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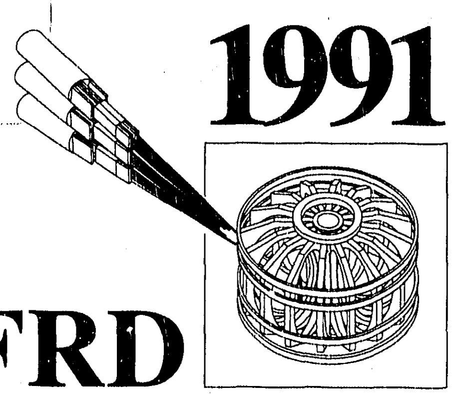

AFRD

accelerator & fusion research division

summary of activities

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

December 1991

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accelerator and fusion research division

1991 Summary of Activities

Lawrence Berkeley Laboratory
University of California
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December 1991

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- Office of High Energy and Nuclear Physics (High Energy Technology Division, Nuclear Physics Division, and High Energy Physics Division).
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- Office of Superconducting Super Collider.

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Contents

Foreword

Nineteen ninety and ninety-one were characterized by further efforts to take advantage of major opportunities. Plans were put forth, jointly with the Chemical Sciences Division, 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 Lawrence Livermore National Laboratory (LLNL) completed a Conceptual Design Report 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 (ITER), and those in heavy-ion inertial-confinement fusion are finalizing the design of the Induction Linac Systems Experiment, the logical next step on their road to a fusion driver. Both ITER and heavy-ion drivers received strong endorsements from the Fusion Policy Advisory Committee.

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 target for 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.

Our program in superconducting magnets continued its progress on two complementary fronts: magnet development for the Superconducting Super Collider and research and development aimed at superconducting materials and magnets for the future. The first prototype of a full-length quadrupole for the SSC collider rings was tested in 1991, and a technology-transfer effort called the Magnet Industrialization Program currently has technical representatives from private industry working alongside LBL personnel to learn how to produce the magnets.

Support from the Department of Energy (DOE) Division of Nuclear Physics for the Bevalac heavy-ion accelerator complex is slated to end after fiscal year 1994; however, the National Aeronautics and Space Administration (NASA) is interested in an extensive, multiyear program to study space effects. We have submitted a proposal to NASA to use the Bevalac's ability to simulate cosmic rays for this program. In another spinoff of Bevalac research and technology development, we have become involved in the early design of a proton-therapy initiative put forth by the University of California-Davis Medical Center.

AFRD researchers were given a number of awards in 1990 and 1991. In 1990, R&D 100 awards— *Research and Development Magazine's* recognition for the year's 100 most significant technical innovations—were won by the inventors of the SXSA-447 Soft-X-Ray Small-Angle Scattering Apparatus (James Underwood, Rupert Perera, and student Dana Berkeland) and of the High-Fluence Laboratory XUV Source (a joint effort with Lawrence Livermore National Laboratory, with Underwood representing LBL). A 1991 R&D 100 award went to the High-Resolution Scanning Photoelectron Microscope; Erik Anderson represented LBL in this project, which also involved the State University of New York at Stony Brook, Brookhaven National Laboratory, and IBM. Alpher A. Garren and Klaus Halbach (an Engineering Division staff member in the employ of AFRD) were named Fellows of the American Physical Society in 1991. Ronald Scanlan was given an Institute of Electrical and Electronics Engineers Accelerator Technology Award, and Glen Lambertson won the U.S. Particle Accelerator School Prize. And in 1990, Andrew Sessler was named to the National Academy of Sciences.

In the midst of these achievements came the Tiger Team Assessment, a comprehensive environment, safety, and health inspection conducted by the DOE. The inspection went on for more than four weeks and preparation for it took several months. In AFRD and in LBL generally, the Tigers found no problems severe enough to shut down any research operations, and they cited the Laboratory's strong management commitment to improvement. We have come a long way in formalizing and strengthening our ES&H activities, and we will continue to incorporate them into our programs.

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. It is with pride and fond memories that I move on to an associate laboratory directorship and leave the Division to acting director Richard A. Gough.

Klaus H. Berkner
Associate Laboratory Director for Operations
December 1991

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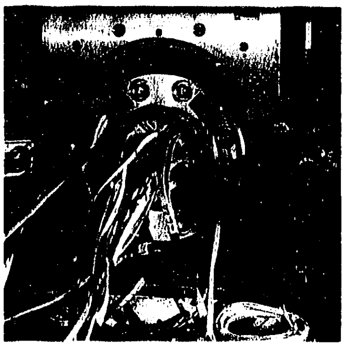
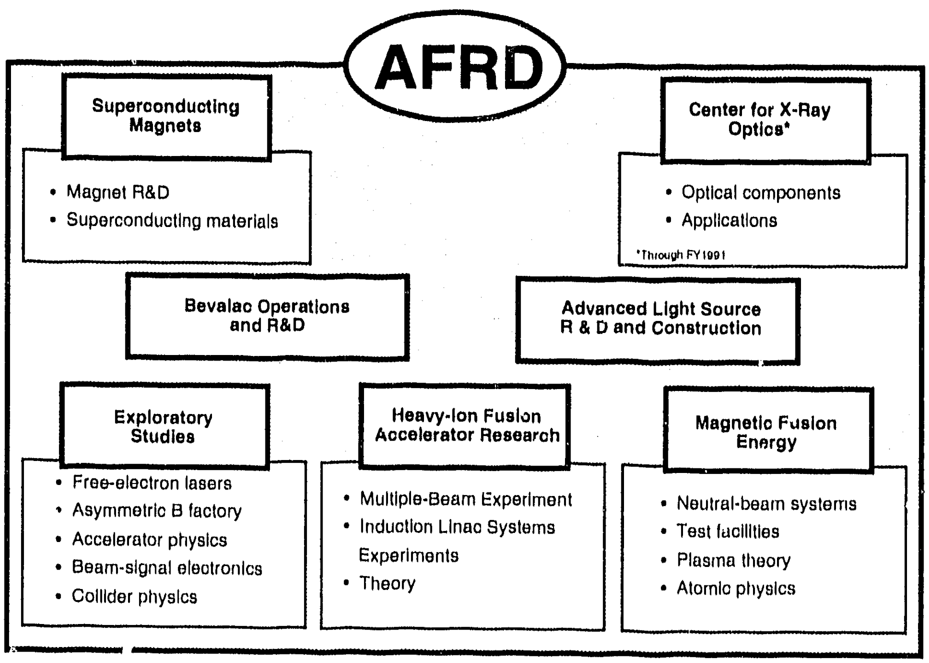


AFRD: DIVERSITY WITH A COMMON THEME

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.



XBL 9112-6884

These efforts share a foundation in 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.

Fusion Energy: Immense Promise and Challenges

As the industrialized world contemplates its dwindling fossil-fuel supplies and 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 would not leave the long-lived, high-level radioactive "ash" associated with fission.* Unfortunately, the only existing large-scale examples of fusion are stars and hydrogen bombs; controlled, self-sustaining fusion on a power-plant scale remains decades away.

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 move fast and collide hard.) 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 occurred. 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 major 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, the standard neutral-beam plasma-heater for U.S. fusion experiments, and released it into commercial production in

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* The neutrons emitted by fusion can activate the materials they strike, including materials in the reactor, 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 a fusion reactor can be made—without reliance on active safety systems or containment buildings—that will not, under any conceivable circumstances, produce radiation approaching lethal levels at the site boundary.
** And, in a 1991 experiment of the Joint European Torus, a deuterium-tritium plasma

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 proof-of-principle accelerator and a test facility for it is being refined by the group.

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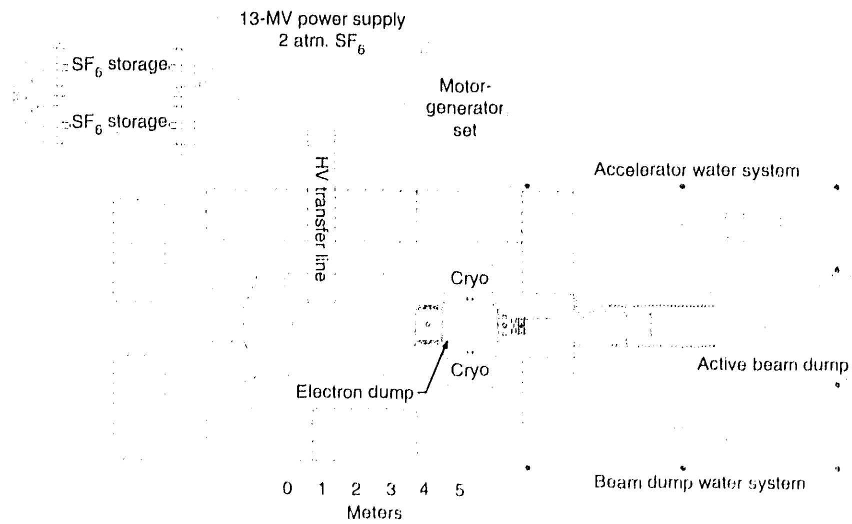

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The HIFAR Group's MBE-4 apparatus and the MFE Group's proposal for a negative-ion accelerator and test facility for ITER neutral-beam injection are among AFRD's recent contributions to the attempt to harness fusion power.

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 for 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 possibilties for using 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. The group recently concluded a multiyear experimental program with MBE-4, a four-beam induction linac designed to provide basic data on beam control from which information useful in the design of a fusion driver can be extrapolated. The next step, now in the engineering design phase, is ILSE, the Induction Linac Systems Experiments. ILSE will contribute further knowledge toward the goal of a full-scale driver.

ALS and CXRO: Seeing the Future in a New Light

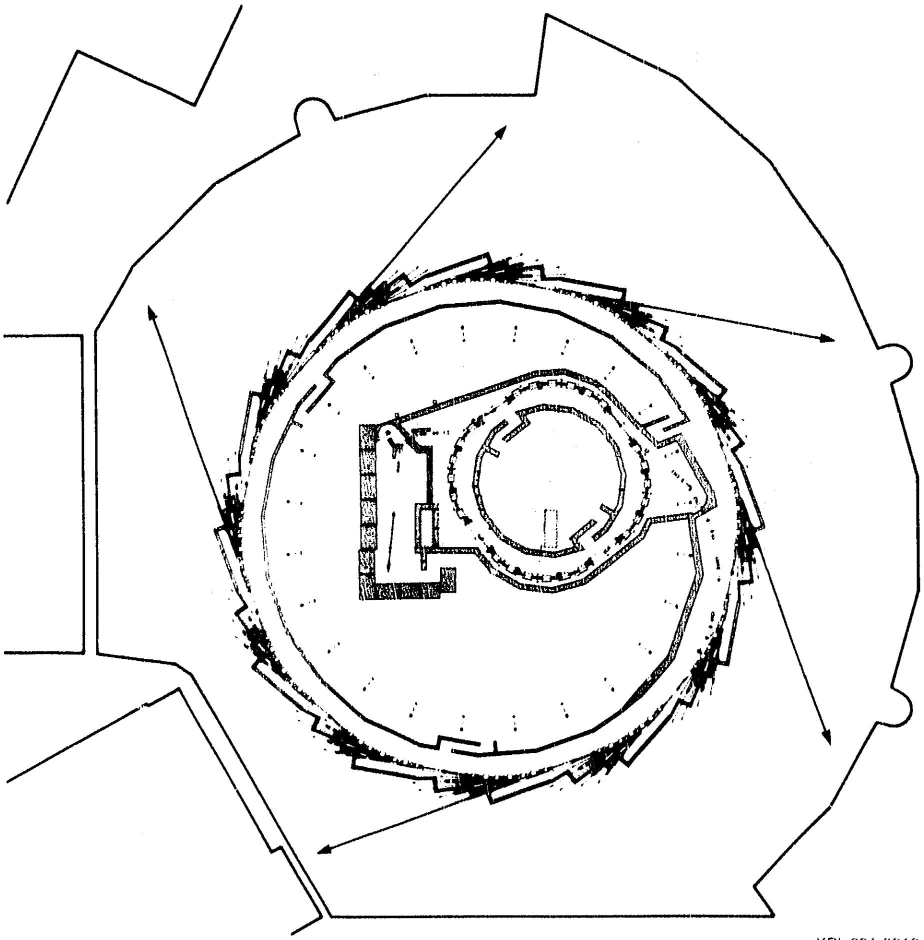
The discovery of the x-ray in 1895 revolutionized not only the work of physicians, but also that of physicists. In two decades of excitement that helped set the stage for today's knowledge of the atom, they studied the interaction of x-rays and matter. The results and the investigators—Roentgen, Compton, 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 qualities other than sheer power: tiny, intense beams, perhaps of just one precise "color," perhaps coherent, almost like a laser beam.

