. 27-Oct. 1, 2004), pp. 152-155; LBNL-54188.

A. Anders, E. M. Oks, G. Y. Yushkov, and I. G. Brown, "Measurement of total ion flux in vacuum arc discharges," in *Proceedings* of the 21st Int. Symposium on Discharges and Electrical Insulation in Vacuum (Yalta, Ukraine, Sept. 27-Oct. 1, 2004), pp. 272-275; LBNL-54682.

Plasma and Ion Source Technology Group

Refereed Literature

G.A. English, D.L. Perry, J. Reijonen, B. Ludewigt, K-N. Leung, R.B. Firestone, G. Garabedian, G. Molnar, and Zs. Revay, "The characterization of legacy radioactive materials by gamma spectroscopy and prompt gamma activation analysis (PGAA)," Nucl. Instrum Meth. B **213**, 410 (2004); LBNL-50944.

L.R. Grisham, S.K. Hahto, S.T. Hahto, J.W. Kwan, and K.N. Leung, "Experimental evaluation of a negative ion source for a heavy ion fusion negative ion driver," in *Proceedings* of the 2004 International Symposium on Heavy Ion Inertial Fusion, Nucl. Instrum. Meth. A (in press); LBNL-57402.

S.K. Hahto, S.T. Hahto, Q. Ji, K.N. Leung, S. Wilde, E.L. Foley, L.R. Grisham and M. Levinton, "Multicusp ion source with external rf antenna for production of protons," Rev. Sci. Instrum. **75**, 2 (2004), pp. 355-9; LBNL-53548.

S.K. Hahto, S.T. Hahto and K.N. Leung, "Fast ion beam chopping system for neutron generators," Rev. Sci. Instrum. **76**, 2 (2005); LBNL-56399.

S.K. Hahto, S.T. Hahto, J. Kwan, K.N. Leung, L.R. Grisham and K. Saadatmand, "Negative ions for heavy ion fusion and semiconductor manufacturing applications," in Proceedings of the 10th International Conference on Ion Sources (JINR, Dubna, Russia, September 2003), Rev. Sci. Instrum. **75**, 5 (2004), pp. 1799-1802; LBNL-54804.

S. K. Hahto, K-N. Leung, J. Reijonen, Q. Ji, D. Schneider, R. Bruch, S. Kondagari. and H. Merabet, "Permanent magnet microwave source for generation of EUV light," in M. Leitner, ed., *Proceedings* of the 16th International Workshop on ECR Ion Sources (LBNL, Berkeley, CA, Sept. 2004), AIP Conf. Proc. **749**; accepted by Rev. Sci. Instrum. (in press); LBNL-57286.

Q. Ji, L. Ji, Y. Chen, and K.N. Leung, "Combined electron- and ion-beam imprinter and its applications," Applied Physics Letters **85**, 4618 (2004); LBNL-56384.

Q. Ji, X. Jiang, L. Ji, and K.N. Leung, "Formation of nanopore-arrays by plasma-based thin film," submitted to Nature (3/18/05); LBNL-57321.

Q. Ji, K.N. Leung, T.J. King, X. Jiang, and B. Appleton, "Development of focused ion beam systems with various ion species," in *Proceedings* of the 18th International Conference on the Application of Accelerators in Research and Industry (Fort Worth, TX, October 2004), Nucl. Instrum. Meth. B (in press).

Q. Ji, Y. Chen, L. Ji, S. Hahto, K.N. Leung, T.G. Lee, and D.W. Moon, "Development of C60 plasma ion source for time-of-flight secondary ion mass spectrometry applications," submitted to J. Vacuum Sci. Technol. A (3/29/05); LBNL-57440.

H. Merabet, S. Kondagari, R. Bruch, S. Fülling, S. Hahto, K-L. Leung, J. Reijonen, A.L. Godunov and V.A. Schipakov, "EUV Emission from xenon in the 10-80 nm wavelength range using a compact ECR ion source," in *Proceedings* of the 18th International Conference on the Application of Accelerators in Research and Industry (Fort Worth, TX, October 2004), Nucl. Instrum. Meth. B (in press); LBNL-57401.

R. Pedrak, T. Ivanov, K. Ivanova, T. Gotszalk, N. Abedinov, I.W. Rangelow, K. Edinger, E. Tomerov, T. Schenkel, and P. Hudek, "Micromachined atomic force microscopy sensor with integrated piezoresistive sensor and thermal bimorph actuator for high speed tapping mode atomic force microscopy phase imaging in higher eigenmodes," J. Vac. Sci. Techol. B **22**, 1 (2004), p. 16; LBNL-54818.

A. Persaud, T. Schenkel, I.W. Rangelow, S.J. Park, J.A. Liddle, and J. Bokor. "Single ion implantation with scanning probe alignment," in *Proceedings* of the 48th International Conference on Electron, Ion, and Photon Beam Technology And Nanofabrication (June 1-4, 2004, San Diego, CA); J. Vac. Sci. Technol. B **22** (2004), p. 2992; LBNL-54264.

A. Persaud, S.J. Park, F.I. Allen, J.A. Liddle, I. Rangelow, J. Bokor, T. Schneider, and T. Schenkel, "Integration of ion beams with scanning probes for single atom device," Spring Meeting of the American Physical Society,(Montreal, Canada, March 2004); LBNL-54450 Abs.

