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1989
AFRD
**accelerator
&
fusion
research
division**

summary of activities

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

June 1990

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accelerator and fusion research division

1989 Summary of Activities

Lawrence Berkeley Laboratory
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Berkeley, CA 94720

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Foreword

Nineteen eighty-nine was a year of working toward future opportunities in AFRD. Plans were put forth for a Chemical Dynamics Research Laboratory, the centerpiece of which will be a state-of-the-art infrared free-electron laser. In high-energy physics, LBL, the Stanford Linear Accelerator Center, and the California Institute of Technology collaborated on an innovative design for a B-meson "factory" based on the PEP storage ring at SLAC. Our researchers in magnetic fusion energy continued refining their plans to help support the proposed International Thermonuclear Experimental Reactor, and those in heavy-ion inertial-confinement fusion continued planning and component development for the Induction Linac Systems Experiment, the logical next step on their road to a fusion driver. We also participated in early conceptual planning for a Biomedical Heavy-Ion Center to provide the ion species, energies, and dedicated beamtime needed for biophysics research and radiation treatment.

The Advanced Light Source, a national user facility designed to be at the forefront of synchrotron-radiation research well into the 21st century, remains on schedule and within budget as we work toward its planned 1993 completion. Anticipating the availability of high-brightness beams from the ALS, and continuing a variety of collaborative programs with other institutions, the Center for X-ray Optics is pioneering new applications for ultraviolet light and x-rays, along with associated instrumentation.

Even as preliminary plans were made for decommissioning the Bevalac accelerator complex, researchers continued adding to the bounty of knowledge amassed there. The system's ability to provide intense beams of any naturally occurring element remains unique in the U.S.; seven years after the Bevalac set the energy-per-nucleon record with uranium, beamtime is still in great demand. Nuclear-science and biomedical research have continued apace; thanks to an ongoing program of refinements in technology and operating procedures, a new high mark for research beamtime (4162 hours) was established in 1989.

Behind all these plans and achievements are the skilled, creative, and hardworking people of AFRD. Perhaps it is a cliché to say that "their dedication made it possible," but there is no other way to put it. They may take great pride in the accomplishments described in this report.

Not all of the news has been good. Early in March 1990, we were surprised and saddened by the death of heavy-ion fusion pioneer Denis Keefe, a widely respected accelerator physicist and a good friend to many of us. Only 60, he passed away unexpectedly and much too soon, but he lived to see the approach to fusion that he had championed begin to gain wide recognition as a candidate for aggressive development. We were fortunate in that Roger Bangerter of Lawrence Livermore National Laboratory, himself a veteran researcher in the field, was willing to move to LBL and take over the program on short notice, carrying on toward the elusive dream of fusion energy.

Klaus H. Berkner
Director, Accelerator and Fusion Research Division
June 1990

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AFRD: VARIATIONS ON A THEME

The Accelerator and Fusion Research Division is not only the largest scientific division at LBL, but also one of the most diverse. Major efforts include

- Investigations in both magnetic and inertial-confinement fusion
- Design and construction of the Advanced Light Source, a state-of-the-art synchrotron-radiation facility
- Research into advanced applications and instrumentation at the Center for X-Ray Optics
- Theoretical studies of accelerator phenomena and characteristics
- Research and development in support of the Superconducting Super Collider and other high-energy accelerators
- Operation of a heavy-ion accelerator complex, the Bevalac, for nuclear science and biomedical research

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Through the diversity there runs a common theme: the physics and technology of beams of ions, electrons, and photons. This introductory section gives an overview of AFRD's fields of inquiry and their relevance to current issues in science and technology. Later chapters go into greater detail on each topic.

As the industrialized world contemplates its dwindling fossil-fuel supplies and comes to terms with the environmental costs of energy production, nuclear fusion looks ever more appealing. One of the most potentially efficient of all physical processes that release energy, it is also attractive from a pragmatic viewpoint. The fuel (the hydrogen isotopes deuterium and tritium) could be readily obtained, and the reactions do not leave the long-lived, high-level radioactive "ash" associated with fission.* Unfortunately, the only existing examples of self-sustaining fusion are stars and hydrogen bombs; controlled fusion on a power-plant scale remains a distant goal.

The work being done today addresses two fundamental problems. One is how best to get the reaction started; a temperature of about 100 million degrees Celsius is required before random thermal interactions force the nuclei close enough to each other to fuse. (The nuclei are all positively charged and therefore repel each other; to make them fuse when they meet, the temperature must be kept high, meaning that they collide at high speeds.) The other problem is how to keep the reactants close enough together for long enough; the product of density and confinement time must reach a very high value known as the Lawson criterion. Researchers in AFRD are organized into two groups corresponding to different basic approaches to these problems.

Magnetic fusion, probably the most familiar scheme, uses a magnetic field of great strength and rigorously maintained geometry to confine a continuously reacting plasma and keep it away from the reactor walls. In the largest and newest tokamak reactors, magnetically confined deuterium plasmas have been heated to temperatures at which fusion reactions took place. The best of these "shots" have released about 80% as much energy as was required to heat the plasma, or about 10% of the energy that would be needed for ignition (self-sustaining fusion). In the tokamak projects, which tend to be very large and, increasingly, international, Lawrence Berkeley Laboratory has played a supporting role. The effort focuses on development of neutral-beam injector systems that pump large quantities of energetic hydrogen or deuterium atoms into a tokamak, thereby heating the already-hot plasma to thermonuclear temperatures.

This presents scientific and engineering challenges: the atoms must initially be charged so they can be accelerated, but then they must be neutralized so they can penetrate the tokamak's magnetic field. AFRD's **Magnetic Fusion Energy (MFE) Group** supports magnetic-fusion experiments by developing ion sources, accelerators, and neutralizers. The group developed the Common Long-Pulse Source, a standard neutral-beam plasma-heater for

Fusion Energy: Through Hardships to the Stars

* The neutrons emitted by fusion reactions can activate the materials they strike, but careful choice of designs and materials can reduce the production of long-lived nuclides to small amounts. There is also a tritium inventory that must be controlled. Fusion is therefore not completely "clean." However, recent work shows that, without reliance on active safety systems or containment buildings, a fusion reactor can be made that will not, under any combination of circumstances, produce radioactivity approaching lethal levels at the site boundary.

U.S. fusion experiments, and released it into commercial production in the mid-1980s. They are now following up that achievement by designing ion sources and accelerators for next-generation tokamaks such as the proposed International Thermonuclear Experimental Reactor (ITER). In order to maintain larger plasmas at higher temperatures for longer periods, these reactors will require neutral-beam systems based on a different technical concept. A proposal for a Test Facility for Accelerators (TFA), including specific scaled components of a prototype ITER neutral-beam system, is now being refined by the group.

The HIFAR Group's MBE-4 apparatus (*right*) and the MFE Group's proposal for a negative-ion accelerator and test facility for ITER neutral-beam injection (*below*) are among AFRD's recent contributions to the attempt to harness fusion power. Another area of considerable success—one with many secondary "spinoff" benefits—has been development of ion sources. In one of its configurations, the versatile multicusp source developed by the group could help greatly increase the sensitivity and affordability of radiocarbon dating (*below right*).

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Another approach to the two basic problems is inertial-confinement fusion, which begins not with a plasma but with a pellet of deuterium-tritium fuel. The pellet is shot at from many directions at once with beams of laser light or energetic particles. This energy bombardment heats and compresses the pellet enough to induce fusion; the reaction is over so quickly that the balance of forces from all sides is enough to provide containment and satisfy the Lawson criterion. (An inertial-fusion power reactor would operate in rapid pulses, as opposed to the continuous "burn" in a tokamak.) Heavy ions (as opposed to lasers or lighter ions) appear to be the best candidates to give the repetition rate, reliability, and efficiency that would be needed in a power plant. In AFRD, the **Heavy Ion Fusion Accelerator Research (HIFAR) Group** theoretically and experimentally evaluates the technical merit of heavy-ion beams as drivers for inertial-confinement fusion.

Since 1982, they have been progressively scaling up systems that transport and accelerate beams of heavy ions. Currently they are working with MBE 4, a four-beam induction linac designed to provide basic information that might be extrapolated in the design of a fusion driver. The proposed next step would be ILSE, the Induction Linac Systems Experiment. With its 16 beams, ILSE would contribute further knowledge towards the goal of a full-scale driver. The HIFAR group has completed the conceptual engineering design of ILSE and is developing individual components for it while continuing to learn from MBE-4.

The discovery of the X-ray in 1895 revolutionized not only the work of physicians, but that of physicists as well. In two decades of excitement that helped set the stage for today's knowledge of the atom, they studied the interaction of X-rays and matter. The results and the investigators—Roentgen, Compton, Laue, the Braggs—are familiar from freshman physics and from the roll of Nobel laureates.

After that heady beginning, the scientific and industrial uses of x-rays continued to progress, growing very subtle and sophisticated. Nonetheless, a backlog of interesting and potentially useful X-ray work began to accumulate, including studies of processes at interfaces and surfaces, microscopy and holography, and the probing of chemical reactions. The conventional means of producing x-rays, which involves striking a material with a beam of electrons, could generate tremendous power, but the backlogged ideas needed beams with qualities other than sheer power: tiny, intense beams, perhaps of just one precise "color," perhaps coherent, almost like the beam from a laser.

The solution was found in the late 1940s in what seemed to be a completely unrelated realm: the electron synchrotron. When a magnetic field makes an electron beam change direction, photons are given off. This effect was at first considered a nuisance for robbing power from the beam and

ALS and CXRO: New Lights, New Ways of Seeing

heating the accelerator and the experimental apparatus. But beginning in the 1950s, scientists began to realize that this nuisance had desirable qualities—that x-rays of unparalleled intensity could be obtained. The pioneers of synchrotron-radiation work obtained the light “parasitically” from electron accelerators meant for high-energy physics.

In the 1970s, there appeared a second generation of synchrotron-radiation sources: a generation of electron storage rings whose reason for existence was the production of synchrotron light. AFRD advanced this new field by developing practical versions of magnetic insertion devices called “wigglers” and “undulators” that could further manipulate an electron beam, producing radiation with selectable characteristics of bandwidth and coherence.

During the early and mid-1980s, AFRD began designing a third-generation synchrotron-radiation facility. The hallmarks of the third generation are high-quality electron beams (small source diameter and low transverse energy), along with a ring design that lends itself, both mechanically and in terms of maintaining beam quality, to the insertion of numerous wigglers and undulators. In 1986, the groups within the **Advanced Light Source** project officially began the detailed design of the ALS, a national user facility expected to be commissioned in 1993. The most publicly visible 1989 accomplishments involved construction work at the ALS site, but considerable progress was also made on the accelerator, beamline, instrumentation, control, and power systems that will make up the heart of the ALS.

One of the organizations eagerly awaiting completion of the ALS (and meanwhile contributing to its design and helping establish its user programs) is the **Center for X-Ray Optics**. The CXRO has a twofold charter in basic and applied research: demonstrating the capabilities and usefulness of x-rays and developing technologies to make x-rays more accessible as a tool for science and engineering. By itself and through extensive collaborative efforts, the CXRO has established an impressive program of scientific demonstrations and technology development.

Some of the most immediately attractive applications are found in the electronics industry, which, in its quest to miniaturize integrated circuits, is approaching the fundamental limits of lithography and inspection techniques based on visible light. X-rays are also being used for imaging and characterization in materials and surface science and in the life sciences.

A measure of the Center’s success in translating new ideas into practical systems was an R&D 100 award from *Research and Development Magazine*, given in 1989 for the invention of an x-ray microprobe that gives unprecedented spatial and elemental resolution. Nineteen eighty-nine also saw particular progress in the development of x-ray optical components and detectors. Together, the ALS and the CXRO offer the promise of scientific excellence with which to begin the second century of the x-ray.

The multiple straight sections in the ALS (left) can each accommodate a magnetic insertion device to enhance synchrotron-light production; the bending magnets between the straight sections produce useful synchrotron radiation as well. Research with synchrotron radiation is both conducted and supported by the Center for X-Ray Optics; examples of recent work include a Fresnel zone-plate lens for x-ray microscopy (below left) and an award-winning hard-x-ray microprobe (below right).

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The Biggest of the "Big Machines"

The proposed Superconducting Super Collider, the most ambitious of particle accelerator projects, will have a pair of storage rings, 52 miles in circumference, in which protons circulate in opposite directions. The two beams, each with an energy of approximately 20 TeV, will cross and collide in several "interaction halls." The high-energy physics community, in its search for the basic nature of matter, needs such energies to put its hypotheses to experimental test. SSC energies will be the hunting grounds for particles that have been postulated but never observed and measured, such as the top quark and the Higgs boson. Perhaps its users will even find particles, phenomena, or parameters that do not fit today's theories at all—an exciting prospect that has been a hallmark of accelerator-based physics.

The design and construction of such a large facility has occupied researchers from many laboratories. Investigators within AFRD's **Superconducting Magnet Group** have played a key role in the SSC effort for several years, concentrating on the design and manufacture of the superconducting wire and the cable made from it, and on design and testing of full-bore, partial-length models of the magnets.

The superconducting wire, developed in collaboration with the University of Wisconsin and with industry, is a composite material—niobium-titanium superconductor in a copper matrix—that is somewhat difficult to work with. Furthermore, the preferred type of cable for superconducting magnets—the flat, keystone "Rutherford-style" cable—could not be manufactured by existing machines in the quantity and quality needed by the SSC. Consequently, members of the group specified, designed, and prototyped a cabling machine with the necessary performance, then transferred this technology to the private sector. (Approximately 13 000 miles of cable will be needed, and it was clear from the start that private industry would have to produce it.) In 1988, several years of work culminated in delivery of the first commercially built version of this machine; it is now installed at a commercial cable factory, both for production purposes and for process development by industry representatives. Our machine-development program continues, anticipating additional requirements for different cable designs.

The group's magnet research and development during 1989 concentrated primarily on the quadrupole magnets that focus the beam in the collider rings. These magnets have to meet exacting performance specifications, especially in terms of magnetic-field uniformity. They must also be extremely reliable in order to give users the high experimental statistics needed at the frontiers of high-energy physics. Much effort has gone into optimizing seemingly minute design details that would affect performance under those conditions.

Other contributions to high-energy accelerators come from members of the **Beam Signal Electronics Group**. Their research emphasizes detection of beam behavior and active measures to "cool" the beam (i.e., to correct the tendency of some particles to travel at different speeds than others or move in directions other than directly along the beamline axis). The group has devised a highly sensitive Schottky detector for analysis of the beam at the Fermilab Tevatron collider. Members of the group who are skilled in electromagnetic analysis have also conducted a detailed beam-impedance study of the ALS, verifying the acceptability of the design.

The press shown at left is used for molding the cable windings of a full-size (5-m-long) prototype of an SSC quadrupole magnet. The windings of superconducting cable are squeezed into place on a mandrel, and heat sets an epoxy that holds them in place during the rest of the assembly process. The digitized photos below compare lightly and heavily compacted sections of cable from a magnet; note the "sausaging" distortion of the central core of superconductor. This kind of image analysis is being introduced into our superconducting-cable development to provide more-sensitive and more-quantitative results than traditional techniques of optical metallurgy.

CBB 904-3490

XBL 906-5894

A Hand with the Present, An Eye to the Future

"Nothing happens unless first a dream."
—Carl Sandburg

The **Exploratory Studies Group** functions as a key element in several of AFRD's diverse activities, not only assisting with immediate programmatic needs, but also laying foundations for future research. The Chemical Dynamics Research Laboratory, a new initiative designed for synergism with the ALS, was an important area of contribution. Members of the group designed the heart of the CDRL facilities: an infrared free-electron laser (IRFEL) that features tunability, high power, and narrow resolution. By bringing together the IRFEL, undulator and bending-magnet beams from the ALS, optical beams from a variety of lasers, and cold molecular beams, the CDRL will offer unprecedented opportunities for studying pure and applied reaction dynamics and a variety of topics in materials and surface science.

Topics of special relevance to the high-energy-physics community also figure prominently in Exploratory Studies efforts. Another major initiative being spearheaded by the ESG staff, working with colleagues from the Physics Division, the Stanford Linear Accelerator Center, and Caltech, is a B-meson "factory" based on the existing PEP storage ring at the Stanford Linear Accelerator Center. Creating B mesons and their antiparticles in electron-positron collisions that have a moving center of mass, an idea originated by P. Oddone of the Physics Division, would spatially separate

CBB 905-3635

"Pump-probe" or "two-color" experiments are among the many types of research that will be carried out at the proposed CDRL. It is part of the Combustion Dynamics Facility, a joint undertaking with sites at LBL and Sandia National Laboratories in Livermore, CA. The CDRL will offer an unprecedented opportunity to bring together various technologies for probing energetic, transient chemical reactions at a very fine level of detail. The community of potential users is putting together a broad program of pure and applied studies, ranging from reaction dynamics to work that might ultimately help reduce air pollution.

CBB 880-11812

the decay products, making detection simpler than it would be if the center of mass were fixed. This will enable high-energy physicists to study CP violation and rare B-meson decays. In 1989 the B factory went from an idea to a feasibility study; LBL and SLAC are now working to produce a conceptual design for this important and technically challenging facility.

In 1989, members of the group added to their significant contributions to the SSC. Even as they did so, others in the group looked beyond it. The SSC probably represents the practical limit of synchrotron-based technology because of the sheer size and expense of the apparatus. Accordingly, they continued collaborating in basic and applied research for the generation of high-energy accelerators beyond it. Their efforts focused on a futuristic electron linac called the two-beam accelerator, driven by microwave power from either a free-electron laser or a relativistic klystron.

A research complex that has been a centerpiece of LBL facilities for many years remains in demand today: the system of two accelerators known as the Bevalac.

The older of the two, the Bevatron, was the most powerful proton synchrotron of the early 1950s; there the antiproton was discovered. Two decades and a "zoo" of subatomic particles later, the accelerator was thought to be nearing the end of its career, but thanks to an innovative idea, some of its brightest days were still ahead. The idea was to feed the Bevatron with the beam from the nearby SuperHILAC heavy-ion linear accelerator, which itself was well-known as the discovery tool for several transuranic elements. When the SuperHILAC-to-Bevatron transport line was completed in 1974, the result was a unique system that could accelerate heavy nuclei to GeV-per-nucleon energies. (Both machines retained independent capabilities as well). In 1983 the Bevalac set a record, which still stands, by accelerating uranium to 960 MeV per nucleon.

This high-energy, heavy-ion capability gave rise to the "Bevalac era" in nuclear science. The facility still enables research that cannot be performed anywhere else—particularly studies of the behavior of nuclear matter at extremes of temperature and pressure. It also provides ion beams for thriving and innovative biomedical programs whose highlights include experimental therapy of otherwise-untreatable cancers.

Despite worsening budgetary constraints, in 1989 the Bevalac posted some of the most favorable operating statistics of its recent history. Improvements are regularly developed and implemented, and the operations group continues to strive for greater efficiency and better service to users.

The "Bevalac Era" Continues

CBB 899-8246

Right: An aerial photograph, with the beam path superimposed, shows how a geographical coincidence inspired a singularly successful idea. *Above:* The final version of a detector called a time-projection chamber (TPC), tested earlier in prototype form, will soon be added to the Heavy Ion Superconducting Spectrometer (HISS) facility in the Bevalac's external particle beam hall.

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1.

HEAVY-ION FUSION ACCELERATOR RESEARCH

*... heavy-ion accelerators
as igniters, or "drivers,"
for inertial-confinement
fusion ...*

THE MISSION OF THE HEAVY-ION FUSION ACCELERATOR RESEARCH (HIFAR) group at the Laboratory is to assess the suitability of heavy-ion accelerators as igniters, or "drivers," for inertial-confinement fusion. A prototype power plant is decades away, but a series of experimental successes indicates that the specific technology being studied by the HIFAR group—the induction linear accelerator—is a prime candidate for the driver and that development of this technology should be pursued over the next several years.

The HIFAR program, over the past decade or so, has involved a series of ever larger and more-complex acceleration and beam-transport experiments. The first was a 1-A cesium source and drift-tube accelerator module. This was followed by SBTE, the Single-Beam Transport Experiment, designed for studying beam stability at high currents. SBTE became operational in 1983 and was superseded in 1987 by MBE-4, a Multiple Beam Experiment with which to explore acceleration. Table 1-1 shows how these experiments relate to each other and to a postulated driver.

Experiments with MBE-4 will continue into 1991. Meanwhile, the group is designing components for a proposed accelerator called ILSE—the Induction Linac Systems Experiment. ILSE will address most of the remaining beam-control and beam-manipulation issues on a scale large enough for assessment of practicality in a driver.

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Table 1-1. Key parameters of three HIFAR experiments and a postulated driver.

Parameter	SBTE	MBE-4	ILSE	Driver
Ion species	Cs ⁺	Cs ⁺	C ⁺	Bi ³⁺ or Hg ³⁺
Number of beams	1	4	16→4	64→16
Injection voltage (MV)	0.16	0.2	2	3
Final voltage (MV)	0.16	1	10	3300
Final beam current (A)	0.023	0.24	15	6000
Final beam energy (J)	0.07	0.08	55	3 × 10 ⁶
Final ion velocity/c	0.0016	0.004	0.04	0.3
Accelerating gradient (MV/m)	n/a	0.07	0.22	0.8
Initial bunch length (m)	8.0	1.1	5.6	70
Pulse width (μs)	20	2→0.4	1→0.35	24→0.1

In 1989 experiments continued on MBE-4, providing data with which to model and study several of the phenomena we expect to encounter in a heavy-ion fusion driver. Amplification of voltage and current, if not done properly, can excessively degrade the quality of the beam. As we progressively scale up our studies toward the eventual goal of a driver, these effects will remain important, and their study and control will continue to be an essential part of the HIFAR program.

Since 1983, U.S. heavy-ion fusion accelerator efforts have been directed toward the induction linac. This device is conceptually simpler than the rf linac, whose fusion applications are being investigated in Western Europe, Japan, and the USSR. More importantly, at least for the goals of the HIFAR program, the parameters and properties of the induction linac can be scaled up more readily as experiments become progressively more complex and energetic. The MBE-4 design effort drew heavily upon our previous experience with SBTE, and, in turn, the MBE-4 experience is benefitting the ILSE program.

Figure 1-1 illustrates the concept behind MBE-4. Cesium ions are injected into each of the four beamlines at 200 keV. Another energy boost of up to 30 keV is given at each of 24 accelerating gaps for a final kinetic energy of 920 keV.

Reaching the necessary power calls for amplification of beam current, which is a function of the speed and line density of the bunch of charged particles. The speed is determined by the accelerated energy and the ion mass; the density can be increased through pulse compression, which is achieved by accelerating the rear particles in the bunch more than the front ones. The parameters of the accelerator set the ability to change these factors.

This procedure has several known complications. For example, errors can cause the beam to wander as it moves down the accelerator. This loss of control can lead to a reduction of beam quality and thus affect interaction between beam and target in a driver, so it must be minimized.

Research with MBE-4

MBE-4: The Induction- Linac Approach

Figure 1-1. MBE-4, the four-channel Multiple-Beam Experiment, became fully operational late in 1987. (Its modular design had already permitted nearly three years of limited experimentation.) With MBE-4, we are studying the behavior of space-charge-dominated heavy-ion beams undergoing current amplification. The information gained will be useful in the design of any induction-linac heavy-ion fusion driver.

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Transverse Beam Dynamics and Current Amplification

The MBE-4 experiments have consistently shown that acceleration accompanied by current amplification causes a slow increase in the normalized emittance. There are a number of possible reasons for such an increase. For example, if the bunch length is compressed during acceleration, the energy carried by the beam's space-charge field is converted into emittance. In addition, if the beam is off axis and has very low emittance, it interacts with imperfections of the quadrupole focusing fields, and with "image" charges induced on the electrodes, in such a way as to cause the emittance to grow. For "warmer" (higher-emittance) beams, the relative emittance growth is smaller and more difficult to detect. The measurements are difficult to make, because the emittance is quite small even after current amplification—less than 0.1 mm-milliradian at the halfway point along the accelerator—and because, in this low energy regime, the effects of space charge dominate the beam's behavior.*

In addition to using better measurement apparatus, we modified the post-extraction geometry to select the more-uniform core of the 10-mA beam. This reduced the current to 5 mA, simultaneously halving the emittance and

* Measurements reported in early 1987 gave emittance values in excess of 0.2 mm-mrad with no emittance growth during acceleration. However, at high emittance, it is difficult to detect relatively small values of emittance growth. With careful calibration procedures, such as checking of the single-particle betatron tune and correct matching at all observation points, we should be getting more-trustworthy data.

making the beam even more dominated by space charge. To provide a longer-term solution, we began working on an improved injection diode to make the 10-mA beam more uniform.

Attempts to reconcile the MBE-4 results with computer simulations led to further theoretical work because SHIFTXYA, our upgraded version of the SHIFTX computer code, predicted a smaller increase in emittance. (The upgraded program takes current amplification into account; amplifying the current by compressing the beam increases the electrostatic beam energy because the positively charged particles are forced closer together.) The latest version of SHIFTXYA gives results that are closer to experimental values, as shown in Figure 1-2. We also developed an analytical theory of emittance growth, extending the familiar emittance formula to include the effects of acceleration and longitudinal beam compression. The analytical theory is in good agreement with recent numerical simulations; if further confirmed by MBE-4 measurements, it could be used to model transverse emittance growth in a fusion driver more confidently.

How might the MBE-4 results be interpreted in terms of an actual driver? As presently envisioned, each of the many beams in a driver would undergo current amplification by a factor of about 200. This results from a fiftyfold increase in velocity accompanied by compression of the beam to one-fourth its original length. After the accelerator, the beam would be compressed by a further factor of 10. The most "aggressive" current amplification trials in MBE-4 have involved a velocity increase of $2.1 \times$ accompanied by a $3.8 \times$ bunch-length reduction. The velocity increase of a real driver cannot even be approached in such a short accelerator (although the voltage is expected to

Scaling Up the Results

Figure 1-2. A recent simulation with the latest version of the SHIFTXYA code, using an initial value close to the "intrinsic" beam emittance (the minimum value limited by radius and temperature of the ion source), gives a fairly accurate prediction of emittance growth along the accelerator. The simulation takes into account the behavior of 100% of the particles, whereas the analysis of experimental data only follows the 90% of the particles that comprise the main part of the beam, ignoring "halo." In the notation used here, the matching section of MBE-4 extends from Lattice Period -4 to LP 0, and the accelerator extends from LP 0 to LP 30. The nominal beam current in the simulations, as in most MBE-4 experiments, was 10 mA.

XBL 906-5877

scale up straightforwardly). On the other hand, bunch-length manipulation is actually much more demanding in this short apparatus than it would be in a driver.

During aggressive current amplification, the final pulse shape in MBE-4 is dominated by rise-time effects: in a pulse whose initial width is about 2500 ns, rise-time effects account for 150–250 ns. A driver would initially use much longer pulses, typically 10 to 20 μ s, and rise-time effects would not make up such a significant percentage of the pulse width (hence our rationale for working primarily with “gentler” acceleration, with amplifications on the order of $4\times$ and below).

Scaling of certain other parameters is similarly encouraging. The effects of space charge, for instance, should be proportionally less severe in a 10-GeV, 20-kA driver than in an MBE-4 beamline. However, one must be cautious in using the term “scaling.” MBE-4 and ILSE are experiments, not scale models; we expect to continue learning as we progress toward a driver, and extrapolations must be qualified carefully.

Long-term stability of operation—i.e., shot-to-shot reproducibility—is important for effective gathering of data (and will be essential in a driver as well). We study this subject by taking data at various locations along the length of the apparatus; at each point we measure the beam position and angle coordinates and the density distribution in phase space. Acquiring such data is more difficult in MBE-4 than it was in SBTE. All these quantities must be measured as a function of time within each pulse. Furthermore, the energy and energy spread can be measured precisely only at the end of the accelerator (although a computer simulation tool, the SLIDE macroparticle code,* usually allows good inferences about the energy at other points). And, of course, each of these issues must be multiplied by four beams; ILSE, with 16 beams, will be even more complex. We continually improve and extend our beam-diagnostic capabilities to meet these challenges.

Induction Linac Systems Experiment

As the HIFAR group continues its mission—evaluating and validating the concept of heavy-ion drivers based on induction linacs—a step beyond MBE-4 will soon be needed. Of the concepts envisioned thus far, the most promising is ILSE, the proposed Induction Linac Systems Experiment. At an incremental cost of about \$40 million 1990 dollars spread out over five years, ILSE would provide more than a thousand times as much peak power on target as MBE-4. It would also introduce several significant new capabilities, thus far untested, that would be required (on a larger scale) in a driver. They include

- Combining parallel ion beams dominated by space charge
- Making the transition from an electrostatic to a magnetic beam-transport system
- Magnetically bending space-charge-dominated ion beams
- Amplifying current by “drift compression”
- Focusing ion beams precisely onto a small spot

* SLIDE stands for Study of Longitudinal Ion Dynamics—Extended; it is an enhanced version of the AFRD-developed particle-in-cell code SLID. SLIDE allows particles to overtake one another and is optimized for short machines and low currents.

HEAVY-ION FUSION ACCELERATOR RESEARCH

Figure 1-3 illustrates the ILSE concept. Sixteen beams are produced in the 2-MV injector now being developed. Then the beams are accelerated to 4 MeV, and their current is amplified, as in MBE-4 but on a larger scale. The 16 beams are combined into 4, then accelerated to 10 MeV, with magnetic focusing rather than the electrostatic focusing employed in earlier stages. Finally, one beam is bent, subjected to further longitudinal compression for current amplification, and focused onto a pea-sized simulated fusion target.

The basic requirements for ILSE were defined in 1988 in the course of the ILSE Conceptual Engineering Design Study. In 1989 we built on this foundation by designing and developing suitable hardware, including the injection system and accelerator components such as induction cells and electrostatic and magnetic devices. The effort has been aided not only by a strong team of mechanical and electrical engineers from LBL, but also by the part-time participation of engineers from the Beam Research Group at Lawrence Livermore National Laboratory who have extensive experience in building electron induction linacs.

Meanwhile, our HIFAR Theory section, looking both toward ILSE and an eventual driver, analyzed the way perturbations in the beam current can be amplified by interaction with the resistive component of the impedance of the accelerating modules.

As we move from today's apparatus toward a full-scale driver, the energy and current requirements placed upon the ion injector become greater. ILSE calls for a 16-beam, 2-MeV injector that can provide currents of several amperes. Constraints in the first parts of the accelerator will limit the current to 5.4 A in actual ILSE operation, but a current of 8 A is the goal for a stand-alone test of the injector (planned for early 1990). Additionally, ILSE will use carbon ions instead of the cesium ions in MBE-4, so the 16 high-current beams must be derived from a fundamentally different kind of ion source. (The lighter carbon ions will allow us to incorporate magnetic focusing in the experiments at energies as low as 4 MeV.) In earlier years, a collaborative effort with other institutions had produced a satisfactory carbon-arc ion source; we are now working to improve its operating characteristics, and then we must make 16 of these sources function within the 2-MV injector.

Through ILSE to a
Driver

Ion-Source and Injector
Development

Figure 1-3. In ILSE, sixteen C^+ beams will be accelerated, current-amplified, and combined into four beams, which will then be accelerated further. Finally, one of the four will be bent, subjected to additional current amplification, and focused onto a simulated target. (Carrying only one of the four beams through the final stages helps control costs while still providing the desired data.) The ILSE specifications call for a kinetic energy of 10.2 MeV and a current of 3.8 A in each of the four final beams, with a final pulse length of 4.4 ns (0.355 μ s).

The ILSE ion source (Figure 1-4) is a carbon-arc device that turns on and comes up to full current rapidly, based on a prototype developed by S. Humphries of the University of New Mexico. The source has proven its performance in terms of current density and beam quality. Present work is

Testing for Reliability

Characterizing the reliability and performance of the carbon-arc source has been complicated. The source is not as simple as, for example, an electron tube, which either works from the outset or falls victim to "infant mortality." A more physically complex device, the ion source undergoes an early conditioning period—we "burn it in" with several hundred shots before taking data—and then settles into a long period of satisfactory operation. Later, it sometimes degrades for a time, then undergoes some change, not immediately apparent, that resurrects its performance.

We performed emittance scans downstream from a double slit during a long series of shots. Each scan lasted for 900 shots, and the beam's variation in phase space brought it into the scanned area during about 300 shots. This procedure measured the consistency of the beam's size in phase space (emittance) in the long term, yet it also revealed detail, since the pulse shape of an individual shot depends on localized beam behavior. During the other 600 or so shots, we could detect malfunctions by observing a misfire of the arc-discharge pulse or by reading an out-of-range emittance signal.

The object of such lifetime studies is to obtain statistical data on the source's reliability and life cycle: the number and distribution of true failures as a function of the cumulative number of shots. Then we hypothesize about the causes of the failures and modify the source accordingly. The source's life history since the conversion to a single cathode can be thought of in four parts.

Run I: 0–9580 shots. Very reliable operation, with a good-shot rate of 99.6%, except for one less-successful scan (97.5%) in the middle, after which the source recovered spontaneously. At the end of the run, the plasma switch grid was replaced with a new unit of the same design.

Run II: 9580–27 600 shots. Similar to Run I.

Run III: 27 600–34 200 shots. Less successful (90%). Replacement of the plasma switch grid and then of the exit grid did not improve performance.