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 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 this radiation "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 devices called "wigglers"

The multiple straight sections in the ALS 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 this Fresnel zone-plate lens whose uses include an award-winning x-ray spectromicroscope.



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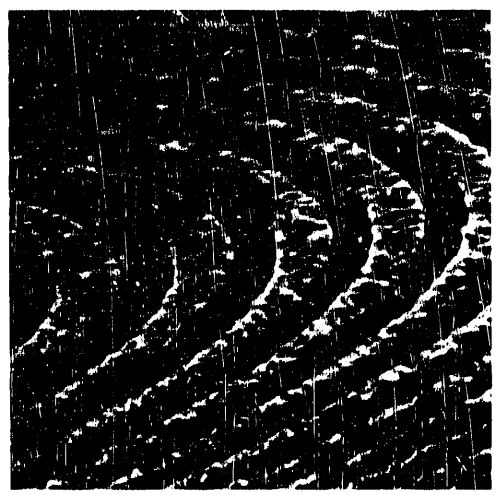

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and "undulators" that could further manipulate an electron beam, producing radiation with selectable characteristics of bandwidth and coherence.

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. By the end of fiscal 1991, the booster synchrotron was being commissioned with rf applied (that is, the beam was being accelerated in it). Meanwhile, work continued on construction of the storage ring and in design and fabrication of insertion devices and beamlines.

One of the organizations eagerly awaiting completion of the ALS 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.

One measure of the Center's success in translating new ideas into practical systems has been its five R&D 100 awards from *Research and Development Magazine*, including two in 1990 and one in 1991. Nineteen ninety-one also saw particular progress in the development of x-ray optical components and detectors.

At the close of fiscal 1991, the CXRO was transferred to LBL's recently formed Materials Sciences Division, where its strengths will complement new and existing research programs. Continuing close ties with AFRD are expected, particularly through use of the ALS. Together, the ALS and the CXRO offer the promise of scientific excellence with which to begin the second century of the x-ray.

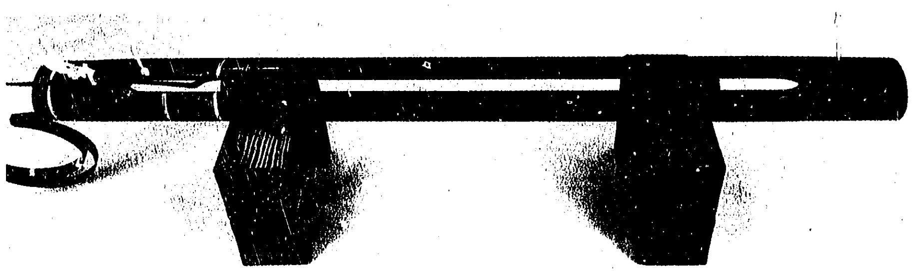
Magnets for the SSC and Beyond

The proposed Superconducting Super Collider, the most ambitious of particle accelerator projects, will have a pair of underground 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 should 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. AFRD's **Superconducting Magnet Group** has 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 the dipole and quadrupole magnets used in the collider-ring lattice.

The magnet-development effort has culminated in testing of full-length collider quadrupole magnets. 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.

Anticipating the need for private industry to mass-produce the SSC's thousands of magnets, we have embarked upon a Magnet Industrialization Program to transfer the technology for building them. Engineers from a consortium of Babcock and Wilcox and Interatom are currently on the LBL site, working alongside us to build collider quadrupoles. Our machine-development program continues, anticipating additional requirements for different cable designs. Meanwhile, we continue exploring the science and technology of superconducting materials and magnets, including not only high-field accelerator magnets but also non-accelerator applications of high-field magnets (such as nuclear magnetic resonance), and new or neglected superconducting materials.



Several laboratories are working to support the magnet R&D needs of the SSC. LBL's current roles include development of the collider quadrupole magnets, such as this partial assembly of a full-scale prototype. The technology for building these magnets is being transferred to the private sector through the Magnet Industrialization Program.

CBB 915-4055

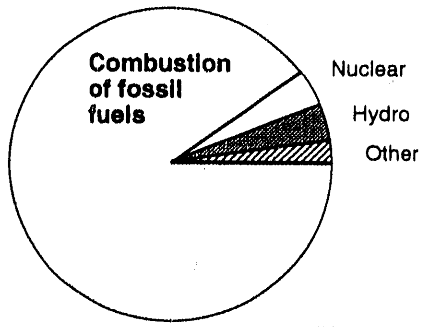
"Nothing Happens Unless First a Dream"

The **Exploratory Studies Group** functions as a key element in several of AFRD's diverse activities, assisting with immediate programmatic needs and—as indicated by the Carl Sandburg quotation at left—also laying foundations for future research. The Chemical Dynamics Research Laboratory, a new initiative designed for synergy with the ALS, continued to be an important area of contribution in 1991. Members of the group continued the detailed design of the heart of the CDRL facilities: an infrared free-electron laser (IRFEL) that features tunability, high power, and fine resolution. By bringing together the IRFEL, undulator and bend-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 Lawrence

Livermore National Laboratory, 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 LBL's Physics Division, will spatially separate 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 charge-parity violation and rare B-meson decays.

U.S. ENERGY CONSUMPTION



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The United States currently gets more than 90% of its total energy from combustion, so even small improvements in combustion efficiency could have tremendous benefits. The proposed CDRL is part of the Combustion Dynamics Initiative, 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 applied work that might ultimately help increase engine efficiency or reduce air pollution.

The **Collider hysics Group** within Exploratory Studies continued collaborating in basic and applied research for the generation of high-energy accelerators beyond the SSC. 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. Other contributions to high-energy accelerators come from members of the **Beam Signal Electronics Group**. Their research emphasizes electromagnetic analysis and various radiofrequency "gymnastics" to ensure proper beam behavior—a set of skills that have contributed to a variety of projects in recent years, including the ALS and the Tevatron, and are now being brought to bear on the B factory.

Promise of a New Era for the Bevalac

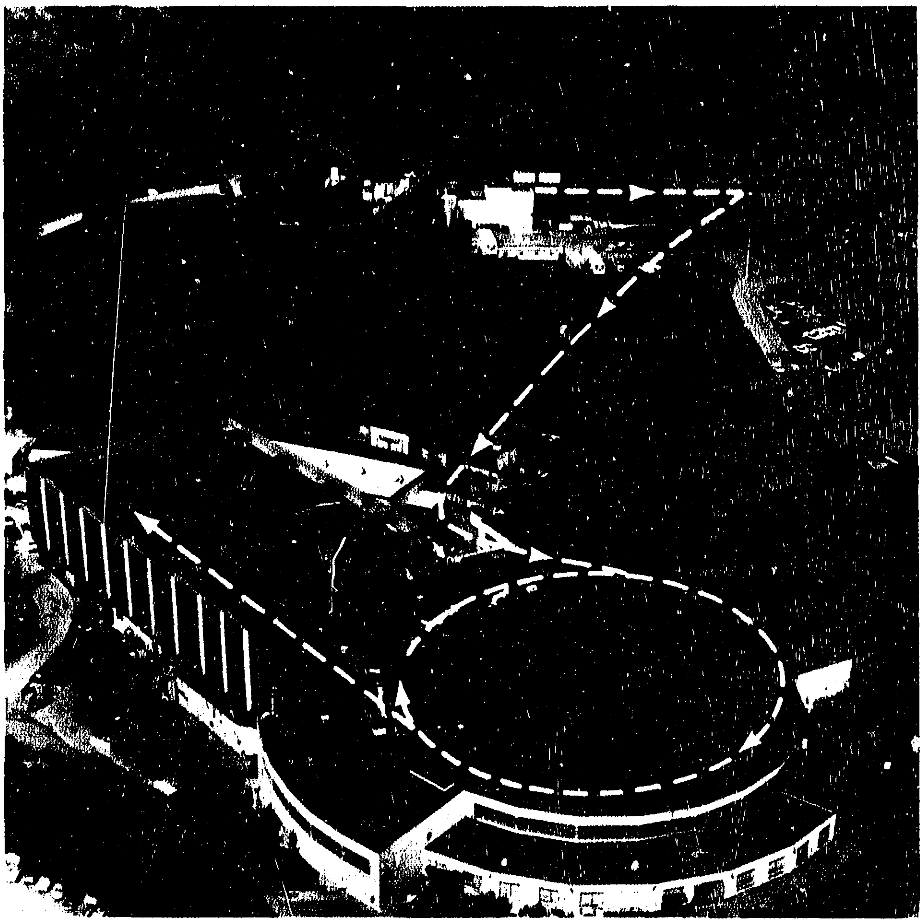
A research complex that has been a centerpiece of LBL facilities for many years remains in demand today: the system of two accelerators known as the Bevalac.

The older of the two, the Bevatron, was the most powerful proton synchrotron of the early 1950s. It was there that Segrè and Chamberlain discovered the antiproton, an achievement that won them the Nobel Prize. 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. 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.

Support of the Bevalac by the Department of Energy's nuclear-science program will be phased out in the mid-1990s. However, based on discussions with the National Aeronautics and Space Administration, we anticipate support for a new program that will use the Bevalac as a "cosmic-ray factory" to evaluate the radiation hazards of interplanetary manned space exploration.

An aerial photograph, with the beam path superimposed, shows how a geographical coincidence inspired a singularly successful idea. The Bevalac's combination of energies and ion species have ensured it a long and scientifically productive life, which, we hope, will continue for at least the next several years as nuclear-science research gives way to space-radiation studies on behalf of NASA.



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HEAVY-ION FUSION ACCELERATOR RESEARCH

EXPERIMENTAL SUCCESSES INDICATE THAT THE TECHNOLOGY being studied by AFRD's Heavy-Ion Fusion Accelerator Research (HIFAR) group—the induction linac—is a prime candidate for further technology development toward the long-range goal of an inertial-confinement fusion driver. The program addresses the generation of high-power, high-brightness beams of heavy ions; the understanding of the scaling laws that apply in this hitherto little-explored physics regime; and the va..uation of new, potentially more economical accelerator strategies. (The economy issue is especially important because an inertial-fusion power plant will have to be a success not only in physics and engineering, but also in commerce.) Key specific elements to be addressed include:

- Fundamental physical limits of transverse and longitudinal beam quality.
- Development of induction modules for accelerators, along with multiple-beam hardware, at reasonable cost.
- Acceleration of multiple beams, merging of the beams, and amplification of current without significant dilution of beam quality.
- Final bunching, transport, and focusing onto a small target.