A. Persaud, S.J. Park, F.I. Allen, J.A. Liddle, I. Rangelow, J. Bokor, D.H. Schneider, and T. Schenkel, "Formation of impurity spin qubit test structures in silicon by scanning probe," Spring Meeting of the American Physical Society (Montreal, Canada, March 2004); LBNL-54451 Abs.

A. Persaud, S.J. Park, F.I. Allen, J.A. Liddle, J. Bokor, and T. Schenkel, "Activation of ultra low dose, low energy phosphorus implants in silicon," Spring Meeting of the American Physical Society (Montreal, Canada, March 2004); LBNL-54452 Abs.

Dale L. Perry, Gerald A. English, Richard B. Firestone, Ka-Ngo Leung, Jani Reijonen, Bernhard Ludewigt, Glenn Garabedian, Gabor L. Molnar and Zs. Revay, "The use of prompt gamma activation analysis (PGAA) for the analyses and characterization of

materials: photochromic materials," Nucl. Instrum Meth. B, **213**, 527 (2004); LBNL-54806.

J. Reijonen, F. Gicquel, S. K. Hahto, M. King, T- P Lou and K-N Leung, "D-D neutron generator development at LBNL," 8th International Conference on Applications of Nuclear Techniques (Crete, Greece, September 2004); Journal of Applied Radiation and Isotopes (in press); LBNL-56673.

J. Reijonen, K.-N. Leung, R.B. Firestone, J.A. English, D.L. Perry, A. Smith, F. Gicquel, M. Sun, H. Koivunoro, T.-P. Lou, B. Bandong, G. Garabedian, Zs. Revay, L. Szentmiklosi and G. Molnar, "First PGAA and NAA experimental results from a compact high intensity D-D neutron generator," Nucl. Instrum Meth. A **522,** 598 (2004); LBNL-52675.

T. Schenkel, A. Persaud, S.J. Park, J. Nilsson, J. Bokor, J.A. Liddle, R. Keller, D.H. Schneider, D.W. Cheng, and D.E. Humphries, "Solid state quantum computer development in silicon with single ion implantation," Quantum Info. Processing **3**, 233 (2004); LBNL-54820.

T. Schenkel and K.J. Wu, "Probing nano-environments of peptide molecules on solid surfaces by highly charged ion secondary ion mass spectrometry," Int. J. Mass Spectr. **229**, 47 (2003); LBNL-54822.

Unrefereed Conference Proceedings and Other Publications

Y. Chen, L. Ji, B. P. Akker, Q. Ji, K.N. Leung, and W.J. Siekhaus, "Ion beam imprinting system," 30th SPIE International Symposium on Microlithography (San Jose, CA, 26 February-4 March 2005), Proc. SPIE (in press); LBNL-57442.

K.N. Leung, X. Jiang, L. Ji, Y. Chen, Q. Ji, and J. Vujic, V. Miljevic, "Large volume rf driven plasma generator for the removal of toxic gas in fossil fuel power plants," presented at the Fifth Yugoslav Nuclear Society Conference (September 27-30, 2004, Belgrade, Serbia & Montenegro); LBNL-57441.

Q. Ji, B. Appleton, L. Ji, S. B. Wilde, and K.-N. Leung, "An integrated FIB/SEM system for direct doping/modification," abstract for the 48th International Conference on Electron, Ion, Photon Beam Technology And Nanofabrication (June 1-4, 2004, San Diego, CA); LBNL-54266 Abs.

S.J. Park, J.A. Liddle, A. Persaud, T. Schenkel, X. Meng, and J. Bokor. "Development of single electron transistors as sensitive charge sensors for impurity spin qubits in silicon," abstract for the 48th International Conference on Electron, Ion, and Photon Beam Technology And Nanofabrication (June 1-4, 2004, San Diego, CA); LBNL-54236.

J. Reijonen, F. Gicquel, S. K. Hahto, K. N. Leung, T. G. Miller and P. K. Van Staagen, "Advanced neutron generator development at LBNL for home land security applications," CAARI 2004: 18th International Conference on the Application of

Accelerators in Research and Industry, October 10-15, 2004, Forth Worth, Texas; LBNL-56672 Abs.

T. Schenkel, "Progress in impurity spin qubit integration," abstract for the 18th International Conference on the Application of Accelerators in Research and Industry (Fort Worth, TX, October 2004), Nucl. Instrum. Meth. B (in press); LBNL-57421 Abst.

T. Schenkel, A. Persaud, I. W. Rangelow*, K. Ivanova*, J. Shangkuan, S. J. Park, and F. I. Allen, "Integration of ion beams with scanning probes for local doping and chemical analysis of materials," 51st International Symposium of the American Vacuum Society (Anaheim, CA, November 2004); LBNL-57420 Abs.

T. Schenkel, J.A. Liddle, J. Bokor, I.W. Rangelow, S.J. Park, and A. Persaud, "Towards quantum information processing with impurity spins in silicon," International Conference on Microelectronics and Interfaces (Santa Clara, CA, March 2004); LBNL-54449 Abs.