Run IV: 34 200–36 000 shots. Back to 99.7% after manual cleaning of the flashover trigger surface.

Subsequently we performed large-aperture Faraday-cup measurements to check the total beam current, then returned to the emittance scans for an additional 3600 shots. However, the good-shot rate had dropped below 90%.

This history is actually a confirmation of success and a foundation for further work. The single-arc source lasted three times as long as the best of its three-arc predecessors, and between discrete, major problems, it gave thousands of shots at an average good-shot rate of better than 99.5%. Component aging effects have been identified and can be studied further. Work is in progress on a new version of the source that uses tantalum rather than copper for the trigger wires, and planned investigations include ways of cleaning the trigger without removing or dismantling the source.

focused on improving its lifetime and reliability. Three areas are being explored simultaneously: small modifications of the design geometry; substitution of different materials (in the trigger electrode, for instance); and means of refurbishing a faulty source without dismantling the apparatus, such as glow-discharge cleaning. Early tests show a mean interval between failures of about 10 000 shots, where failure is defined as a drop in shot-to-shot reliability to about 90%, as compared to the usual 99% or better.

Until July 1989 we used a three-arc design that typically lasted about 10 000 shots before the cathode eroded into the blast shield and repair was needed. Since then we have been using a single-arc design, hoping that a single massive cathode would last longer than three slender ones. The performance picture (*sidebar*) is complicated and not yet well understood, but we have determined that the single-arc source runs at a good-shot rate of better than 99.5%, with a cathode lifetime on the order of 30 000 shots.

The carbon-arc source will be incorporated into the 2-MV, 16-beam injector that will be used for ILSE (Figure 1-5). The 1989 work was highlighted by a significant confirmation of the high-voltage system's basic geometry: an open-circuit "ring-up" of the inductively graded Marx generator to a full 2 MV without breakdown from the dome to the wall. That test was conducted with ten trays in place; later tests with all 18 trays achieved 1.3 MV by the end of 1989. Further work involves the design of inductors that are more resistant to damage; reduction of the effects of transients; and improvement of the triggering circuitry. Progress was also made on construction and test of the 16-beam electrostatic accelerating column.

Figure 1-4. ILSE reaches into an energy realm where cesium beams become impractical due to contamination, so a carbon source has been developed over a period of several years. It generates a plasma in a carbon arc, then confines it behind an electrically biased grid. To extract a beam pulse, a positive voltage is applied between the grid and the grounded extractor plate. The 1989 work focused on improving the lifetime and reliability of the source; after a single robust cathode replaced three slender ones, the lifetime went from 10 000 pulses to more than 30 000.

These tests were conducted using the original input-power concept: a 3.5-kW alternator inside the dome, driven by a Lucite shaft running the length of the Marx generator. This driveshaft scheme was supplanted in late 1989 by a hydraulic drive, and results to date have been very encouraging.

Work is underway to adapt a modular, distributed control system, which is becoming an AFRD standard, for use in the injector and on ILSE generally.* The system (Figure 1-6) uses computer cards called Intelligent Local Controllers to perform much of the processing at the controlled equipment. A personal computer and commercially available software form the user interface.

We plan to bring these injector components together in 1990 for a single-beam test at 1 MV before integration of the full 16-beam hardware.

In the matching, electrostatic-acceleration, and beam-combining sections of ILSE, the beam will be focused by electrostatic quadrupoles, as shown in Figure 1-7. Precise beam control requires dimensional tolerances of ± 0.002 inch in this unit as assembled. Because tolerances might "stack up" during assembly, the individual parts have to be fabricated to nearly ± 0.0001 inch.

One approach to achieving such precision would be plastic forming of titanium-alloy sheets. This new technology could elegantly and accurately form the electrodes and quad plate as one monolithic piece, but since ILSE will need only 32 such assemblies, the initial tooling costs could not be justified. We found that fabrication of individual parts using conventional computerized numeric control machining, followed by careful assembly in a cleanroom, could give the needed precision. The first prototype was completed in 1989, and, after dimensional verification by a metrology specialist, was used for high-voltage tests in vacuum.

* The basic design was originated in the early 1980s for the Uranium Beams project at the Bevalac, a heavy-ion synchrotron. A refined version is being set up at the Advanced Light Source and will be copied for the infrared free-electron laser at the proposed Chemical Dynamics Research Laboratory.

Accelerator Component Research and Development

Figure 1-5. In the ILSE injector, a 16-beam electrostatic accelerator powered by an inductively graded Marx generator will accelerate ions from the carbon-arc source. The design goals for the injection system are an energy of 2 MeV and a current of 8 A in stand-alone testing (the system is required to deliver 2 MeV, 5.4 A for injection into ILSE). A successful open-circuit "ring-up" to 2 MV with 10 of the 18 inductor trays installed was among the 1989 highlights.

XBB 899-7593

CBB 870-10194

Beyond the beam combiner, the energies are higher and it becomes more sensible to use magnetic focusing. The challenging component development tasks identified in the ILSE Design Study last year included the design and fabrication of quadrupole magnets, including combined-function dipole/quadrupole magnets that perform bending as well as focusing. The magnets must have great field uniformity; this permits the beam to occupy a large amount of the field area, so the bends can be made sharper. It is also desirable to use "current-dominated" magnets, avoiding the usual iron pole pieces, so that quadrupole windings can be layered atop the dipole windings and controlled separately without affecting the dipole field. A current-dominated magnet also allows a much more densely packed matrix, an essential quality in a multiple-beam accelerator.

To meet these requirements, we chose the basic design shown in Figure 1-8. The basic cosine- θ pattern of the outer (quadrupole) windings is modified slightly, compensating for the fact that their effective length, as seen by the beam, is slightly longer than that of the dipole windings. An iron yoke returns flux outside the beam aperture.

The next step will be the fabrication of one or two prototypes. Attention will also have to be paid to manufacturability. Each pole consists of 24 turns

CBB 893-1699

Figure 1-6. The computerized control system for the 2-MV injector uses a highly distributed architecture, with intelligent local controllers (ILCs) doing most of the processing at the controlled equipment. The control system is patterned closely on that of the Advanced Light Source, a 1-2 GeV synchrotron radiation facility now being built at LBL.

XBL 902-656

of wire placed within ± 0.003 inch of their ideal positions. The manufacturing method should require as little labor as possible and should locate the windings with inherent, reproducible accuracy. It might not be feasible to form the stiff 2-mm copper wire onto cast-resin wire forms with such accuracy, so alternative methods are being investigated. They include chemical milling of thin-wall copper tubes, five-axis numerically controlled machining of solid copper, laser cutting, electrodeposition, lamination of thin copper on Kapton substrates (like a flexible printed circuit board), and resin casting of many fine wires connected in parallel.

Nineteen eighty-nine also saw the beginning of design work on the induction accelerator cells for ILSE. The beams will be accelerated from 2 to 10 MeV as they pass through 56 of these cells. The basic 16-beam cell configuration will have two nested Metglas accelerator-core packages driven by two 90-kV pulsers in parallel.

Taking the long view toward heavy-ion drivers that will need 1000 or so induction cores apiece, we have been thinking not only about the scientific

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XBC 903-1923

Figure 1-7. In the relatively low-energy section of ILSE (matching, electrostatic accelerator, and beam combiner), cost and performance requirements favor electrostatic focusing. A prototype of this 16-beam electrostatic quadrupole assembly was built in 1989 and is now being tested. With state-of-the-art manufacturing technology, monolithic units could be fabricated from a titanium alloy sheet, but since precise hand assembly seems capable of achieving the required tolerances, the small number of quadrupoles needed for ILSE would not justify the tooling costs.

Figure 1-8. The magnet planned for use in the ILSE bend section combines dipole windings that bend the beam and quadrupole windings that focus it. (The dipole windings, not shown here, would be layered outside the quadrupole windings.) Work has begun to find a cost-effective means of fabricating such a magnet with the required degree of precision.

XBL 892-569A

HEAVY-ION FUSION ACCELERATOR RESEARCH

performance needs of ILSE but also about engineering issues such as materials cost, manufacturability, and failure modes and long-term reliability. For example, the ILSE cores will be backfilled with a fluorocarbon dielectric fluid rather than, for instance, transformer oil; thus any leaks into the beamline would be much easier to clean up. The mechanical design makes leaks into the air more probable than leaks into the beamline in the event of most breakdowns, and structural factors such as handling and seismic loads are being considered. We are also working with industry on insulating laminates (which separate the Metglas layers) that would provide good efficiency, keep costs low, and survive the annealing process.

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2.

MAGNETIC FUSION ENERGY

... in addition to their primary role of heating the plasma, injected neutral beams help confine and control it ...

HEATING A PLASMA TO THERMONUCLEAR TEMPERATURES is one of the many significant challenges in fusion-energy research. In all of today's major magnetic-confinement fusion experiments, the plasma is heated largely by neutral beams of hydrogen isotopes; the primary focus of the MFE Group at LBL is development of the neutral-beam injector systems. The group's 19 years of work began with the invention of novel multiampere positive-ion sources and of improved, computer-optimized acceleration systems. The most prominent achievement thus far has been the design, development, and transfer to industry of the Common Long-Pulse Source (CLPS), which is used in the Tokamak Fusion Test Reactor at the Princeton Plasma Physics Laboratory and the DIII-D tokamak at General Atomics, the principal magnetic fusion experiments now running in the U.S.

The CLPS has been highly successful, but its positive-ion approach has a fundamental energy limit around a few hundred keV. In the next generation of tokamaks, larger plasmas will require higher injection energies—around 1 MeV, as opposed to the 120-keV performance of the CLPS—to ensure adequate penetration. One can start instead with negative ions, accelerating them to the necessary energies and subsequently neutralizing them by the simple process of detaching the extra electron. In contrast to systems based on positive ions, the neutral-particle yield does not decrease with increasing energy. However, it is difficult to produce large quantities of negative ions. Efforts to develop suitable sources of negative hydrogen ions at the ampere or multiampere level are now underway at several laboratories.

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Design, construction, and testing of prototype accelerator systems must go hand in hand with development of a negative-ion source, so a substantial effort has been devoted to accelerator development as well. Since 1988 the major portion of our Department of Energy-funded work has been directed toward the ITER Project, the International Thermonuclear Experimental Reactor. As a major initiative in this effort, we propose to design a test facility capable of accommodating a 2-MV negative-ion system at currents of 1 A or better. (After our design and testing efforts, production of the full complement of neutral-beam systems would presumably be handled by industry on behalf of the user, as with the CLPS.)

Our expertise in ion-source and accelerator development is not limited to fusion research; activities have been diversified considerably during the past few years. Energetic negative hydrogen ions and neutral-beam systems are of interest for the Strategic Defense Initiative, for example. Sources and accelerators for various ion species have industrial uses such as ion implantation for semiconductor processing and metal surface hardening. And, we have maintained an academic component of our program, centering on advanced plasma theory.

*In ITER (Figure 2-1), a total of about 75 MW of neutral deuterium beams will be injected to heat the plasma and to drive the toroidal current during steady-state operation (see sidebar). The energy required, 1.3 MeV at maximum, is an order of magnitude greater than that of the CLPS. Beam steering is another necessary feature. One of the most challenging requirements is pulse length; one of the key features of the ITER experimental program is eventual steady-state operation for as long as two weeks. To meet these needs, we are proposing a neutral-beam injection system based on negative-ion sources and our constant-current, variable-voltage (CCVV) accelerator. A basic design is in place and will be refined in the course of extensive, ongoing interaction with our fellow participants in the ITER Conceptual Design Activity.**

The proposed ITER neutral-beam injection (NBI) system is shown in Figure 2-2. The D^- beam is extracted from a negative-ion source and its energy is boosted by a CCVV accelerator. This energetic beam of negative ions is converted into a beam of neutral atoms by detaching the extra electron from most of the ions; the detached electrons and remaining ions are swept away electrostatically, leaving a 1.3-MeV D^0 beam that, if it were charged, would have a current of 7.7 A. As implied by the name of the CCVV accelerator, the voltage, and thus the beam energy, can be varied without loss of current or beam quality. (The energy must be kept low at startup to prevent "shine-through," then ramped up as the plasma density increases.) The beam can also be steered to tailor the spatial profile of the plasma current and to control power deposition in the center of a burning plasma. The floor space required is always an issue in designing a tokamak, as complete NBI systems, including the arrays of cryopanels that maintain the vacuum, tend to be quite large. To minimize the "footprint" of the ITER systems, the NBI modules are stacked three high.

* Nineteen-ninety is the third and final year of the Conceptual Design Activity. The next step, given continued support by the four ITER parties (the US, the European Communities, the USSR, and Japan), would be an Engineering Design Activity that would advance to a reasonable starting point for fabrication and construction.

Neutral-Beam Injection for ITER

Neutral-Beam System and Beamline Layout

XBL 908-5557

Figure 2-1. The proposed International Thermonuclear Experimental Reactor is an ambitious scientific and technological step toward a demonstration power reactor. LBL's role within the U.S. effort involves the design and development of neutral-beam systems to heat the plasma and drive the toroidal current. The artists' renderings show approximately how ITER's "core" compares in size to that of the Tokamak Fusion Test Reactor at the Princeton Plasma Physics Laboratory, typical of today's larger experiments. (After PPPL and LLNL artwork.)

XBL 908-5560

XBL 905-1822A

Figure 2-2. The ITER conceptual design calls for three stacks of three 1.3-MeV neutral-beam injectors providing a total of 75 MW. Each injector can provide 10 MW, so ITER can continue to operate if one of them is down for repair or modification. The performance specifications are ambitious, especially in terms of pulse length—two weeks, as opposed to a few tens of seconds for today's NBI systems. (Overall layout diagram courtesy of LBL and Grumman.)

Beamline Cluster (One of Three)

XBL 908-5558

Development of an NBI system for ITER will require a new test stand considerably larger than the Neutral Beam Engineering Test Facility where we developed the CLPS. The requirements include shielding from neutrons generated in the beam dump and from x-rays generated by high-energy electrons. There must also be adequate clearance around the high-voltage supply. We propose to build a Test Facility for Accelerators (TFA) at LBL and demonstrate a 1.3-MV, 1-A negative-ion accelerator system as a proof of principle. The facility's preliminary design is shown in Figure 2-3. This facility could be readily expanded for testing of a complete beamline, scaled down to about 2 A (about one-fourth of the delivered neutral-beam current of an ITER beamline) but at the full 1.3-MeV energy.

The proposed location for the TFA is adjacent to existing MFE Group facilities in Building 5 at LBL. An LBL location offers advantages for the multinational ITER collaboration, including accessibility to international airports and absence of classification and citizenship restrictions.

Test Facility Initiative

Figure 2-3. An ITER NBI test facility at LBL could be located adjacent to the current MFE Group buildings. The conceptual design, still being refined, could be upgraded for 2-MV, multiampere operation for ongoing usefulness. Intended initially for accelerator testing, it could be readily expanded to accommodate testing of a scaled-down ITER NBI beamline (2.5 MW of D^0 at 1.3 MeV).

Neutral Beams and Current Drive

In addition to their primary role of heating the plasma, injected neutral beams help confine and control it. In a tokamak, the plasma is confined by the combination of two principal magnetic fields, as shown in simplified form by Figure 2-4: a toroidal field in the plane of the torus and a poloidal field wrapped around it.

A plasma is very hot, i.e., the particles move at high speeds. In the absence of a magnetic field, they move randomly; the toroidal field guides them circumferentially through the torus, spiraling along the lines of force. This field is generated by external coils. Under the influence of the toroidal field alone, the plasma would move toward the outer wall, so a poloidal field is added. The poloidal field is the result of a very large electrical current—about 20 MA in ITER—coursing through the highly conductive plasma.

This current in the plasma is initiated inductively by the poloidal-field coils; they may be thought of as the primary of a transformer in which the plasma is the secondary. During the initial physics phase of operation, when ITER will be used for "shots" less than 200 seconds long, the plasma current can be driven by the coils alone. However, the subsequent technology-experiment phase will involve sustained burns of up to two weeks; this is far beyond the ability of a transformer system to store and deliver power, so supplemental noninductive drive will be required. In these longer experiments, the bulk of the current will be driven by the neutral beams, which primarily affect the center of the plasma. Additionally, up to 45 MW of rf power will drive the current around the edge of the plasma.

Figure 2-4. This highly simplified and generalized sketch of the tokamak concept shows the two principal magnetic fields—toroidal and poloidal—that work together to confine and stabilize the plasma.

It is not yet clear which of several negative-ion source technologies will be best suited to the high-current, long-pulse needs of future NBI systems. One of our earliest efforts, a "surface-conversion" source in which hydrogen ions were produced on the surface of a cesium-coated molybdenum electrode in a hydrogen plasma, achieved the first steady-state yield of more than an ampere of H^- . However, the partial cesium coating—required in order to optimize the ion yield—had the undesirable side effect of contaminating the accelerator downstream.

Work continues on surface-conversion sources, using cesium and less-volatile coating materials such as barium and magnesium. Another strong component of our ion-source program focuses on "volume-production" sources that produce ions throughout a volume of gas rather than on the surface of an electrode. The main goal is to increase the steady-state current capability of these sources. In the meantime, we have resumed development of a promising rf-driven surface-conversion scheme; it could eventually supplant both the volume-production and the thermionic surface-conversion sources for very-long-pulse operation.

In volume-production sources, gas-phase reactions, as opposed to electron capture on a metal surface, are thought to play a major role in forming H^- ions. (There is evidence that surface processes at the discharge-chamber walls are also significant.) However, there is serious concern, that obtaining the needed production rate from a volume source would require unacceptable extremes of background gas density or power density in the discharge. Further parameter studies, aided by our recently developed vacuum-ultra-violet diagnostic technique, are in progress, as described in the Plasma Diagnostics section below. This year, while experimenting with the positions and shapes of the filaments, we achieved an output of 1 A/cm^2 using a fairly high gas flow with a cesium additive (Figure 2-5).

Ion Sources

Volume-Production Sources

XBL 887-2636

Figure 2-5. This small multicusp plasma source is being used to study the effects of various technologies and parameters on volume production of H^- ions. This small device can produce current densities in excess of 1 A/cm^2 with the introduction of cesium vapor or 250 mA/cm^2 without it. The multicusp source was developed at LBL in 1983; it was the first successful H^- volume-production source. Its name comes from the topology of the magnetic field that confines the plasma.

CBB 865-3985

Free electrons are abundant in a negative-ion source, so electron suppression is an important aspect of performance. We found that a positively charged "collar" on the small multicusp source has a noteworthy beneficial effect on the ratio of electrons to ions, as shown in Figure 2-6. The addition of cesium or barium also improves this ratio. So does a lowering of the plasma potential (at the cost of some reduction in current).

An actual NBI system would use deuterium instead of hydrogen, so we have begun testing D^- yields as well. Generally speaking, our deuterium runs have yielded about 70% as much current density as the hydrogen runs, with an electron-to-ion ratio three to four times greater.

The basic technology used for the small multicusp source has a variety of possible applications, including many that involve positive ions. Previously we had developed a source of atomic N^+ of exceptional purity (better than 98%). It could prove useful in ion implantation for surface hardening of steel, where ionized molecular nitrogen (N_2^+) would result in an undesirably shallow implant layer. In 1989 we built on this work by demonstrating production of a variety of other positive ions, including B^+ and C^+ and, with sputtering targets, various metals such as Cu^+ . Operating at a low arc voltage with CO gas, we also produced a C^- beam.

Figure 2-6. Several approaches have been shown to reduce the ratio of electrons to ions in the small multicusp volume-production source. A positively charged collar can draw off the electrons; its position and voltage can be chosen for the desired tradeoff between effectiveness at electron removal and perturbation of the ion beam. Adding gaseous Cs^+ or Ba^+ also improves the electron-to-ion ratio, and so does lowering the plasma temperature (at the expense of output).

XBL 897-2571A

XBL 896-2459A

The availability of a noncesiated source of copious C^- opens up a variety of possibilities. Cyclotron-based techniques for radiocarbon dating and for medical "tracer" sample analysis could be reinvigorated, for instance. There are also possibilities in materials science, including the deposition of thin films of diamond, as well as attempts to synthesize a class of carbon nitrides that, according to some theoretical calculations, might turn out to be even harder than diamond.

Our 1989 research on surface-conversion sources centered around a 15-cm-diameter multicusp "bucket" that can be equipped either with tungsten filaments and a separate conversion electrode or with barium-oxide cathodes.* The goal of the experiments was to examine the yield and the energy distribution as a function of the bias voltage on the converter, which has implications for the basic processes involved in H^- formation at surfaces

(*sidebar*). In one series of experiments we used an "all-in-one" bariated cathode, as opposed to separate tungsten heating filaments and bariated converter, to determine whether tungsten contamination compromises the effectiveness of the converter. The before-and-after data indicated that this is not a significant concern, at least at the low power levels we used.

In working with tungsten filament and a separate converter, we found that the results were very sensitive to the preparation of the converter surface and to the effectiveness of *in situ* cleaning techniques. Suspecting that material coming from the filament might be contaminating the converter surface, we switched to a barium-oxide cathode—a coaxial, resistively heated, porous tungsten cylinder impregnated with barium oxide. Although the shapes of the energy spectra are different, the yields are comparable, indicating that contamination of the converter surface by cathode material is not a serious problem at these low power levels.

Surface-Conversion Sources

Production of Negative Ions

Volume production and surface conversion are two fundamentally different ways of producing negative ions. Both types begin with a gas of the desired species (hydrogen or deuterium in our work) that is partially ionized by any of several means, but thereafter they diverge at the level of basic chemical physics.

In surface conversion, a negatively charged element (either a coated cathode or a separate, coated converter element) draws positively charged ions from the plasma. Some of them are backscattered, a process in which they sometimes become transformed into negative ions by capturing two electrons from the metal surface. Meanwhile, the surface has been adsorbing the species that makes up the plasma. Of the incoming positive ions that are captured rather than backscattered, some sputter these adsorbed atoms out of the surface; these can likewise emerge as negative ions. In either case, the sheath separating the plasma from the converter—a sheath a few tenths of a millimeter thick in an intense discharge—accelerates the negative ions. Those that leave the source by this means are said to have been "self-extracted."

In volume-production sources, gas-phase reactions are dominant (though surface conversion can take place at the chamber walls) and vibrational excitation of diatomic hydrogen atoms is thought to play a key role. Our model involves a two-step reaction:

- (1) $H_2(v'' = 0) + e^- (\geq 25 \text{ eV}) \rightarrow H_2(v'' \geq 6) + e^-$
- (2) $H_2(v'' \geq 6) + e^- (\approx 1 \text{ eV}) \rightarrow H^0 + H^-$

Reaction (2) can also work in reverse, which is thought to be an important mechanism for H^- loss in the discharge.

* The conversion electrode is cooled, and is biased negatively at a few hundred volts to draw positive ions from the plasma and propel the negative ions toward the extraction aperture. It does not play a significant role as a secondary cathode.

Sheet-Plasma-Discharge Surface-Conversion Source

A different way to circumvent converter-surface pollution from cathode material is to position the cathode far from the converter and create a magnetically confined plasma column (Figure 2-7). The apparatus is a variation of the Uramoto-type sheet-plasma source we had experimented with in earlier years; we have modified that volume-production source in order to place a surface-conversion electrode near the plasma. One of the main drawbacks of the sheet-plasma source was inefficiency at converting positive ions to negative ions. Using the new source, we continued to study conversion efficiency. Figure 2-8 compares our early results to those obtained at the FOM Institute in Amsterdam using a different sheet-plasma surface-conversion source; barium converter electrodes were used throughout. FOM observed a dramatic increase in conversion efficiency with increasing positive-ion density, whereas we have consistently observed a slight drop in efficiency. (Note that these curves are for "self-extracted" negative ions, i.e., no extraction voltage is applied.)

We attribute the difference to the higher electron temperature and primary-electron density in our source. Both of these factors increase the barium-ion density in the discharge and thus the barium-ion bombardment of the converter surface. The higher density of Ba^+ (and electrons) near the converter tends to destroy negative ions, and the increased bombardment is thought to sputter off the hydrogen accumulated in the surface layers of the target.

Figure 2-7. After disappointing volume-production results with our Uramoto-type sheet-plasma ion source, we recently modified it to accept a surface-conversion electrode. In this program, we are studying and trying to improve the conversion of positive ions to negative ions.

CBB 875-3848

XBL 906-2175A

Figure 2-8. As shown here, a hollow-cathode source at the FOM Institute in Amsterdam appears to give better conversion efficiency as the density of positive ions increases, whereas our results show decreasing efficiency and only slightly higher yield. Explaining the difference may lead to a better understanding of the phenomena occurring near the converter electrode.

High-frequency rf (around 1.7 MHz in our present work) offers a different and potentially more robust approach to generating the plasma in both volume-production and surface-conversion sources. Our rf-driven source is based on the same "bucket" with a multicusp magnetic field as the thermionic-cathode ion source. However, it has a glass-coated antenna instead of a filament or cathode. The antenna is immersed in the plasma instead of external to the discharge chamber as in some older designs. The rf energy sets up an oscillating magnetic field, which, in turn, produces an electric field. Voltage is applied to the antenna intermittently with a pulse length of 1 ms and a repetition rate of about 100 Hz.

The maximum H^- output current for both rf induction and dc filament discharges is presented in Figure 2-9. When compared with the same input power and at the same source pressure, rf discharges generally produced at least 40% more current than dc filament discharges. The extracted electron to H^- ratios are about the same throughout the range of discharge power tested. Unlike dc filament discharge, the shape of the H^- pulse was very uniform even though the source pressure was maintained at 15 mTorr. When the rf plasma was operated at a pressure higher or lower than 15 mTorr, the H^- current level would decrease but the pulse shape always remained uniform.

The rf source, with no filaments or cathode to burn out, seems to be a very attractive candidate for long-pulse fusion applications and for a great many other uses as well. A development program is already underway to develop rf sources for the Superconducting Super Collider: one for calibration of detectors, which will be an essential step in the experiments there, and another as a backup for a more conventional ion source in the injector system.

RF-Driven H^- Source

CBB 906-4886

Figure 2-9. The hot tungsten cathode in a multicusp-filtered "bucket" source has been replaced with a water-cooled rf antenna consisting of a few turns of glass-coated copper tubing. When energized by a few kW of rf power in the 1-2 MHz range, electrodeless (induction) discharges occur. These discharges are suitable for ion production without the tungsten contamination and cathode-life limitations of the hot-cathode version.

XBL 906-2206A

Charge Neutralization for Semiconductor Processing

Among the more recent technology spinoffs from our fusion-energy research is an improved electron-beam charge neutralization system for ion implanters, which we developed under the sponsorship of Extrion Division, Varian Associates. The neutralizer, shown in Figure 2-10, is an improved means of delivering electrons to silicon or other semiconductor wafers to neutralize the positive charge that builds up during ion implantation. It incorporates a large, directly-heated lanthanum hexaboride (LaB_6) cathode like those developed for our MFE research, along with a magnetic beam-guiding system. This beam-based system has several advantages over the comparatively haphazard electron flooding techniques that are used today, in which primary electrons at about 350 eV strike a production target, giving off secondary electrons at various energies that bounce off the chamber walls and make their way to the wafer. In particular, the output is free of damaging, higher-energy electrons, and its flow is even and predictable.

In our system, the accelerated electrons begin their course perpendicular to the ion beam and then merge with it after going through a 90° bend induced by the magnetic field of a curved solenoid. The bend keeps the cathode out of the line of sight of the wafer so that it does not interfere with the ion beam. An opening in the solenoid allows the ion beam to enter and merge with the electron beam;* this mingling also provides space-charge

* The magnetic fields used are too weak to have a significant effect on the ion beam, which is far more "rigid" than an electron beam of comparable energy because ions are so much more massive than electrons.

MAGNETIC FUSION ENERGY

XBL 903-883

XBL 903-882

CBB 890-9201

Figure 2-10. This charge-neutralization system for ion implantation in semiconductors was developed by the MFE Group on behalf of Extrion Division, Varian Associates, which sponsored the research and has applied for patents. The electron beam (left) comes from the source, goes through the curved solenoid with Helmholtz coils above and below, and merges with the ion beam. One of the bucking coils is visible in the foreground.

compensation for better ion-beam propagation. In order to steer the low-energy electron beam around the corner, a vertical or perpendicular component of the magnetic field is employed; this component is generated by a pair of Helmholtz coils.

The 100-mA beam arriving at the wafer is very uniform in its density. The energy distribution also has good uniformity: within a circle of 5 cm diameter, Langmuir-probe traces show electron energies of 30 eV and below, with the majority under 10 eV.

The development of more-efficient, higher-current negative ion sources requires a thorough understanding of the physical and chemical processes within these devices. We had earlier developed a vacuum-ultraviolet laser absorption spectroscopy technique to measure the concentrations of neutral hydrogen (H^0) within the plasma discharge volume. The experimental apparatus is shown schematically in Figure 2-11. The technique has recently been extended to measure the concentration of molecular hydrogen (H_2), the other major neutral species present.

Ion-Source Chemical Physics

In a variation on the general theme of Raman spectroscopy, we can also determine the energy content of each species, i.e., the translational energy distribution for the atoms and the translational, rotational, and vibrational energy distributions for the molecules.* Such measurements are critically important because the reactions governing H^- formation and destruction in volume plasma sources are sensitive to these parameters. Studies of the hydrogen molecules in the volume source indicate that a large fraction of them are vibrationally and rotationally excited. Quantized rotational levels as high as $J'' = 8$ are well-represented. Vibrational levels as high as $v'' = 8$ have been observed (though the lower quantum vibrational levels are much more abundant, as shown in Figure 2-12).

The vibrational results are especially intriguing, as the distributions do not agree at all with what existing models would lead us to expect. Figure 2-13 gives an example of the data: the logarithmic dependence of high- v'' populations on vibrational energy has a straight negative slope, whereas we expected a "plateau" of positive deviation from this monotonic slope from $v'' = 5$ to $v'' = 11$. We believe, however, that the H^- production mechanism that has been proposed is qualitatively accurate and that the disagreement results from inaccurate cross sections in the model of the H_2 vibrational distribution. Research continues as we seek a better understanding of the phenomena involved in this important process.

Figure 2-11. In our laser absorption spectroscopy technique, the nonlinear optical technique of four-wave sum-frequency mixing produces tunable 20-ns VUV pulses. The wavelengths for source diagnostics (94–125 nm) are produced by using various resonance levels in the mercury-vapor mixing medium. The wavelength parameters shown are for generation of Lyman- β radiation. A wide variety of gas- and plasma-phase absorption measurements can be made. This typical absorption spectrum obtained using Lyman- γ radiation indicates a H^0 density of 9.4×10^{12} atoms/cm³.

* The atoms, ions, and molecules undergo translational motion through space. The molecules also rotate, or tumble, about various axes, and, on a much faster time scale, they exhibit vibration, which may be interpreted as expansion and contraction of the bonds between their atoms. Translation occurs in the classical continuum, whereas the rotational and vibrational states are quantized (though described well by semiclassical treatments).

Figure 2-12. Quantized rotational levels as high as $J'' = 8$ are well-represented in the volume-production ion source. Vibrational levels as high as $v'' = 8$ have been observed, though the lower quantum vibrational levels are much more abundant. Note that the rotational distributions of all vibrational levels are similar.

XBL 906-2172

Figure 2-13. The dependence of high- v'' populations on vibrational energy is logarithmic, with a straight negative slope, whereas we had expected a positive deviation from this, or a "plateau," from $v'' = 5$ to $v'' = 11$.

XBL 908-2650

Materials Modification and Synthesis

The performance, durability, and economic attractiveness of today's "high-tech" products are often predicated on advanced metals and other materials and on effective, affordable techniques for manufacturing them. Closely allied with our ion-source R&D is an ongoing investigation of suitable technologies and applications for ion beams and plasmas in this field. These programs involve close interdisciplinary collaboration with colleagues from LBL and elsewhere.

In 1989 we continued development of the Metal Vapor Vacuum Arc (MEVVA) ion source, which works on different principles than the ion sources described in the previous section, and demonstrated its usefulness for large-scale, high-dose ion implantation in metal surfaces. Another program relates to the quest to deposit industrially useful diamond coatings on surfaces. In our work, which yielded its first results in 1989, we deposited diamond on a surface by a Plasma Assisted Chemical Vapor Deposition (PACVD) process.

MEVVA Development and Characterization

The MEVVA ion source has enjoyed widespread use since it was invented at LBL; universities and government laboratories in Australia, China, West Germany, Japan and the Soviet Union established MEVVA R&D and application programs. We are in communication with these workers and have set up some collaborative research programs.

In 1989 we built a new MEVVA source designed specifically for implanting ions in the surfaces of metals. (Generally speaking, industry would do this to smooth and harden the surfaces of metal parts.) The effectiveness of the MEVVA technology for high-dose metal-ion implantation was successfully and thoroughly demonstrated. The MEVVA program comprises three parallel components: ion-source development, ion-beam characterization, and ion-implantation research.

In the new source, MEVVA V (Figure 2-14), a vacuum-arc discharge creates an intense plume of highly ionized metal from the cathode. The ion beam is formed using a 10-cm-diameter set of extractor grids. MEVVA V incorporates the multi-cathode "Gatling-gun" feature that was developed for MEVVA IV. This feature allows rapid switching among 18 separate cathodes, so it is easy to change metallic species or substitute for a spent cathode without breaking vacuum.