The experimental program at MBE-4, the Multiple-Beam Experiment, was completed in April 1991. The HIFAR Group is developing a concept called ILSE, the Induction Linac Systems Experiments. ILSE will address

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most of the remaining beam-control and beam-manipulation issues at approximately 1/10 of a driver's scale in several key parameters, such as the number of focusing elements and lattice periods. Moreover, the line charge density and consequently the size of the ILSE beams will be at full driver scale.

A theory group closely integrated with the experimental groups continues to support present-day work and also to look ahead toward larger experiments and the eventual driver. Much of the theory group's effort in both areas during 1990 and 1991 focused on studies of longitudinal instability. The resistive and inductive components of acceleration-module impedances can lead to beam instabilities that would become significant at the high-current end of a driver. Because the heavy ions would be subrelativistic even at the high-energy end of a driver, these longitudinal instabilities would be much more severe than for, say, electron beams. (Most of today's experience base with high currents has been obtained with electron beams. Because of the low mass of the electron, they behave relativistically, and thus become immune to these instabilities, even at low energies.) Therefore, we must learn how to reduce and suppress these instabilities effectively and economically. The theory group has also published a new technique for calculating electric fields in complicated three-dimensional geometries, which agrees well with measurements of the effective length of quadrupoles and the strength of dodecapole fields in MBE-4.

Research with MBE-4

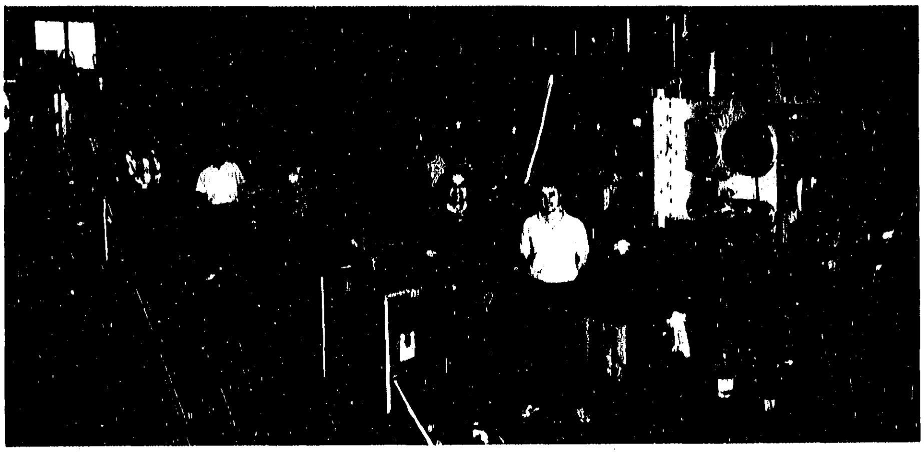
Our group concentrates on the multiple-beam induction linac incorporating current amplification as well as acceleration, a concept that we consider to be a leading candidate for an inertial-fusion driver. The ultimate beam characteristics (including energy, power, pulse length, and various measures of quality such as transverse and longitudinal emittance) are established by the needs of the inertial-fusion target, so it is important to control the lengths of the beam bunches precisely, with minimal degradation, throughout acceleration. The accelerating waveforms must be shaped carefully in order to shorten the bunch length (thus amplifying current) and to control longitudinal space-charge forces. Small errors, especially in the low-energy end of the system, can lead to current spikes and beam spill and/or to unacceptable increases in emittance. The focusing and transport system faces demanding requirements as well; the speed of the beams increases by as much as 20% during the length of a pulse. The six-year MBE-4 program, which concluded in 1991, provided abundant data toward an experimental understanding of these phenomena and constraints.

Selected Highlights of the MBE-4 Program

In MBE-4 (Figure 1-1), 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. Current is amplified by increasing the speed (through acceleration) and the line density of the charged particles. The line charge density is increased through pulse compression, which is achieved by accelerating the rear particles in the bunch more than the front ones.

The parameters of MBE-4 gave beam dynamics similar to those expected in the lower-energy, electrostatic-focusing end of a driver. In the first three years (during which MBE-4 provided useful data even at partial stages of completion), longitudinal beam dynamics and control were studied; in the last three years, using the complete machine, we concentrated on transverse beam control and the study of emittance growth during acceleration.

Figure 1-1. The MBE-4 apparatus, now idle, has supported a highly productive experimental program for the past several years. It has been used to study acceleration of multiple beams in a single induction core, amplification of current through pulse compression, and issues related to transverse and longitudinal emittance.



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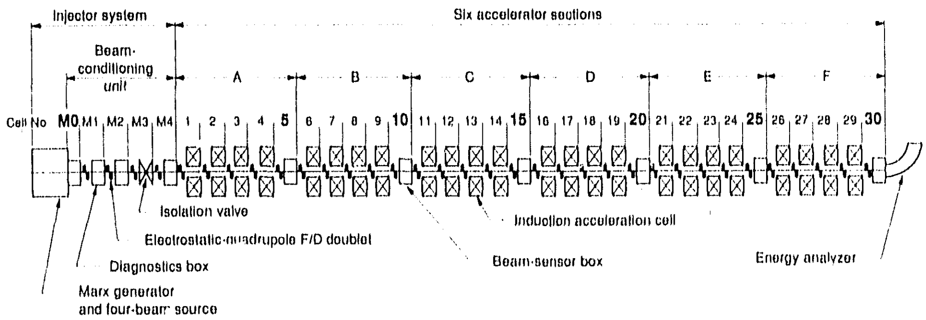

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Longitudinal Beam Dynamics

The charge distribution along the length of a bunch generates a longitudinal electric field that will lengthen the bunch unless the accelerating voltages compensate for it. One of the important results of the MBE-4 effort was the development of a scheme for devising the proper waveforms. This scheme was embodied in a computer program called SLID (Study of Longitudinal Ion Dynamics) and its extended version SLIDE, which accounts for particles overtaking one another during current amplification. SLID was used iteratively during the design of the pulsers. The upstream (low-energy) pulsers were designed according to the ideal waveforms from SLID; then, to compensate for their nonideality, actual measurements were fed into SLID to design subsequent pulsers. Theoretical studies of the effects and propagation of errors were also conducted.

Transverse Beam Dynamics and Current Amplification

The latter parts of the MBE-4 program concentrated on understanding the forces that affect the beam transversely—particularly the problem of accelerating the beam and amplifying its current without spoiling its normalized transverse emittance. In the earlier experiments, we had found that the normalized emittance tended to increase and that measurements varied by as much as twofold over long periods (a matter of months). The transverse-emittance increases appear to be caused in part by improper centering, matching, and alignment. The beam radius is comparable to the aperture, so without care in these matters, the outer portions of the beam may be outside the linear, "good-field" region. There they encounter dodecapole nonlinearities in the focusing fields, and the effect of image charges on the focusing electrodes is also exacerbated.

Studying emittance growth in experiment (and, with excellent qualitative agreement, in simulation), we found that the rms emittance varies rapidly along the length of the accelerator. It appeared to be modulated at a wavelength corresponding to 2.3 lattice periods and also oscillated about the accelerator aperture by 4–5 mm, or nearly 20% of the aperture. These variations were a consequence of a focusing imperfection that kicked the beam off axis, causing it to oscillate back and forth in the transport channel. The most recent experiments have concentrated on carefully matching and centering very "cold" beams in the channel to demonstrate current amplification at constant normalized emittance. As expected, when the beam was properly centered, the normalized emittance was preserved under drift or acceleration.

The Lessons of MBE-4

In conclusion, MBE-4 was both a successful experiment and a harbinger of the work yet to be done. It quickly relieved an initial concern that the multiple beams might interact with each other; this happened only at low energy in the injector, where the beams "see" each other's radial space-charge electric fields for some distance. (At higher energies, magnetic interactions play a stronger role, and some periodic coupling phenomena might conceivably arise.) MBE-4 also showed that current amplification is possible and that longitudinal control can be exerted over the beam by tailoring the pulser waveforms, although pulsers more versatile than the thyratron-based units in MBE-4 will be required.

Preservation of low emittance continues to be an important issue in our experiments and scaling exercises. Acceleration errors can be partially corrected downstream of the point where they occur (the closer the better). Although these corrections contribute to longitudinal emittance, extrapolations from MBE-4 data lead us to believe that this emittance growth might not unduly compromise the final focusing of the beam onto the target. The admittedly long extrapolation to a driver showed a momentum spread ($\Delta p/p$) of 1×10^{-3}, which is considerably better than the 1×10^{-2} limit suggested by theoretical final-focus studies.

Figure 1-2 compares emittance growth in MBE-4, both in experiment and in numerical simulation, under two sets of circumstances. In both cases, the beams injected into the accelerator were very "cold," that is, the initial emittance was near its minimum possible value.* With great care in matching and centering of the beam, we accelerated it without increasing the normalized transverse emittance, the value of which was slightly below 0.03 mm-milliradian. In initial experiments without such painstaking matching and centering, the emittance had increased, but not to a very high value. We are now exploring this phenomenon in longer devices, such as a driver, through numerical simulation and extrapolation.

We speculate that over the length of a driver, emittance will reach an asymptote, hopefully at an acceptable level. Thus a driver might not need the great care we had to take in matching, centering, and alignment; the beams would center and match themselves, and the accompanying increase in emittance may be affordable. Obviously, much more research is needed, especially

* An ion source has a minimum intrinsic emittance determined by the radius of the source and the random thermal energy of the emitted ions.

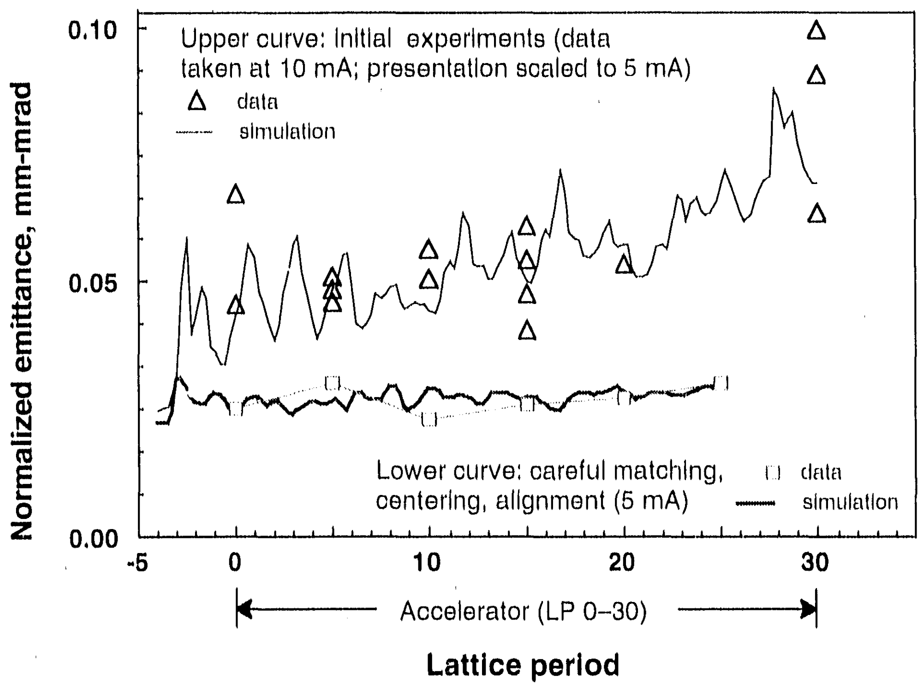

Figure 1-2. Emittance growth in MBE-4 has been extensively studied both in experiments and in numerical simulations. With great care in matching and centering of the beam, we accelerated it without incurring a net increase in the normalized transverse emittance. Without such care, the emittance increased by a factor ranging up to 2×. We are now exploring this phenomenon in longer devices, such as a driver, through numerical simulation and extrapolation.

considering the extent of the extrapolation and the paucity of experimental knowledge about long induction ion linacs. This will be among the issues explored in the additional steps between MBE-4 and a driver.