Figure 2-14. The MEVVA V ion source was designed specifically for ion implantation. It incorporates a broad-beam extractor (10 cm in diameter) and a multiple cathode assembly (18 separate cathodes). The "Gatling gun" cathode array, like the MEVVA concept itself, is a fairly direct spinoff from injector research and development for the SuperHILAC heavy-ion linear accelerator.

The maximum beam extraction voltage is 100 kV, and since the ion charge states vary typically from 1 to 5 (depending on the metal), the ion energy in the extracted beam can be up to several hundred keV. The record beam current extracted is 3.5 A; the beam is delivered in 250- μ s pulses at a repetition rate of up to several tens of Hz. We have carried out an extensive study of ion beam characteristics as a function of various source parameters for both the MEVVA IV source, which is now being commissioned in the injector beamline at the SuperHILAC heavy-ion linear accelerator, and MEVVA V.

In this work, we examined the charge state distribution of the ion beam produced from 48 different elements—nearly all of the solid metallic elements. Besides being a unique and important contribution to vacuum-arc physics, these data are important for ion implantation. We also investigated the spectra of ions produced from a number of different alloy and compound cathodes. The beam current was measured as a function of source parameters such as arc current, extraction voltage, cathode species, and extractor grid spacing; beam divergence and cathode erosion rates were also measured. Finally, a parametric study of the beam “noise” (fractional current fluctuation level) was completed in collaboration with GSI in Darmstadt, West Germany. The beam noise was found to reach its minimum at an arc current corresponding to the perveance match condition. In other words, there is an ideal plasma density for any given geometry of the beam-formation electrodes; at this density, the beam current is maximized and the beam divergence and noise are minimized. These results provide a guide to optimal source operation; they are especially important when MEVVA sources are used as injectors for accelerators.

We have carried out a wide range of ion-implantation “mini-programs” to demonstrate applications of MEVVA V. Some highlights are listed below.

Superconducting Thin Films. We have used high-dose metal ion implantation as a means of fine-tuning the composition of high temperature superconducting thin films. In these experiments, carried out together with LBL’s Applied Science Division, thin films of Y-Ba-Cu-O that had been deposited by rf magnetron sputtering from a single target were implanted with Cu. As shown in Figure 2-15, this altered their composition and raised their critical zero-resistivity temperature or T_c .

Metallic Oxidation Resistance. The first major phase of a collaborative research program with LBL’s Materials and Chemical Sciences Division has been completed. We have been investigating how the high-temperature oxidation properties of a Fe-Cr-Al alloy of the kind used for high-temperature turbine blades might be improved by high-dose implantations of Mg, Ti, Y, Zr, Mo, Pd, Hf, W, or Th. Results are now being analyzed.

Steel Surface Hardening. In an experiment that is now in an exploratory phase, we are collaborating with the Naval Research Laboratory to study the implantation of Ti, and, separately, the mixed Ti/C beam obtained from a TiC cathode, into Type 440C hard steel. Such implantations could improve the wear and hardness characteristics of the steel surface. The experiments involve very high doses—in the range of $1 \times 10^{18} \text{ cm}^{-3}$. Several rounds of LBL implantation followed by NRL analysis have been carried out.

MEVVA V “Mini-Programs”

Figure 2-15. Implantation of Cu ions into a Y-Ba-Cu-O film greatly improved its superconductivity characteristics. The Cu:Y ratio, initially too low for good superconductivity at 2.0:1, was increased to 2.2:1 by the implantation.

XBL 908-5905

Implantation-Depth Research. A study of the implantation depth profiles of a range of metal ion species (Ti, Cr, Y, Zr, Nb, Mo, Pd, Ba, Dy, Ta, W, Ir, Pt, and U) in a carbon substrate was carried out collaboratively with the U.K. Atomic Energy Agency in Harwell, England. This fundamental investigation will clarify the effect of the broad distribution of ion charge states (and hence the broad energy spectrum) of MEVVA-produced ion beams, thus improving the interpretation of surface-modification work.

Field Modification of Equipment. The Corpus Christi Army Depot has begun an ion-implantation project, part of which involves MEVVA technology. The program focuses on helicopters, which have a great many moving parts and notoriously high maintenance needs. The goal is to demonstrate the usefulness of metal-ion implantation as an overhaul procedure to improve existing machinery. One 1989 run involved the implantation of Mo into Al coupons for enhanced corrosion resistance; corrosion testing is presently in progress. We are now fabricating a target manipulator for use in the implantation of Pt into steel bushings that are used in helicopter engines.

Diamond Synthesis

Along with LBL's Materials and Chemical Sciences Division, we have established a program to investigate the synthesis of polycrystalline diamond thin films on substrates that are of technological value. The metallic substrate is immersed in a microwave-produced hydrogen/methane plasma, and diamond films grow from the plasma state by chemical vapor deposition. The goal is to develop industrially applicable techniques for depositing diamond thin films onto large, three-dimensional substrates. Figure 2-16 shows the results of the initial experiments: the early growth stages of a thin film, consisting of faceted diamonds about 1–2 μm in size.

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In our first experimental PACVD diamond synthesis system, microwave energy is provided by a 500-W magnetron at 2.45 GHz. The microwave power is delivered to a simple plasma chamber via standard waveguide components, and a hydrogen/methane plasma is established. During processing, the sample is situated inside a quartz vessel and immersed in the discharge; substrate temperature is monitored by a two-wavelength infrared pyrometer. Further steps in this program include optimizing process control in order to form uniform thin films, along with investigation of possible techniques for bonding the film to the substrate more strongly—an important requirement for moving such diamond films out of the laboratory and into applications.

XBB 905-3633

XBL 901-112

Figure 2-16. Scanning electron microscopy reveals the first faceted diamond crystals synthesized in our microwave-plasma device. The crystals are about 1–2 μm in size. The diagonal band of heavy deposition marks the location of a scratch provided to promote nucleation. Longer processing would have resulted in more-complete coverage. The Raman scattering spectrogram by MCSD shows the distinctive signature of true, high-quality diamond: a strong peak at 1332 cm^{-1} . The large peak on the right is from the silicon substrate.

Accelerators for Negative Ions

The experimental fusion reactors now being planned or proposed—the ones in which experimenters hope to attain “ignition,” or a self-sustaining fusion reaction—will have substantially larger plasmas than today’s experiments. High neutral-beam energy will be crucial for penetrating these larger plasmas. Furthermore, variable beam energy is highly desirable; the energy can be kept low initially to prevent “shine-through,” then raised as the plasma density increases. Our efforts have been concentrated on development of high-current, high-energy negative-ion accelerators whose energy can be varied without sacrifice in current. We have found a promising way to accomplish this with a Constant-Current, Variable-Voltage (CCVV) accelerator using electrostatic quadrupole (ESQ) focusing. A prototypical section of this accelerator was completed and tested in 1988, and experimentation with it continues.

CCVV Accelerator Testing

The CCVV accelerator is intended for dc operation in the MeV energy range but can be tuned for lower energy without reducing beam current. (The current is fixed by the ion source and preaccelerator.) ESQ focusing reduces the risk of voltage breakdown as compared to the conventional Pierce-type accelerator column because the transverse electric fields that provide focusing also sweep out secondary ions and electrons that could trigger breakdowns. These features are useful for fusion-reactor startup and, coincidentally, for industrial spinoff applications such as processing of semiconductors and surface hardening of materials.

A CCVV accelerator using ESQ focusing is being developed at LBL to accelerate negative ions efficiently to the energy range that the next generation of tokamaks will require. Our existing 200-keV single-beam prototype system (Figure 2-17) is designed to accelerate up to 200 mA of H^- or an equivalent current of heavier ions, such as 140 mA of D^- . The accelerator is modular. A matching-and-pumping stage focuses and transports a 100-KeV beam without acceleration; then a CCVV accelerating stage increases the beam energy by up to 100 keV. (The CCVV stage can also transport a beam at constant energy or even decelerate it.) Both stages use electrostatic quadrupoles for focusing.

Using two of these two-stage modules, we have accelerated a 42-mA H^- beam to an energy of 200 keV for a period of 200 ms. At the slightly reduced energy of 180 keV, we accelerated a 40-mA beam for more than 400 ms. When the matching-and-pumping stages are tuned properly, the beam loss can be less than a few percent and emittance growth is insignificant.

Plans for 1990 include testing of the system with higher beam currents at 200 keV. Among of the limitations of the test program is the intensity of beams from the available negative-ion sources. Continued progress in the ion source development program should alleviate this problem, allowing eventual testing of the CCVV accelerator at its full capacity.

For NBI applications, a CCVV accelerator only needs to have an energy range of about 2:1. In other applications, such as semiconductor processing, surface hardening, or fusion-plasma diagnostics, much wider energy ranges may be needed. The output beam energy may be varied not only by adding or removing CCVV modules, but also by suitably tuning the acceleration voltages and the ESQ focusing voltages (which may be performed rapidly without altering the accelerator’s configuration). Numerical simulations that we performed in 1988 demonstrated that the energy of a CCVV stack could be tuned from 1 MeV down to 20 keV without any change in mechanical configuration or reduction of beam current.

MAGNETIC FUSION ENERGY

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Figure 2-17. This constant-current, variable-voltage (CCVV) accelerator module is based on electrostatic-quadrupole (ESQ) technology. Each module consists of a matching-and-pumping stage (the part with a dark insulator band) and a 100-keV acceleration stage. CCVV modules can be cascaded to obtain the desired beam energy. The apparatus at the far left is a test stand for the accelerator; at far right is a volume-production ion source. Below: work on the matching-and-pumping stage affords a view of the internal structures.

Computer Modeling

The design of CCVV systems relies heavily on computer modeling, most of which has been done with a simple code that describes the beam envelope. A typical result is shown in Figure 2-18, which traces the beam envelope through 10 complete modules of a 1-MeV accelerator. We have also used the WOLF particle code to model the preaccelerator, and another code, faster and simpler but less accurate, to model the electron trap.

In 1989 we began a project in which the 3-d particle code ARGUS is used to model the entire 200-keV prototype of the CCVV accelerator, including the preaccelerator and electron trap, the ESQ matching stage, and the CCVV accelerator stage. ARGUS, developed by Science Applications International Corp. and adapted for our use, has already provided accurate modeling of ion and electron behavior in the preaccelerator/electron trap section. When the ESQ portion of the code is fully operational, we will be able to check the accuracy of our envelope-code models by making detailed comparisons between the models' output and experimental results.

One of the problems that can arise in an NBI system is the generation of secondary electrons in ionizing collisions between D^- particles and back-ground-gas molecules. If these electrons are propagated through the accelerator long enough to reach high energies, they can produce damaging x-rays when they strike metal surfaces such as the accelerating and focusing electrodes. The findings, based on a computer model called SECONDARIES, were reassuring: of all the secondary electrons born in an early accelerating gap, only 2% make it through two more gaps, and only 0.5% survive all the way through the accelerator. Most of the secondary electrons are swept out by the transverse electric fields in the quadrupole sections before they gain much energy. The mean energy of the electrons that stop in the accelerator is only 25.4 keV, which leads us to believe that x-ray damage to insulators will not be a problem in a 1-MeV CCVV accelerator.

Figure 2-18. The SECONDARIES program traced this beam envelope through a CCVV accelerator with a bariated surface-conversion source. Here a 140-mA, single-channel beam is accelerated to 1.3 MeV. One finding from our simulations was that with a surface-conversion source, both the space charge of the source beam and the source temperature appear to be significant factors in scaling of the ESQ focusing voltage as energy increases. With a volume-production source, by contrast, only the space charge need be considered. Also shown here is the accelerator layout assumed in the model.

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To construct a high-energy accelerator, we would stack the modules described above to obtain the required beam energy. Previously, we had completed a detailed design for a 1-MeV single-channel system, as well as a conceptual design for a multichannel system that would accelerate 10 A of D^+ to 1–2 MeV. The multichannel system could be used, in conjunction with a suitable D^+ source and a plasma neutralizer, as part of a neutral-beam injector for ITER.

A spinoff from our CCVV accelerator research—an electrostatic low-energy beam transport system, or LEBT—appears to be well suited for use in the injector systems of accelerators for high-energy physics, such as the SSC or the proposed Large Hadron Collider at the European Center for Nuclear Research. The injectors for these machines are operated with short pulses at low duty cycles. Under these conditions, stable gas neutralization of the low-energy beam, as needed in most magnetic LEBTs, is hard to achieve. Our LEBT incorporates ESQ focusing in the beam-transport stage, along with an electrostatic ring lens to match the beam into an rf-quadrupole accelerator (RFQ). Computer modeling and test-stand measurements (with a simulated RFQ entrance) indicate that the system is noise-free and stable and causes negligible emittance growth in H^+ and He^+ beams. In cases where pumping is of no concern and the distance between the ion source and the first accelerating structure must be kept as short as possible, the system can be reduced to one or two simple electrostatic ring lenses.

Fusion research owes a great debt to complex theoretical studies conducted on the borderline between physics and mathematics. The MFE Group at LBL maintains a plasma-theory branch whose pure and applied studies help other researchers understand the phenomena observed in hot plasmas and the possibilities for future development. The plasma theorists have sought new ways of comprehending gyroresonant absorption; their goal is to understand the physics of the phenomenon and thereby describe it in simpler mathematical terms. Their work has yielded not only simplified mathematical approaches, but also insights into the geometry of wave propagation in a plasma, and into differences between the behavior of the incoherent waves typical of natural phenomena and the behavior of coherent waves.

In 1989, an important focus of our theoretical studies was the investigation of the basic properties of wave systems, especially in the area of short-wavelength asymptotics, i.e., WKB theory. We have also investigated the nonlinear dynamics of classical Hamiltonian systems, along with related topics in statistical mechanics. These areas of research reinforce one another, since the short-wavelength asymptotics of wave fields incorporates not only the entire framework of classical Hamiltonian dynamics, but also additional structures relevant to wave systems. Because of this connection, WKB approximations are sometimes called “semiclassical” methods.

Our group’s approach to these problems in nonlinear dynamics is to apply forefront ideas from theoretical physics and modern mathematics. Especially relevant are the physical concepts of invariance and covariance, in which the properties of a physical theory are, respectively, independent of or dependent upon the observer and the system of coordinates. Such ideas have long been a driving force in theoretical physics; they underlie such

Future CCVV Systems

Electrostatic LEBT for High-Energy Accelerators

Plasma Theory and Nonlinear Dynamics

Wave Dynamics and Gyroresonant Energy Absorption

fields as the special and general theories of relativity, or the classical mechanics of Hamilton and Jacobi.

The immediate purpose of this work is to understand heating and transport of plasmas—in particular, gyroresonant absorption of energy. One of the main heating schemes for tokamaks involves irradiation of the plasma by a coherent magnetosonic wave. This radiation is partially absorbed at a resonance layer, where the wave frequency ω is either twice the local gyrofrequency of a dominant ion species or the fundamental gyrofrequency of a minority species.

In studying gyroresonant absorption, it is important to understand mode conversion (how and where the waves couple into one another) inside a tokamak. A significant advance, beginning in the early 1980s, was the introduction of the wave-phase-space viewpoint. It was shown that the waves are separated by their characteristic ray paths, and that they typically meet pairwise at the sites of mode conversion. Simplifying the physical picture to a succession of pairwise conversions allowed an analytically intractable fourth-order differential equation to be reduced to two second-order equations.

In search of better understanding and further simplification, we have looked at the problem in terms of two waves: a magnetosonic wave traveling in x -space and a "pressure-anisotropy wave" that travels through wave-vector or k -space. Figure 2-19 shows a typical gyroresonance process. Because the particles within a tokamak gyrate at different rates, depending on the local magnetic field, the wavelength of the pressure-anisotropy wave changes as the wave propagates through the plasma; in other words, the wave moves through phase space. The successive mode conversions are linked by the pressure-anisotropy waves. With this understanding, each mode conversion can be modeled in wave-vector space with a single first-order ordinary differential equation.

This approach, which incorporates several techniques that we originated, represents a significant advance over the standard treatment of gyroresonant absorption, which uses the local dielectric tensor (which is rapidly varying at the resonance) and the wave electric field in x -space. Our approach uses several new techniques to replace approximate numerical solutions with explicit, exact analytical solutions. These techniques include

- congruent reduction, which yields coupled equations for linear mode conversion with slowly varying dispersion functions for the various modes
- wave propagation in k -space for the modes involved in the resonance absorption process
- metaplectic transformations that locally convert partial differential equations into first-order ordinary differential equations, which are much easier to solve analytically
- identification of absorption as linear conversion to a continuum of Case-van Kampen modes, which are then spectrally transformed to explicitly uncover the Landau-damped collective modes.
- recognition of the energy conservation problem in terms of wave-action conservation in phase space, which can be obtained through Weyl symbol calculus

Figure 2-19. This schematic phase-space diagram depicts a typical gyroresonance process. An incident electromagnetic ray comes in on the upper dispersion surface. As it crosses the gyroresonance layer, it excites a continuum of gyroresonant ballistic waves (GBWs), which then propagate in six-dimensional phase space. They may come across the dispersion surface of the reflection branch (the lower surface), in which case each GBW mode-converts to a reflected ray.

We have produced a complete solution for the one-dimensional slab model of second-harmonic absorption, and are currently generalizing this work to include minority heating. Future plans include extension of our understanding to two- and three-dimensional models.

In treating the nonlinear interaction of extended systems (such as electromagnetic fields and distributions of charged particles) it is highly desirable to formulate a variational action principle. The primary advantage is that, in making transformations of variables appropriate for various approximation schemes such as expansions in wave amplitude or eikonal expansions, a variational approach yields self-consistent equations appropriate to the particular approximation. Further, such an approach implies continuous symmetries, such as invariance with respect to space-time translations or wave phase shifts, that yield the local conservation laws appropriate to these approximations.

Covariant Lagrangian Field Theories

The implications of these studies could reach beyond fusion. Wave phenomena are ubiquitous in nature. Semiclassical methods in wave dynamics have a vast range of applicability, from quantum mechanics at the nuclear, atomic and molecular levels to a new field of astrophysics called helioseismology in which the propagation of shock waves through stars is studied in order to infer their internal characteristics. These semiclassical methods are also commonly used in studies of optics, radio transmission, and acoustic phenomena, including the detection of cracks or other faults in metals and the propagation of sound waves through the ocean or earth.

Further Applications

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3.

ADVANCED LIGHT SOURCE

*...impressive progress
toward the expected spring
1993 commissioning ...*

A WIDE VARIETY OF SCIENCES AND TECHNOLOGIES, ranging from atomic physics to examination of integrated circuits, can benefit from synchrotron radiation beams of high quality. The ALS, a Department of Energy national user facility, is one of the first in a new generation of dedicated synchrotron light sources. It is based on an electron storage ring designed to accommodate long magnetic insertion devices (known as "wigglers" and "undulators") that enhance production of synchrotron radiation. The undulators will provide photon beams of unprecedented brightness in the extreme-ultraviolet and soft-x-ray regions of the spectrum, whereas the wigglers and the bending magnets will contribute high-quality broadband radiation reaching into the hard-x-ray region.

The project includes an initial complement of four insertion devices and two beamlines. Additional experimental facilities will be built with funding support from other sources. Work on the ALS began in December 1986, and the coordinated efforts of several design and development teams and construction crews have resulted in impressive progress toward the expected spring 1993 commissioning.

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ADVANCED LIGHT SOURCE

As Figure 3-1 shows, the ALS will consist of an electron source, a linear accelerator, a booster synchrotron, and a low-emittance storage ring with insertion devices and synchrotron-radiation beamlines. The storage ring has 12 long straight sections, 10 of which can accommodate insertion devices. Additionally, there are provisions for 48 radiation ports at the bending magnets, which also produce synchrotron radiation.

When the user program begins, chemistry and surface science can benefit from ultraviolet light from the ALS (see the discussion of the Chemical Dynamics Research Laboratory (CDRL) initiative in Chapter 5, "Exploratory Studies"). Higher-energy photons, in the soft-x-ray region, are useful for thin-film and interface studies, atomic physics research, studies of living cells, and industrial applications such as high-resolution characterization of integrated circuits. Applications for hard x-rays from wigglers include structural studies of crystallized viruses and proteins, as well as elemental probes of materials.

Nineteen eighty-nine saw excellent progress in construction work, and the mechanical, electronic, and accelerator systems continued through the prototyping, ordering, manufacturing, and inspection phases. Experimental systems also showed substantial progress as user requirements and details of theory and practice that affect performance were more sharply delineated.

The scientific program progressed from expressions of interest to formal beamline proposals. The year ended with the naming of nine insertion-device Participating Research Teams (PRTs) that intend to finance various portions of their experimental facilities in exchange for guaranteed shares of beam time. The response to the call for proposals was quite strong and closely mirrored the letters of interest received earlier, further validating the relevance of the ALS and the appropriateness of the user program.

Figure 3-1. High-energy electrons are provided by a 50-MeV rf linac feeding a 1.5-GeV booster synchrotron. The electrons are then sent into a storage ring optimized for use at 1.5 GeV, which is the site of synchrotron-radiation production. Synchrotron radiation is produced by the bending magnets and by magnetic insertion devices ("wigglers" and "undulators") in the straight sections; both bending-magnet and insertion-device beamlines will be available to meet experimenters' needs.

CBB 880-11806

Interaction with the User Community

When one examines the complexities and lead times of designing, building, and commissioning insertion devices and experimental facilities, the spring of 1993 does not seem very far in the future. Accordingly, close and extensive interaction with prospective users has been a hallmark of ALS program planning, which began in earnest with a series of user workshops in 1987 and 1988.

A call for letters of interest issued in 1988 was followed by a call for formal proposals to form PRTs. Eighteen responses were received, covering a wide spectrum of research. The proposals may be thought of in four categories:

- Materials, interface, and surface sciences.*
- Atomic, molecular, and chemical sciences.*
- Life sciences.*
- Instrumentation and component research and development.*

Nine insertion-device PRTs were approved. The strong response confirms the user demand for the ALS and augurs well for an active scientific future at the facility.

These activities are now being supported by a Scientific Program Coordinator who represents the ALS to the user community and acts as scientific and administrative liaison between users and ALS and LBL management.

Finally, the Science Policy Board and the Program Review Panel, two advisory bodies that will provide broad policy guidance and specific recommendations on proposals for research, were convened.

Call for Proposals

Eighteen PRT proposals, involving 208 researchers from universities, government laboratories, and private industry, were received in response to the Call for Proposals issued in March 1989. Six of the proposals were for bending-magnet PRTs; evaluation of these was tabled until 1990.

The twelve proposals from insertion-device teams were evaluated by the ALS staff and the Program Review Panel. Team representatives met with the ALS experimental systems staff to discuss design and planning of insertion-device beamlines; then the Scientific Program Coordinator encouraged mergers among teams with congruent interests. The Program Review Panel interviewed representatives of the candidate teams at its November meeting, and its recommendations were passed along to the LBL director. This process resulted in the December announcement of nine approved PRTs, as described in Table 3-1, subject to their ability to obtain the needed funding within one year.

Each PRT will build and operate its facilities under a memorandum of understanding, a "dynamic document" that can be modified as circumstances warrant. Its purpose is to foster a common understanding of the resources, effort, and schedule needed to implement the proposal. The Program Review Panel will also use the memorandum of understanding, among other criteria, in frequent performance reviews of the PRT.

ALS Advisory Panels

Two committees began meeting this year to provide advice on ALS planning and operation to the LBL director. The eight-member Science Policy Board (see Table 3-2) provides advice on high-level policy issues affecting the ALS. At its first annual meeting, held in February, it generally endorsed the ALS plans and progress and specifically commended the "strong commitment to establishment and support of a diverse user community representing an appropriate balance of scientific and institutional interests."

Table 3-1. ALS Participating Research Teams (PRTs)

Insertion Device	Scientific Focus	Spokesperson	Type (see sidebar)
U10.0	Chemical dynamics (associated with Combustion Dynamics Facility initiative)	Tomas Baer, Univ. of North Carolina	C
U8.0	Atoms, molecules, and ions	Denise Caldwell Univ. of Central Florida	A
U8.0	Pump-probe, other timing experiments; dynamics studies	Victor Rehn, Naval Weapons Center, China Lake, CA	C
U5.0	Surface and interface studies	Brian Tonner, Univ. of Wisconsin-Milwaukee	A
U5.0	Surface and interface studies	Joachim Stöhr, IBM-Almaden Research Center, San Jose, CA	B
U5.0	Materials sciences	Stephen Kevan, Univ. of Oregon	C
U3.9	Soft-x-ray imaging and optics for the life and physical sciences	Stephen Rothman, UCSF and LBL	C
W13.6	Atomic, molecular, and optical physics with x-rays; materials science	Bernd Crasemann, Univ. of Oregon, and Phil Ross, LBL	B
W13.6	Life sciences	Alexandre Quintanilha, LBL	C

The nine-member Program Review Panel (Table 3-3) gives advice on the scientific program. Until the ALS is commissioned in spring 1993, the panel's main task will be evaluation of PRT proposals. As appropriate, the scope of its activity will broaden to include performance reviews of existing PRTs and evaluation of beamtime proposals from independent users. The panel met in August and November and plans to meet at least twice a year.

Classes of Research Teams

As part of a user policy designed to make the ALS accessible to all qualified researchers, users are classified either as members of PRTs or as independent users. PRTs invest their own effort and their institutions' resources in constructing, commissioning, and operating experimental facilities. In return for this commitment, each team receives a guaranteed fraction of the ALS operating time at its beamline. Independent users submit proposals for specific experiments or research programs to be run on the appropriate beamline during periods not reserved for the PRT.

PRTs working with undulators or wigglers and the associated beamlines are called insertion-device teams. These are subdivided into three types that get different percentages of beamtime, depending on how much of the system they fund; details vary with individual circumstances. A Type-A team pays for the experimental end station only. A Type-B team, which funds the end station and beamline, or a Type-C team, which funds the end station, beamline, and insertion device, would get a larger share of the beamtime. In each case, the balance of the beamtime will be made available to independent users.

Other PRTs work with bending-magnet beamlines (i.e., they use light from the bending magnets, as opposed to insertion devices in the straight sections).

ALS Users' Association

The ALS Users' Association held its second annual meeting in August at the Sixth National Conference on Synchrotron Radiation Instrumentation (hosted by LBL and held at the Clark Kerr Campus, University of California at Berkeley). The meeting emphasized selection of the initial PRTs and related topics. Five topical workshops related to the ALS were held at SRI '89 under the sponsorship of the association.

The main order of business was nomination of candidates for the three open slots on the ALS Users' Executive Committee, which communicates the users' needs to the ALS staff. The September election resulted in three new members (Table 3-4).

Table 3-2. ALS Science Policy Board, 1990

Dean E. Eastman, IBM Thomas J. Watson Research Center (chair)
 Richard Bernstein, University of California at Los Angeles
 E. Morton Bradbury, School of Medicine, University of California at Davis
 William F. Brinkman, AT&T Bell Laboratories
 John C. Browne, Los Alamos National Laboratory
 Bernd Crasemann, University of Oregon
 Herbert H. Johnson, Cornell University
 J. McEwan Paterson, Stanford Linear Accelerator Center

Table 3-3. ALS Program Review Panel, 1989-1990

Neville V. Smith, AT&T Bell Laboratories (chair)
 C. Richard Brundle, IBM Almaden Research Center
 Sheldon Datz, Oak Ridge National Laboratory
 Michael L. Knotek, Battelle Pacific Northwest Laboratories
 Robert I. Macey, University of California at Berkeley
 Giorgio Margaritondo, University of Wisconsin-Madison
 Keith Moffat, Cornell University
 Joe Wong, Lawrence Livermore National Laboratory
 J. Michael White, University of Texas at Austin

Table 3-4. ALS Users' Executive Committee, 1990

Charles S. Fadley, University of Hawaii (chair)
Tomas Baer, University of North Carolina at Chapel Hill
Wolfgang Eberhardt, Exxon Research and Engineering Co.
Cynthia Friend, Harvard University *
T. Kenneth Gustafson, University of California at Berkeley
Stephen D. Kevan, University of Oregon
Melvin Klein, Lawrence Berkeley Laboratory
Manfred O. Krause, Oak Ridge National Laboratory
Dennis W. Lindle, National Institute of Standards and Technology
Rupert C. Perera, Lawrence Berkeley Laboratory *
Piero Pianetta, Stanford Synchrotron Radiation Laboratory *
Stephen S. Rothman, University of California at San Francisco

* indicates new member

Lines on paper turned into concrete and steel in 1989 as the renovation of the former 184-Inch Synchrocyclotron building was completed and the framework of a 61 000-square-foot addition took shape around it (Figure 3-2). Meanwhile, the mechanical, electrical, electronic, and accelerator systems that make up the heart of the ALS continued their progress from design into fabrication, both by LBL and by private industry. Throughout these activities, extensive testing and verification work was performed under the comprehensive quality-assurance policies of the ALS project.

Design, Fabrication, and Construction

The general contractor, C. Overaa Construction Company, moved onto the ALS site in December 1988 to begin work, monitored by the architectural firm of Keller and Gannon-Tudor for technical compliance with plans and specifications. The remodeled Building 6, which formerly housed the 184-Inch Synchrocyclotron, was taken over by LBL crews on schedule in January 1990. This historic building will house the ALS injector complex. Around it, the contractor completed the foundation, floor slab, and steel skeleton for the addition, where the storage ring, beamlines, and experimental stations will be installed. A massive concrete retaining wall was built on the steep slope between the ALS site and Building 2, the new Advanced Materials Laboratory.

Conventional Construction

Utility installation was another significant 1989 accomplishment. A maze of existing utilities, including an electrical substation, had to be relocated with a minimum of disruption to other Laboratory activities. The complex task of activating the new substation was completed by May 1989 so ALS foundation work could proceed at the old substation site. Mechanical and electrical utilities for the linac and booster synchrotron, along with renovated lighting, were installed in Building 6.

LBL engineering effort continued on the design of precast shielding for the linac and storage ring, as well as on the design of the ALS control room in Building 80. Control-room construction began in December and will continue through summer 1990.

Figure 3-2. Passers-by could see the architect's vision of the ALS building take physical shape in 1989. The injection complex, including the booster synchrotron, is being built under the dome—a Berkeley landmark preserved in the ALS design. The storage ring will be installed on the ground floor of the 61 000-square-foot addition surrounding the dome, and provisions are included for eventual construction of office and laboratory space on the floor above.

CBB 879-7610

CBB 876-4518

CBB 901-532

Electronic systems have always been key components of accelerator facilities, and, with the advent of computerized control, the role of electronics has become more prominent than ever.

Control System. Most of the 1989 control system work was focused on design, documentation, and purchase of the electrical and electronic systems for the injection complex (electron gun, linac, and booster synchrotron) so that the injector can be installed and commissioned while work on the storage ring is underway. A prototype of the ALS control system, comprising all major parts of the final system, was installed at the linac test stand, as shown in Figure 3-3. This prototype gave accelerator physicists their first "live" experience with the system's interactive user interface.

Beam Position Monitors. The beam position monitoring system chassis went into production, and 50 of these "crates" were completed. The beam position monitoring system is quite important because it provides high-quality diagnostic and status data concerning the position of the electron beam; this information is provided to the beam-stability feedback systems for the storage ring. Each crate has an onboard computer that can correct for known systematic errors. The net result is the ability to determine the beam position to within 20 μm .

Linac. The first third of the 50-MeV electron linac—the most critical parts, including the electron gun and subharmonic bunchers—delivered its first beam on schedule in April 1989 at the newly constructed test stand. The test stand (Figure 3-4) is being used to examine the transverse shape and temporal characteristics of the beam and to study single- and multi-bunch operation. The transverse emittance was less than 10 π -mm-milliradians, which is at least four times better than the requirement and slightly better than the electron-gun manufacturer's estimate. The remaining linac components, except for the S-band waveguide, were received in 1990 and are being prepared for installation.

RF components. The 300-kW rf system for the storage ring was ordered and should be delivered this fall. A high-power test stand for the rf systems of the various accelerators was installed so the booster-synchrotron and storage-ring rf cavities can be tested upon their arrival in early 1990. The test stand has delivered 30 kW into a dummy load.

Booster Magnet Power Supplies. The technically challenging power supplies for the quadrupole magnets in the booster synchrotron were undergoing factory testing at the end of the year. These 75-kW power supplies must have exceptionally quick response so that the quadrupole magnetic fields can track the dipole fields to within 10 μs . The other commercial power supplies for the booster-synchrotron magnets and the 1000-kW supplies for the dipoles have been received.

Radiation Safety Review. The devices that ensure personnel safety amid the radiation and other operational hazards of an accelerator also come under the purview of the ALS electronics group. Their design for an overall ALS radiation safety system was favorably reviewed by experts from LBL, the National Synchrotron Light Source at Brookhaven National Laboratory, and the Stanford Linear Accelerator Center. An appropriate subset of this safety system, incorporating commercial radiation monitors and associated electronics, will be in place for the July 1990 commissioning of the linac.

XBL 902-656

CBB 893-1699

Figure 3-3. The computerized control system for the ALS uses a highly distributed architecture, with 600 intelligent local controllers (ILC) doing most of the processing at the controlled equipment. The linac test stand was equipped with a prototype control system that was essentially a scaled-down version of the final system, containing all major components. Thus the controls and displays that will be used after the ALS goes "on the air" in 1993 could be tried out.

CBB 890-8620

CBB 890-9124

During 1988, the ALS mechanical-systems efforts moved from prototype testing of various magnets and of vacuum-system components to assembly of the production versions. All work is on schedule to meet the overall project milestones.

Magnets. By the end of the year, the full complement of magnets for the booster synchrotron had been completed. Production of the sextupole magnets for the storage ring was well under way, and the storage-ring gradient (dipole) and quadrupole magnets were approved for production. Figure 3-5 shows magnet production activities in the LBL mechanical shops.

Along with production went magnetic measurement, a critical quality-assurance activity in light of the machine's stringent performance specifications. In 1989, all components of the booster's magnetic lattice—24 dipoles, 32 quadrupoles, 20 sextupoles, 32 correctors, and spares for each type—were examined. The level of quality and uniformity proved to be high enough to eliminate the need for sorting.

Considerable progress was made in the design and fabrication of support systems for the magnets. Here, too, the overall ALS performance requirements led to exacting subsystem specifications; the mounts have to lend themselves to precision alignment and must provide a high degree of vibration damping and isolation. Seismic safety must also be engineered in. To solve these problems, a six-strut kinematic support system was devised;

CBB 890-9389

Figure 3-4. Characterization tests of the 50-MeV linac began in April at this test stand. In tests to determine the transverse quality of the beam, it was aimed through a "pepper-pot" collimator (essentially a plate with holes drilled through it) and onto a phosphorescent screen. A television camera recorded the results, which were then processed by a computer, assigned color codes to indicate intensity, and displayed on a monitor. Even in this black-and-white rendering, one can see a large central region of fairly uniform intensity, indicating high beam quality.

Mechanical Systems

CBB 893-2560

Figure 3-5. Laminations for the booster-synchrotron dipole magnets were distributed for shuffling into core assembly stacks. The completed cores were then matched with the coils that can be seen on the racks in the background. Because the magnets have to meet exacting specifications in order to ensure the desired ALS performance, quality control plays a key role in the production effort. Quadrupole magnets for the booster are shown undergoing acceptance testing and characterization in the new magnetic-measurement facility.

CBB 890-9070

Figure 3-6 shows booster-synchrotron magnets mounted on a support girder. By the end of the year, all girders and magnet mounts for the booster were on hand, and survey preparations were under way for the first installation activities.

Vacuum Vessel. The curved vacuum vessels for the storage ring (Figure 3-7) are among the more innovative mechanical features of the ALS. Each vessel is machined from two billets of solid aluminum, and the machined pieces are then welded together. The shape is complex and the workmanship must be precise, but the necessary tooling and expertise turned out to be available in the aerospace industry.

The fabrication contractor unexpectedly filed for bankruptcy before the first article was delivered, but swift and decisive action by LBL engineering and purchasing staff members averted what could have been a major setback for the project. Another vendor completed the prototype vessel, and successful tests of welding and photon-stop and vacuum-pump installation were performed. The contract to fabricate the 12 production vacuum vessels was

CBB 901-401

CBB 890-9187

Figure 3-6. To isolate the accelerators from vibration that could compromise electron-beam quality, special girders and magnet mounts were developed. Studies had shown that without such measures, even the vibration from a passing truck could cause slight but noticeable performance degradation. Here, two booster dipoles, three quadrupoles, and three sextupoles are mounted on a support girder, which stands on a precision six-strut kinematic mounting system. The magnets are mounted on the girders; then the completed assemblies are lowered by crane into the shielded booster area. The inset shows details of the dipole mounts.

awarded to a new vendor in November, and no impact on the overall project schedule is anticipated.

As the ALS progressed toward construction, the Experimental Systems Group expanded its activities. The insertion-device engineering project that began in 1988 bore fruit with the issuance of the U5.0 Conceptual Design Report, and work began on the three other insertion devices that will be built with ALS funds. Beamline engineering began in earnest as the PRTs' performance requirements became more clearly defined.

Insertion Devices. A major effort that began in 1988 and increased considerably in 1989 was the design of the first insertion device, with the larger goal of arriving at a generic design. The first design was for U5.0 (Figure 3-8), a soft-x-ray undulator that can be used for high-resolution spectroscopy to support materials, surface, and interface studies. It should produce a spectrum starting at 52 eV and extending, through undulator harmonics, to 1900 eV. The "5.0" refers to the device's 5.0-cm magnetic period. The same basic design will be used for the other ALS insertion devices, as well as for the undulator in the infrared free-electron laser at the proposed CDRL (see Chapter 5, "Exploratory Studies").

Experimental Systems

CBB 890-10809

CBB 890-10805

Figure 3-7. The first full-length prototype of a curved (arc-sector) vacuum chamber for the ALS storage ring underwent acceptance testing in 1989. To form the complete storage ring, twelve of these curved vacuum chambers will be interspersed with twelve straight sections. The tall assemblies extending above and below the chamber are photon stops with their actuators. Associated with each photon stop, below the chamber, is a titanium sublimation pump. The pumps are located to optimally remove molecules desorbed from the photon stops, but cumulatively they also provide a great deal of pumping for the storage ring.

XBL 893-7092

Figure 3-8. The undulator U5.0 (at least two of which will be installed in the ALS) is now being designed in detail. The same basic design will be used for other ALS insertion devices, as well as for the undulator in the CDRL infrared free-electron laser.

XBL 901-278A

The ALS will fund four insertion devices. Two identical U5.0 undulators will be built, one for a Type-A and one for a Type-B PRT. Another undulator, U8.0, is meant for atomic and molecular physics on behalf of a Type-A PRT. There will also be a two-tesla wiggler, W13.6, to produce hard x-rays for a large Type-B PRT interested in atomic, molecular, and optical physics and in materials science.

Additional insertion devices might be built for Type-C PRTs if their funding is granted. Undulator U3.9 would support soft-x-ray imaging and related technology development for the proposed Life Sciences Center. Duplicates of U8.0, for timing and dynamics studies, and of W13.6, for life-sciences applications including protein crystallography, would also be built. A third U5.0 for materials science is under consideration. Another device, U10.0, will be prepared after initial ALS commissioning to provide x-rays for the CDRL.

Beamlines. High-performance beamlines with spherical-grating monochromators will be designed and built by the ALS for U8.0 and for one of the two U5.0 undulators. Other beamlines will be provided by their users.

Experimental Systems Quality Assurance. A wide variety of measures are being taken to ensure that the photon beams can be consistently generated and delivered with the expected degree of quality and precision. Error control in insertion-device fabrication is a prime example, because both manufacturing errors and variations in the characteristics of the permanent-magnet blocks manifest themselves in the spectral performance of the device.

Major progress has been made in the theoretical and experimental study of such errors. This knowledge is being reduced to practice, and the ALS undulators are being constructed to exceptionally close tolerances in the most important areas. Field errors of 0.25% rms or below are expected, a level of design compliance seldom before achieved for permanent-magnet undulators. This quality will, for the first time, allow experimenters to reliably use the fifth harmonic of the undulator's fundamental wavelength.

Achieving such close tolerances involves the precise characterization of thousands of permanent-magnet blocks. Novel, semi-automated measurement systems allow rapid, on-the-fly Hall-probe readings and new surface-field measurements that have never before been applied to insertion devices. New methods of block selection and undulator-field data analysis are also expected to be developed as this work continues.

Optical metrology—the evaluation of optical surfaces—will play an important role at the ALS for testing and diagnostic work on optical elements. Two interferometric optical profilers will be built. One will be kept at LBL for research and development and for quality control of optics bought from outside vendors, and the other will be loaned to the vendor (yet to be selected) that makes the mirrors and grating blanks.

A prototype feedback system that includes high-precision photon beam position monitors and active mirror supports is being built. Thermal stability, an important related issue, continues to be studied at some length; the ALS is the first synchrotron radiation facility to examine it in such detail before construction. The study has resulted in the addition of temperature-stability systems, including air conditioning of the experimental floor and storage-ring tunnel, shunt regulators for cooling-water temperature, and thermal compensation devices for various mechanical supports.

Accelerator Systems

The Accelerator Systems Group within the ALS project works with the engineering groups on a wide variety of tasks. During 1989 its emphasis began to shift from "paper studies" to evaluation of production hardware. The group was closely involved with the testing of accelerator magnets, the linac, and insertion devices, as described in earlier sections, and it participated in the first-article tests of the curved vacuum vessel (Figure 3-9) by measuring its impedance. Theoretical studies were also an important aspect of the group's activities.

During 1989 the theoretical efforts were mainly focused on understanding the perturbations of single-particle behavior that stem from imperfections in the synchrotron magnets and from the complicated magnetic fields of insertion devices. Both factors proved to have significant implications for the dynamic aperture (the maximum transverse aperture throughout which the beam remains stable) and for Touschek scattering.* Touschek scattering is the most important factor that determines overall beam lifetime in low-energy storage rings, and dynamic-aperture limits must be understood because they bear upon the injection process and help determine the lifetime of the beam.

Previous studies indicated that the dynamic aperture would be fairly forgiving of magnetic errors. In response to suggestions from a review panel, we examined these phenomena in more detail. These studies revealed that storage-ring performance is not especially sensitive to small (<1 mm) distortions of the ideal closed orbit, and that, if necessary, alternative configurations of the magnetic optics could be found that would increase the dynamic aperture without the need for additional quadrupole magnets.

Ways of compensating for the beam-quality effects of wigglers, which have stronger magnetic fields than undulators, were studied in detail for the

Figure 3-9. The "first article" of the curved section of the storage-ring vacuum vessel is prepared for rf tests.

CBB 897-6038

* Large-angle scattering caused by interactions between particles in the beam.

first time. The compensation schemes useful for undulators proved to be ineffective for wigglers unless sets of wigglers are placed symmetrically across the ring. However, the study concluded that, by judicious tuning of the full complement of independently powered quadrupole magnets, schemes could be found to compensate for the effects of any combination of wigglers and undulators.

Timing, Survey and Alignment. The ALS comprises a number of accelerators that must operate together in the proper cadence. This implies a need for timing systems of considerable precision and stability to supply trigger pulses to more than 100 pulsed accelerator components. The timing system must be flexible as well; some user experiments might require the storage ring to carry only a few bunches of electrons, as opposed to the usual mode of operation in which 250 of the 328 available rf "buckets" are filled. The Accelerator Systems group developed a timing algorithm that is capable of filling the 328 buckets in any pattern without jeopardizing the beam quality or the transfer efficiency.

Precise component placement and alignment constitute another ALS requirement. The project benefited from the considerable expertise developed in this field by the Stanford Linear Accelerator Center (SLAC). ALS and SLAC personnel developed an observation plan for the ALS survey monuments that uses the SLAC software package GEONET, which gives error ellipses smaller than 50 μm in the relative positions of the monuments. The ideal fiducial positions of all booster girders and magnets were also calculated.

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4.

CENTER FOR X-RAY OPTICS

... demonstrating the capabilities and usefulness of the x-ray and ultraviolet regions of the spectrum and developing equipment and techniques to make those capabilities widely and readily available ...

IN 1989, THE CENTER FOR X-RAY OPTICS continued its two complementary roles: demonstrating the capabilities and usefulness of the x-ray and ultraviolet regions of the spectrum and developing equipment and techniques to make those capabilities widely and readily available. We continued our collaborations with scientists outside LBL through participation in research projects at several facilities. Our University Research Initiative contract enabled us to maintain a student-training effort with both graduate and undergraduate research involvement. We also continued to participate in the organization of an Applied Science and Technology Program on the University of California at Berkeley campus.

Ongoing efforts in soft-x-ray imaging saw significant achievement. In collaboration with IBM, we improved the spatial resolution of zone-plate lenses made by electron-beam lithography to the 300-Å level; then we tested these focusing elements by using them in an imaging x-ray microscope at the Berlin Electron Synchrotron (BESSY). We also initiated a second round of biological imaging experiments with the scanning x-ray microscope at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory.

In the long-term effort to develop high-reflectivity multilayer coatings for extreme-ultraviolet and soft-x-ray optical elements, such as mirrors and gratings, we investigated the structure and stability of W/C, Mo/Si, Ru/C and other multilayer pairs by means of high-resolution transmission electron microscopy. We experimented at the Hamburg Synchrotron Laboratory (HASYLAB) to study the benefits of premirrors for the next-generation synchrotron facilities, where thermal loading will be particularly intense. Also, we improved the spatial resolution of our hard-x-ray (6–14 keV) microprobe to 2 µm. The microprobe won an R&D 100 award from *Research and Development Magazine*.

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In spectroscopy, we continued to pursue cost-saving high-resolution monochromators and spectrometers based on varied-line-space gratings, and led an experiment with colleagues at Lawrence Livermore National Laboratory (LLNL) to make time-resolved measurements of x-ray laser line widths.

The extension of high-resolution imaging techniques to the soft-x-ray spectral region offers several special advantages. With relatively short wavelengths, ranging from several Å to perhaps 100 Å, one can "see" and "write" smaller patterns. Furthermore, the range of associated photon energies, from approximately 100 to several thousand electron volts (eV), spans the core-electron resonances of many elements. Resonances constitute a sensitive mechanism for identifying and mapping elements and, in some cases, for determining chemical bonding. During the past year, we advanced the technology of soft-x-ray imaging and demonstrated some potential applications in the physical and life sciences. The spatial resolution achieved in x-ray microscopy is now approaching 300 Å, with further improvements in sight. Our goals include forming a true image of a single ribosome ($\approx 250\text{--}300$ Å) within a living cell and studying surface states, grain boundaries, and other materials properties on a similar scale.

Soft-X-Ray Imaging

The soft-x-ray spectral range offers many unique properties, such as sharp element-specific absorption resonances, that lend themselves to high-resolution microscopy. The key optical component, which ultimately determines performance, is the objective lens. Ordinary refractive lenses like those used for visible light, which transform the phase of a wave front without changing the amplitude, cannot be used at x-ray wavelengths because available materials do not give enough phase shift and are not sufficiently transparent. Reflective optics can be used in the low-energy ($\approx 100\text{-eV}$) part of the soft-x-ray region, where efficient high-reflectivity multilayer coatings can be fabricated, but to date their resolution has not been not as high as that of Fresnel zone plates, which are thus the lenses of choice for the highest spatial resolution.

Microscopy with Fresnel Zone-Plate Lenses

A Fresnel zone plate has concentric circular zones—alternate bands of transparent and opaque materials. Because of diffraction, this structure has lens-like properties. A perfect (i.e., diffraction-limited) zone-plate lens could focus radiation to a spot size of about $1.2 \Delta r$, where Δr is the line width of the outermost and therefore smallest zone, as shown in Figure 4-1. A zone plate has characteristics very similar to those of a transmission diffraction grating. For example, it is highly chromatic and has a first-order diffraction efficiency of only about 10% when the dark zones are completely opaque. (Our goals include making zone plates that are more efficient.)

Although the concept was invented over a hundred years ago, the techniques for making zone plates useful for x-ray microscopy are at the cutting edge of microfabrication; our best zone plates have a Δr of 300 Å. We fabricate them at IBM's Thomas J. Watson Research Center in Yorktown Heights, New York, as part of an ongoing collaborative effort in which a CXRO scientist works in IBM's Nanotechnology Group, fabricating zone plates and related nanometer-scale structures.

The process starts with a silicon nitride membrane coated with (among other substances) a "resist," an electron-sensitive polymer. A high-resolution electron-beam lithography system writes the pattern, a solvent removes the

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Figure 4-1. An oblique scanning electron micrograph of our latest gold zone plate lens, which has a smallest zone width of 300 Å. Also shown is a scanning transmission electron micrograph of the outermost zones of the lens, which was used in the imaging microscope at BESSY to produce near-diffraction-limited x-ray micrographs. The diagram shows how a more efficient nickel lens might be used for high intensity diffractive focusing experiments at the Advanced Light Source (ALS).

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resist that was exposed to the beam, and a metal such as nickel or gold is electroplated onto the resulting rings where there is no resist. Recent refinements in the electron-beam writing technique include new methods to measure and correct for the distortion in the beam deflection field, thus permitting more-accurate control of critical zone positions even at larger radii (100-Å accuracy at a 50-μm radius).

A set of zone plates has been used as the objective lens to examine test patterns in the microscope beamline developed at BESSY by collaborators at the University of Göttingen Institute for X-Ray Physics. The x-ray optical arrangement is similar to that of a visible light microscope in the transmission mode. Broadband synchrotron radiation from a bending magnet is filtered by a condensing zone-plate monochromator before illuminating the test object. The x-rays transmitted through the object are diffracted by the zone-

plate objective lens, thereby forming an enlarged image on film. The test objects were made by the same process used for the zone plates. The patterns were selected to allow quantitative analysis of the lens's image-forming capabilities.

Figure 4-3 shows an x-ray micrograph taken with the 300-Å zone plate. The test structure consists of 128 radial spokes. The Rayleigh resolution, $1.2 \Delta r$, is 360 Å for this zone plate; features of such dimensions are well-resolved, and features as small as 300 Å are clearly identifiable in the inner regions of the spoke pattern, albeit with less contrast. To our knowledge, this is the best spatial resolution ever obtained in x-ray microscopy. The improvements in zone-plate fabrication technology translate directly into better performance of x-ray microscopes (usually replacement of the objective zone plate will suffice). Our recent success with 300-Å lenses for imaging microscopy gives us confidence that this high resolution can be used in a variety of applications. Next year we will emphasize improved diffraction efficiency in these high resolution lenses.

Imaging and Scanning X-ray Microscopes

X-ray microscopes fall into two basic categories: scanning systems in which the zone plate forms a very small probe beam through which the sample is scanned, and imaging instruments in which the zone plate is used as a high-resolution lens to produce a magnified image on a detector such as film or a charge-coupled-device (CCD) camera. Figure 4-2 illustrates the two concepts. Zone plates appropriate for both types have been fabricated, tested, and used.

The imaging microscope has the chief virtue of mechanical simplicity, so resolution is limited primarily by the zone plate itself. The disadvantage is that the inefficient zone plate is placed between the object and the detector, making necessary a higher radiation dose to the object. In a scanning instrument, the object is downstream from the zone plate and receives only what one might call the "net" radiation dose. The disadvantage is that complex mechanical and electrical systems are required.

A scanning x-ray microscope provides various signals that can be used for spatially resolved measurement. Transmitted x-ray intensity is the signal usually associated with x-ray microscopy, but other types of information, such as energy-resolved photoelectron flux and fluorescent x-ray emission, have also been used. By measuring the energy of photoelectrons emitted from the x-ray spot, surface maps that combine high spatial resolution with elemental and chemical information can be produced. Such a system is under development at NSLS using zone plates produced through the CXRO/IBM collaboration, and initial results show very good promise for studies of surfaces.

Microscope

Scanning microscope

Figure 4-2. Zone plates can be used in either scanning or imaging microscopy systems.

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Figure 4-3. This x-ray micrograph was made with our 300-Å line-width zone plate in the x-ray microscope at BESSY. The test pattern consists of 128 radial spokes, so the spatial period is a linear function of distance from the center of the circle. Details are well resolved to the Rayleigh limit of 360 Å, indicating that the zone plate is free of aberrations such as astigmatism and misplacement of zones. Details as fine as 300 Å can be discerned in the inner regions of the test pattern, but with reduced contrast.

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Biological X-Ray Microscopy

The techniques we are developing are especially attractive for life-sciences research. X-ray microscopy offers resolution extending well into the domain once exclusively occupied by electron microscopy, along with the hope of direct observation of native (chemically and physically unaltered) subjects in a sample chamber that simulates their physiological environment; see Figure 4-4. Electron microscopy, by comparison, requires extensive preparation—fixing, staining, dehydrating, etc.—that alters the object's form and content.

When we began this program five years ago, x-ray imaging in the U.S. was limited to resolutions of 1000–2000 Å, hardly better than visible and UV imaging, and crucial sample-handling methodologies were virtually nonexistent. Zone plates from the CXRO/IBM collaboration have allowed us to push the resolution to 360 Å, and we expect to continue that progress towards the 200–300 Å region—the size of a ribosome—over the next few years.* Along a parallel path, we have begun native-state imaging experiments, working with colleagues from the State University of New York at Stony Brook and the NSLS, while aiming at more-advanced capabilities at the ALS.

Our work has emphasized studies of the secretion process. This ubiquitous and important process has been well studied by other means, giving us a foundation to build on, but certain aspects have never been directly observed. Further, the sizes of the interesting objects neatly fit the progress goals of our program. There are also significant opportunities for qualitative and quantitative analysis of elemental and, eventually, chemical content. Our first observations have been modest but interesting; not surprisingly, they are different from observations made with other microscopy techniques.

* A ribosome is the subcellular structure where protein is synthesized.

Figure 4-4. This sample chamber, designed and built at CXRO, holds zymogen granules in a fluid environment resembling that of a living cell. When the chamber is placed vertically in the horizontal x-ray beam, the granules rest on the small shelves (chevrons) deposited in the window. Etched input and output ports can accommodate small needles so the experimenter can alter the fluid contents of the chamber during viewing.

Research underway on the new scanning x-ray microscope at the NSLS X-1 beamline will focus in the near term on the internal organization and physical behavior of the zymogen granule, a protein-containing component we extract from the secretion cells of the mammalian pancreas. In other work at X-1, we are studying these granules and other structures involved in the secretion process *in situ* (i.e., within the secretion cell).

Two of the observations made in this ongoing research are especially significant. First, we have found that the granule is structured; its contents are asymmetrically distributed, and the distribution of protein along the margins, or "capping," is a common feature (Figure 4-5). Such higher-level organization has not been observed in electron micrographs, perhaps because the preparation homogenizes these matrix structures or perhaps because the contrast is inadequate.

Second, the structure of the granule has been seen to change with time; they can lose content and shrink. The density of protein within the object remained essentially constant (in the 200 mg/ml range) as size decreased and material was lost. We were also able to follow the appearance of protein in the surrounding medium over time. Although such changes had been suggested by numerous published observations, both *in situ* and *in vitro*, dating back more than 100 years, these x-ray microscopy studies, with their combination of high spatial resolution and a near-native environment, are the first that allow us to follow changes as they occur. Indeed, this is the first time that real-time changes have been observed in any isolated biological object at such high resolution. As the program continues, we will pursue goals in three general areas:

- Better (more-detailed and more-quantitative) studies of the zymogen granules and the secretion cells will be made, and a structural model of the granule will be developed
- The observational methods will be extended to other problems in the life sciences
- Microscope technologies will be continually refined. Our goals, which we hope to achieve at the ALS, include shorter exposure times (less than 1 ms), multiple viewing angles, and clear monitoring with visible-light microscopy during x-ray exposure.

Image analysis methods to display and analyze the data are being developed. We are also working toward prealignment and other preparatory schemes that minimize set-up, alignment, and other causes of inefficient use of beamtime. These efforts will culminate in the construction of a new microscope, for eventual use at the ALS, with the ambitious resolution goal of 200 Å.

Figure 4-5. This zymogen granule was imaged by the new Stony Brook (X-1) scanning microscope at the National Synchrotron Light Source (NSLS), Brookhaven National Laboratory. The granule contents are shown to be asymmetrically distributed, with a marginal "cap" of protein. The time sequence shows how a single granule slowly lost some of its contents in some regions over a 30-minute time span; note the increase in debris just outside the granule. (The images were made at 6-minute intervals, with an exposure time of 1 millisecond per pixel.) Further sequence studies to separate the effects of time and radiation are under way.

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Multilayer coatings are effective reflectors of x-rays over a broad wavelength range. They consist of multiple ultrathin layers of alternating high- and low-atomic-number materials, each only a few atomic dimensions thick, that are applied to flat, curved, or compound focusing optics. In effect, multilayer coatings are artificially structured crystals, so the wavelengths and angles of incidence for which they are highly reflective are determined by the Bragg equation with the d spacing equal to the period of the multilayer; that is, the sum of the thicknesses of one high-Z and one low-Z layer. Our effort encompasses fabricating multilayers via sputtering techniques, advancing the applications of multilayers in a variety of forefront experiments, and conducting fundamental research into multilayers themselves to improve them and elucidate their performance limits.

In the U.S. and abroad, multilayers fabricated in our laboratory have been incorporated into a wide variety of x-ray optical systems operating at photon energies ranging from the XUV to the hard-x-ray regions of the spectrum. In the hard-x-ray region, we use multilayers on curved mirrors at grazing incidence to focus synchrotron sources to a small spot with unprecedented intensity, forming the basis for a superior x-ray microprobe. At longer wavelengths, there is widespread interest in the use of compound, multilayer-coated, near-normal-incidence Schwarzschild objectives in various applications, including soft-x-ray projection lithography for semiconductors. Currently, with collaborators who are developing soft-x-ray lasers at LLNL, we are using multilayer-based optics both to study and enhance the lasing process itself and to apply the radiation generated by these lasers in experiments such as x-ray holography.

Multilayer-coated optics have interesting optical applications at near-normal incidence.* At wavelengths near the multilayer's Bragg peak, these optics provide orders of magnitude more reflectivity than bare surfaces in the XUV and soft-x-ray regions. Molybdenum/silicon multilayers have been demonstrated to have normal-incidence reflectance values approaching 50% for a limited range of wavelengths longer than 124 Å, which corresponds to the silicon L_{2-3} edges. This high reflectance has led to many applications. Mo/Si multilayers reflect well in this range partly because Si is relatively transparent at energies below its absorption edge, but for shorter wavelengths the imperfections associated with the interfaces begin to dominate the layered microstructures, thus reducing their reflectance.

We continue to search for new element combinations that will result in improved normal-incidence reflectance into the soft x-ray region. Two problems are faced in this effort: identifying combinations whose bulk optical properties give theoretically high reflectances and fabricating high-quality multilayers out of these materials. The latter problem is more difficult, and becomes worse at shorter wavelengths because the individual layer thicknesses scale with the wavelength: only a few atomic layers for soft x-rays near the carbon K edge (44.1 Å). At these dimensions, the effects of imperfections at interfaces begin to dominate the structures, resulting in multilayer reflectance far below ideal values.

An example of our efforts to improve normal-incidence reflectance at shorter wavelengths is shown in Figure 4-6. The reflectance of this CXRO-fabricated ruthenium/carbon multilayer at 82.1 Å was measured in collaboration with scientists from AT&T Bell Laboratories. To our knowledge, these

Multilayer Reflective Optics

Improving Multilayer Reflectance

* Normal in the geometric sense of "perpendicular," as opposed to shallow "grazing" or "glancing" angles.

XBB 903-1210

Figure 4-6. Our newly developed Ru/C multilayers have been shown to have significant near-normal-incidence reflectances at 82.1 Å, which is in the soft-x-ray region. The measured data points (circles) and calculated fit (dashed line) are for a 50-period structure and assume a specific value for roughness at the interfaces between the Ru and C layers. Another calculated curve (solid line), with a greater peak reflectance, corresponds to a 150-period structure with the same roughness. The high-resolution transmission electron micrograph at the right shows that the individual carbon- and Ru-rich layers are quite distinct when these layers are roughly 20 Å thick. Note that the light C-rich layers are amorphous, whereas the dark Ru-rich layers are partly crystalline.

XBL 904-5835

measured and projected values are the highest yet reported at these wavelengths. However, ideal Ru/C multilayers would have shown reflectances of 30–40%, so obviously the research is far from complete.

Near-Normal-Incidence Focusing Optics

Multilayer-coated optics at near-normal incidence are needed for many high-throughput imaging applications. In previous years we obtained images of scientifically interesting phenomena, including a solar active region and an imploding glass microsphere of the kind used for research in inertial confinement fusion, at the wavelengths of the Si^{+11} 2p-3d lines at 44.021 and 44.165 Å. This doublet is especially interesting; it appears strongly in the spectrum of a hot plasma containing silicon, and, because its energy is just below the K edge of carbon, efficient multilayer reflectors can be made for it using carbon. With colleagues at the University of Central Florida, we are investigating the possibility of using a silicon plasma, produced by a laser at a high repetition rate, as a light source for scanning microscopy. We have coated a small Schwarzschild objective with a W/C multilayer to reflect the Si^{+11} lines and are using it to demagnify (focus) this light.

The strong curvature of the optical elements in an imaging system such as the Schwarzschild microscope imposes restrictions on the d spacings of the multilayer coatings and the conditions under which the coatings may be sputtered onto the optics. In general, for maximum spatial resolution and optical efficiency, the multilayers must be laterally graded. We have made a detailed study of these effects and have devised methods for masking and substrate positioning that produce the required variations in modestly curved optics. These methods were applied in the coatings for the Si^{+11} microscope and for the MAXIMUM project at the University of Wisconsin Synchrotron Radiation Center.

Other projects involving near-normal-incidence multilayer mirrors are underway. In particular, we are collaborating with LLNL to produce cavity mirrors for x-ray lasers, a new kind of power meter for measuring x-ray-laser output, and Schwarzschild microscopes.

A recurring theme in the history of the integrated circuit has been the attempt to "write" smaller patterns. Today's visible-light and UV lithography techniques, although highly refined and well understood, are beginning to approach their limits; the smallest feature sizes on the chips are near the wavelengths of the light used for lithography. Those techniques probably cannot be extended beyond the range of 0.5–0.35 μm . To make "nanochips" with features much smaller than 1 μm , laboratories in both government and industry are exploring x-ray lithography using synchrotron radiation.

In collaboration with the University of Wisconsin's Center for X-ray Lithography, we have been studying the utility of normal-incidence reflective optics in projection x-ray lithography. These experiments use synchrotron radiation and state-of-the-art optics in pursuit of demanding performance goals: 0.1- μm feature sizes combined with a useful field of view (interpreted here as the width of the printed pattern). Projection lithography uses demagnifying optics to project a mask pattern onto a wafer "through the wrong end of a telescope." Instead of a lens, a Schwarzschild objective (Figure 4-7), an arrangement of near-normal-incidence reflective optics, forms the reduced image.

The reduction lithography experiment will be performed on the MAXIMUM (Multiple Application X-ray Imaging Undulator Microscope) beamline at the University of Wisconsin Synchrotron Radiation Center. Mask patterns with 2- μm features will be reduced 20:1 to achieve 0.1- μm feature sizes at the image plate, using a Mo/Si-coated Schwarzschild objective. Masks with tungsten absorbers on a transmissive silicon nitride membrane have been made in the Microfabrication Laboratory at the University of California at Berkeley, and freestanding masks have been produced at IBM. The reduced patterns will be recorded on photoresist. Results are expected in 1990.

Projection X-Ray Lithography

Smaller Features, Bigger Challenges

One technique for writing a mask pattern onto a chip is proximity printing (shadow casting), which is very much like making a contact print of a photographic negative, albeit with a small gap. This is the more immediately available technique because no x-ray optics are required. However, the features on the mask, the "negative" that serves as the master for the circuit pattern, must be very nearly as small as those on the chip itself. Such a mask is obviously difficult and expensive to make and repair. Further, the close proximity, on the order of a few μm , can result in mask damage in a production environment where silicon wafers must be "stepped" through the system rapidly.

Circuit patterns can also be printed by projection lithography, a technique closely analogous to printing a photograph with an enlarger, but in reverse. AT&T has made great progress in this technique in their experiments at the NSLS. A major obstacle to projection lithography is the need for focusing optics that give high reflectivity, along with sufficient resolution and breadth of field, corresponding to a small, uniformly good pattern across a large chip. The SRC experimental work will use a Schwarzschild objective, coated with Mo/Si multilayers by the CXRO laboratory. Optics suitable for manufacturing will be far more complex and demanding.

Figure 4-7. In collaboration with colleagues from the University of Wisconsin Synchrotron Radiation Center, we are developing normal-incidence optics with multilayer coatings for use in the Schwarzschild configuration. The basic Schwarzschild objective can be used either for magnification, as in the photoelectron-emission microscope discussed later in this chapter, or for demagnification, as in projection lithography.

Fundamental Materials Studies of Multilayers

Because the optical properties of multilayers, including reflectance, depend on details of their microstructure, we continue to pursue investigations of structure/property relationships. Elucidating the nature of the material phases and their stability in these nanometer-scale structures is itself a good reason; further, the understanding we gain might lead to new materials or processing techniques for better multilayer performance.

Our characterization techniques include x-ray specular and nonspecular reflectance measurement at various wavelengths; large-angle x-ray scattering, including grazing-incidence scattering, to study interatomic structure; high-resolution transmission electron microscopy (TEM) in collaboration with LBL's National Center for Electron Microscopy; and a wide array of other techniques available at LBL. In 1989 our cross-sectional high-resolution TEM study of W/C multilayers was expanded to include plan-view imaging of these structures and other material combinations, including Mo/Si, Ru/C, and tungsten carbide/carbon.

Plan-view TEM studies have proven to be especially valuable in understanding the crystalline morphology within the individual layers and the development of this morphology with thermal annealing. This is illustrated in Figure 4-8, which shows high-resolution cross-section and plan views of both as-prepared and annealed W/C multilayers with a period of roughly 40 Å. The annealed samples were held in high vacuum at 500°C for 4 hours. Phase identification of these microcrystals in a cross section is difficult because only small regions of lattice images are available and only a small amount of material contributes to the diffraction pattern. The plan view provides much more information for phase identification because of the increased volume of material sampled.