Induction Linac Systems Experiments

The next logical step on the road to a driver is ILSE, the Induction Linac Systems Experiments. The multi-beam apparatus will provide the first data on several significant capabilities 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.*
- *Magnetic bending of space-charge-dominated ion beams.*
- *Amplifying current by "drift compression."*
- *Focusing ion beams precisely onto a small spot.*

Conceptual studies of the apparatus are in progress, and it will be proposed for a construction start in fiscal year 1994.

ILSE Physics Point Design

The original ILSE conceptual design, published in 1988, called for 16 beams to be accelerated and electrostatically focused, then combined into four beams (thus providing data on a key driver feature). The beams are further accelerated, this time with magnetic focusing—another important driver feature. Then three beams are dumped and the fourth is used for experiments in drift compression and final focus.

In light of the knowledge gained from MBE-4, as well as developments elsewhere in the heavy-ion fusion community, we have begun redesigning

ILSE. The new configuration, shown in Figure 1-3, starts with four beams and combines them into one. This cost-reducing simplification was made possible by the success of MBE-4 and by some prototype assembly work of components for the first ILSE design; multiple-beam induction cores and other components proved to be more straightforward than we had expected. The new configuration is otherwise similar to the original.

The design has been improved in a variety of ways. It takes advantage of recent technology developments, including better Metglas induction-core material, commercially available alignment systems that can achieve 0.001-inch precision, and better control and data-acquisition systems.

The new ILSE also has the same line charge density, in beampipes of the same diameter, as the electrostatically focused section of a postulated driver. ILSE will thus allow us to test this driver parameter at full scale. Other parameters (Table 1-1) are scaled down compared to those of a driver. Another important change that may turn out to be highly relevant to a driver is a set of provisions for recirculating acceleration.

Economic studies of recirculating induction ion accelerators, performed at Lawrence Livermore National Laboratory (LLNL) in collaboration with our group, have indicated that such a driver might be considerably less expensive than the nonrecirculating induction linacs that we have been envisioning. However, much less is known about the physics of recirculating induction ion accelerators. Various schemes are being studied to possibly extend the ILSE sequence of experiments to cover the essentials of the recirculating approach, assuming that theoretical studies confirm the desirability of performing these experiments in ILSE.

The result of the physics design effort, which is still underway, will be a "point design" — a self-consistent design, selected from a broad continuum of possibilities, that best addresses our experimental needs within our funding prospects. Later we plan to prepare a Conceptual Design Report. Construction of the accelerator would start in fiscal 1994 under the current proposal.

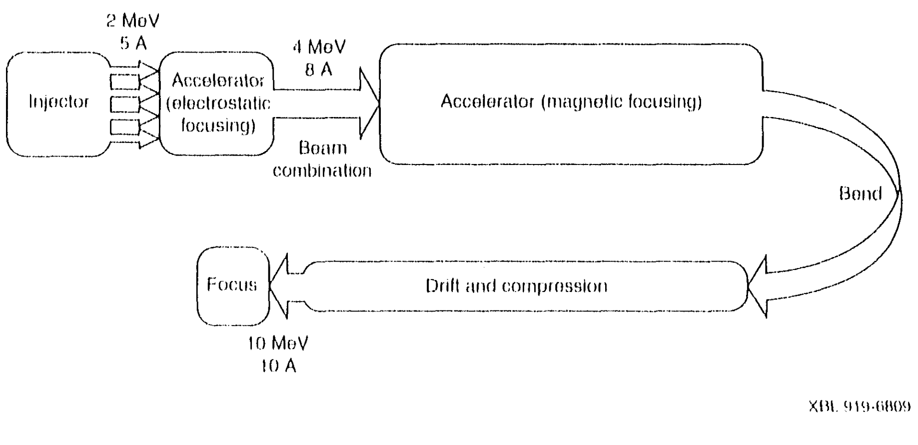

Figure 1-3. ILSE, the Induction Linac Systems Experiments, is the next step in our experimental program. Originally proposed in 1988, ILSE is now being redesigned in anticipation of a construction start in fiscal 1994.

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

	SBTE	MBE-4	ILSE (1988)	ILSE (1991)	Postulated driver
Ion species	Cs^{+}	Cs^{+}	C^{+}	Ne^{+}	Bi^{3+} or Hg^{3+}
Number of beams	1	4	16→4	4→1	64→16
Injection voltage (MV)	0.16	0.2	2	2	3
Final voltage (MV)	0.16	1	10	10	3300
Final current per beam (A)	0.023	0.24	4	10	6000
Final beam energy (J)	0.07	0.08	55	87	3×10^{6}
Final ion velocity/c	0.0016	0.004	0.04	0.03	0.3
Accelerating gradient (MV/m)	n/a	0.07	0.22	0.22	0.8
Bunch length (m)	8.0	1.1→0.25	5.6→4.4	8.8→8.8*	70→10*
Pulse width (µs)	20	2→0.4	1→0.35	2→1	24→0.1

* These pulse lengths are given at the end of the accelerator section. In a driver, drift compression would further shorten the pulse. Note also that smaller, less intense beams can be compressed further.

Meanwhile, the search for an ILSE site continues. The leading candidate, whose dimensional constraints are being assumed in the point design, is Building 58 (Figure 1-4), which currently houses MBE-4 . However, we are also weighing the merits of other possible locations on the LBL grounds.

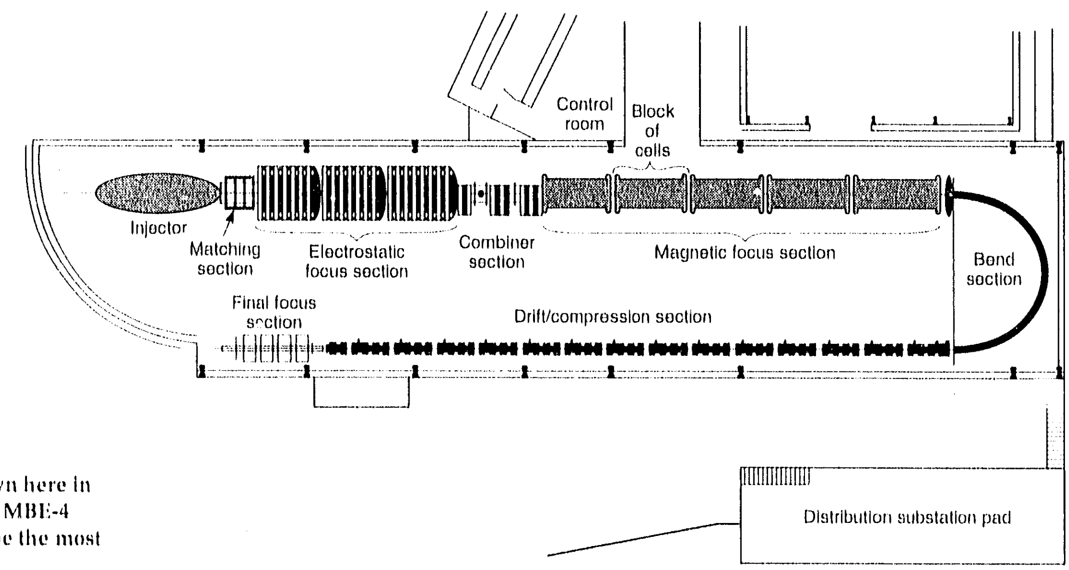

Figure 1-4. ILSE is shown here in Building 58 (the current MBE-4 site), which appears to be the most probable location.

Ion-Source and Injector Development

Until 1991, most of the ILSE ion-source effort concentrated upon a carbon-vacuum-arc device that turned on and came up to full current rapidly, based on a prototype developed by a group from the University of New Mexico. It was used in conjunction with an electrostatic plasma confinement device, or "plasma switch," which allowed beams to be extracted not from the noisy stream of plasma from the cathode spot, but rather from a layer of ions captured by space-charge forces near the grid of the plasma switch. While studying ways to optimize the performance of the carbon-arc source and plasma switch, we used it for tests of the 944-kV first-half column of the 16-beam injector.

The source has also successfully produced long pulses (about 50 μs) at a current of 210–230 mA, which was limited by the extraction geometry used in this test. It was encouraging to see that such long pulses could be transported reliably at the full voltage of the half-column. Despite considerable efforts, though, it appeared that the emittance of this source would exceed ILSE's tolerances. Accordingly, we began R&D on other ion-source approaches.

The new ILSE point design uses a 25-cm-diameter rf-powered source in which the plasma is confined by a multicusp magnetic field, much like the Magnetic Fusion Energy Group sources described in Chapter 2 of the *AFRD Summary of Activities*. The very low ion temperatures reported for these sources should permit development of flexible, low-emittance sources suitable for our needs. The higher line charge density of these beams also supports the goal of modeling some characteristics of a driver. Finally, these sources can provide a variety of ion species, including various noble gases, which is interesting because ILSE can be operated with ion species ranging in mass from carbon to potassium. The choice of ion species is a complex issue (*sidebar*); the physics point design assumes that ILSE will accelerate Ne^+. Backup work on thermionic Cs^+ and K^+ sources is also being continued.

Selecting an Ion

ILSE could accelerate a range of elements at various charge states. Choosing the best one for a particular experiment is subtle and complex.

In ILSE, the capabilities of the magnetic beam-transport section will play a major role in the decision, as they will in subsequent systems. The force that can be exerted by a given magnetic field depends on the velocity, and thus the energy, of the ion beam. The heavier the ion, the bigger and more expensive the accelerator required for a given energy. In ILSE, a 5-MeV beam of an ion species of moderate mass, such as C^+ or Ne^+, will allow approximation of the beam physics of 85-MeV U^+.

Also important are the ease and reliability with which multiampere quantities of the ion can be produced in the desired charge state. The rf-driven sources from the MFE Group readily produce high currents of the gaseous elements with reasonable transverse emittance.

In principle, higher charge states are desirable because they multiply the force that a given electric or magnetic field can exert upon the ion. (The charge of an ion is the "handle" by which it is manipulated.) In practice, however, sources capable of higher charge states tend to put out the lower ones as well. Separating the undesired species does not appear practical for the purposes of ILSE. Another factor, more significant for future experiments than for ILSE, is that the actual beam current is likewise multiplied, possibly crossing into a region of high-current instability for the energy in question.

Subject to these considerations, Ne^+ was chosen for the ILSE physics point design. Ar^+, which, within the ILSE parameters, requires magnetic focusing forces that are stronger by about the square root of two, is also being considered. (The rf-driven ion sources are quite flexible.)

As heavy-ion IFE progresses to target shots, the desired power deposition in the target will become an important factor. The driving beams have to deposit roughly 10^{15} W cm^{-2} in the outer shell of the target over a period of about 10^{-8} s. To achieve the correct combination of power and range, heavier ions need higher energies but correspondingly lower currents, which helps avoid high-current instabilities. Economic considerations also come into play; doubling the current would double the risk of high-current instabilities (and the required strength of the focusing fields) but would also halve the length of the accelerator. Studies indicate that Bi and Hg— probably in a charge state as high as +3, with the +1 and +2 ions magnetically separated—are promising candidates.

Long-Range Research and Development

Although present-day and near-future research programs occupy most of our attention, we also engage in various experimental and conceptual efforts (ourselves and in collaboration with colleagues in the inertial fusion energy community) that look further down the road to a driver.