Figure 4-8. Cross-section (upper) and plan-view images of a W/C multilayer, having a period of roughly $40 \text{ \AA}$, show the effect of moderate annealing on these structures. The "before" images are shown on the left. The plan views, especially, show that annealing caused partial crystallization of the W-rich layers (the dark layers) into carbide microcrystals with high aspect ratios. Nevertheless, the samples retain their layered structures. It is remarkable that these crystals can nucleate and grow within W-rich layers that are only about $20 \text{ \AA}$ thick without drastically disturbing the layered nature of the multilayer sample. These basic studies of phases and their stability may lead to multilayers with improved performance.

The ability to control and alter the polarization state of x-rays incident on or emanating from samples could be useful in nearly all scientific disciplines that use x-ray probes. Conversion between linear and circular polarization is of special interest. This can be accomplished with quarter-wave plates, which introduce a relative phase change of 90° between two components of a linearly polarized beam. They are commonly used in the visible and ultraviolet range and have been demonstrated (albeit with low efficiency) in the hard-x-ray region above 20 keV , but components appropriate for the soft-x-ray region, where materials are more absorbent, have not yet been made. We have begun investigating, theoretically thus far, how multilayers might be used for this purpose; the idea could also be applied to natural crystals.

Both the reflection and transmission geometries, as shown in Figure 4-9, are being considered; the transmission geometry is favored from the viewpoint of optical-system design but requires transmission multilayer structures of high optical quality, which are hard to fabricate. Calculations show that the required relative phase change can, under certain conditions, be obtained via transmission through a multilayer without excessive loss of flux

Polarization-Controlling Optics

Figure 4-9. Our theoretical investigations into x-ray quarter-wave plates show that multilayers can convert linear to circular polarization (and vice versa) under certain conditions. Although devices based on both reflection and transmission are in principle capable of operating as quarter-wave plates, transmission devices are especially attractive from an optical design standpoint. Such devices are of interest to a wide variety of disciplines that use x-ray probes for scientific studies.

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due to absorption in the multilayer. These calculations lay the groundwork for experimental investigations, which could extend the energy range of efficient quarter-wave plates to the soft- and hard-x-ray regions of the spectrum.

Power Filters for Synchrotron Radiation Beamlines

Because of the wavelength selectivity of multilayer mirrors, they can be used in synchrotron radiation beamlines to reduce the power at unwanted photon energies incident upon downstream optical elements. Calculations show that the unwanted power can be reduced by a factor of ten. Even so, designers of beamlines for the upcoming high-brightness synchrotron radiation sources are reluctant to include multilayer power filters because of questions regarding the stability of these inherently metastable material composites under the unprecedented x-ray intensities in these beamlines.

To investigate multilayer stability under intense x-ray loading, we initiated collaborative experiments at HASYLAB using the intense white-radiation beam from a wiggler on the 5.4-GeV storage ring DORIS. Studies to date have included limited exposures of several cooled multilayer samples and comparison of the x-ray reflectance properties of exposed samples with those of unexposed control samples. Also studied are the effects of thermal annealing of multilayers, which may differ from the effects of radiation absorption.

Results thus far show that radiation damage effects are small for limited exposure, but not always absent. Subtle changes in multilayer period have been observed, coupled with slight decreases in reflectance. Exposure-induced effects appear to depend sensitively on both the multilayer's period and its constituent materials. Further studies should lead to multilayer systems resistant to the harsh radiation environments at the new, high-intensity 1.5- and 7-GeV radiation sources.

As mentioned earlier, the general category of scanning microscopes includes a number of different instruments with which various kinds of data can be obtained. One of the principles now being explored for microscopy is photoelectron emission from the surface of a material at the spot being illuminated with x-rays. We are among the collaborators in MAXIMUM (Multiple Application X-ray Imaging Undulator Microscope), a new experiment that takes advantage of this effect, at the University of Wisconsin Synchrotron Radiation Center.

Recently we participated in the commissioning of the scanning photoelectron-emission microscope MAXIMUM at SRC. The innovative characteristics of this apparatus, which is diagrammed in Figure 4-10, include the use of near-normal-incidence multilayer-coated x-ray focusing optics and undulator radiation. In the initial phase of the project—demonstration of technical feasibility—several suboptimal but time-saving devices and techniques were adopted. Nonetheless, the photoelectron yield was large: several pA between sample and ground, and several μ A after amplification by a microchannel plate.

Because of geometrical constraints, photoelectron detection during these early experiments employed a microchannel plate with a grid system for energy analysis. The performance was consistent with the less-than-ideal alignment scheme used in this early phase. A spatial resolution of approximately 0.5 μ m was demonstrated by line scans and micrographs. These preliminary results demonstrated that a scanning x-ray microscope can be based on multilayer-coated, normal-incidence reflective focusing optics.

In future iterations specially designed high-quality Schwarzschild objectives will be used to focus the x-rays, and a double-pass cylindrical-mirror analyzer will be used for photoelectron spectroscopy. The new Schwarzschild focusing optics have a measured rms roughness of less than 8 Å. They have already been coated with a Mo/Si multilayer to work in the vicinity of 77 eV of photon energy (160-Å wavelength). With these components installed in the beamline, the SRC/CXRO group expects to obtain chemical maps of semiconductor surfaces with spatial resolution of about 0.1 μ m and an energy resolution of 0.2 eV.

Photoelectron Microscopy

Semiconductor Studies at MAXIMUM

XBL 898-6588B

Figure 4-10. A schematic diagram of the MAXIMUM scanning photoemission microscope at the Synchrotron Radiation Center, University of Wisconsin, and an illustration of the new Schwarzschild focusing optics. This beamline, using CXRO coated optics, will be used to study semiconductor surface states. It uses the same basic Schwarzschild geometry as the projection lithography experiment at Wisconsin.

Hard-X-Ray Microprobe

We have continued to improve the capabilities of our hard x-ray (6–15 keV) microprobe. Such microprobes detect trace amounts of elements within a specimen; they are useful in physics, materials science, geophysics, biology, and many other disciplines. A major advantage of the x-ray microprobe is that the specimen does not have to be kept in vacuum or subjected to special contrast-enhancing preparation. The mirror system at the heart of the microprobe—an example of the utility of multilayer-coated mirrors at glancing incidence—was given an R&D 100 award in 1989 by Research and Development Magazine as one of the year's 100 most significant technical innovations.

Multilayer Mirror Assembly

Our microprobe (Figure 4-11) is based on a pair of concave, spherical multilayer mirrors that focus an x-ray beam from a synchrotron radiation source. The mirror system can be applied to other microprobes as well. It produces a very small spot size much more effectively than would a pinhole collimator, plus a dramatic increase in x-ray flux; a mirror that intercepts a projected

Figure 4-11. The hard-x-ray microprobe has been used to achieve 2- μm spatial resolution, along with femtogram elemental sensitivity, at Brookhaven National Laboratory's National Synchrotron Light Source. The heart of the microprobe is a pair of W/C multilayer mirrors used at grazing incidence in Kirkpatrick-Baez geometry. They focus the beam of synchrotron radiation to a small, intense spot on the object, which fluoresces with x-rays characteristic of its elemental composition. The fluorescence x-rays are detected and analyzed by a lithium-drifted silicon detector, which is placed orthogonally to the incident beam to reduce the scattered background. The vertical and horizontal spatial resolutions shown here were obtained by scanning a sharp knife edge across the beam. The resolution in both cases is 2 μm full width at half maximum.

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area of 0.25 mm^2 with 50% efficiency and focuses down to a spot diameter of $2 \mu\text{m}$ would pass 3×10^4 more photons in a given time than would a $2\text{-}\mu\text{m}$ -diameter pinhole.*

The mirrors, coated with W/C multilayers, characteristically act as broadband filters. The bandwidth (about 1 keV centered around 10 keV for these particular mirrors) combines good coverage with rejection of scattered background. Quantitative, nondestructive detection of elements is achieved by measuring the wavelengths and intensities of the characteristic fluorescent x-rays emitted from the irradiated sample. By scanning a sample through the focused beam, the spatial distribution of many elements can be measured with excellent sensitivity (femtogram quantities of the elements K through Zn can be detected with counting times on the order of 30 s) and good spatial resolution.

This year, in an experiment at NSLS, we used two sets of beam-defining apertures to improve the focused beam size to a diameter of approximately $2 \mu\text{m}$, as compared to the $6\text{--}7 \mu\text{m}$ achieved in earlier years. As an example of the applications of the microprobe, we analyzed the concentration of a thin chromium overlay on a processed lead sulfide sample (Figure 4-12). The microprobe has also demonstrated that the optical surface quality of commercially available spherical mirrors, when combined with high-quality multilayer coatings, is sufficient to make very useful optical elements for hard-x-ray beam lines. The mirrors can also be used with rotating-anode x-ray generators to improve the performance of laboratory x-ray microprobes.

Development and experimentation are continuing. In 1990 we expect to use this instrument to measure a wide variety of samples during a longer run at NSLS. Such instruments will be particularly valuable in realizing the potential of the proposed high-brightness hard-x-ray beamlines at the Advanced Photon Source now under construction at Argonne National Laboratory.

Figure 4-12. The spatial and elemental resolution of the hard-x-ray microprobe can be applied in both the physical and the life sciences. Left: Segregation of chromium on a lead sulfide semiconductor surface resulted from a reaction between aqueous chromium salts and the surface at 100°C . The areal mass density of Cr in the peak at lower left is $2.6 \text{ fg}/\mu\text{m}^2$. Right: An x-ray microprobe scan of a rat-kidney tissue section shows the spatial concentration of iron. The contour interval is 25 parts per million ($\mu\text{g}/\text{g}$) and the peak Fe concentration is 250 parts per million. The observations were made at the NSLS.

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* Two μm is excellent resolution, considering the energy. Zone plates could focus soft x-rays into a much smaller spot, as discussed earlier, but even the best ones that can be fabricated today are virtually transparent above several keV. Multilayer-coated glancing-incidence mirrors appear to provide the highest resolution for hard x-rays.

Spectroscopy with X-Rays

The Center for X-ray Optics has always been strongly involved in the design, construction and implementation of new types of x-ray and XUV spectroscopic instrumentation, both for synchrotron radiation research and for other applications. The ultrahigh-resolution x-ray spectrograph described below is one result of this effort. Another is the high-throughput monochromator using spherical gratings, the first of which was constructed for Sandia National Laboratories and delivered in 1987. We have continued our efforts to develop new spectroscopic instrumentation with desirable properties such as high resolution, high throughput, simplicity and low cost.

XUV Monochromators and Spectrometers

The interest in intense sources of soft-x-ray and XUV radiation is motivating the development of new grazing-incidence spectroscopic instrumentation for the 10–300 Å range. High spectral resolution ($\lambda/\Delta\lambda > 10\,000$) is required, as is high throughput, defined as the product of optical efficiency and solid angle.

We have designed and built a monochromator having a throughput of 10^{-4} steradians for use with a laser-driven x-ray source. This instrument, which uses a simple spherical grating scanned about its pole as the monochromatization element, together with a bent glass mirror to correct astigmatism, is now in use at Sandia National Laboratories in Livermore, CA. Other versions of the spherical grating device are used at LBL and at SRC, as described in the earlier section on photoelectron microscopy. Among the other organizations that have requested our assistance in building such an instrument is the Royal Institute of Technology in Stockholm, Sweden.

To achieve high resolution, we have continued our investigations into monochromators, spectrometers, and spectrographs using plane gratings with varied line spacing. Such gratings allow a flat (or erect) focal plane and can thus be scanned in wavelength without the complex scanning mechanisms required by more-conventional designs, such as spherical grating monochromators. One product of this work has been the High Resolution Streaked Spectrograph described below. In addition, we have continued our studies of advanced monochromator and spectrometer designs for synchrotron radiation applications. They will have applications in the bending-magnet and undulator beam lines at the ALS and for performance improvements at existing facilities.

These studies have established that the varied-line-spacing designs can achieve resolution at least as high as more-conventional designs with the same tuning range, as shown in Figure 4-13. Their advantages include simple optical surfaces (planes and spheres) and a simple energy-scanning motion, i.e., rotation of the grating about its pole. Alignment is simpler because the plane gratings bring first-order visible light (e.g., He-Ne laser beams) to the same focus as the zero-order synchrotron beam. By comparison, spherical-grating monochromators require translation of the entrance and/or exit slit to maintain their optimum resolution as the energy is scanned. The simplicity of the varied-line-space grating designs is expected to lead to lower construction costs as well.

XBL 903-5797A

Figure 4-13. A variable-line-spacing plane-grating spectrometer has been designed for use on a U5.0 undulator beamline at the ALS. High spectral resolution, high throughput, small spot size, and fixed slits are attributes of this new system, as well as reduced cost and simplicity of alignment.

The high-resolution x-ray spectrograph designed and built at CXRO was installed on the two-beam chamber at LLNL's Nova laser. In previous laboratory tests at LBL, using a Penning gas discharge source, the spectral resolution of this instrument was measured at 35 000. The instrument has since been aligned at LLNL and coupled with an x-ray streak camera to measure the widths of x-ray laser lines and their variation with time and with the gain length of the laser.

The first line observed was the 206.3 Å line of the 206–209 Å doublet in the neon-like selenium x-ray laser.* The spectral resolution achieved in our first tests was better than 10 000 (a tenfold improvement over previous techniques) and allowed the sub-Doppler width of the line to be measured (see Figure 4-14). With further alignment and adjustment, the resolution is expected to reach 35 000. This performance will allow an unambiguous time-resolved measurement of laser-line gain narrowing, and possibly the line splitting that has been predicted by some workers.

Observations are planned on x-ray lasers of shorter wavelength; optical elements of the spectrograph will be coated to provide enough sensitivity for observation of the 44.83-Å line of the nickel-like tantalum x-ray laser. This instrument also has potential for use in other studies, such as the observation of line coincidences, for use in x-ray pumping schemes.

X-Ray Laser Spectroscopy

* Nova is a neodymium glass laser, presently the world's most powerful. Used primarily for inertial fusion experiments, it also supports an x-ray laser program in which two visible Nova beams ionize and excite atoms from foil targets in such a way as to provide the necessary population inversions. Expressions such as "neon-like selenium" refer to partly ionized atoms with electronic configurations resembling those of elements lower in the periodic table.

XBB 903-2576

XBL 866-2213A

Figure 4-14. A schematic diagram of a high-resolution streak spectrograph for time-resolved measurements of x-ray-laser line widths. This instrument was recently installed on the two-beam Nova chamber for joint experiments with LLNL. The streak-camera image shows the 206-Å laser line from a 4-cm-long x-ray laser using neon-like selenium. Sub-Doppler line narrowing, as observed here, is a characteristic of lasing.

X-Ray Interaction Coefficients

In order to design and interpret experiments or predict the performance of optical components, one must know the optical constants that describe the interaction of radiation with matter. For example, designing optical components and applying them to x-ray spectrometry at the new, intense synchrotron and high-temperature plasma radiation sources requires analytical models based on these constants.

In the XUV region, the optical constants for a material may be expressed in terms of the real and imaginary parts of the atomic scattering factor: $f = f_1 + if_2$. Revised tables have been completed that extend f_1 over the range 50–10 000 eV and f_2 over the range 10–10 000 eV, and work is under way to extend this compilation upward in energy to 30 keV. A complete set of data for the elements from hydrogen to plutonium has been published and is available, on a floppy disk, upon request.

Coronary Angiography

For several years, we have joined with scientists from Stanford University, the Stanford Medical School, SSRL, and NSLS to investigate synchrotron-radiation imaging of human coronary arteries. The goal of this work is to develop a coronary angiography technique less invasive than the one used today.

In the new method, an iodine-based contrast agent is injected into a vein some distance from the heart. This is much safer than the conventional method, in which the catheter that delivers the contrast agent is inserted into a peripheral artery and threaded to the entrance of the coronary artery. Arterial catheterization carries a small but real risk of dislodging plaque from an artery, which can cause a heart attack or stroke. Using a venous catheter is much safer, but the image quality is lower because of contrast-agent dilution. This problem is corrected by using a tunable synchrotron radiation source that permits imaging at wavelengths just above and below the iodine absorption edge. The data are processed with an image-

subtraction technique to determine how much of the x-ray flux was absorbed by the iodine-based contrast agent. One of the key components of the imaging system is a 600-element lithium-drifted silicon detector designed and built in collaboration with LBL's Office of Electronics Engineering.

The detector has two rows of elements with a center-to-center spacing of 0.5 mm. The lithium-drifted silicon detector is 5 mm thick and has an efficiency of 70% for detection of 33-keV x-rays. It simultaneously measures the intensities of x-rays transmitted through the patient at two wavelengths, one just above and one just below the K edge of iodine. The difference between the two intensities is attributable to absorption by the iodine, and we can therefore produce an image with enhanced sensitivity to contrast agent and reduced sensitivity to intervening tissue and bone. The detector system

600-Element Detector

Figure 4-15. This synchrotron-radiation transvenous coronary angiogram of a human patient was obtained in 1989 using an upgraded imaging system. The experiment was conducted at SSRL by the angiography collaboration, which includes Stanford University, LBL, SSRL, the NSLS, and the Veterans Administration Medical Center in Palo Alto. The patient, a 62-year-old man, has a history of severe coronary-artery disease and underwent bypass surgery in 1985. In this 30° right anterior oblique view, the left internal mammary artery supplying the left anterior descending artery (LIMA/LAD) is distinctly visible, as are several metal surgical clips (CL), the vein bypass graft (VBG), and larger structures such as the left ventricle (LV) and aorta (AO). A key to the success of this technique is the new high-spatial-resolution, 600-element position-sensitive silicon detector fabricated with the help of LBL's office of electronics engineering. The detector is mounted in a thermoelectrically cooled cryostat.

includes special electronics with extended dynamic range (40 000:1) to measure accurately the difference between the two images.

The feasibility of this approach was demonstrated in earlier years with a prototype system, using dogs and humans as subjects. This year an up-graded system suitable for clinical-quality imaging was tested at SSRL (Figure 4-15). The image quality is better because the new dual-element detector effectively increases the utilization of the available flux by a factor of 2.5. The new detector system also helps to eliminate artifacts from the time-subtraction process used in an earlier version and thus brings the image quality to a state approaching clinical standards.

In 1990 the system will be moved to the NSLS, where it will be installed in a special medical suite. The NSLS effort employs a special wiggler beam-line, thus providing a further increase of x-ray fluence (by at least a factor of 4) that will produce a further improvement in image quality. A medical research team will then begin to use this technique, studying the effect of various medical treatments on the progression of coronary artery disease.

Support for the Advanced Light Source

Scientists within CXRO have been involved in ALS activities from the outset, working with others in the scientific community to organize workshops and demonstrating new capabilities and accomplishments with improved imaging and spectroscopic techniques. As various Participating Research Teams (PRTs) have formed around projected ALS capabilities and these new techniques, it has been natural for CXRO scientific staff to continue their ALS planning assistance.

This involvement has ranged from providing technical advice to participating actively in the scientific and technical programs being proposed and conducted. Members of CXRO belong to three approved undulator teams, two wiggler teams, and one bending-magnet team. The scientific and technical breadth of these teams extends from materials and surface sciences to applications in the life sciences and also includes a calibration and standards beamline effort being organized among the national laboratories.

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5.

EXPLORATORY STUDIES

... assisting in the research and development tasks now at hand and laying the foundations for future research in particle accelerators ...

NOT ONLY BY ASSISTING in the research and development tasks now at hand but also by laying the foundations for future research in particle accelerators, the Exploratory Studies Group functions as a key element of AFRD. Two major initiatives were launched in 1989 with the group's support.

Our ongoing research into free-electron lasers and high-brightness electron and photon sources is coming to fruition in the proposed Chemical Dynamics Research Laboratory initiative, which features a high-performance infrared free-electron laser (IRFEL). By providing this powerful, very precise IRFEL, two Advanced Light Source (ALS) beamlines, and a variety of conventional lasers, the CDRL will enable a wide variety of investigations in pure and applied chemical reaction dynamics and in material sciences.

Another initiative brought forth in 1989 was a "B factory" based on the PEP (Positron-Electron Project) ring at the Stanford Linear Accelerator Center (SLAC). In the proposed facility, fundamental CP-violation studies and topics in B-meson physics would be advanced by creating pairs of B mesons and their antiparticles in electron-positron collisions. One of the colliding beams would be substantially more energetic than the other, so the center of mass of the collision would move in the laboratory frame of reference. This scheme, originated at LBL, separates the decay products of the short-lived mesons in space and time, making their detection simpler.

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EXPLORATORY STUDIES

Support for the ALS also figured importantly in our efforts. By assisting the ALS project, we have shed light upon fundamental issues of accelerator physics that will apply to other third-generation synchrotron-light sources, free-electron lasers based on storage rings, and damping rings for future high-energy linear colliders. Advances have also been made in mathematical and theoretical techniques for analyzing the nonlinear dynamics of storage rings and other accelerators.

Other topics of special relevance to the high-energy-physics community play prominent roles in our research. We added to our contributions to the Superconducting Super Collider (SSC), while at the same time looking beyond it. The multi-billion-dollar SSC, whose 20-TeV proton collider rings will be 52 miles in circumference, is commonly thought to represent the geographical and financial limit of synchrotron technology. Mindful of this, physicists have turned toward linear electron-positron colliders in their long-range thinking. With the Lawrence Livermore National Laboratory (LLNL) and SLAC, we have been exploring the potential of a futuristic linac called the two-beam accelerator, which might derive its microwave power from a free-electron laser or a relativistic klystron. If the two-beam accelerator fulfills its early promise, it might be used in a new class of efficient and relatively compact electron-positron linear colliders envisioned for the early 21st Century.

Combustion and other energetic molecular processes represent one of the most scientifically and economically significant frontiers in chemistry and chemical physics. These processes will be explored at the CDF, or Combustion Dynamics Facility, a multi-site initiative being proposed by LBL and by Sandia National Laboratory at Livermore. Under this proposal, researchers would use the Chemical Dynamics Research Laboratory (CDRL) at LBL to gain a rigorous molecular-level understanding of reaction mechanisms.

The proposed CDF research program ranges from basic reaction-dynamics studies to more-applied experiments that may ultimately lead to increases in fuel efficiency or reductions of pollution. In-house and outside users at the CDRL will focus on elucidating the production, structure, and reactivity of critical reaction intermediates and the dynamics of elementary chemical reactions. The sister facilities at Sandia (which has a strong combustion research program) will carry out applied as well as basic studies.

Research in combustion and reaction dynamics is generally dependent upon advanced technologies and techniques. At LBL, a national user facility called the CDRL will bring the key technologies together for the first time, as shown in Figure 5-1. One of these technologies is the IRFEL, which has been the subject of a great deal of work by our group. The IRFEL, together with two ALS beamlines, various optical lasers, and state-of-the-art molecular beam apparatus, will create opportunities for fundamental research that will have a great impact on our understanding of the important field of combustion chemistry. The CDRL will also advance the broader field of chemical dynamics in general, and the opportunities for related benefits to science and society are considerable.

The IRFEL will be installed in a new building adjacent to the ALS (Figure 5-2) so that beams from both facilities can be delivered to experimental reaction chambers. The ALS beamlines have been another area of study and

Chemical Dynamics Research Laboratory

CDRL: A Unique Combination of User Facilities

CBB 905-3635

Figure 5-1. A key to the scientific potential of the CDRL is the unprecedented integration of several technologies across a wide spectral range. The "two-color" pump-probe study illustrated at right represents one of several classes of experiments that require multiple tightly focused, high-resolution beams at different wavelengths. Tunability, synchronization capabilities, and time resolution on the order of picoseconds are among the other important features of the proposed facilities.

CBB 880-11812

Figure 5-2. The four-story CDRL building will be located adjacent to the ALS so that IRFEL and conventional-laser beams can be brought together with UV and soft-x-ray beams from the ALS. The CDRL main experimental hall, on the first floor, will be served by one bending-magnet beamline and one insertion-device beamline from the ALS. The upper stories will provide office space for CDRL users; the large IRFEL will be built in a radiation-shielded vault in the basement.

XBB 901-322

EXPLORATORY STUDIES

development by our group, in collaboration with the ALS staff and the Center for X-Ray Optics. Optical lasers are being designed by colleagues from the University of California at Berkeley Chemistry Department, who have been deeply involved in the design of technical facilities and in the development of the user program.

During 1989 we undertook the conceptual design of an IRFEL to meet the requirements of potential CDRL users. The IRFEL offers coherent, narrow-bandwidth radiation of high peak power, tunable across a spectral region (3–50 μm) that is of great importance for chemistry. In particular, it allows studies of the dynamics of chemical (molecular), atomic, and electronic transitions in the gas, liquid, and solid phases. Such capability will open up new scientific opportunities in the infrared region, where tunable coherent radiation is not available from the usual laser techniques based on atomic and molecular resonances (see Figure 5-3). The IRFEL pulses can be synchronized to those of the ALS, an important feature for timing experiments such as pump-probe studies.

Our proposed IRFEL will be a high-performance, user-oriented system, as indicated in Table 5-1. Although the physics and technology of IRFELs are rather well understood, the CDRL user requirements for reliability and stability are exceptionally stringent. The system must be available for frequent, extensive use, and various stability fluctuations—jitter in intensity, wavelength, direction, etc.—must be reduced to an unusually low level. The design process has therefore called for a careful examination of all accelerator and FEL components.

IRFEL Conceptual Design Study

Figure 5-3. Many important phenomena in chemical physics can be probed with infrared radiation, yet this spectral region represents a gap in the coverage of other radiation sources. The IRFEL at the CDRL, with its 3–50 μm tunability and high intensity, will enable a significant step forward in such research. We are also investigating future FEL applications in the ultraviolet region, where conventional lasers and harmonic-generation devices are inadequate.

XBL 881-8811

Table 5-1. Main Characteristics of IRFEL for the CDRL.

Parameter	Requirements
Wavelength range	$3 \mu\text{m} < \lambda < 50 \mu\text{m}$
Micropulse energy	100 mJ
Micropulse duration	variable, 10 – 20 ps
Micropulse repetition rate	36.6 MHz
Macropulse duration	100 μs
Macropulse repetition rate	60 Hz
Average power	20 W
Bandwidth	transform-limited ($\frac{\Delta\lambda}{\lambda} = 0.001$ for $\lambda = 3 \mu\text{m}$, $t = 10$ ps)
Bandwidth stability	< 0.001
Intensity stability	< 0.1

Generic studies relevant to high-power, stable free-electron lasers, particularly IRFELs, have been under way for several years at LBL, providing a foundation for ongoing design work to meet these challenging requirements. These continuing studies are evolving toward testing—with hardware under laboratory conditions—of various design concepts for the IRFEL and the ALS beamlines, including high- and low-level rf feedback, jitter control, and beam diagnostics. In addition, attempts are being made to improve our theoretical understanding of the performance limitations of the proposed design. This work includes extensive FEL simulations, accelerator beam dynamics studies, and further theoretical investigations of FEL stabilization.

Figure 5-4 shows the IRFEL design, as proposed in the CDF/LBL Conceptual Design Report.* It is based on a 1.3-GHz (L-band) standing-wave rf linac with side-coupled rf cavities. The IRFEL wavelength stability requirements demand an rf linac with a relative energy stability ($\Delta E/E$) of 5×10^{-4} . To achieve this goal, close attention is being paid to the design of the rf structures and their dynamic and passive control. Amplitude and phase feedback are provided at all stages of electron beam acceleration and transport. In addition, care is taken to make the electron beam transport from the exit of the linac to the undulator entrance sufficiently isochronous (and achromatic) to preserve the electron beam quality and ensure the specified FEL performance.

The IR beam is generated in an optical cavity with an undulator based on the generic insertion-device design used throughout the ALS. An optical-beam transport system carries the infrared beam up to the CDF/LBL main experimental hall, where it can be used together with the ultraviolet and soft-x-ray beams from the ALS and the beams from conventional lasers.

* The CDRL was being referred to as the CDF/LBL (Combustion Dynamics Facility at LBL) when a number of official documents, including the Conceptual Design Report, were published.

EXPLORATORY STUDIES

XCG 899-4700

Figure 5-4. The IRFEL for the CDRL is shown here in conceptual and schematic form. At the heart of the IRFEL is a lasing cavity containing an undulator that causes the electrons from the linac to emit photons. The photon wavelength can be adjusted by varying either the undulator gap (and hence the magnetic field felt by the electrons) or the electron-beam energy. Four standard electron energies will provide coverage of the full 3–50 μm range.

XBL 908-5920

B-Factory Studies

In recent years the high-energy physics community has become increasingly interested in "B factories," which would produce $B\bar{B}$ pairs for fundamental studies of CP violation and rare B-meson decays. Several schemes for copious $B\bar{B}$ production in electron-positron collisions have been advanced in the literature, including one that offers some intriguing advantages: a collider with one relatively high-energy storage ring and one lower-energy ring (9×3 GeV, for example).

Of all the schemes that would provide sufficient experimental statistics within a reasonable period of operation, this asymmetric or heteroenergetic collider was one of the lowest luminosity demands. This is true because, in an asymmetric collider, the center of mass of the collision moves in the laboratory frame of reference, giving rise to decay products that are separated in space and time. Detection is thus made easier and more efficient.

In collaboration with SLAC and the California Institute of Technology, we have published a feasibility study of an asymmetric B factory using the high-energy PEP ring at SLAC. Such a collider would be scientifically and economically attractive.

Feasibility Study

During 1989 we refined our investigations into the feasibility of a B factory in which a 9-GeV electron beam from PEP would collide with a 3.1-GeV positron beam from a new storage ring (Figure 5-5). This energy combination reaches the $T(4S)$ resonance for production of abundant $B\bar{B}$ pairs.

Figure 5-5. The general location of the proposed B-factory collider is shown in this partial site plan of SLAC. Two scenarios have been explored: one in which the low-energy ring is one-third the circumference of PEP, and the more recent one, shown here, in which the low-energy ring shares the PEP tunnel. Also shown for orientation are the Stanford Positron-Electron Accelerator Ring and parts of the Stanford Linear Collider.

XBL 902-5762

In any B-factory scheme, the most challenging goal is achieving the required luminosity. The initial luminosity would be $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, which is considered a good compromise between experimental statistics and technical feasibility. This is more than an order of magnitude beyond the luminosities previously achieved in electron-positron colliders. Future improvements could push the luminosity as high as $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The simulation results shown in Figure 5-6 suggest that the required luminosity can be achieved.

Since the example design was published in October 1989, we have advanced an alternative in which the low-energy ring has the same circumference as PEP and could thus be installed in the PEP tunnel. (The tunnel was designed for the addition of a proton ring that was never built.) This design offers several advantages in accelerator physics and engineering. The low- and high-energy rings could readily be filled with the same number of beam bunches; according to our understanding of coherent beam-beam interactions, this greatly reduces the risk of instabilities. Further, each individual bunch in the low-energy ring would undergo collisions less often, so the stored beam would have a longer useful life. It would also be possible to include two interaction points for user experiments.

Figure 5-6. Simulations of the two B-factory scenarios (one-third-circumference at left, same-circumference at right) with "energy-transparent" operating parameters show that the dynamic beam-beam tune-shift values are close to the nominal values in both cases. The + and - curves in each scenario are for the low-energy positron ring and the high-energy electron ring, respectively. The figures at the bottom show the nominal and calculated luminosity for each scenario.

XBL 904-5852

Synchrotron-radiation power loading is another reason to choose a ring with a larger radius and hence a lower field in the bending magnets.* A 300-m-circumference, 3-GeV ring carrying a total current of slightly more than 2 A would have a 10-kW/cm^2 x-ray beam sweeping out a narrow path along the inside of the vacuum chamber. This entails not only the risk of damage, but also severe degradation of the vacuum by desorbed gas. Although the heat loads could be dealt with by technical means, it might be better to circumvent the problems by using a larger ring.

A disadvantage of using a larger low-energy ring is that the damping decrement, or radiation damping per revolution, is smaller. It is desirable to make the damping decrement as large as possible, preferably equal to that of the high-energy ring. This helps satisfy the "asymmetric energy transparency" condition, which requires the two beams to behave symmetrically, despite the energy difference, while undergoing beam-beam interaction, radiation damping, and quantum fluctuations. Our proof-of-principle design uses wigglers (short-period magnetic insertion devices) to control the damping decrement independently without affecting the other parameters. The power loading caused by the wigglers would be isolated and could be dealt with locally.

PEP would probably require modification for use as the high-energy ring. Its luminosity is limited by several factors, some more amenable to correction than others. These factors include limits on the rf power that can be provided to the beam; limits on the amount of synchrotron radiation the vacuum chamber can absorb safely (and a related limit on the ability of the vacuum system to maintain the required beam-pipe pressure of 10 nTorr or lower in the presence of high desorption); and the effects of coupled motion of multiple electron bunches.

PEP has a formidable 120-cell rf system (24 cavities with 5 cells each) characterized by substantial higher-order-mode impedance. The higher-order modes generate multibunch coupled motion. This could be addressed with a high-power feedback system. However, a comprehensive upgrade, perhaps involving 20 single-cell cavities, similar in shape to those used in CERN's Large Electron-Positron collider, operating at 353 MHz, would give substantially greater reduction of coupled-bunch motion.

PEP would also need a new vacuum chamber—perhaps made of copper, like that of the Hadron Electron Ring Accelerator at the Deutscher Elektronen-Synchrotron (DESY), rather than aluminum—and a better cooling system. (At the design maximum of 9 GeV and 3 A, the high-energy ring would have a synchrotron-radiation power loading of 10 kW/cm^2 , which is too much for the aluminum vacuum chamber now in use at PEP).