Model Driver Core

As part of our program to evaluate longitudinal instability at driver parameters, we fabricated a model of an induction-accelerator core at nearly full scale. The model duplicates the rf properties of an actual acceleration module from a driver. Data from these rf studies will be used to validate our computer models of how the ion beam in a driver would react with the accelerating units at frequencies relevant to the longitudinal instabilities. ILSE will not be long enough to fully test these instabilities.

The model core, shown in Figure 1-5, is quite large, with an inner diameter of 1 m and an outer diameter of 2 m. The area between would be filled with ferromagnetic material in a real core. In this model, about 1 out of every 10 cm along the radius is filled with Metglas 2605 CO ferromagnetic tape; the rest is filled with aluminum ducting to maintain the approximate capacitance of a real core. This allows us to test the core at 20 kV rather than 200 kV and also provides a way to probe voltages and currents at various points within.

The Road Ahead

Figure 1-6 shows an artist's conception of an inertial-confinement power plant based on a heavy-ion driver. Obviously this installation will be much larger than the present-day experimental systems. Between ILSE and a driver, at least one intermediate step will be needed, probably at an energy of about 10–100 kJ. This will allow us to understand two key areas of physics that cannot be addressed at a smaller scale.

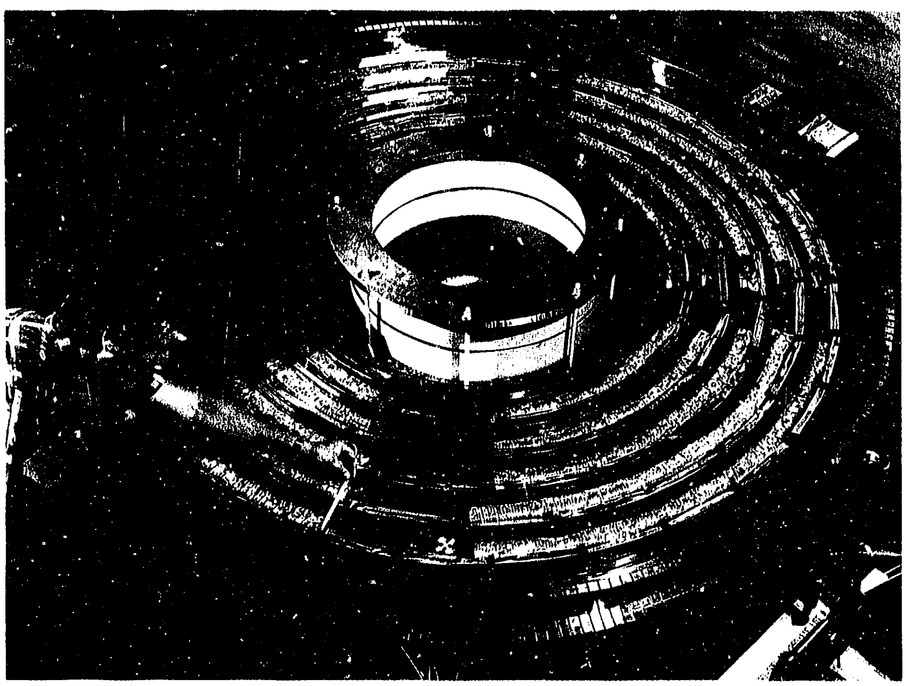

Figure 1-5. In an early look at some characteristics of a driver, we are experimenting with this model of a driver-sized induction core. It is only 10% filled with ferromagnetic material, so we can experiment at about 10% of a driver's voltage. The aluminum ducting helps model the capacitance of a driver core, overcoming the effects of the partial filling.

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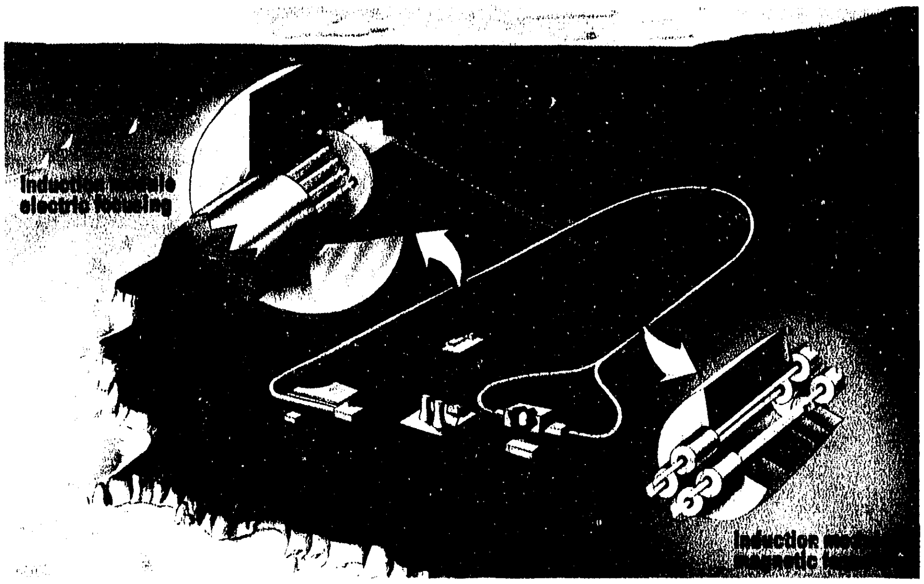

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Figure 1-6. A conceptual drawing shows the scale and some postulated technical details of a power plant that uses heavy-ion induction linacs as drivers for inertial fusion energy. (LLNL illustration)

The first key physics area that would be explored is cost-effective avoidance or control of possible high-current instabilities; such research can be done with good confidence only in an experimental test at this scale. The second key physics area is the interaction of high-power ion beams with a high-temperature, solid-density plasma (at a temperature of approximately 100 eV, as compared with the 200–250 eV needed in a power-plant target).* By proceeding directly from the "front end" of ILSE rather than building the two projects in strict serial order, 10-kJ results could arrive before the year 2000. (The front ends of both machines are similar; the difference comes further downstream, where many more accelerating units are needed to reach 10 kJ.)

It may prove to be prudent to have another experiment at about the 200-kJ level: a few times more energy than is currently produced by the Nova laser at LLNL, but at an accelerator's rate of pulses per second rather than the pulses per day of present laser technology (*sidebar*). This apparatus, which could conduct target experiments at some 200 eV in plasma temperature, would validate the final driver technology at a satisfactorily large scale. From this level onwards, the approach would be to build hardware large enough to re-use as part of a full-scale driver (implying that design work on megajoule heavy-ion facilities should be getting underway).

* The 10-to-100-kJ target will not resemble an actual deuterium-tritium power-plant "pellet," which might be either a one- or two-stage direct-drive ablative target or an indirect-drive target of the currently classified type used in thermonuclear weapons. Thus the research could be conducted in an open environment. ILSE will be a beam-manipulation apparatus that will not involve a pellet.

Meanwhile, research in other areas will have begun at other laboratories. The critical technologies of inertial-confinement fusion—driver, target pellet, mass-production pellet factory, and reactor—are all equally necessary, like the four legs of a stool. There has been strong support in major review committees for a facility that would use 1– to 2–MJ lasers to explore pellet-implosion physics in the ignition regine with significant gain. Preliminary planning for such a facility is beginning at several DOE laboratories.

Reactor ideas have also been investigated at several laboratories and industrial firms worldwide. It would be appropriate to begin their further development in earnest as the pellet-implosion results become available.

The decision point for extending driver development to the megajoule level is at least 15 years in the future, and will depend on two main factors: results from the target experiments and the national need to move forward to the Engineering Test Reactor (ETR). The ETR would bring together the essential new pieces of an ICF power plant: the reaction chamber from the new reactor-studies program; targets designed in the LMF program and mass-produced in the pellet factory; and heavy-ion driver experience from the 10-kJ-plus test facilities. We define the ETR as a full-scale test of everything involved in a reactor except conversion of fusion energy into electricity and recovery of tritium. Given adequate support, the ETR could be operational in the 2015-2020 period.

Driver Candidates

There are a variety of ways to "drive" a deuterium-tritium target, or impart sufficient energy to it (about 10^{15} W) to cause fusion. LBL is investigating one of these approaches—the heavy-ion induction linac. Other laboratories are studying and experimenting with lasers and beams of lighter ions (to date, ranging from protons through lithium), and the German laboratory GSI is pursuing rf-accelerator options for heavy-ion drivers. The requirements for a driver are quite stringent; they include

- Power.
- Repetition rate (a few pulses per second, mandated by the thermal equilibrium of the reactor chamber).
- Shot-to-shot reliability combined with long lifetime.
- And, because a power plant must have a very substantial net output, efficiency.

Lasers, such as Nova at LLNL, have been investigated for some time in the context of inertial-confinement fusion. Glass lasers like Nova can be made quite powerful, but presently have low repetition rates because of the time needed for the glass to cool between "shots." The cooling restriction may be less severe for gas lasers. However, like glass lasers, they are currently only a few percent efficient, whereas heavy-ion drivers are projected to achieve operating efficiencies of 30% or more.

For an economical power plant, the product of driver efficiency and target gain will have to be greater than 10. Because target gain (the ratio of reaction energy to driving energy) is expected to be on the order of 100, driver efficiency is a stringent criterion. Lasers definitely have a place in inertial-confinement fusion and in defense research as the most-advanced drivers for target experiments, but their candidacy as power-plant drivers will remain uncertain until the efficiency and repetition-rate issues are resolved.

Light-ion diode accelerators are also being studied for this purpose, notably at Sandia National Laboratories. The disadvantage of light ions is that much greater beam current is needed to achieve sufficient power at the proper energy. The proper energy, in turn, is a function of the necessary range of target penetration. For heavy ions, the energy is higher (a few GeV versus tens of MeV) but should nonetheless be attainable. The beam current, a more troublesome parameter, is lower for heavy ions (kA versus MA), suggesting that collective effects might be much less severe. Both the Fusion Policy Advisory Committee and a National Academy of Sciences panel have recommended that the heavy-ion approach be developed further.

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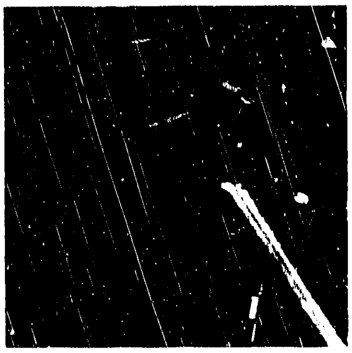

2. MAGNETIC FUSION ENERGY

THE PROPOSED INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR, or ITER, is the next logical step in the worldwide magnetic-confinement fusion program. Its goals include "ignition" of the plasma and self-sustaining "burn" for as long as two weeks at a time. Since 1988, the major portion of our Department of Energy-funded work has been directed toward this ambitious project. In 1990 and 1991, we continued refining our design for a prototype neutral-beam injection system for ITER and our proposal to build a test facility capable of accommodating a 1.3-MV negative-ion system at currents of 1 A or better. We have also continued development of ion sources and accelerators.

Our expertise in these areas is not limited to fusion research; activities have been diversified considerably during the past few years. Ion sources and accelerators have industrial uses such as ion implantation for semiconductor processing and metal surface hardening. Our program also has an academic component centering on advanced plasma theory.

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Neutral-Beam Injection for ITER

Heating a plasma to thermonuclear temperatures is one of the many significant challenges in fusion-energy research. The primary focus of the MFE Group at LBL is development of neutral-beam injector systems for this purpose. The group's 20 years of work in this field 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). It is used in the Tokamak Fusion Test Reactor (TFTR) at Princeton and the D-IIID tokamak at General Atomics, two of the principal MFE experiments now running in the U.S.

The CLPS has been highly successful, but its positive-ion approach to neutral-beam production 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. Accordingly, we 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 here and at several other laboratories.*

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.

After our design and testing efforts, production of ITER's complement of full-scale neutral-beam modules would be handled by private industry, as with the CLPS.

Neutral-Beam Test Facility Initiative

In ITER, neutral deuterium beams with a total power of about 75 MW will be injected to heat the plasma and to drive the toroidal current in the center of the plasma during steady-state operation, as shown in Figures 2-1 and 2-2 and explained in the sidebar. The energy needed to ensure the required plasma penetration, 1.3 MeV, is an order of magnitude greater than that of the CLPS. Beam steering is another necessary feature, as is steady-state operation for as long as two weeks. This combination of energy, current, and pulse length has never been achieved; further, the plasma generator and accelerator must be compatible. To meet these needs, we are proposing a neutral-beam injection system based on negative-ion sources and our constant-current, variable-voltage (CCVV) electrostatic accelerator design. A basic design is in place and is being refined in the course of extensive, ongoing interaction with our fellow participants in the ITER Engineering Design Activity.**

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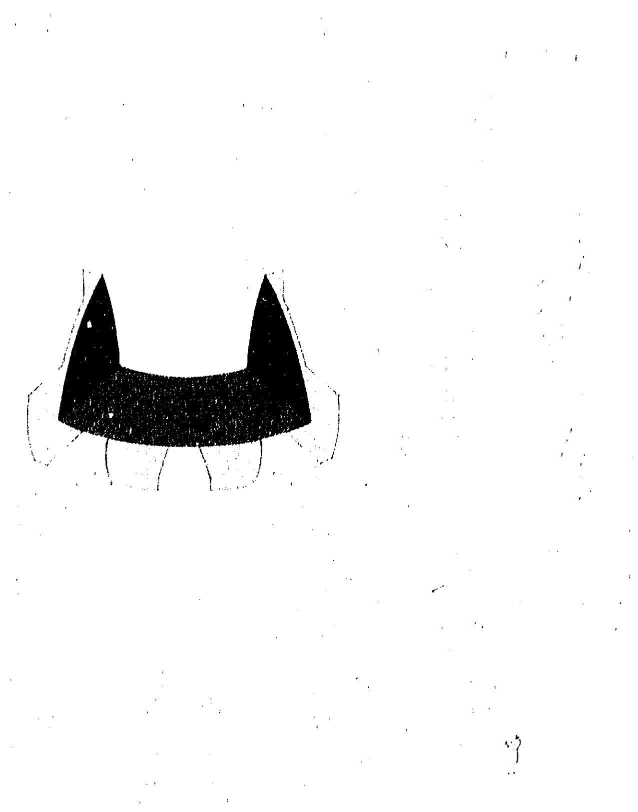
* Positive ions could be accelerated just as well at higher energies. The problem is in the neutralizer, where the desired effect, electron capture, is outweighed by the increasing probability of restripping.

** The other three ITER partners (the European Communities, the USSR, and Japan) are examining variations of a different electrostatic accelerator technology that uses electrostatic weak focusing for space-charge control and magnetic fields for secondary-particle control. Because of the risk and the tight deadline, the ITER R&D plan calls for concurrent development of both approaches.

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" *(right)* compares in size to that of the Tokamak Fusion Test Reactor now running at the Princeton Plasma Physics Laboratory. *(above)* (After PPPL and LLNL artwork.)



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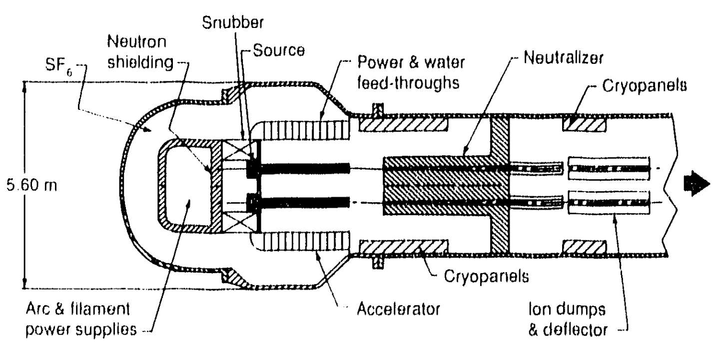

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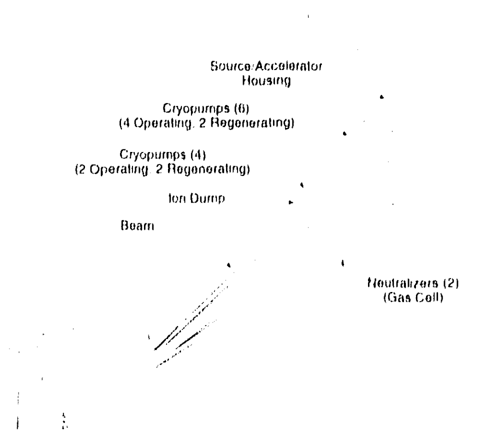

Figure 2-2. The ITER conceptual design calls for three stacks of three 1.3-MeV neutral-beam injector modules providing a total of 75 MW. Each injector can provide 10 MW, so ITER can continue to operate if one of them is down for repair or modification. The performance specifications are ambitious, especially 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.)

XBL 908-5558

After several years, development of the experimental CCVV accelerator has turned increasingly toward the ITER initiative. After pre-acceleration of the beam to 250 kV, a short matching stage focuses the beam and accelerates it to 300 kV; then each acceleration stage increases the beam energy by as much as 250 keV. The acceleration stages use electrostatic quadrupoles for focusing. The proposed LBL proof-of-principle test for the ITER accelerator design is shown in Figure 2-3. The hardware will be built at an existing site, suitably modified, within the Bevatron accelerator complex. This is already a controlled-access radiation area, and features such as enclosed floor space, a large overhead crane, adequate utilities, and concrete shielding blocks are available.

The goal of the test is to accelerate 1.4 A of H^- to 1.3 MeV for two seconds. This test will represent a single channel of the accelerator portion of the actual multichannel accelerator module for ITER neutral-beam injection. Each of the 16-channel ITER beam modules will also also include a beam neutralizer and ion-beam dumps. The system must provide a 1.3-MeV D^0 beam that would have a current of 7.7 A if charged.

An important objective of this effort is the transfer of technology to U.S. industry. According to the ITER R&D Plan, the two accelerator designs—ours and that of the other ITER partners—will undergo proof-of-principle tests. The design that is selected will be incorporated in a Scalable Model Beamline Demonstration, which will deliver two-week-long D^0 pulses at the full energy and about one-fourth the power of an ITER neutral-beam module. Our proof-of-principle test is expected to include industrial involvement so that potential bidders in the private sector can ramp up toward the Scalable Model Beamline test and the actual ITER systems.

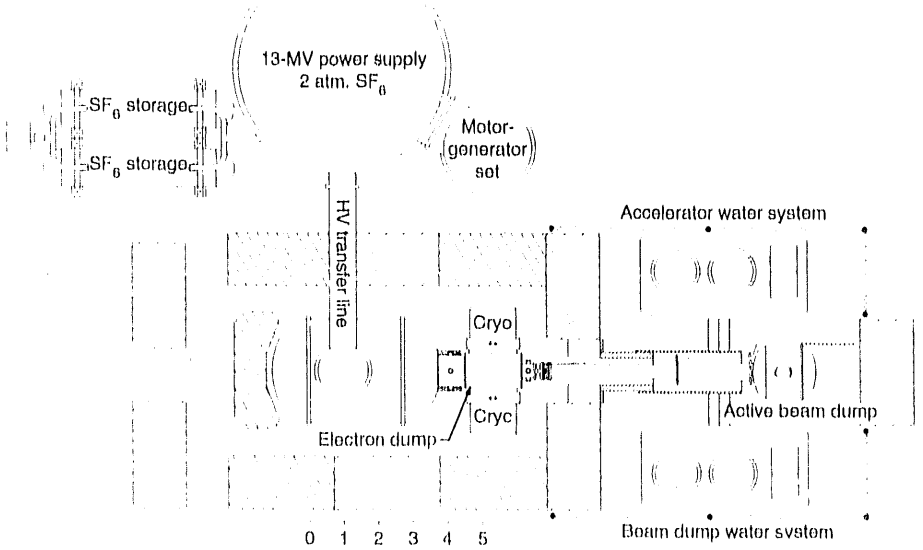

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Figure 2-3. The goal of the LBL proof-of-principle test is to accelerate 1.4 A of H^- to 1.3 MeV for two seconds in this proposed facility, which could be built in the Bevalac complex. This test will represent a single channel of the accelerator portion of the actual multi-channel accelerator module for ITER neutral-beam injection. Each ITER neutral-beam module will also include a beam neutralizer. It must provide a 1.3-MeV D^0 beam that would have a current of 7.7 A if charged.

CCVV Accelerator with ESQ Focusing

The CCVV accelerator concept is at the heart of our ITER neutral-beam initiative. Thus far we have successfully tested the two-module prototype at energies as high as the design maximum of 200 keV and a current of 100 mA of He^+ in pulses of 1 s. This is equivalent in space-charge effects to the design's operating point, 140 mA of D^-. (This performance significantly exceeds the best 1989 measurement: 42 mA of H^- accelerated to an energy of 200 keV for 200 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.

For ITER neutral-beam-injection applications, a CCVV accelerator needs to have an energy range of 2:1. The output beam energy may be varied by tuning the acceleration voltages and the ESQ focusing voltages; this may be performed rapidly without altering the accelerator's mechanical configuration. Because the electrostatic quadrupoles provide strong focusing (as contrasted with designs that depend on the accelerating electrodes for weak focusing), the energy can be varied without requiring a change in the current. The average accelerating gradient can be kept as low as 3–5 kV/cm to reduce the chance of high-voltage insulation breakdown. Another advantage is that the transverse electric fields sweep away electrons at a mean energy of 64 kV (in the ITER design), minimizing x-ray hazards. Secondary positive ions are similarly swept away.

Figure 2-4 shows the proposed accelerator in schematic form. This new accelerator will have quadrupole units approximately 2.5 times larger in length and diameter than the unit described in the 1989 *AFRD Summary of Activities*, but will use approximately the same field strength. Thus it will achieve an acceleration of 250 keV per module, reaching the final beam energy of 1.3 MeV with only four stages, given a 300-keV pre-accelerated input beam.

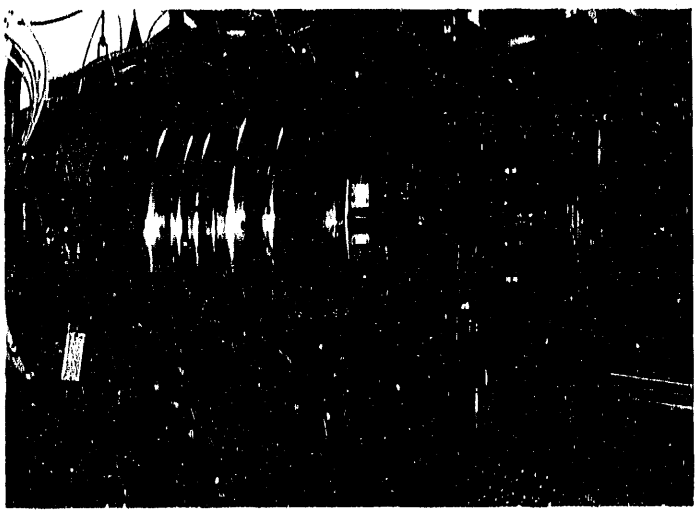

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Figure 2-4. The accelerator that would be used for the ITER proof-of-principle test is a CCVV accelerator with ESQ focusing, shown here in schematic form. It is a scaled-up version of one we have been working with since 1987 (*photo*) with quadrupole units approximately 2.5 times larger in length and diameter.