The beam-beam interaction could contribute to limiting the luminosity of a B factory. As the two bunches cross at the interaction point, each one feels a strong transverse force from the collective electromagnetic field of the other. During its lifetime, a bunch could receive as many as a billion consecutive transverse kicks in this manner. The kicks could cause transverse beam blowup and/or loss of particles. We have addressed beam-beam issues through theoretical studies and simulations, with particular attention

* The luminosity requirements lead to multi-ampere currents in both rings, so the heat load is about 10 times higher than is typical of a high-energy-physics machine of the same energy. Note also that, because of the "sweeping searchlight" pattern of bending-magnet synchrotron radiation, the most important issue is the flux across the area actually swept by the beam.

EXPLORATORY STUDIES

to the optimum beam shape, the importance of damping time, and the proper balance of various parameters for maximum luminosity.

Attention must also be paid to the design of the collision optics and interaction region. The issues include producing "round" beams (i.e., with equal horizontal and vertical emittances) and making them collide head-on. Alternate schemes, such as "crab crossing" of flat beams, are also being considered. Another substantial problem is how to shield the detectors and the small-radius beam pipe near the interaction point from the intense synchrotron radiation produced by the separation and focusing magnets.

Although it will not be easy, the project appears feasible, and the scientific rewards would be considerable. High-energy physicists at SLAC, LBL, and elsewhere have been pursuing the design of detectors and of a user program. A more formal joint study by SLAC and LBL, now under way, will culminate in a detailed conceptual design and a formal proposal to the Department of Energy.

Members of the Exploratory Studies Group have been involved in the ALS project from its earliest days, focusing primarily on the immediate needs of the project but also investigating many basic physics issues involving high-brightness electron storage rings with numerous insertion devices. Much of this research is highly generic and is relevant, for the most part, to any third-generation source, as well as to storage-ring-based free-electron lasers and to compact damping rings envisioned for high-energy linear colliders.

Singly and collectively, the numerous undulators and wigglers in third-generation facilities like the ALS have strong linear and nonlinear effects on single-particle dynamics. The linear effects include breaking of the symmetry of the magnetic lattice, which results in phase changes between the sextupole magnets that correct for chromaticity. Nonlinear effects include beam distortion and amplitude-dependent tune shifts. In previous years, we systematically analyzed these effects and worked out scenarios for compensating for the linear effects of a single insertion device.

In 1989 we found that, by taking advantage of the independent controllability of the storage ring's 48 quadrupoles, we could compensate for the linear effects of any number of insertion devices placed in any pattern. An algorithm for controlling the quadrupoles appropriately could be built into the computerized control system for the ALS. (The nonlinear effects, which are most pronounced in the shorter-period devices, do not lend themselves to practical correction; designers must minimize them insofar as possible and build in tolerance for the consequences.)

Another significant achievement came out of a detailed study of beam lifetime in the ALS ring. This study, which included computer simulations, revealed that one particular loss process—a version of Touschek scattering—will be especially important among the factors that limit beam lifetime. In this process, the interaction of various resonances was seen to reduce the dynamic aperture* of the ring for off-momentum particles when synchrotron

Accelerator Physics for the ALS

Linear and Nonlinear Effects of Insertion Devices

Beam Lifetime

* The dynamic aperture is the area within which the particles exhibit stable betatron and synchrotron oscillations; the beam can be contained magnetically within it. Particles that go beyond the dynamic aperture are lost due to various nonlinear, dynamic processes.

oscillations were taken into account. The loss mechanism seems related to combined effects of symmetry breaking, strong x-y coupling, and effects of overlapping resonances sampled by a particle via modulating synchrotron oscillations. In the presence of these phenomena, large-angle Coulomb scattering will lead to loss of the off-momentum particles in the vertical plane. As shown in Figure 5-7, this will make the beam lifetime slightly lower than expected. We expect that small adjustments of the overall tune of the storage ring might partially compensate for this effect; we are now exploring this possibility more deeply.

The computer simulations that led to the scattering-loss findings were highly detailed, taking into account realistic magnetic errors, the effects of insertion devices, and synchrotron energy oscillations. The loss phenomenon has been observed in the SuperACO light source at Orsay and the main ring at Fermilab's Tevatron; when we modeled SuperACO in our simulations, the results agreed well with actual observations.

Control System

We also modeled the behavior of the ALS to first order, and the information was used by the ALS project in the development of the control system. Figure 5-8 shows the usage scenario for the latest version of our accelerator analysis and simulation code TRACY2. The code provides an efficient, integrated environment in which physicists can develop model-based control algorithms. The user can program the procedures using a dedicated version of the Pascal language and pass them to the control system for debugging and experimentation on actual hardware.

Figure 5-7. A combination of several resonance effects limits the dynamic aperture of the ALS storage ring for off-momentum particles. This reduces the beam lifetime, as shown in this plot of beam current vs. time for various degradations (1.5%, 2.5%, and 3.5%) of the energy aperture of storage ring. The plot assumes a 1-cm (worst-case) gap at the insertion devices and realistic errors in magnetic fields.

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XBL 905-5850

Figure 5-8. The accelerator analysis and simulation code TRACY2 can be used as an integrated environment for developing model-based control algorithms. Off-line activities can be performed under the VMS operating system on a VAX computer or under OS/2 on an IBM desktop computer. Then, given a control system using IBM computers like that of the ALS, testing with actual accelerator hardware can be performed.

In 1989, we continued our theoretical investigation of nonlinear dynamics, exploring the outer limits of perturbation theory as applied to nonlinear dynamical maps. In particular, we showed how to obtain invariants beyond "islands" by renormalizing the tune in phase space. The method is similar in its general spirit and goals to work by R. Warnock at SLAC, and to some extent, the work of F. Willeke (DESY) and F. Schmidt (CERN). We collaborated with J. Irwin at SLAC to complete the nonlinear map picture by providing a prescription to analyze any map dominated by a single resonance. The method uses a rather unconventional "co-moving" map technique. The techniques involving fitted maps on an action-angle grid have been successfully combined with canonical transformations written with specially created Lie polynomials. Two versions of the symplectic Lie factorization have been implemented for use in symplectic tracking, with applications to the SSC. In addition, these codes provide tools for producing exactly symplectic and invertible canonical transformations.

We also performed a first-order linear calculation of equilibrium emittances of an electron beam in a storage ring in the GEMINI and FUTAGO nonlinear dynamics codes, which we had developed previously. The method relies heavily on the modern differential-algebraic approach and is fully three-dimensional plus one-half.* These tracking codes can be used separately or together as shown in Figure 5-9.

Nonlinear Dynamics and Mathematical Physics

Code Development

XBL 895-6242

XBL 895-6243

Figure 5-9. The GEMINI and FUTAGO programs can be used independently or together. The diagram at left shows their relationship; the diagram at right illustrates the interworkings of the various components of GEMINI.

* In this context, it is common to speak in terms of the x, y and z spatial dimensions, plus momentum in each of those directions.

With applications to compact storage rings and fringe-field-dominated transport lines in mind, we also developed a new beam dynamics code, COSY INFINITY, based on an updated and enhanced differential-algebra package. Unlike previous codes, COSY INFINITY can compute maps of any order and account for arbitrary electromagnetic fields; in particular, fringing-field effects can be determined and the true Hamiltonian can be used. The maps are computed using a numerical integrator; because of the differential algebra technique, the order of integration does not significantly affect the computation time. The core of COSY INFINITY is written in Fortran 77 for speed and portability; the program also has an object-oriented command language, with somewhat the flavor of Pascal, in which an adept user can write the physics description of the simulation.

SSC Support

Because of its scope, complexity, and importance, the SSC project has drawn upon resources throughout the U.S. accelerator-physics community. After several years of involvement, we continue to collaborate with the recently established SSC Laboratory. Our 1989 efforts included assistance with the redesign of the Low-Energy Booster as the original, generic SSC conceptual design underwent site-specific modifications. We also worked on a new overall layout in which experimental areas are clustered together, refining an idea for diamond-shaped "bypass" sections.

Main-Ring Layout

The original SSC layout, put forth as part of the Conceptual Design in 1986, had two clusters of four straight sections each: two for experiments and two for utility functions (injection, beam abort, and rf). However, all the utility functions took place in one of the clusters. The other cluster was reserved for future conversion to collision experiments.

In 1989 a new, diamond-shaped bypass structure, as shown in Figure 5-10, was conceived and incorporated into the design. Beams can be directed down either branch of the diamond, so while experiments are taking place on one branch, modifications or repairs to the detectors on the other branch can be made. The new design also streamlines the logistics of operating the SSC by concentrating the four experimental regions and most of the "machine functions" into a single area, comparable in area to the present accelerator laboratories, on one side of the ring. The number of utility straight sections is reduced to two—one on each side of the ring. One of these is reserved for future conversion to an interaction region for experiments.

Injector Complex

One of the most significant injection-complex changes is injection into the collider rings at 2 TeV rather than 1 TeV, a change that has repercussions throughout the injection chain, including the series of three booster synchrotrons. In 1989 we participated in the redesign of the low-energy booster (LEB), in the writing of the supplemental conceptual design report, and in the establishment of the ramping cycles for all four machines (the low-, medium-, and high-energy boosters and the collider rings themselves). We also recalculated the impedances and the impedance thresholds for the new LEB design and helped estimate the costs of the LEB and other SSC components.

The extraction momentum from the LEB has been increased from 8.5 to 12 GeV/c, and the dispersion is lower. The lattice is altogether different, with an increase in superperiodicity (the number of identical sections in the

Figure 5-10. The new, site-specific layout for the SSC concentrates four interaction points and most machine functions in a single, relatively small and accessible area, as opposed to older layouts (insets). To show more detail in the main area, the latest drawing is distorted and not to scale.

XBL 905-5851

magnetic lattice) from 5 to 6 and a circumference increase from 250 to 540 m. As in the old design, there is no transition crossing in the new LEB lattice. In addition to working on the overall lattice design, we collaborated in the establishment of the basic parameters of the dipole magnets, extraction kicker and septum, injection septum, and rf system.

Significant effort was put into development of codes and calculation of the ramping cycles for all the SSC machines, yielding parameters such as voltage, synchronous phase, space-charge tune shift, and impedance thresholds. Among the results was RAMPREF, a family of VAX codes with applicability beyond the SSC. RAMPREF, which calculates relevant longitudinal phase-space quantities for synchronous acceleration, can handle either resonant-circuit machines such as the LEB or programmed-energy machines such as the other three in the complex. Along the way we calculated some analytic approximations for the moving-bucket quantities and incorporated them into the code; they run much faster than comparable numerical calculations.

Collider Physics

Of the many ideas that have been proposed for the electron-positron colliders of the next century, the two-beam accelerator, or TBA, appears to be one of the more promising. Conceived at LBL, it is now being investigated, in several configurations, for major research programs at many of the world's accelerator laboratories.

The TBA leaps a hurdle in the development of linear accelerators: the difficulty of efficiently producing extremely high-power microwave energy. Figure 5-11 illustrates the concept. The first of the two beams is a "drive" beam, generated by an induction linac, that has high current but relatively low energy (perhaps 3 kA, 10 MeV in a full-scale TBA). This beam is passed through either an undulator-based free-electron laser (FEL) or a relativistic klystron (RK), generating microwave power on the order of 1 GW per meter of length. The power is applied to an adjacent high-gradient acceleration structure, which accelerates a second electron beam to high energy.

Today, the TBA technology is in the early stages of development; designs are being developed and evaluated by LBL researchers, in collaboration with colleagues from LLNL and SLAC.

Another promising subject that has received attention from the Collider Physics investigators at LBL is the interaction of a beam and a plasma. Various exotic technologies for improving the performance of accelerators and FELs are undergoing theoretical investigation and awaiting time and funding for further exploration.

TBA Concept

Many challenges, both in microwave power generation and in high-gradient acceleration, must be met before a full-scale TBA for user experiments can be designed and built. However, some basic concepts have been demonstrated, and, as construction and operating costs and sheer physical size begin to impose practical limits on present accelerator technologies, the 200-MeV/m gradients possible in a TBA become increasingly attractive. Two approaches to generating the rf power—the FEL and the RK—are being evaluated.

XBL 901-5730

Figure 5-11. As shown in the TBA sketch above, a high-current, low-energy drive beam is used for generating rf power that is applied to a high-gradient acceleration structure, where a low-current load beam is accelerated to high energy. The diagram below shows the progress of the drive beam through the rf generating devices (FEL wigglers in this example) and the reacceleration units that replenish the drive beam in between.

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FEL-Based TBA. In earlier work, an FEL based on an experimental undulator designed and fabricated by the LBL-LLNL-SLAC team produced more than 1 GW of peak power at 35 GHz with an efficiency of over 35%. Initial experiments explored the microwave breakdown limits of the septum coupler that extracts the microwaves from the FEL and tested a short prototype of a high-gradient accelerator (HGA). The experimental program was suspended in 1986 because the LLNL Electron Laser Facility accelerator that provided the high-current drive beam was rebuilt and subsequently became unavailable for this application.

A high-quality, 10-cm-long, 34-cavity HGA has since been fabricated to LBL specifications by the Haimson Research Corp. We have arranged to test it at the Massachusetts Institute of Technology, using a research version of a cyclotron auto-resonance maser instead of an FEL as a power source. These tests, scheduled for 1990, will probe the breakdown threshold of the HGA at 33.31 GHz and at power levels of 20–50 MW. Acceleration gradients of 200–300 MeV/m are expected.

In the meantime, we have performed extensive theoretical studies of how the quality of the microwave output depends on the stability of the drive beam's energy and current. Parameters have been found that will provide adequate quality for about 100 m of acceleration structure, after which the drive beam would be reaccelerated. (Studies indicate that significant savings can be achieved by reaccelerating the drive beam instead of building a complete separate accelerator for each FEL.)

We are also exploring ways of extracting microwave power from the FEL and introducing it into the HGA. Figure 5-12 shows several of the extraction schemes being investigated.

RK-Based TBA. In recent years we have been exploring the possibilities of a TBA that derives its power from an RK, an idea originally proposed by W.K.H. Panofsky of SLAC. Figure 5-13 shows the internal structure of such a system. The drive beam threads its way through a klystron made up of a series of standing-wave transfer cavities. In collaboration with LLNL and SLAC, we have investigated both this concept and an alternative in which traveling-wave structures are used. The tests were performed at LLNL's Accelerator Research Center using a 1.0–1.5 MeV, 500–1000 A bunched electron beam.

In earlier experiments with single-cavity, standing-wave RKs, it proved difficult to achieve the predicted maximum power output without either microwave breakdown or excessive electron loading (in which the RK fills up with electrons stripped from its walls by the high fields). The most significant factor is inherent in standing-wave structures: surface electric fields that, at peak, are much larger than the accelerating gradient. After achieving a maximum rf power of 200 MW, we turned to traveling-wave devices; for a given accelerating gradient, they operate with lower surface electric fields.

Using the 11.4-GHz traveling-wave structure shown in Figure 5-13, we generated 330 MW of microwave power from a 1.2-MeV, 600-A electron beam. When this power was coupled to a 30-cavity HGA built by SLAC (Figure 5-14), a gradient of 84 MeV/m was produced without breakdown, and electrons were accelerated to 17 MeV.

During the 1988 and 1989 experiments, cavities were used for klystron-type bunching of the drive beam. Because an increase in drive-beam energy

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Figure 5-12. Extracting rf power from the FEL gracefully (i.e., in a device of practical length without excessive beam disturbance) involves a number of tradeoffs. The quasi-optical reflector (a) is known to extract rf efficiently, but the electron beam must be steered around the mirrors, causing either unacceptable energy dispersion or excessive length. Beam deflection could be avoided with miter extractors. In the asymmetric miter (b), the output mode after the taper matches the fundamental mode of the miter bend, minimizing reflection and mode conversion. However, the asymmetry causes imbalanced wall currents whose fields may perturb the beam excessively, and because the beam exit hole is the site of the highest rf power density, a long taper is needed to cut down rf leakage through the hole. The problem of imbalanced wall currents is solved in the chisel-point symmetric miter (c), but the mode matching is lost, causing mode conversion and inefficiency. A modified symmetric miter (d) with a mode converter is free from the problems of the other miter designs, but it is larger, and breakdown may occur inside the mode converter at high power levels.

XBL 901-5728

to 3 MeV is scheduled for 1990, we plan to use a microwave-driven beam chopper for bunching. Although less efficient, this bunching method has several important advantages, including greatly reduced sensitivity to beam energy. The assembly we will test is shown in Figure 5-5.

TBA-Related Studies. A problem that must be addressed in any beam transport system is beam breakup caused by beamline resonance and positive feedback. When the beam first excites resonant structures along the beamline, it sets up a transverse wake—electric and magnetic fields that act on later portions of the beam, causing transverse displacement. This displacement excites even-larger fields, causing even more displacement. If this

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Figure 5-13. The SL4 RK uses a traveling-wave structure for output coupling. (The standing-wave cavity bunches the beam.) The oscillogram at top right shows a typical output power level; we have obtained outputs as high as 330 MW with a 600-A electron beam. The RK may be thought of as an efficient electron decelerator that converts drive-beam energy into microwave energy.

Figure 5-14. The latest high-gradient acceleration structure (shown here undergoing low-power tests) was powered by the SL4 klystron in the experimental setup shown below, achieving an acceleration gradient of 84 MeV/m and a final energy of 17 MeV.

CBB 901-573

Figure 5-15. This new RK, to be installed and tested in future TBA experiments, uses a microwave-driven chopper rather than a standing-wave cavity to bunch the drive beam. This lowers the efficiency but provides several important operational benefits, including a great reduction in sensitivity to beam energy. (LLNL photo)

CBB 901-577

"vicious circle" of positive feedback is strong enough, the beam will hit the beam-pipe wall and be lost.

For the TBA to progress through larger-scale experiments and eventually to a collider, this class of problems will have to be understood. We and our LLNL colleagues have developed computer codes, which run on the Cray supercomputers at the National Magnetic Fusion Energy Computing Center, to address these issues. The LLNL team has developed a code called amos (for Azimuthal Mode Simulation) that computes the wakefield for a particular structure, a complicated problem that can sometimes be solved analytically but usually has to be approximated numerically. The amos results are transferred to other codes at LBL that compute the growth of the resulting beam displacement. In particular, we are investigating transverse resistive-wall instability in the high-gradient accelerator and beam breakup caused by the induction modules in the linacs that reaccelerate the drive beam.

Concepts for Beam-Plasma Physics

Over the years, the interaction of beams and plasmas has emerged as an interesting but nonetheless little-explored area of physics. The number of physically sound beam-plasma concepts, all worthy of further study, has grown beyond the funds and personnel available to work on them at the moment, but the field holds the promise of growth for the future. Some of the more-promising ideas are described below.

Plasma Adiabatic Compression. When a relativistic electron beam enters a plasma channel, it is focused to a spot by a radial pinch force. The spot size is determined by the beam emittance and by the betatron wavelength, which is a function of the plasma density. By tailoring the gas density through differential pumping, and then ionizing the gas with a laser pulse (as in the laser guiding technique used successfully to suppress beam breakup at LLNL's Advanced Technology Accelerator), one could obtain a

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very small spot size without the great expense and exceedingly close magnet-alignment tolerances required to achieve the same result with magnetic optics.

A number of experiments in beam-plasma physics could use a relativistic electron beam focused down to a small spot. A plasma adiabatic compressor might also be used in the field of high-energy physics as the final-focus device in an electron-positron collider, though the technique would cause background events.

Ion-Focused Free-Electron Lasing. In an FEL, the gap between two wiggler pole pieces could be filled with a neutral gas, which would be ionized by a laser just before a relativistic electron beam was sent through the wiggler. Because of the stronger focusing of the electron-beam spot, this device would provide stronger coupling to the radiation field than a conventional (hard-vacuum) wiggler and would therefore be more efficient. We have developed parameters for a 50-nm FEL based on this principle, and theoretical work is continuing.

Plasma Compensation. A relativistic electron beam passing through an "underdense" plasma* drives return currents through the plasma that tend to cancel the beam's magnetic field. Plasma lenses and conventional ion-guiding techniques rely on space-charge neutralization and do not attempt to neutralize the return currents, whereas plasma compensation does both. Plasma compensation has been suggested as a means of reducing beam-strahlung (radiation emission by a single particle in the magnetic field produced by colliding beams) at the interaction point in electron-positron colliders, and has been the subject of extensive analytical and numerical investigation. Here, as in the plasma adiabatic compression discussed earlier, the key issues include the background problem caused by interactions of the compensated beams with hadrons in the plasma.

Ion-Channel Laser. A relativistic electron beam, when injected into an underdense plasma, expels plasma electrons from the beam volume and beyond, producing a "channel" of unneutralized ions that focuses the beam and causes it to radiate incoherently. This radiation is amplified through a "bunching" of the beam, which can produce intense, coherent radiation in a manner analogous to a planar wiggler FEL. This device, which has been dubbed the "ion-channel laser," offers the possibility of achieving high power at short wavelengths extending into the x-ray regime. Two key features are the short betatron period—much shorter than conventional FEL wiggler periods—and dielectric guiding by the ion channel due to the radially decreasing dielectric constant. Numerical simulations have been developed, and possibilities for experimental work are being explored.

* A plasma less dense than the particle beam interacting with it.

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6.

HIGH-ENERGY PHYSICS TECHNOLOGY

... contributions to the SSC include designing and developing superconducting magnets and materials ...

THE LARGEST SCIENTIFIC INSTRUMENT that man has ever attempted to build, the Superconducting Super Collider, draws upon resources throughout the U.S. high-energy physics community. LBL's contributions include designing and developing superconducting magnets, long an area of special expertise within AFRD. We have also been responsible for developing the superconducting materials, in collaboration with the University of Wisconsin and with industry.

Because the private sector will mass-produce the SSC magnets and the superconducting cable used in them, technology transfer has been an important focus of our work. For instance, a cabling machine specified and designed at LBL became commercially available in 1988. It is the only machine that can make the needed type of cable with sufficient speed and quality. We are continuing to explore cabling technologies, anticipating the need for additional cable designs for various magnet windings.

Although the importance and the pressing nature of the SSC work have naturally led it to dominate our activities, we maintain a broad perspective on the needs of the high-energy physics community and on the potential of superconducting magnets in general. For example, we are investigating ways of making magnets that are easier to assemble and have more-uniform magnetic fields. We have also begun exploring a promising new line of research that uses "artificial pinning centers" to concentrate magnetic lines of force in the superconducting material.

Superconducting Magnets

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HIGH-ENERGY PHYSICS TECHNOLOGY

AFRD support for high-energy physics also involves a program called Beam Signal Electronics that concentrates on advanced technologies for signal detection that can be applied to accelerator diagnostics and control. In 1989 we achieved dramatic success in testing an innovative Schottky-signal beam monitor at the Fermilab Tevatron. We also put our expertise in electromagnetic measurement to work in quality-assurance support for the Advanced Light Source project.

Some of the most significant challenges associated with the SSC arise from the superconducting magnets. All of them must meet exacting specifications for precision and durability; furthermore, the magnets in the main collider rings must lend themselves to industrial mass production because the pair of 52-mile-circumference rings will need more than 10 000 of them. In 1989, after two years of design and development efforts by our group and by Brookhaven National Laboratory and Fermilab, the standard dipole (bending) magnet for the collider rings was taken over by the SSC Laboratory in Dallas. We then resumed work on the quadrupole (focusing) magnet, which began in 1987 but was suspended so we could concentrate on the dipole. Meanwhile, work continues on features that might improve dipole performance.

Because the SSC design called for dipoles 17 m long, well beyond the capacity of our test facilities, our efforts focused on basic design and development. We worked with full-bore, partial-length working models that were 1 m long; most issues in magnet design and superconductor performance can be examined in this scaled fashion. But the quadrupoles will be only 5 m long, so we have taken on the entire effort, including fabrication and testing of full-sized magnets and subsequent transfer of the technology to industry

In its initial phase, the quadrupole work involves 1-m-long models, as did the dipole project; later we will move on to full-length prototypes. The design we are working on now, designated "QC," is shown in Figure 6-1. In 1989 we set up tooling for both the 1-m models and the 5-m prototypes, and construction of models began.

Figure 6-2 shows successive stages in the fabrication of one of these magnets. First, the superconducting cable is formed into the proper shape on a mandrel. (For short magnets the cable supply spool and tension control remain stationary while the mandrel revolves. In 1989, for making 5-m magnets, we developed equipment in which the mandrel remains stationary while the cable spool travels around in a "racetrack" path.) The cable and mandrel are inserted in a precisely machined molding cavity where heat is applied. A heat-activated B-stage epoxy on the windings holds them in place until laminated-metal collars can be installed with a hydraulic press. The result is a low-cost yet rigid structure that maintains the coil positions accurately even under the stress of multi-tesla magnetic fields.

Superconducting Magnets

Quadrupole Development

Figure 6-1. In 1989, work on the SSC collider-ring quadrupole magnet was resumed after a two-year hiatus during which we concentrated on dipole R&D. LBL has assumed responsibility for the entire quadrupole program, from design through technology transfer.

XBL 9010-5936

Engineering these magnets is an iterative process. Although physicists understand quite well how to build adequate magnets of this type, a great many potentially beneficial innovations have yet to be tested. Typically, several variations on the basic design are built, each incorporating some feature that we think will improve performance, reliability, or manufacturability. Then the basic test common to all the magnets is performed: operation in a cryostat at ever-increasing current until we detect a "quench," which is a rapid heating and consequent loss of superconductivity. Each unit is equipped with extensive instrumentation, such as load cells to measure the forces developed in the windings and voltage taps to pinpoint the origin of quenches.

The plan is to begin testing the 1-m models in May 1990 and move on to 5-m models in early 1991. Later that year we will begin transferring the fabrication technology to industry so the SSC can order the 1564 collider quadrupoles. In the anticipated transfer process, industry representatives will work alongside LBL employees to get hands-on experience, an approach whose merit was demonstrated earlier with the cabling machine.

CBB 905-3690

CBB 905-3686

CBB 905-3688

CBB 878-7135

CBB 905-4515

CBB 904-3490

Figure 6-2. Stages in the assembly of a magnet include: winding the layers of superconducting cable on a mandrel, compressing and heating this assembly inside a precision mold, and finally installing collars. During magnet collaring, a hydraulic press compresses the collar pack enough for tapered keys to be driven into the slots in the collar as the external pressure is relieved. The collar pack is thus drawn tightly around the coils, resulting in a stable assembly that puts a pressure of several thousand pounds per square inch on the windings. The details at far left show how the parts of the collar pack for a quadrupole fit together.

High-Field Test Magnet

Superconducting magnets retain the desired electrical properties only up to a certain critical current; above that level, they regress to ordinary conduction. (Current density, temperature, and magnetic field interact in this regard; the superconducting regime is often graphed along three axes and referred to as the " J_c , T_c , B_c surface.") To support development of superconducting cables and of machines to make them, we built a special dipole magnet, similar in general size and shape to a model SSC dipole, that achieves high magnetic fields. It will be used by the SSC Laboratory to generate high field in which the critical current of cables can be measured. The magnet has a unique structure to control coil precompression throughout assembly and cooldown.

Figure 6-3 shows the test magnet, D16B1, a 1-m-long dipole with a 5-cm bore diameter. A vertically split iron yoke fits closely around the two coil layers and provides all the necessary precompression and structural support for the coil. A unique feature of this magnet design is that between the yoke halves is an aluminum-alloy spacer. The spacer maintains a predetermined gap between the halves at room temperature but allows them to shrink together tightly at cryogenic temperatures. This prevents the windings from shrinking faster than the iron yoke during cooldown. Such differential contraction would relieve the compression of the windings that is necessary to minimize "training" and to allow the ultimate magnetic field to be reached.

XBL 906-2293

Figure 6-3. Dipole D16B1, an R&D "trial horse" similar in overall configuration to a model magnet for the SSC, is designed to be easily rewound with new types of cable that we want to test. One of its innovative features—an aluminum-alloy spacer block—might find its way into production magnets for the SSC or other accelerators.

XBL 906-2294

Each of several short sections of yoke is secured by an aluminum-alloy structural ring shrink-fitted over it. (If the spacer-block idea were adopted for actual accelerator magnets, the individually shrink-fitted rings would be replaced with a full-length shell squeezed into place with a hydraulic press and then welded together.)

In its first training quench, the high-field test magnet reached a central field of 7.0 T at a temperature of 4.3 K. Training over several additional quenches brought it to 7.6 T. Lowering the temperature to 1.8 K, which allowed higher currents, raised the magnetic field to 9.4 T.

Experimentation with superconducting magnets reveals several interesting phenomena, including one that has come under close scrutiny: persistent currents. Persistent currents can cause nonuniformities in the magnetic field—a significant drawback for accelerators. We hope to develop a better understanding of the underlying physics so that the effects can be corrected, or at least predicted and controlled.

At low values of current and magnetic field, varying the field of a superconducting magnet can induce persistent, local eddy currents in the filaments. Eddy currents in ordinary materials die out rapidly when the field stops changing, but these currents decay with a time constant of many hours. Persistent currents make the strands appear to be diamagnetic when the field is increasing and paramagnetic when the field is decreasing. The otherwise uniform magnetic field in the bore is thus distorted. The effect must be understood because the ability to predict and control the magnetic field is essential to successful operation of an accelerator—especially since low fields are used during the injection cycle, when the beam's relatively low energy makes it vulnerable to anomalies. The mechanism of the decay of persistent currents is still under investigation, but there appears to be an effective way to reduce the central-field distortion.

The fairly well-known idea we have adopted is "passive correction." To demonstrate its applicability to SSC magnets, we install a few pieces of superconducting wire lengthwise on the outside of the bore tube in carefully determined azimuthal positions. When the magnet is energized, current is induced in the passive correctors, and

Persistent Currents and Passive Correctors

"Breaking In" a New Magnet

Nearly all of our tests involve training, the process by which a very strong superconducting electromagnet is brought up to its full capability in several steps. The predominant theory about the mechanism of training centers on small, unavoidable mechanical instabilities in the windings that are activated during use of the magnet. When the magnet is first energized, the windings, which are themselves affected by the magnetic field, move slightly as they bed in. This motion, although miniscule, is enough to cause frictional heating, and at liquid-helium temperatures even a small amount of heat can make part of the winding go from a superconducting state into a normal, resistive state. Then the entire magnet heats up, or quenches, and the energy has to be removed from it quickly. Measures can be taken to control a quench gracefully and avoid ruining the magnet, but a quench in an SSC collider ring would halt operation for several hours while the problem was resolved and the ring was reloaded with accelerated protons.

The need for training can be circumvented, or at least greatly reduced, through a procedure called conditioning, which we demonstrated in 1986. To condition a magnet, we temporarily reduce the temperature below the design value, which enables us to increase the current and therefore operate for a time at a higher magnetic field than the magnet was designed for. This results in considerable overpressure; once a magnet has been conditioned, the remaining quench-causing mechanical instabilities will not be triggered by normal operation. The SSC plans to use conditioning. Nonetheless, we are continuing to work with nonconditioned magnets that must be trained; the training behavior of a magnet offers great insight into design and performance, and such detailed knowledge may point the way to building magnets that give their full performance without either training or conditioning.

In 1988 we learned that very small changes in the coil-support structure can cause significant differences in training behavior. For example, when the collars are removed from a trained magnet and then put back around the same coils in even a slightly different fashion, the magnet must be retrained. Thus we can test the influence of changes on training without having to build completely new magnet parts for each test.

they set up their own magnetic fields. If the sizes and locations of the passive correctors are appropriate, their fields "buck" (oppose) the fields from the persistent currents, nearly canceling the distortion. Figure 6-4 shows model dipole D15C2 with a passive corrector consisting of 40 strands of commercial multifilamentary Nb-Ti wire made up of 20- μm -diameter strands. Note that, as their name suggests, the passive correctors are not connected to the power supply; they need not be insulated from the beampipe or from each other.

Field distortion in an accelerator magnet is usually described in terms of the strength of multipole components of the field relative to the strength of the dominant dipole component; this ratio is called the multipole coefficient. To measure field distortion in the model magnets, we use a set of precision coils, which can be rotated to measure separately the field uniformity of the central section and of each end. Figure 6-5 shows how the sextupole coefficient b_2 in model dipole D15C2 varies as the current is cycled from 50 A to 6600 A and back again, both with and without passive correction. (These currents correspond to magnetic fields ranging from 0.33 T, which is the

Figure 6-4. Another experimental magnet with a feature that could be adopted by the SSC is dipole D15C2. Its "passive correctors"—strands of superconducting wire that are not connected to the power supply—give off small magnetic fields of their own because of currents induced in them by the field of the magnet windings. These fields essentially cancel the magnetic-field distortions caused during low-field operation by persistent currents in the windings.

XBL 906-5889

Figure 6-5. The magnitude of the sextupole coefficient b_2 , a measure of distortion, in magnet D15C2 is shown to be greatly decreased by passive correctors. In these tests, the current is cycled from 50 A to 6600 A, corresponding to the range of magnetic fields from injection energy to full collider energy, and back again. (Because the interesting magnet behavior occurs at low fields, most of the cycle is omitted here for reasons of space.)

nominal value for 1-TeV acceleration into the collider rings,* to 6.6 T, a typical value for 20-TeV operation). Data are presented for both 4.3 K and 1.8 K to show that, at the lower temperatures, the effect of the passive correctors scales with the increase in the magnetic field distortion (the corrector and the main windings are both affected in nearly the same way by temperature changes). Note that the passive corrector reduces not only the value of b_2 , but also the hysteresis in b_2 caused by magnetization. Encouraging results such as these have led the SSC Laboratory to consider incorporating passive correction in the production SSC dipoles."

The SSC will require more than 13 000 miles of superconducting cable, a quantity that clearly requires production by private industry. This cable—formed into a rectangular shape called "Rutherford-style" that is preferred for superconducting particle-accelerator magnets but is seldom used elsewhere—must be fabricated to stringent specifications. Existing cable-winding machines had proven to be inadequate, so, in a multiyear effort, we developed a new machine. In 1988 the first commercially produced version of this machine was delivered and tested in a cable plant; soon it began providing cable for the national SSC effort while industry representatives studied its operation to prepare for manufacturing efforts of their own. Because the SSC will probably call for cable with more strands than this particular machine can accommodate (especially considering the likelihood that the

Superconducting Cable and Technology Transfer

* The injection energy has since been changed to 2 TeV, implying that very-low-current behavior will be less critical. However, Figure 6-5 shows significant benefits even at the higher dipole currents used during 2-TeV injection.

** A large, high-technology apparatus that must be completed in a timely manner, be it an aircraft, supercomputer, or accelerator, cannot necessarily incorporate all the latest innovations. As improvements are invented, the advantages they offer must be weighed against schedules and budgets, a rule that will become more and more stringent as the project progresses and components go into mass production.

bore of the dipole magnets will be changed from 4 to 5 cm),* and because of new cable designs that may offer advantages for future accelerators, we continue to work on machine development.

We have also continued our involvement in research with general applicability. Much of this work involves powerful, relatively new techniques for digital image analysis that allow finer and more-quantitative examination than the traditional techniques of optical metallurgy.

Cable and Cabling-Machine Development

For the past few years a major goal of our superconductor R&D program has been to develop improved techniques and tooling for the fabrication of Rutherford-style cable (Figure 6-6), which has become the preferred type for accelerator magnets. We had to develop a special cable to meet the rigorous requirements of the SSC. Further, we had to develop a new high-speed cabling machine (Figure 6-7) to supply the needs of the project—approximately 70 million feet of cable supplied over 4 years or so—with acceptable economy. Quantity production of this cable will be undertaken by industry, using technology developed and transferred to the private sector by LBL.

Meanwhile, in 1989 we fabricated several cables for special-purpose dipoles used in our magnet R&D programs. One of them, a dipole for a cable test facility, was optimized for low current and low helium consumption; it requires four different cable designs with 14, 15, 19, and 19 strands of wire, respectively. Another test dipole, the D16B1 unit described earlier, called for two wide cables with 28 and 36 strands. In addition, we made cables of the same general configuration as the standard SSC cables—23 strands for the inner windings and 30 strands for the outer windings—with a wide variety of experimental keystone angles and compaction factors. In the course of this activity, we have developed a set of cable scaling guidelines that enable us to develop new cables efficiently, with only a few iterations.

Figure 6-6. A close-up of this representative Rutherford-style cable shows how thousands of fine filaments of niobium-titanium superconductor in a copper matrix are braided into strands of wire. The strands are then woven into a flattened, keystone-shaped cable.

CBB 850-9140

* The change to 5 cm is meant to ensure a sufficient transverse "good-field" region in the dipoles and will probably not be needed for the other magnets. Note that it refers to the magnet bore, not the bore of the beam pipe within the magnet.

CBB 851-489

Figure 6-7. After several years of designing, prototyping, and testing (top), LBL specified a production design for the SSC cabling machine in 1988 and began a program of experimentation and demonstration aimed at transferring this technology to the private sector. The commercial version from the Belgian firm Dour Metal (bottom), installed at New England Electric Wire, has produced cable for the SSC dipole program and has been used for a series of workshops conducted for U.S. wire and cable companies. This particular machine is limited to 30-strand cable; because it now appears likely that 36-strand cable will be needed for larger-bore SSC dipoles, we are fine-tuning the technologies and techniques for making 36-strand cable and are preparing to transfer them to industry.

This ability to scale the parameters was put to use in 1989 when the standard bore size of the SSC dipoles was changed from 4 to 5 cm. Design studies indicated that the new magnet could best be made using 30-strand cable on the inside and 36-strand cable on the outside. Both are similar to cables we developed for D16B1; the 30-strand inner cable is similar to the 28-strand cable, and the 36-strand outer cable is the same in both magnets. Having produced sample quantities of both cables, which are now being used for coil-winding studies at BNL and Fermilab, we are fine-tuning various parameters and preparing to transfer the 36-strand technology to industry.

A cable that appears outwardly to be in good condition can actually have several kinds of defects that only microscopic examination of the wire strands, and the filaments within them, will reveal. One such defect is a lengthwise "sausaging" deformation of the filaments that make up the wire strands; another is cross-sectional damage to the filaments at the edges of the cable. Several years of experience at making wire and cable have reduced these defects to a level where the traditional techniques of optical metallurgy are difficult to use. Besides, those techniques are nonquantitative and therefore do not provide the level of rigor that we desire both for scientific

Computerized Image Analysis

understanding and for quality assurance. To continue pursuing the defects beyond these thresholds, we have adapted quantitative image analysis to our work.

Presently we are using these techniques for three purposes: to quantify the degree of filament instability in various superconducting composites; to measure accurately the local ratio of copper matrix to superconducting filament; and to measure the reduction in superconductor cross section that occurs as the strands near the edge are compacted in the cabling machines. The data obtained through microscopy are digitized and then analyzed by computer. Computer processing not only facilitates measurements that would be difficult and tedious to make by hand, but also eliminates guesswork about the nature and severity of a deformation. Figure 6-8 shows a typical measurement of filament-area distribution in two multifilamentary strands of a 30-strand cable—a measurement typical of the detailed, quantified results provided by these techniques.

Filament area statistics for Figure 6-8 samples:

	Strand 9	Strand 19
Number of data points	580	904
Maximum value (μm^2)	32.11	31.63
Minimum value (μm^2)	20.90	9.82
Average value (μm^2)	26.25	23.50
Standard deviation	1.88	2.42
Std. dev. as % of average	7.15	10.28
Magnification (x)	1000	1000
Nominal filament area (μm^2)	6	6

Figure 6-8. This cross-sectional image of filaments from a 30-strand cable (Sample SC61-435) reveals distortion of edge filaments from the cabling process. Compare the typical filament from strand 19, in a heavily compacted part of the cable, to one from strand 9, in a less-compacted region. (The strands were nearly identical before being woven into a cable.) The pictures show the deformation qualitatively, which any microscope could have done, but the computer-generated statistics and graphs reveal even more: not only is the filament area reduced, but also, as shown by the histograms, the variability among filaments is increased. This type of filament distortion can degrade the critical current of the superconducting cable—a strong incentive to study it both closely and quantitatively with the latest image-analysis techniques.

XBL 906-5893 (left graph), XBL 906-5892 (right graph), XBL 906-5894 (images)

One of the main areas of expertise of the Beam Signal Electronics group is, as its name implies, detection of the radio-frequency signals given off by a particle beam moving within an accelerator. Detection of such signals is necessary for measuring and controlling the beam properties. Much of this expertise was originally developed in connection with the "beam cooling" project for the antiproton source at Fermilab's Tevatron Collider. Cooling the beam (i.e., reducing the velocity spread of the particles) required extremely sensitive detectors for very weak Schottky signals. The experience in developing high-sensitivity pickups has recently been applied to the development of a Schottky-signal detector for the high-energy beams within the Tevatron itself. This state-of-the-art beam monitor, which performed with great success when tested during collider operation, has the virtue of providing a wealth of information about the beam's behavior without perturbing it in any way.

Another area of expertise within our group is the study of accelerator beam impedance. We have been applying this capability in support of the Advanced Light Source as its accelerator systems move from design to construction. Measurements and detailed design guidance have ensured that the dense electron bunches in the ALS will not be dispersed by self-excited instabilities.

Schottky signals are electrical signals generated by a particle beam as a result of the fluctuations in the instantaneous current and position of the particles. A Schottky-signal detector can measure beam properties such as width, position, and energy spread, essentially taking a close look at the internal behavior of the beam, without perturbing the beam in any way.* Schottky signals are intrinsic to a beam consisting of a finite number of particles. However, in an accelerator such as the Tevatron in which the beam is bunched, detecting Schottky signals is not easy. A bunched beam produces *coherent* signals, i.e., signals generated by each bunch moving as a collective entity. (This coherent signal is what conventional beam monitors sense.) For a beam consisting of N particles (N is typically $\geq 10^{11}$), the coherent signal power is N times as great as the fluctuation or *incoherent* signal power. A Schottky detector must somehow distinguish between the Schottky signal and a coherent signal that is more than eleven orders of magnitude larger!

Our solution was not so much to overcome the problem as to finesse it. At frequencies above those that are characterized by the width of the individual beam bunches (200–300 MHz for the Tevatron collider), the coherent signal falls off rapidly. We hypothesized that a high-gain device, operating at a much higher frequency (2 GHz) where the coherent signal is much less intense, would enable detection of the incoherent signal. The frequency and gain requirements pointed to a high- Q resonant cavity, as in the detector shown in Figure 6-9.

The detector was fabricated in 1987, but at that time the only opportunity to test its beam response was during fixed-target operation of the Tevatron. In this mode of operation the beam was constantly being manipulated, resulting in coherent motion with a frequency spectrum broad enough to overwhelm the detector. The first opportunity to test the detector under the relatively quiet conditions of collider operation came in early 1989.

Beam Signal Electronics

Schottky-Signal Beam Monitor

* This capability is extremely desirable for colliders, where beams are stored for many hours and degradation of beam properties must be minimized.

Figure 6-9. This LBL-developed Schottky-signal beam monitor, designed for extremely high sensitivity within its narrow bandwidth, was reinstalled at the Tevatron for use with the collider program. The challenge is to detect the extremely small signals that indicate deviations from the proper course while ignoring coherent beam signals and other interference from a noisy environment, all at a frequency of 2 GHz. This particular unit is now being used as an on-line emittance monitor, and devices based on this principle may be adopted by the SSC.

CBB 873-1723

Before discussing the results, it is helpful to describe the expected frequency spectrum of the output signals. The detector is designed to be sensitive to the transverse motion of the beam. Consequently, it will produce signals in response to either of two occurrences: an offset in the beam's position relative to the center of the detector or an oscillation of the particles about the beam's nominal equilibrium position. The offset-from-center signal shows up at integer multiples of the revolution frequency of the beam; these frequencies do not vary with operating conditions. The oscillation signals are shifted in frequency due to the modulation of the revolution frequency by the transverse oscillations (betatron oscillations) that the particles undergo in any synchrotron; this frequency shift does vary with operating conditions.

In any real accelerator, the particles will exhibit a spread of beam energies, and, therefore, of revolution frequencies, so the revolution-frequency spectrum will consist of bands rather than sharp lines. The spectrum one might expect to see from a Schottky detector is shown in Figure 6-10. Note also that the coherent signal may still appear, but that a characteristic "signature" distinguishes it from the Schottky signals. (The width of the Schottky bands is determined by the spread in the energies of the individual particles, whereas the width of the coherent signals is determined by the energy variation of the beam as a whole; hence the coherent signal appears as a narrow band superimposed on the broader Schottky band.)

Figure 6-10 also shows the betatron-oscillation signal. Like the revolution-frequency signal, it consists in principle of a narrow coherent band superimposed on a broader Schottky band. The coherent band represents macroscopic "sloshing" of the entire beam; the Schottky band comes from the betatron motions being executed by individual particles. Here, however, the intensity of the coherent relative to the Schottky signal is further decreased by the ratio of the size of the coherent betatron motion to the size of the incoherent betatron motion of the individual particles (i.e., the beam width). If the coherent betatron motion is small compared to the incoherent betatron motion, as is typically the case, there may not be any observable coherent betatron signal.

XBL 906-5890

Figure 6-10. This typical spectrum from the Schottky detector shows the revolution lines, comprising both coherent and Schottky signals, and the betatron lines, which are shown to be free of coherent contaminants. The vertical-output spectrum shown here, compiled from actual output data, very closely approximates the theoretical predictions, providing an impressive proof of concept for the new detector.

The experimental results from the collider runs indicate that the detector was a spectacular success; the idealized spectrum presented in Figure 6-10 consists of actual data taken during collider operation at 273 GeV. The coherent signal in the revolution line has been suppressed by more than eight orders of magnitude. Moreover, because the coherent betatron motion is small relative to the beam size, the Schottky betatron lines are almost entirely free of coherent-signal contamination. The spectrum shown here represents signals resulting from vertical motion of the beam. A second set of signals from the same cavity yielded comparable information on horizontal motion.

The Schottky peaks in Figure 6-10 are not actually smooth curves. Rather, they are split into a set of closely spaced narrow peaks, the so-called synchrotron "sidebands" or "satellites." Modulation of the revolution frequency by the synchrotron oscillation of the beam causes this splitting. A greatly expanded view of the center of a revolution line, from a collider run at 900 GeV, is presented in Figure 6-11. This figure shows the central line (which may be thought of as the "carrier frequency" between the sidebands) as well as the first two satellites on either side. The separation of the sidebands is equal to the modulation frequency, i.e., the synchrotron-oscillation frequency. From the width of the central peak, we see that the instrument's frequency resolution is better than 1 Hz, or, at an actual frequency of about 2 GHz, better than 1 part in 10^9 .

The spectra obtained from the detector provide a wealth of information about the beam. Some of the more obvious data are the betatron oscillation frequencies (obtained from the centroid of the betatron lines), the transverse emittance (from the area under the betatron lines), and synchrotron frequency (from the spacing of the synchrotron satellite lines). Additional information is available from such features as the fine structure of the synchrotron satellites and the time-varying shape of the envelope of the coherent peak, though analysis of these features is less straightforward. At

Figure 6-11. Central synchrotron satellites observed during operation at 900 GeV. Since these data result from the revolution frequency being modulated by the synchrotron oscillations, one can think in terms of a modulated carrier signal; thus the satellites are sometimes referred to as "sidebands." The spacing of the peaks gives the frequency of the synchrotron oscillations. The line width of the central peak indicates that the obtainable frequency resolution is better than 1 part in 10^9 .

XBL 906-5891

present, Fermilab is planning to use the detector as an on-line emittance monitor and has asked us to build a pair of phased detectors so that the proton and antiproton signals can be separated.*

ALS Beam Impedance Study

In support of the Advanced Light Source project at LBL, members of our group who are skilled in rf measurements and electromagnetic analysis have been performing detailed beam-impedance studies. In 1989, mirroring the fabrication progress of the ALS, their work moved on from theoretical analyses and measurements made with models to testing of actual hardware.

Exceptional brightness, combined with short pulse duration, is a major design goal of the ALS. To achieve this property, the bunches of electrons in the storage ring must be short and narrow, yet dense. Because of their intensity, the bunches can be subject to strong dispersive forces, which may be thought of as arising from the bunches' own electrical images in the beampipe or from the electromagnetic wake function of the surroundings. This reaction to the beam's passage is known as beam impedance. To avoid any spreading of the compact bunches, the beam impedance of the ALS vacuum chamber must be not only small on average but also free of harmful resonances. (Disruptive higher-order effects can arise from parts and structures that are quite small compared to the fundamental rf wavelength in question.)

The geometry of the ALS vacuum chamber is unprecedented in electron storage rings. The goal was to have as little electromagnetic interaction with the bunched beam as possible, yet to provide good opportunities for vacuum pumping and for graceful exit of intense synchrotron radiation. The result-

* In the Tevatron Collider, proton and antiproton beams circulate in opposite directions through a single beampipe, so the detector actually sees the superposed signals from both beams.

ing design, shown in Figure 6-12, consists of a smooth, highly symmetrical, small-diameter beampipe connected by a 1-cm-high slot to a large antechamber. The antechamber provides room for pumping, and its shape could be tailored to accommodate synchrotron-radiation ports and ancillary equipment without affecting the beam. To verify that this idea works as predicted, we performed a battery of impedance measurements on the first curved-section vacuum chamber received by LBL. (The chamber is about 10 m long. Twelve curved chambers will be interspersed with 12 long straight sections to form the storage ring.)

The task presented a great many practical difficulties. The most obvious was that the chamber could not be tested with an actual beam. Furthermore, the shortness of the beam bunches (about 3 cm) implied the presence of strong electromagnetic fields at frequencies as high as 20 GHz. Seemingly straightforward measurement equipment becomes ill-behaved at such high frequencies. For example, a 10-m length of coaxial cable will attenuate the signal by 30 dB (1000 $\times$). And signals above the 5-GHz cutoff frequency of the beampipe can propagate as traveling waves in free space without needing a wire conductor; this property can be put to use, but it can also cause misleading signals and reflections.

To obtain useful data under those conditions, we developed new techniques for measuring simulated beam signals in the region beyond cutoff. In one method, a 1/8-inch-diameter wire suspended down the center of the beampipe carried a current that simulated the bunched beam. In another method, traveling waves were launched from a special antenna at one end and received for analysis at the other end. A key to both methods was the tailoring of absorbers for the ends of the chamber to prevent the traveling waves from being reflected. Changes in the signals as they passed through the chamber were interpreted in terms of beam impedance.

The results of the studies were very favorable. The average impedance in the range of 1–26 GHz proved to be less than 5% of the maximum acceptable level, and no contributions to beam impedance from the antechamber could be detected. We also clearly observed small peaks in impedance when diagnostic parts and test objects were inserted into the beampipe. These observations help to confirm the credibility of the data.

CBB 890-10807

XBL 881-8812

Figure 6-12. The ALS vacuum chamber has a separate beampipe and antechamber to prevent the gas-desorbing effects of intense synchrotron radiation from compromising the ultrahigh vacuum near the electron beam. Synchrotron radiation goes cleanly into the antechamber; there it is either dumped into photon stops, where local sublimation pumps remove desorbed gases, or allowed to continue onward into experimental beamlines. (The tall assemblies extending above and below the chamber are photon stops with their actuators. Associated with each photon stop, below the chamber, is a titanium sublimation pump.) RF measurements confirmed designers' predictions that the design would have a low beam impedance and, in particular, that the antechamber would not add appreciably to the impedance.

CBB 897-6038

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Publications and Presentations

7.

BEVALAC OPERATIONS

... record uranium-beam
intensity ... over 24 hours,
the average was 5×10^7
particles per pulse ...

SEPARATELY AND TOGETHER, THE BEVATRON and the neighboring SuperHILAC have enabled decades of fruitful research. The Bevalac (Figure 7-1) effectively established two new scientific disciplines: relativistic heavy-ion physics and heavy-ion biomedical research and treatment. The system's capabilities are still unique, and beamtime remains in great demand for the physical and life sciences.

As a national user facility, the Bevalac is available to qualified researchers from around the world; about half of the available beamtime is used by scientists from outside LBL. Over the last five years, researchers representing more than 40 U.S. institutions, as well as another 40 international ones, participated in Bevalac experiments. Education, too, is served by the facility; some 80 students have based their doctoral dissertations on Bevalac-related research, and nearly 50 graduate students are currently taking part in experiments there. The focal point of support for this user community is the

Bevalac

J. Alonso (operations manager)
B. Feinberg (deputy manager;
head of planning and development)
G.F. Krebs (head of research coordination)
R.M. Miller (head of operations)
R. Stevenson (head of administrative services)
J.B. Abenoja*
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R.V. Aita
D.P. Almeida*
T.E. Althar
D. Anderson**
R.L. Anderson**
L. Archambault**
J.J. Ayers**
B.J. Bailey**
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D. Beck**
G. Behrsing**
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J. Brown
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J.P. Burch**
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R.L. Callaway
J. Calvert**
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J.R. Dougherty**
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R.S. Everett
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W. Faust**
M. Felix*
K. Fellers**
K. Finegan**
L. Finsch**
I. Flores**
E. Fong**
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K. Fowler**
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D.S. Garfield*
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T.L. Gimpel
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D. Greaves
J.D. Gregor**
J.R. Guggemos
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J. Henderson**
E. Henson**
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P. LaPlant**
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†† Nuclear Science Division

BEVALAC OPERATIONS

XBB 766-4673A

Figure 7-1. The Bevatron, a synchrotron, accelerates beams from either its local injector or the SuperHILAC heavy-ion linear accelerator. The dotted lines in the picture show the beam path from the SuperHILAC through the Bevatron. The SuperHILAC, which has three complementary ion sources, is used when higher energies and heavier ions are needed, i.e., in most of the nuclear-physics programs. The beams are delivered to a variety of users in the External Particle Beam hall. The faint dashed lines in the drawing correspond to the circular and rectangular buildings shown in the photograph. The various experimental areas are separated by a "maze" of shielding blocks.

XBL 909-5927

Accelerator Research Coordination Office at the Bevalac; it handles all stages of interaction between users and LBL, from proposal submittal through experimental runs.

Program Advisory Committees (Table 7-1) meet annually to review proposals from prospective users and to apportion beamtime accordingly. In addition, several Users' Associations, whose executive-committee members are listed in Table 7-2, recommend operational and procedural improvements and facilitate the exchange of information.

Funding limitations have ended operation of the SuperHILAC as a stand-alone user facility with extensive programs and technical support for experimenters.

These panels of experts recommend beamtime allocations. The LBL scientific director of each program may allocate about 10% of the beamtime on a discretionary basis. The SuperHILAC committees are now inactive because of the curtailment of the user program there.

Table 7-1. Bevalac Program Advisory Committees for 1989.

Bevalac Nuclear Science PAC

R. Madey, Kent State University (users' representative)
 S. Datz, Oak Ridge National Laboratory
 B. Feinberg, LBL (acting operations manager)
 C. Gelbke, Michigan State University
 F. Goldhaber, State University of New York at Stony Brook
 W. Henning, GSI, Darmstadt, FRG
 G. Krebs, LBL (research coordinator)
 F. Lothrop, LBL (scheduling coordinator)
 P. McMahan, LBL (executive secretary)
 F. Plasil, Oak Ridge National Laboratory
 L. Schroeder, LBL (scientific director)
 V. Viola, Indiana University (chair)

Bevalac Biomedical PAC

S.J. Adelstein, Harvard University (chair)
 E.A. Blakely, LBL
 J.D. Chapman, Cross Cancer Institute
 E.R. Epp, Memorial General Hospital
 B. Feinberg, LBL (acting operations manager)
 R.J.M. Fry, Oak Ridge National Laboratory
 F. Hutchinson, Yale University
 G. Krebs, LBL (research coordinator)
 F. Lothrop, LBL (scheduling coordinator)
 R.E. Krisch, University of Pennsylvania
 W. Schimmerling, LBL (executive secretary)
 R.C. Urtasun, University of Alberta

SuperHILAC PAC (disbanded after 1989)

P. Armbruster, GSI, Darmstadt, FRG
 H. Britt, Lawrence Livermore National Laboratory
 T. Khoo, Argonne National Laboratory (chair)
 W. Meyerhof, Stanford University
 R. Nix, Los Alamos National Laboratory

Table 7-2. Bevalac Nuclear Science Users' Association Executive Committees for 1989.

W. Benenson, Michigan State University
 P. Brady, University of California at Davis
 J. Carroll, University of California at Los Angeles (chair-elect)
 S.Y. Fung, University of California at Riverside
 R. Madey, Kent State University (chairman)
 M. McMahan, LBL (executive secretary)
 L. Schroeder, LBL (scientific director)
 K. Toth, Oak Ridge National Laboratory
 H. Wieman, LBL

BEVALAC OPERATIONS

A steady program of technology upgrades, combined with long experience at efficient scheduling and with continual fine tuning of operating procedures, has helped the Bevalac staff overcome several years of decreasing budgets and inflationary erosion. Nineteen eighty-nine saw the third consecutive record for experimental beamtime at the Bevalac: 4161 hours, up slightly from last year's 4034 hours.

Accelerator Technology and Operations Summary

Many factors affect beam delivery, including scheduled and unscheduled shutdowns for maintenance, usage for machine studies and tuning, and seasonal fluctuations in the cost and availability of electricity (traditionally, the facility shuts down during part of the summer). Despite these variations, there have been steady improvements.

The physical sciences—mostly nuclear physics—continued to use about two-thirds of the experimental beamtime at the Bevalac. The life sciences, comprising radiotherapy research and basic radiobiology and radiation biophysics studies, accounted for the rest. Table 7-3 summarizes the year's operating statistics and compares them to figures for past years and projections for the future.

Fast Switching

Ion pulses can be injected into the Bevatron from either the SuperHILAC, which supplies the intense beams of heavy ions that are typically required for nuclear science, or the Local Injector, which can deliver beams of lighter ions for radiotherapy. Switching between the two inputs once required a substantial fraction of an hour for retuning of the Bevatron. Today, a fairly drastic switch—from neon at 500 MeV/nucleon to niobium at 1200 MeV/nucleon, for instance—can be performed in two minutes or less. Fast switching is especially advantageous in a mixed-use facility like the Bevalac, because a radiotherapy or radiosurgery treatment lasts about half an hour but involves only a few minutes of actual beamtime.

1989 Performance Statistics

The Bevalac has an ongoing program of technology upgrades designed to increase efficiency, improve user service, and ensure safety. Among them were a comprehensive project aimed at a fivefold increase in the intensity of very-heavy-ion beams from the SuperHILAC, with smaller intensity increases for lighter ions; continued control-room modernization; and a magnet upgrade that is saving nearly 750 MW-hours of electricity per year.

Other significant upgrades included a new electronically controlled beam-spill control system. Progress was also made in two ongoing projects: various electronics upgrades for beamline-tune monitoring systems and a study of possible power-supply modernizations for the main guide-field magnet that would result in much-improved performance during low-field operation.

To complement a recently completed intensity upgrade at the SuperHILAC, the latest generation of the LBL-developed metal-vapor vacuum arc (MEVVA) ion source was installed. In 1989, commissioning of the MEVVA IV source (Figure 7-2) continued for elements ranging from Ti to La. In early tests, we found that the new source delivers 7.5 mA of Ti^{++} to the entrance of the first linac tank while running at about half the maximum arc current and extraction voltage, whereas the older Penning Ion Gauge (PIG) source could provide only 3 mA.

The accelerator improvement program has been vital in keeping the venerable Bevalac useful for today's research, in which the survey experiments have largely been completed and in-depth, high-statistics investigations are becoming the norm. An example of direct user benefit is a new record for uranium-beam intensity, set in late 1989. Over a 24-hour period, the average intensity was 5×10^7 particles per pulse, with a peak intensity of

Accelerator Improvement Projects

Table 7-3. Operating summary, fiscal 1988 and 1989, and projections, fiscal 1990-1991.

Bevalac Operation (hours)	1988	1989	1990	1991
Research	4023	4161	3600	3100
Machine Studies	197	282	250	200
Tuning	<u>706</u>	<u>709</u>	<u>900</u>	<u>600</u>
Total Operation	4926	5350	4750	3900
Unscheduled maintenance	706	707	581	550
Scheduled shutdowns	<u>2837</u>	<u>2703</u>	<u>3429</u>	<u>4310</u>
Total Downtime	3543	3410	4010	4860
Beam Use for Research (hours)*				
Nuclear Science	2727	2712	2400	2067
Life Sciences	1307	1450	1200	1033
SuperHILAC	<u>1749</u>	<u>897</u>	<u>500</u>	<u>0</u>
Total	5783	5059	4100	3100
Number of Bevalac nuclear-science and SuperHILAC experiments receiving beam	49	33	21	15
Number of participating scientists	189	163	145	145
Institutions represented				
Universities	26	19	15	15
National laboratories	5	5	5	5
Other**	<u>15</u>	<u>13</u>	<u>12</u>	<u>8</u>
Total	46	37	32	28
Use of Beamtime (%)				
In-house staff	50	50	50	50
Universities	35	35	35	35
DOE national laboratories	5	5	5	5
Other institutions	10	10	10	10

* This figure includes the SuperHILAC parasitic program and therefore may exceed the research beamtime reported under Bevalac Operation.

** Includes foreign institutions, NASA, some medical institutions, and industrial/commercial investigators.

Figure 7-2. The latest generation of the LBL-developed metal-vapor vacuum arc (MEVVA) ion source, installed at the SuperHILAC as part of the intensity-upgrade project, continued to progress through commissioning in 1989. The ring of protruding cylinders is the multiple-cathode array, which can be rotated to bring different kinds of cathodes into the source one at a time—to provide a variety of ion species for different experiments, for example. In early tests, it provided 7.5 mA of Ti^{++} while running at about half the maximum arc current and extraction voltage, whereas the older Penning Ion Gauge (PIG) source could provide only 3 mA. A variety of MEVVA-related technology-transfer possibilities are also being explored, as metal-ion beams can be used to fabricate and modify various materials.

CBB 860-9309A

9×10^7 ; the extraction efficiency averaged 25%. According to preliminary results, these sustained intense beams enabled experimenters to measure the Lamb shift in three-electron uranium to a precision of about 0.1%—an improvement of two orders of magnitude over previous measurements with two-electron uranium. The work has inspired quantum-electrodynamics theorists to refine their calculations, and it is serving as a benchmark for planned experiments at GSI in Darmstadt, West Germany.

Control-System Updates. One of the major accelerator improvement projects of recent years has been installation of a modern control system throughout the Bevalac complex. The goals are better beam control, including truly reproducible restoration of best tunes; automatic fault diagnosis; uniformity of user interfaces and operating procedures; improved connections with the nuclear-science and biomedical research areas; easier maintenance; and increased safety.

The full complement of 14 control consoles based on Sun workstations has been installed. Subsidiary control rooms for the motor-generators and local injector are now equipped with these consoles, and the SuperHILAC and Bevatron main control rooms now have consoles dedicated to safety alarms. Operators have become adept at producing or modifying the screen templates, whereas any changes to the previous system required the assistance of professional programmers. There have been many enhancements to the user interface, not only through this custom tailoring of screens but also through an increase in the extent to which the accelerator is controlled

through the computers, with a correspondingly lower dependence on physical knobs and buttons.

The next goal is installation of VME-bus systems, interfaced to the control consoles, to control accelerator devices. This plan would bypass the 15- to 20-year-old Modcomp central computers that now hold the accelerator data. This scheme will be tested first in the rf system for the local injector, where it is expected to aid the radiotherapy program by improving the speed and flexibility of fast switching. Other early sites for the new system will include the Experimental Particle Beam (EPB) hall, where it will control collimators and magnet power supplies, and the motor-generator room. Hardware has been ordered, and software is being designed and written.

Future Improvement Projects. The general theme of the accelerator improvement projects now underway is improvement of user service in the EPB hall, a program that goes hand in hand with the control-system update. Modernized controls for the power supplies in the EPB hall will save time by making beamline tunes more easily reproducible. A variety of previously independent systems, including both experimental beam-delivery equipment and safety devices, will be integrated with the central control system.

A 1991 project will modify the power supply for the main guide-field magnet to support a higher duty cycle for many experiments—as much as 80%, as opposed to 25% at present. This will allow the Bevalac to provide better service in light of today's emphasis on high-statistics investigations rather than survey experiments.

Beam quality enhancements are also planned for 1991 and 1992. Delivering intense, high-quality beams at the experimenters' targets can greatly increase the effectiveness of experiments. (For Bevalac purposes, beam quality may be broadly defined as sharp focus at the experimenter's target, combined with pulse shapes that come up to full intensity quickly, carry on evenly with relatively little structure, and then terminate cleanly.) Intensity and quality are affected to some extent by operating techniques, but are intimately linked with technological characteristics such as the "ripple" in magnet power supply voltage. Particularly important among the beam-quality enhancements will be a variety of measures to minimize and strip away beam "halo" and reduce beam emittance, thus cutting the rate of unwanted background events.

Technology Transfer Implications. The technologies developed and deployed through the years have also had ramifications beyond the Bevalac. An example is the rf quadrupole linac (RFQ), which accelerates ions to a few hundred keV.* RFQs may prove to be useful not only in research accelerators like the Bevalac (which has an RFQ in the local injector), but also in commercial and industrial applications.

Airport security is an example. We recently developed an integrally formed RFQ (Figure 7-3) that, unlike previous models, can be manufactured and commissioned in a few relatively simple steps. Because it combines the inherent compactness of an RFQ with unprecedented affordability, it might lend itself to use in a safer explosives-detection system. Instead of using a radioactive source in a public area, a thermal neutron analyzer could use ions from an RFQ to bombard a neutron-production target.

* RFQs, based upon a 1960s Soviet idea and first constructed at Los Alamos National Laboratory in the mid-1970s, have been built and used at many laboratories. The LBL innovation is the integral construction, which gives an order-of-magnitude reduction in assembly time and greatly reduces the need for painstaking alignment by highly skilled technicians.

CBB 882-1567

Figure 7-3. This LBL-designed radio-frequency quadrupole (RFQ) accelerator, shown here with the top vane removed, can be manufactured with conventional, numerically controlled machine tools. The parts align themselves at assembly, without adjustment, to the required vane-tip positional accuracy of ± 0.03 mm. Previous RFQs had been constructed from a number of separate parts that made up the resonator cavity and the vanes inside; these parts had to be painstakingly aligned. This unit can be fabricated and assembled for about one-third the cost of an old-style RFQ; assembly time alone has been reduced from 300 to 30 hours, largely because of the self-aligning nature of the design. Potential uses include particle accelerators for physical research and medical treatment, airport security monitors, industrial ion implanters, and defense systems.