Electrostatic LEBT for High-Energy Accelerators

An electrostatic low-energy beam transport system, or LEBT—a spinoff from our CCVV accelerator research—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) showed that the system is noise-free and stable and that it 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 could be reduced to one or two simple electrostatic ring lenses.

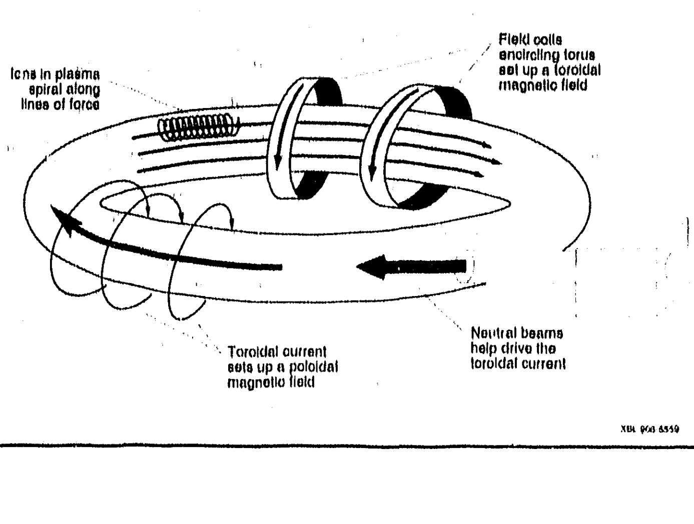
Since the demonstration of the electrostatic LEBT, we have pursued various lines of inquiry to make the design of such devices easier. We have derived simple analytic formulas to replace the complicated Courant-Snyder matrix system in determining various aspects of beam behavior. We have also derived improved envelope equations and incorporated them into a new modeling code, a beam envelope code called ESQACL. This code provides the option of using actual field maps along the beam axis and is designed to interact with a three-dimensional Poisson solver and particle code such as ARGUS.

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: a toroidal field in the plane of the torus and a poloidal field wrapped around it, as shown below.

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-phase experiments 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 50 MW of rf power will drive the current around the edge of the plasma.



Ion Sources

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 neutral-beam injection 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. A second 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 surface-conversion sources for very-long-pulse operation.

Volume and Surface-Conversion Sources

In volume-production sources, gas-phase reactions, as opposed to electron capture on a metal surface, play a major role in forming H^- ions. However, there is evidence that surface processes at the discharge-chamber walls are also significant (*sidebar*). In 1990 we demonstrated that H^- formation in our small multicusp source could be substantially enhanced by seeding the plasma with barium or by placing a barium washer at the extraction aper-

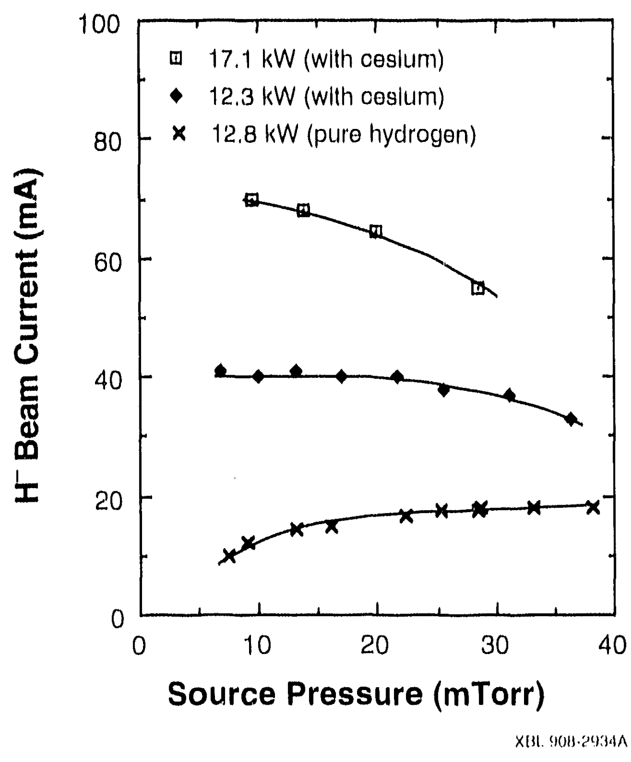


Figure 2-5. One of our volume-production sources, operated with cesium, has achieved a current of 75 mA, at a current density of 48.7 mA/cm², at the extraction aperture in a 270-ms pulse. (The plot does not show the 75-mA datum.)

ture.* The washer and plasma electrode were electrically isolated from the source chamber so that we could bias them at various voltages. The results clearly indicate an enhancement of the H^- signal; the enhancement process is production of H^- on the surface of the barium washer.

As shown in Figure 2-5, one of our volume-production sources, operated with cesium, achieved a current of 75 mA (current density of 48.7 mA/cm^2) at the extraction aperture in a 270-ms pulse. This was a considerable achievement for long-pulse operation of large-aperture sources. Future investigations will include reducing warmup time, reducing cesium consumption (or substitution of a more benign yet equally effective material), and increasing the current density in a way that is relatively uniform across the extraction aperture.

In our ongoing work with surface-conversion sources, we have found that the production of ions at a barium converter depends heavily upon the geometry of the plasma generator. We are now testing a new source that has an annular plasma generator with the intent of optimizing the uniformity and quality of the plasma delivered to the converter. This source is designed to produce 200 mA of D^- in the steady state.

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 the two methods diverge at the level of basic chemical physics.

In surface conversion, a negatively charged element (either a coated converter/cathode or a separate, coated converter element) draws positively charged ions from the plasma. Some of them are back-scattered, 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 the adsorbed atoms out of the surface; the atoms that are sputtered out can emerge as negative ions.

The sheath of positive ions that surrounds 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) $H_2\,(v'' \geq 6) + e^- \,(\approx 1\text{ eV}) \rightarrow H^0\,(v'' \geq 6) + H^-$

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

RF-Driven H^- Source

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 porcelain-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 designs. The antenna's long-term survivability in the plasma has been demonstrated; the porcelain-coated antenna can maintain a clean plasma in continuous operation for a week or more. This is an attractive feature in high-power, steady-state applications. The rf energy sets up an oscillating magnetic field, which, in turn, produces an electric field.

Since our work with it began in 1989, we have made continuing improvements in our rf-driven H^- source. A unit has been developed, under contract to AccSys Technologies, for calibration of detectors at the Superconducting Super Collider. Another is being developed for use in the SSC's

* These are two fundamentally different approaches. The "seed" pellets of barium are placed in the bottom of the source; they are consumed in the discharge and the barium becomes a component of the plasma. The washer, on the other hand, acts as a conversion surface.

Figure 2-6. We recently succeeded in using a nitrogen-laser photocathode system to start the rf-driven H^- source. This scheme will enable us to eliminate the tungsten filament, which has a limited lifetime and contributes impurities to the plasma.

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injection system, either as a backup for a more-conventional H^- source or, possibly, as the primary injection source.

The rf-driven H^- source needs a supply of electrons to ensure reliable plasma breakdown when the rf is applied. Traditionally, the electrons have been provided by a small filament. We recently succeeded in using a photocathode system to trigger the rf-driven source. In this set-up, shown in Figure 2-6, a beam of light from a nitrogen laser illuminated the cathode surface through a small window in the back flange of the ion source. When using magnesium as the photocathode, we found that the photoemission current was large enough to start a discharge in either hydrogen or argon. This photocathode scheme will enable us to eliminate the tungsten filament, which has a limited lifetime and contributes impurities to the plasma.

As part of a study of the H^- production mechanism in rf plasmas, we measured the electron energy distribution. Langmuir-probe samplings taken at different phases of the rf cycle indicate that the electron density does not vary significantly during the cycle.

Cyclotron Mass Spectrometer

In collaboration with LBL's Physics Division, we recently began development of a compact axial-injection research cyclotron based on permanent magnets rather than the usual electromagnets. The new instrument will be used for ultrasensitive accelerator mass spectrometry, replacing the bulky, cumbersome, and much more expensive van de Graaff generators usually employed for this purpose. With its combination of sensitivity and small size—it will be portable, though not in the sense of being carried by hand—the system will have the potential for great practical benefit. For example, exhausts and effluents could be checked for minute quantities of hazardous materials. Moreover, the instrument's predicted sensitivity will allow detection of tiny tracer concentrations of ^{14}C, opening the door to many potential applications in environmental science, biomedical research, and archeology. To facilitate ^{14}C tracer work, the effort also encompasses optimization of a ion source that uses gaseous CO or CO_2 rather than sputtering of solid graphite.

Materials Modification and Synthesis

The performance, durability, and economic attractiveness of today's high-technology products are often predicated upon specialized materials and upon effective, affordable techniques for manufacturing them. A branch of the MFE Group, in close interdisciplinary collaboration with colleagues from LBL and elsewhere, investigates plasma and ion-beam techniques for modifying and synthesizing materials. The program has three parts: development of the Metal Vapor Vacuum Arc (Mevva) ion source, research on techniques for depositing metallic thin films and multilayers using metal-plasma guns, and attempts to deposit industrially useful diamond coatings on surfaces.

Mevva Development and "Mini-Programs"

In 1990 and 1991 we continued development of the fifth version of the Metal Vapor Vacuum Arc ion source (Mevva V, shown in Figure 2-7), characterizing its output and integrating it fully into our activities. The Mevva program comprises three parallel components: ion-source development, ion-beam characterization, and ion-implantation research. Mevva V, built in 1989, is designed specifically for implanting ions in the surfaces of metals. The features of this pulsed source include high current (more than 1 A at peak), broad extracted beam area (10 cm diameter), and, with the 18-cathode "Gatling gun," easy switching from one ion species to another.

The major challenge ahead is development of a direct-current (continuous-beam) Mevva ion source. This requires not only a dc version of the plasma arc itself, but also an extraction area of unusually large cross section to accommodate the high-power beam. Thus far, we have demonstrated dc production of a metal plasma with ion currents as high as 6 A at the extractor location. A 600-mA, 20-keV dc beam of Ti has been produced using an 18-cm-diameter extractor, and a 10-A, 100-keV pulsed beam of Ti has been formed with a 50-cm-diameter extractor (Figure 2-8). Our goal is to integrate these technologies, producing a dc beam with the very large extractor.

The Mevva V test stand has evolved into what may be considered a complete "Mevva ion implantation facility." Ions of 49 different elements have been used, and the effectiveness of the Mevva technology for high-dose metal-ion implantation has been successfully and thoroughly demonstrated.