Nearly 60 years after Chadwick's discovery of the neutron ushered in the modern era of nuclear physics, a great many questions remain about the nature and behavior of the nucleus. With its ability to provide beams of heavy ions in the MeV- and GeV-per-nucleon range (Figure 7-4), the Bevalac lends itself to the study of many aspects of nuclear matter. The Bevalac nuclear-science program focuses upon extreme conditions of temperature and pressure, but many widely diverse investigations have been built upon that common theme. They include studies of

- the equation of state (EOS), which is of interest both in nuclear science and in particle astrophysics
- reaction dynamics
- properties of exotic nuclei
- subthreshold production of pions, kaons, and antiprotons

These studies are carried out by numerous U.S. and international researchers, with AFRD's technical support and scientific collaboration.

Some of the effects of nuclear collisions are rather exotic, as are the means of observation. However, many of the effects are analogous, in considerable detail, to phenomena that one might expect to see in everyday, macroscopic matter. (An example of such behavior is collective flow, which was first observed in the Plastic Ball and Streamer Chamber detectors at the Bevalac.) Depending on temperature and pressure, nuclear matter can be thought of as a solid, liquid, gas, or plasma. The EOS mathematically describes the balance among these phases and the borderlines of the phase transitions.

Nuclear Science

Nuclear Physics and EOS Studies

Figure 7-4. In its ability to provide relativistic beams of all ions up to and including uranium, the Bevalac complements other heavy-ion accelerator facilities now running or being built in the U.S., such as the Alternating Gradient Synchrotron and the Relativistic Heavy Ion Collider at Brookhaven National Laboratory, as well as lower-energy accelerators like the one at Michigan State University.

XBL 875-2271B

Knowledge of the EOS is of great fundamental importance to nuclear scientists. It is also useful to astrophysicists, because certain hypotheses about mechanisms within supernovae and neutron stars are based on assumptions related to the EOS. The hypotheses are especially sensitive to the value of nuclear incompressibility.

Probing the EOS under conditions far removed from the equilibrium state of nuclear matter requires considerable disturbance of the entire volume of interacting matter. This calls for head-on impacts from beams of heavy ions. The greater the mass of the target nucleus and the projectile, the greater the disturbance and the greater the number of participating nucleons. Therefore an ongoing highlight of Bevalac research is exploration of the EOS, as shown in Figure 7-5, at high temperatures (typically 50–100 MeV of thermal energy) and high densities (two to four times normal). The Bevalac energy range is especially appropriate because regions of the EOS far from

XBL 881-8818

Figure 7-5. A schematic phase diagram for nuclear matter, showing some of the states and transformations predicted by various theories. The normal state of nuclear matter can be characterized as a liquid. It may undergo phase transitions to a hadron gas at relatively low densities or, at higher densities, to some condensed phase such as a pion condensate or a superdense nucleus containing thousands of nucleons. Under extreme conditions, the hadrons themselves are expected to break down into "deconfined" quarks and gluons; such conditions are thought to have existed in the first few fractions of a second after the Big Bang, and are thought to exist today in neutron stars and supernovae. Such extreme conditions can be re-created at a laboratory scale through central collisions between nuclei at extreme relativistic energies.

equilibrium can be reached, yet the phenomena are still strongly influenced by the nuclear mean field. In other words, the nucleus still behaves as a unit in the collision, whereas at much-higher energies one enters a regime of "hadrons flying in formation" in which the effects resemble those of elementary particles striking each other.

Time Projection Chamber. Experimenters have found that the heavier reaction fragments appear to fly away from the reaction at an azimuthal angle closer to the reaction plane than do lighter fragments. Furthermore, the in-plane flow momenta of heavier fragments are significantly larger. However, the effective compressibility of nuclear matter remains uncertain to within a factor of 2, so clearly a consensus on the form of the EOS has not been reached. Further research will be aided by a new time projection chamber (TPC), an electronic 4π detector that will fit inside the Heavy Ion Superconducting Spectrometer (HISS) magnet as shown in Figure 7-6.

The TPC is designed for full-solid-angle coverage, hence the term " 4π ." It will be able to identify and analyze the momenta of most of the 200 or so mid-rapidity charged particles (mostly protons, deuterium and tritium nuclei, ^3He and ^4He nuclei, and pi mesons) that are produced when heavy nuclei such as gold collide at Bevalac energies. The TPC is being placed in the HISS dipole because its functions will be complemented there by a variety of existing detectors. In 1988 a scale-model TPC was successfully tested with beams of ^{197}Au (which is highly ionizing and therefore useful as a test of dynamic range) and ^4He (which produces "clean" tracks so performance can be compared with simulation results). The full-scale TPC should come on line in spring 1991.

Dilepton Spectrometer. Another important detector is designed to provide an especially clear view of certain reactions. The Dilepton Spec-

Figure 7-6. The HISS TPC will be a full-solid-angle detector able to identify and analyze the momenta of most of the 200 or so mid-rapidity charged particles (mostly protons, deuterium and tritium nuclei, ^3He and ^4He nuclei, and pi mesons) that are produced when heavy nuclei such as gold collide at Bevalac energies. A prototype was tested in 1988, and the full-scale TPC should come online in summer 1991.

CBB 899-8246

trometer (DLS), a unique detector installed at the Bevalac in 1986, offers special insights into reaction dynamics by watching for a rare event: emission of an electron and positron correlated in their paths and their time and place of origin.

This is thought to provide an especially undistorted view of nucleus-nucleus, proton-nucleus, and proton-proton collisions because leptons interact with other forms of matter through the weak nuclear force and the electromagnetic force. Thus there is only a small probability of scattering or reabsorption on their way out of the reaction area, and reliable data can be obtained on deep and early phenomena of the collision. In particular, dilepton spectrometry might provide insights into one of the key theoretical unknowns of nuclear collisions: the behavior of pions and other mesons. (It is also thought that dilepton production might signify the formation of a quark-gluon plasma in the higher-energy heavy-ion colliders of the future.)

In 1987 the DLS collaboration established that dilepton emission does indeed occur at Bevalac energies. Subsequent work further defined the role of dilepton spectrometry in studying the EOS and other behavioral aspects of hot, compressed nuclear matter. In 2.1- and 4.9-GeV/nucleon $p+^9\text{Be}$ collisions, and to some extent in 1.95-GeV/n $^{40}\text{Ca} + ^{40}\text{Ca}$ collisions, the mass spectra have a sharp peak around 300 MeV, which is twice the rest mass of a pion. A great many models have been proposed to explain the early DLS data; in one of them, the peak might be interpreted as the matter-antimatter annihilation spectrum of pion pairs (π^+/π^-).

To verify this preliminary finding, the dilepton spectrum will be measured for a proton beam and a liquid-hydrogen target. In this collision,

which involves elementary nucleons rather than nuclei with their collective "mean field," the sharp peak is expected to disappear. This would be a dramatic confirmation that dilepton spectra directly reflect the properties and behavior of pions in hot, compressed nuclear collisions. This ability to visualize the early stages of a collision would be a key addition to current techniques, which often cause an interpretational stalemate because they primarily provide data on flow and other phenomena from late in the reaction process.

However, in order to take advantage of this capability, special detection techniques are needed to find the rare correlated leptons amid the hail of other reaction products. Typically these experiments average about one dilepton pair per hour, out of a total of 20 000 or so events. In previous upgrades to the four-year-old DLS, extra drift chamber planes were added, allowing measurements of a great many charged particles. In spring 1989, the system was further enhanced with a conical 96-segment multiplicity array surrounding the DLS scattering chamber. (Both central and peripheral collisions occur in any experiment. Multiplicity arrays allow the centrality of each collision to be determined.) Figure 7-7 shows some examples of significant DLS data taken recently: the response of the multiplicity array to a 2.1-GeV Ca + Ca collision, along with the mass cross section per nucleon for Ca + Ca at 2.0 GeV/n.

Subthreshold Production. A particle that a nucleon-nucleon collision could produce only above a certain threshold energy can be produced by a nucleus-nucleus collision at a considerably lower energy. The implication is that in addition to the internal Fermi energy of the nucleus—kinetic energy from the vibrations of the nucleons—there are "collective" phenomena, occurring in nucleus but not nucleon collisions, that help make up the deficit. Subthreshold production of particles is a prominent area of Bevalac study because it provides insights into collective phenomena. Fittingly enough,

Figure 7-7. Left: DLS data show how a recently added multiplicity detector—a 96-element hodoscope configured as a cone surrounding the target chamber—responds to a 2.1-GeV Ca + Ca collision. The hodoscope detects charged particles and gives information about the centrality of the event. The figure shows the hit distribution on a plane transverse to the beam axis. The elements that show the most hits are oriented at the smaller angles. Right: The mass cross section per nucleon for the reaction $\text{Ca} + \text{Ca} \rightarrow e^+ e^-$ at 2.0 GeV/n was measured with the DLS. The dashed line shows the estimated Dalitz-decay contribution, which cannot account for the true-pair signal for masses above 200 MeV.

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the antiproton is the subject of subthreshold-production study at the accelerator where it was first observed in 1955. Subthreshold production of π and K mesons (pions and kaons) is also studied.

A 1989 Bevalac experiment involving $^{28}\text{Si} + ^{28}\text{Si}$ at 2.1 GeV/n (Figure 7-8) resulted in the first observations of subthreshold antiproton production in a nucleus-nucleus collision. The antiproton yield was more than three orders of magnitude larger than was expected based on calculations that took into account the internal nuclear momentum of the projectile and target nuclei. However, the results from the same set of calculations agreed with experimental data for $p + \text{Cu}$ collisions in the range of 2.9–6 GeV. Research continues at LBL and elsewhere in search of collective phenomena that may account for the discrepancy.

Pion Studies. Pions, the most abundant particles created at Bevalac energies, have long been the subject of experimental scrutiny, especially for studying the effects of central collisions. Pion yields provide unique insights into compressional effects, the π^+/π^- ratio in various regions of phase space can be used to study the role of the Coulomb force in nuclear collisions, and pion interferometry based on the Hanbury-Brown and Twiss effect is used to measure the magnitude of the emission in space and time.

Figure 7-8. A 1989 Bevalac experiment involving $^{28}\text{Si} + ^{28}\text{Si}$ at 2.1 GeV/n yielded these time-of-flight spectra for subthreshold particle production. The topmost illustration is for negative particles prior to vetoing by the aerogel Cerenkov counters. The π^- and K^- peaks are distinct from one another and a small $\bar{p}$ peak is visible. The middle plot is for those negative particles that survived vetoes by both aerogel and liquid Cerenkov counters: 50 antiprotons survived the veto, although only two pions did so. The bottom plot, with the beamline tuned for positively charged particles in the same momentum range, shows π^+ , K^+ , and $\bar{p}$ peaks at the same positions as their π^- , K^- , and $\bar{p}$ counterparts.

XBL 907-2520

In 1989, a Streamer Chamber experiment to study multipion production in Au + Au collisions at 0.8 and 1.2 GeV/n indicated a nonthermal component for pions emitted in the center of mass and at 90° to the direction of the collision fragments (Figure 7-9). This may indicate that pion data can reveal occurrences in the hot participant zone of a collision. Plans for 1990 include a new Streamer Chamber experiment designed to substantially increase the number of very-high-multiplicity ("supercentral") events; in the subsequent data interpretation, experimenters will, for the first time, search for correlations between pion emission and nuclear flow.

Other ongoing pion studies include high-statistics HISS correlations of two- and three-pion emission, as well as systematic pion interferometry using the JANUS spectrometer. The JANUS experiment, which involves La + La collisions, also includes a multiplicity array to distinguish between central and peripheral collisions. As mentioned earlier, subthreshold pion production is also examined as a probe of collective phenomena in heavy-ion collisions.

Substantial interest has developed in exploiting the Bevalac's unique ability to provide beams of the heaviest ions at 20–200 MeV/n. The goal of the program is to produce thermally "hot" nuclei and study their modes of decay. In particular, multifragmentation processes are being studied to explore the "liquid-gas" phase transition. Recent studies in the lower part of that energy range have shown that asymmetric heavy-ion collisions below about 50 MeV/n are dominated by incomplete fusion reactions. These reactions form very hot compound nuclei, which emit light particles and numerous complex fragments ($Z > 2$) as they decay. The angular distributions of the fragments are isotropic. In the range of 80–100 MeV/n, though, the

Intermediate-Energy Program

Figure 7-9. A Streamer Chamber picture shows an Au + Au collision. Analysis of Streamer Chamber data from experiment to study multipion production in Au + Au collisions at 0.8 and 1.2 GeV/n indicated a nonthermal component for pions emitted in the center of mass and at 90° to the direction of the collision fragments. This may indicate that pion data can reveal occurrences in the hot participant zone of a collision.

CBB 898-7314

angular isotropy disappears, the mass distribution is completely different in character, and many multifragment events are observed. A possible explanation is that incomplete fusion gives way to the "fireball" regime in this energy range.

To obtain a relatively undistorted view of the early stages of intermediate-energy reactions, an important Bevalac program uses an array of 18 neutron counters and a charged-particle time-of-flight wall in the HISS facility. The goal is to examine the early, high-density stage of a heavy-ion collision. Neutrons are relatively unaffected by final-stage phenomena—in particular, being neutral, they do not undergo Coulomb interaction. The neutron detectors, covering polar angles of about 3° to 90° , determine the energy of the neutrons as a particle-inclusive experiment. The time-of-flight wall (Figure 7-10) covers about 28° , sampling about half the particles that an ideal 4π detector would see, and determines the azimuthal angle of each neutron relative to the plane of the reaction. With these data, absolute triple-differential neutron cross sections can be determined, along with some of the most detailed information ever obtained on collective flow in nuclear collisions.

Figure 7-10. This charged-particle time-of-flight wall in the HISS facility complements an array of neutron detectors. The goal is to examine the early, high-density stage of a heavy-ion collision. Neutron detection is a challenging task, but is considered worthwhile for this purpose because neutrons are relatively unaffected by phenomena from later stages in the reaction—Coulomb effects in particular. The experiment searches for correlations characteristic of fluid-like collective behavior, or "flow," in nuclear collisions. Such correlations signal the release of compressional energy and provide a relative measure of the peak nuclear pressure achieved in the collision. The time-of-flight wall resolves time to ± 100 ps or closer and indicates the charge of a fragment. Work is now underway on tracking methods that will improve the overall time resolution and diminish the extent to which time resolution depends on position.

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Studies of symmetric systems in the range of 50–100 MeV/n are also underway to examine the transition from sequential decay of composite systems at low energies to multifragmentation at higher energies. The goal is to build a comprehensive database regarding the competition among various reaction mechanisms in composite systems ranging from several hundred MeV to several GeV. IMED, a new Intermediate Energy Detector, is being planned so that the energy range of 50–150 MeV/n can be mapped over the next few years.

As indicated earlier, head-on or “central” collisions are not the only area of interest. A significant program involves peripheral or “grazing” collisions at low and intermediate energies. Such collisions can produce large temperatures at lower densities, permitting exploration of another region of the EOS and addressing an important question—the amount of energy that a nucleus can hold without breaking up. Nuclei are “heated” until their excitation energy exceeds their binding energy; the decay modes and products are then studied.

Grazing collisions tend to produce exotic reaction fragments, some of which have extreme numbers of protons and neutrons. Thus they provide an opportunity to map the proton and neutron “driplines”: the stability boundaries defining the stable region of the chart of the nuclides. The decay of these exotic products is also of interest because it provides information on nuclear structure.

Considerable progress has been made in using projectile fragmentation to produce secondary beams of radioactive nuclei for study. These experiments have shed light upon new features of nuclear structure. The program recently yielded the first interaction radii for ${}^6\text{He}$, ${}^8\text{He}$, and ${}^{11}\text{Li}$. The radius of ${}^{11}\text{Li}$ was found to be much larger than was expected for nuclei in this mass region, and evidence for a diffuse neutron skin was found. The technique has since been extended to unstable *sd*-shell nuclei such as O, F, and Ne by fragmenting ${}^{40}\text{Ar}$ from intense beams. These results will have to be accounted for in theoretical models of low-mass, neutron-rich nuclei. Other recent experiments with radioactive beams have explored

- Energy dependence of the interaction cross sections of unstable nuclei
- Total electromagnetic-dissociation (EMD) cross sections of exotic nuclei
- Energy dependence of fragmentation of very weakly bound systems
- Isospin symmetry in fragmentation of an exotic mirror pair
- Giant resonance in a radioactive nucleus (measured through EMD)

This program of using projectile fragmentation to study the ground-state properties of exotic nuclei is a pioneering effort developed at the Bevalac and well suited to its capabilities.

Another significant collaborative study uses a variety of nuclear-magnetic-resonance (NMR) and polarization-flipping techniques to determine the magnetic moments of short-lived, beta-emitting fragments. Early success with ${}^{43}\text{Ti}$ produced from primary beams of ${}^{46}\text{Ti}$ indicated that this method is effective for studies of nuclear structure in the $f_{7/2}$ nuclear shell and for examination of weak interaction in beta decay. The techniques, now being refined and extended to several other fragments such as ${}^{39}\text{Ca}$, ${}^{37}\text{K}$, and ${}^{55}\text{Ni}$, can be used to help characterize reaction mechanisms at 100–200 MeV/n.

Peripheral Collisions and Fragmentation Studies

Atomic Physics and NASA Instrument Calibration

Fragmentation experiments have been enhanced with the successful operation, using Au beams, of a new tracking detector for HISS. The new detector, named MUSIC II, is the second generation of the Multiple Sampling Ionization Chamber. By combining concepts from traditional ionization chambers and from time projection chambers, it provides charge identification and precise determination of track position and angle for up to 10 particles. MUSIC II is optimized for fragments of intermediate and higher mass (carbon and above), so it complements the existing HISS drift-chamber system. The Au experiments produced a variety of events, ranging from very peripheral binary-fission events with a sum charge near 79 to multifragment events involving as many as 10 charged fragments.

Although the Bevalac is used primarily for studies of the nucleus, a variety of other experiments can be performed there. Atomic physicists use the Bevalac's ability to provide "hydrogen-like" and "helium-like" uranium ions (that is, ions stripped down to one or two electrons). Because uranium has 92 protons, these ions represent an extreme condition of the atom. On their small scale, they have the strongest electric fields found in nature, enabling scientists to address phenomena in quantum electrodynamics, including the Lamb shift.

The experiments with highly stripped uranium may also lead to new experimental techniques for higher-energy machines, such as the Relativistic Heavy Ion Collider (RHIC) being built at Brookhaven National Laboratory. Recent theoretical calculations indicate that the high-Z environment associated with colliding nuclei may be a source of electron-positron pairs; further, the produced electron is thought to be captured by the outgoing nucleus. Measurements scheduled for 1990 at the Bevalac can be used to test the theoretical models.

Bevalac beams are also used for instrument calibration by researchers from the National Aeronautics and Space Administration (NASA) and by other cosmic-ray scientists. They use the beams to calibrate detectors that will be used on balloon, rocket, and satellite flights. The 1990 plans include recalibration of heavy-ion instrumentation aboard the Long Duration Exposure Facility, a satellite that was recovered by the space shuttle in January 1990.

Biomedical Research

The word "radiation" has ominous connotations to many, but radiation can be a lifesaver. One of its therapeutic applications is charged-particle radiotherapy/radiosurgery, in which accelerated ions are delivered very precisely so that a tumor or arteriovenous malformation (AVM) is treated with minimum harm to healthy tissues nearby. Because particles deposit most of their energy abruptly near the end of their travel, the deposition being characterized by a sharp curve known as the Bragg peak, they can be used as a kind of "magic scalpel" to reach places that are surgically inaccessible. (Tumors within the eye and very close to the spinal column are classic examples.) Bragg-peak treatments conducted here over the last several years have resulted in impressive rates of remission for several kinds of tumors. The radiotherapy research continues, focusing on three primary areas:

- *development of technologies and techniques for dose localization*
- *determination of optimal treatment protocols*
- *tracking of patients already treated*

Other life sciences research at the Bevalac, accounting for about 25% of biomedical beamtime, includes basic studies of the effects of radiation on both normal and abnormal cells and tissues. In vivo and in vitro experiments examine such subjects as damage and repair of DNA, cell and tissue kinetics, and radiation tumorigenesis.

These studies and treatment programs are carried out primarily by LBL's Research Medicine and Radiation Biophysics Division and Cellular and Molecular Biology Division, with technical support from AFRD. Scientists from other institutions, including the University of California at San Francisco, the Department of Radiation Medicine of the Massachusetts General Hospital, and the Harvard Cyclotron Laboratory, are also involved through collaborative programs.

As multiyear clinical studies affirmed the effectiveness of ion-beam therapy, a number of medical centers became interested in medical accelerators for treatment and research. In the course of research and treatment at the 184-Inch Synchrocyclotron and the Bevalac, LBL established itself as a leading center for developing and transferring advanced beam-delivery, dosimetry, and patient-positioning technologies. The Laboratory's scientists and engineers, including many from AFRD, have been heavily involved in the planning of medical accelerators at Loma Linda University Medical Center, NIRS (the National Institute for Radiosurgery at Chiba, Japan) and EULIMA (the proposed European Light Ion Medical Accelerator).

Much of the recent R&D activity has focused on beam delivery. To provide radiation fields of the desired diameter and range, a versatile, computer-controlled single-scatterer system (Figure 7-11) was developed. As the beam enters the treatment room, it is spread laterally by a combination of metal scattering foils and a variable-thickness water absorber. All the scattering material is placed as far upstream as possible in order to produce a sharp lateral field edge. In addition to scattering, the water absorber shortens the range of the beam; thus it can be used to "stack" the Bragg peak in 3- or 4-mm steps so that the target volume is covered in depth. The number of particles delivered at each step is set by a computerized dose-minimization procedure. These technologies and techniques result in isosurvival—equal biological effects upon all parts of the target—while minimizing damage to adjacent healthy tissues.

Scattering techniques are best suited to small tumor volumes. For large tumors, their shortcomings include diminished range, lowered intensity of the delivered beam, and nuclear fragmentation caused by the scattering foils. Electromagnetic beam steering avoids these difficulties but is quite difficult to implement because of the "rigidity" of the beam. An innovation currently being developed is the raster-scanner beam delivery system, a step beyond the "wobbler" system now in use (which itself won an R&D 100 award from *Research and Development Magazine* in 1986). The raster scanner moves the beam back and forth somewhat as the electron beam is moved in a television picture tube. This technique offers sharper-edged radiation fields with greater uniformity. In 1989 we continued development of the raster scanner and its control software and performed dosimetry to define the beam characteristics needed for its use.

Other innovations are aimed at quality assurance and safety in biomedical treatments. An example is the LBL-developed dosimetry system shown

Treatment Systems

XBL 896-6557

Figure 7-11. The Bragg peak (right) gives charged particles an advantage over electromagnetic radiation (such as x-rays) for radiosurgery. Electromagnetic radiation grows weaker exponentially as it is absorbed, so delivering an effective dose to a deep tumor means considerable damage to healthy tissues in front of and behind the tumor. Particles, by contrast, lose most of their energy in a relatively narrow part of their range; the location of this "Bragg peak" can be accurately predicted and precisely controlled. In the radiosurgical instrument arrangement diagrammed above, an energy-absorbing wax or Lucite bolus matches the depth of the Bragg peak to the thickness of the tumor, while collimators control the cross section of the beam. Not shown is an upstream "binary filter," or absorber, which draws the beam back in sequential layers. By changing these variables, researchers can fit the treatment area to the tumor across three dimensions.

XBL 737-969

in Figure 7-12, which measures the two-dimensional dose distribution of the radiation field delivered to a patient. This ionization-chamber system has 144 elements, each about 0.2 cm^2 in area, so its resolution is comparable to that of the computerized tomography systems that are often used when diagnosing a tumor and planning its treatment. Its size allows it to be placed very close to the patient, and its water-equivalent thickness, only 0.2 mm , means there is relatively little interference with the radiation beam. Radiation-sensitive films possess similar characteristics, but they provide results only after the fact, whereas the new system shows the radiation dose as it is delivered. This unique combination of features allows physicians to use it not only for treatment planning but also for "real-time" monitoring to ensure that the patient receives the proper dose of radiation in the correct places.

Refinement of systems related to the wobbler continued; the results included improved calibration data and procedures and better plexiglass "propellers" to spread out the Bragg curves. With Ne as well as He now being used in Cave I, computer monitoring of the positions of critical devices on the beam-optics bench has been added. Procedural safety has also been enhanced through the use, in all treatments, of Ne^{9+} , which has a unique charge-to-mass ratio, instead of Ne^{10+} .

CBB 864-2666

Figure 7-12. This LBL-developed dosimetry system gives real-time feedback on the two-dimensional dose distribution of the radiation field delivered to a patient. Its resolution is comparable to that of the computerized tomography systems that are often used when diagnosing a tumor and planning its treatment; its size allows it to be placed very close to the patient; and its water-equivalent thickness, only 0.2 mm, means relatively little interference with the radiation beam.

Clinical research medicine at the Bevalac focuses primarily on stereotactic Bragg-peak radiation treatment. Two general types of treatments are carried out: radiosurgery of intracranial AVMs and radiotherapy of tumors.

Treatment Development and Analysis. The stereotactic radiosurgery clinical research program is currently investigating how life-threatening intracranial AVMs respond to focal irradiation. Another area of effort is development of safe, reliable, and reproducible treatment strategies that can be reproduced at hospital accelerators. The program comprises development of the optimal relationships among dose, treatment volume, ion type, beam delivery, and fractionation of treatment. During the past year, researchers have continued to treat patients under a dose de-escalation protocol and have also analyzed the clinical and neuroradiologic outcomes of treatment.

The ideal outcome, of course, is obliteration of the AVM or tumor with a minimum of complications and without relapse. According to a study of 65 patients, irradiation of the entire arterial phase of the AVM with 90% of the maximum target dose resulted in complete cure. Continued optimization of dose-localization techniques has been performed during the past year through improvements in treatment planning, delivery, and verification. Developing a protocol to optimize the dose and its distribution is important;

Heavy-Ion Radiotherapy and Radiosurgery

the goal is to provide effective treatment while minimizing side effects, including potential delayed radiation injury to critical brain structures nearby.

Heavy-Ion Radiotherapy of Tumors. Previously, a Phase I-II trial of neon-ion irradiation of locally advanced tumors of different anatomical regions delivered promising initial results on glioma of the brain; selected head/neck tumors; tumors of the esophagus, pancreas, stomach, lung, and prostate; and sarcoma of soft tissue, bone, and other sites. Local control rates from 50% to 90% were achieved in lung, locally advanced paranasal sinus and nasopharynx tumors, salivary gland tumors, and sarcoma of bone or soft tissue. Randomized Phase III studies have been established for most of these. In addition, plans are being made for further trials involving other types of tumors at various sites, including "radioresistant" histologies such as melanoma and renal carcinoma.

A new Phase III trial has been started to compare the effects of neon ions, which have high linear energy transfer (LET), against those of the more-familiar, low-LET helium ions. The high-LET ions are thought to offer advantages in effectiveness and dose localization. However, accelerators and related systems for heavier ions are more costly and complex, so it is important to determine whether those characteristics are needed for effective treatment, and, if so, under what conditions. The trial will involve sarcoma in the thoracic and lumbar paraspinal regions and sinus/nasopharynx tumors invading the base of the skull. Another new trial will compare results from the combination of neon ions and chemotherapy against a well-characterized low-LET database for the combination of x-rays and chemotherapy.

Uveal Melanoma Treatment Follow-up Studies. One of the most successful uses of ion therapy has been control of uveal melanoma, an eye tumor that formerly had to be treated by "enucleation," or surgical removal of the eye. Treatment using helium ions began several years ago at the 184-Inch Synchrocyclotron and is being continued at the Bevalac. A local control rate of 97% has been observed over study periods ranging from 3 to 139 months (with a median of 62 months). Tumor control was excellent at all dose levels studied. Overall, 83% of the patients retained the affected eye, and about 40% have regained vision of 20/400 or better. The actuarial survival rate is 80% at 5 years.

Radiobiology and Radiation Biophysics

It was recognized rather early in the study of radiation that different kinds have different degrees of impact on living tissue. More-detailed examinations have shown that this subject has additional layers of subtlety. Not only do ions have different effects than electromagnetic radiation such as gamma rays (corresponding to different mechanisms of energy deposition), but the effectiveness of a given dose depends upon the mass of the ion in ways contrary to previous expectations. Yet another factor that can be examined is the exact effect upon the cell, e.g., damage to DNA, carcinogenesis, and so forth. Because of these issues, the Bevalac is the host of a diverse program in radiation biophysics.

Current research in this area includes the physical characteristics and biological effects of heavy-ion irradiation in the central nervous system and other tissues. Animal models and *in vitro* studies are of primary importance in this research. Considerable progress has been made in understanding the complex interactions among dose-distribution patterns, damage and repair

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of DNA, tissue kinetics, and delayed radiation injury. Also studied are the basic physical and biological characteristics of heavy-charged-particle beams. Some recent highlights are discussed below.

Cancer-Causing Effects of High-LET Ions. One of the ongoing radiation biology programs at the Bevalac examines the likelihood of tumor induction in the Harderian glands* of mice. This model system is used to examine the physical parameters (dose, LET, and fluence) and the biological parameters (cell survival and transformation, hormonal influence, and repair capacity) that affect charged-particle tumor induction. Figure 7-13 shows some preliminary results for tumor prevalence as a function of dose after irradiation with various ions that had LETs ranging from 1.6 to 650 keV/ μm .

Extrapolating from previous knowledge of normal tissue and transformation responses, one would expect the curve of relative biological effectiveness (RBE) versus LET to peak around 190 keV/ μm (i.e., iron at 600 MeV) and then drop off nearly as fast as it had risen. However, it appears from current Bevalac research that there is only a slight dropoff above 190 keV/ μm ; very heavy ions, with their very high linear energy transfer, remain quite carcinogenic, with RBEs between 20 and 30. Note the comparison of the tumor-induction potential of heavy ions to that of low-LET radiation such as the gamma rays given off by cobalt-60. Bevalac experiments using protons will provide RBE data that can be compared on a particle-per-particle basis.

Genetic Damage and Mutagenic Effects. The effectiveness of high-energy ionized particles in the induction of three types of genetic lesions were studied using the nematode *C. elegans*. These gene locations were used to measure dose and fluence response curves. Inactivation cross sections were derived as functions of LET; however, LET alone was not sufficient to account for the observed kinetics.

In other studies, mutational yield was found to be qualitatively different for two human genes: one autosomal gene and one X-linked gene. LET differences in hyperthermic radiosensitization correlated with protein synthesis were seen, but no dose dependence was observed in the oxygen effect in synchronized mammalian cells. (This refutes previously published work and affects theoretical concepts of low-dose radiation responses.) Finally, measurements were made of therapeutic gain for local tumor control and of inhibition of the metastatic spread of tumor by combining cisplatin with high-LET radiation.

Carcinogenic and mutagenic effects of heavy ions were studied for NASA. The effect of energetic protons on cell transformation and mutation were studied to determine the effect of shielding on the energetic iron particles in inducing neoplastic transformation. Methods and techniques for studying radiogenic transformation of human epidermal cells in culture were undertaken. Studies were made of the effects of x rays on cell inactivation and neoplastic transformation, along with molecular mechanisms of neoplastic cell transformation with restriction enzymes.

* The Harderian gland, present in most animals, is found adjacent to the eyeball and is composed of epithelial cells that secrete lipids for lubrication of the eye. To maximize the expression of radiation-induced Harderian tumors, pituitaries from isogenic donors are implanted into irradiated mice; this also reduces the latency period of tumor appearance.

Figure 7-13. These tumor-incidence measurements, made 16 months after irradiation, are among the early results of a Bevalac-based study of heavy-ion carcinogenesis. The study uses an animal model: the Harderian glands of white mice made more susceptible to tumors by pituitary implants. The baseline tumor incidence for the control group is 2.5%; note that the effects of all the heavy ions we studied were at least 100% over baseline at the lowest doses we used. Other radiation-biophysics programs at the Bevalac include studies of genetic damage and mutation.

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Further Applications of Radiation Biophysics Findings

The knowledge gained through radiation biophysics studies is important both as basic science and as background information for those who use radiation as a medical tool. However, it is useful in other fields. One application of particular topical interest is the safety of prolonged space flight, especially beyond the protective influence of the earth's magnetic field.

It has been postulated that, during a three-year interplanetary mission such as a voyage to Mars, up to 30% of the cells in an astronaut's body might be penetrated by highly damaging heavy cosmic rays.* Iron, which is abundant among cosmic rays, might be especially troublesome. For example, its effects stood out in the carcinogenesis studies described above. Further, it is well known that the carcinogenic and mutagenic effects of chronic low-level exposure to radiation are quite different from the effects of acute high-level exposure. The situation is further complicated by the difficulty and expense of carrying shielding material on a space flight. Obviously the biophysical effects of energetic particles ought to be understood more thoroughly before such a mission is undertaken.

* Cosmic rays comprise electrons and a broad mixture of naturally occurring nuclei, some of them quite energetic. In addition to the always-present background level of cosmic rays, an extended manned mission might encounter solar-flare radiation. The bursts of radiation from solar flares are relatively short-lived (several days) but intense.

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