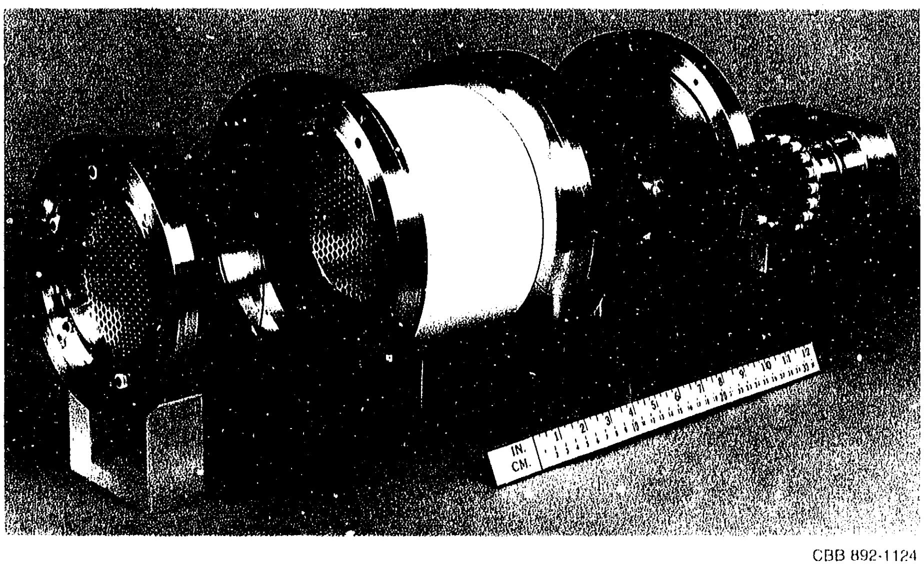

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Figure 2-7. The Mevva V ion source was designed specifically for ion implantation. It incorporates a broad-beam extractor (10 cm in diameter) and a multiple cathode assembly (18 separate cathodes). The "Gatling gun" cathode array, like the Mevva concept itself, is a fairly direct spinoff from injector research and development for the SuperHILAC heavy-ion linear accelerator.

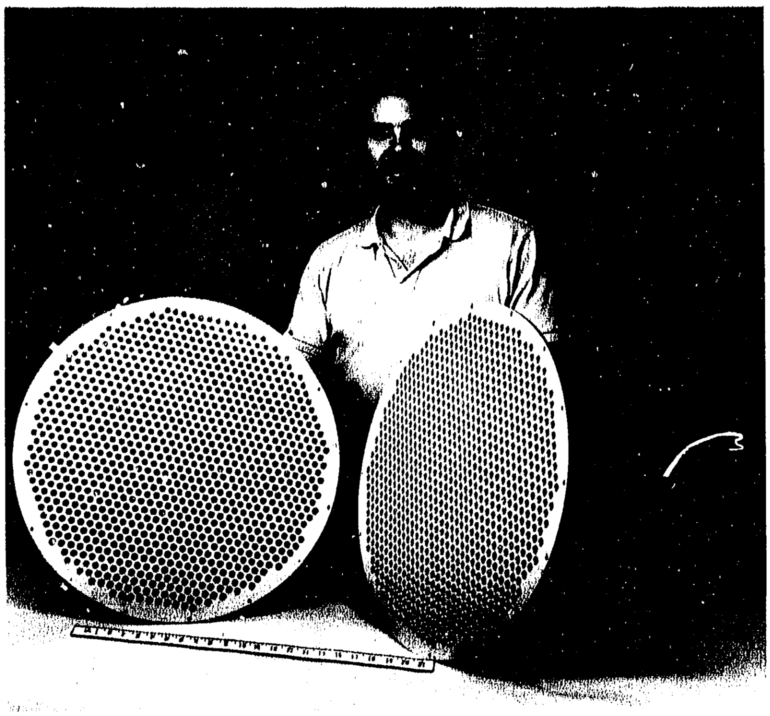

Figure 2-8. This set of 50-cm-diameter beam-formation electrodes was used to produce a 10-A, 100-keV beam of Ti ions.

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We have carried out a wide range of ion-implantation "mini-programs" to demonstrate its applications. Recent additions to our program of collaborative investigations include tribology (the study of frictional characteristics), anomalously deep penetration into a metallic surface, corrosion resistance, and hydrogen embrittlement.

Metallic Thin Films and Multilayers

A new part of our research program, recently funded by the DOE Office of Basic Energy Sciences, will further the applications of our pulsed-metal-plasma-gun technique for fabricating metallic superlattices, multilayers, and thin films—items interesting both for fundamental science and for applications. Multilayers will be synthesized that are relevant to x-ray optics and to magnetic and magneto-optical recording media. Fabrication of thin films of high-temperature superconductors will also be investigated. Our program, in collaboration with materials scientists at LBL and elsewhere, will apply the technique in these three fields. This fabrication technique is new and has not yet been explored except in our preliminary testing.

Diamond Synthesis

Along with LBL's Materials 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. We are now able to grow uniform films of high purity and good crystallinity on substrates of silicon and silicon nitride 1 inch in diameter. The next step is to investigate 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.

Plasma Theory and Nonlinear Dynamics

The MFE Group at LBL maintains a plasma-theory branch operating in the borderland where physics blends into mathematics. Their 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.

Wave Dynamics and Gyroresonant Energy Absorption

The immediate purpose of this work is to understand heating and transport in plasmas—in particular, gyroresonant absorption of energy. Ion cyclotron range of frequency (ICRF) heating, one of the important 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 matches 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. We have obtained the first completely explicit, analytic formula for the conversion coefficient of a magnetosonic wave into an ion Bernstein wave, and also for collisionless absorption associated with the passage of a magnetosonic wave across a minority-ion gyroresonance layer. These results, based on a slab model, agree well with numerical approximations that came from solving the wave equations on a computer. The next step in this research is to treat realistic tokamak geometries.

Working with realistic tokamak geometries, we have come up with the first analytic solution to the reflection problem. In this work, we studied the interaction and propagation of ballistic waves as the mechanism by which magnetosonic waves are reflected by the gyroresonant layer.

The systematic treatment of guiding-center and oscillation-center plasma dynamics by Lie transform methods has been extended from the Hamiltonian Vlasov equation to irreversible kinetic equations describing collisions or other statistical effects. And the linearized Vlasov-Maxwell system, heretofore treated as non-self-adjoint, has been shown to have a Hermitian structure in a Hilbert space with indefinite metric.

A new formulation of wave propagation for multicomponent fields has led to significant corrections to the Bohr-Sommerfeld quantization condition for eigenmodes. This work has applications wherever the Bohr-Sommerfeld quantization condition applies, including not only confined plasmas but also molecular and nuclear structure. In this work, the use of Gutzwiller trace formulas in quantum chaos is interpreted in terms of the geometry of Lagrangian manifolds, leading to deeper understanding and simpler derivations. Because most real systems have some symmetry (leading to conservation laws), the Gutzwiller trace formula has also been generalized to deal with symmetry.

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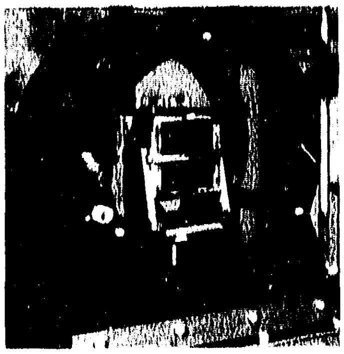

3.

ADVANCED LIGHT SOURCE

THE ADVANCED LIGHT SOURCE, bellwether of the third generation of synchrotron-radiation sources, continues its progress toward the expected spring 1993 startup. Construction of the building is complete. The technical systems continued their steady course through prototyping, ordering, manufacturing, inspection, and, in many cases, installation and commissioning.

The scientific program continued taking shape as well. The major emphasis is on creating a "user-friendly" research environment and on being ready to perform research from the first day of operation. The high brightness of the ALS beams will enable forefront research in a variety of scientific disciplines.

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As Figure 3-1 shows, the ALS consists of an electron source, a linear accelerator, a booster synchrotron, and a low-emittance storage ring. 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 bend magnets, which also produce synchrotron radiation. Of these, 24 will be available for initial development.

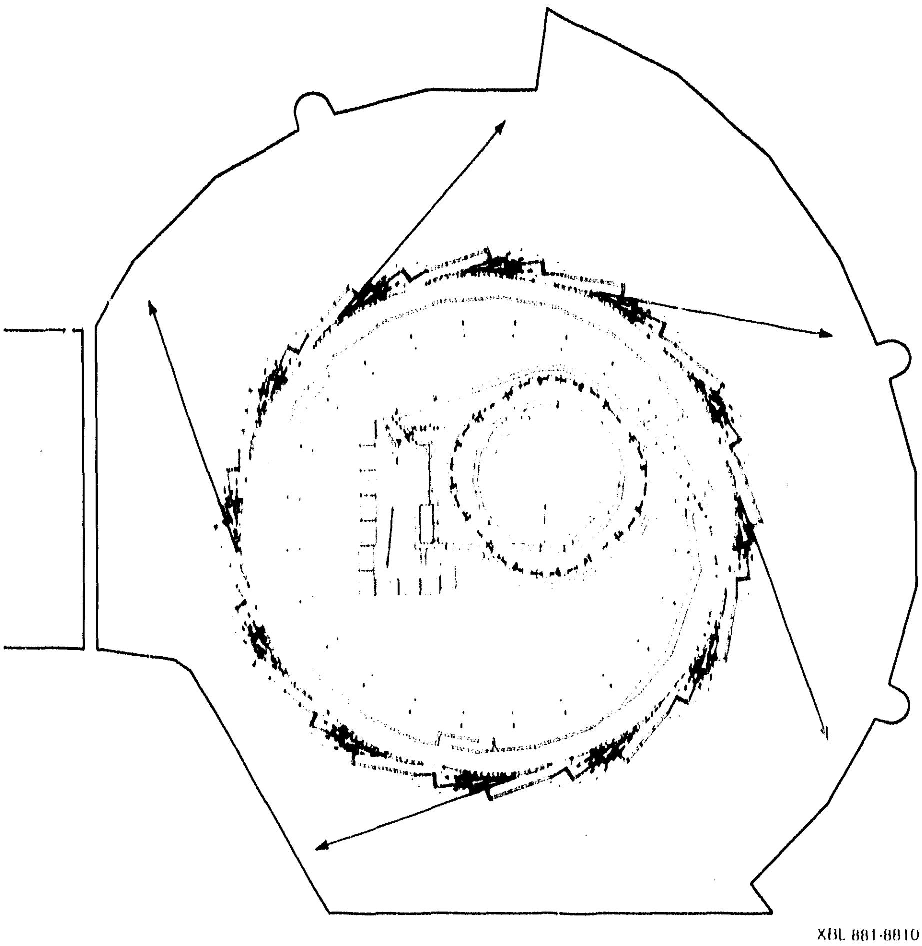


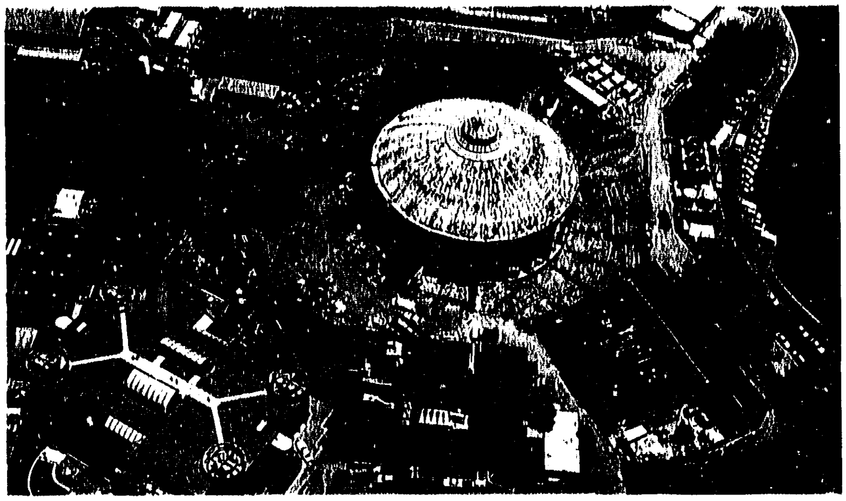
Figure 3-1. In the ALS, a linac and a booster synchrotron inject electron bunches into a storage ring. The multiple straight sections in the storage ring can each accommodate an insertion device to enhance production of synchrotron light from the very-low-emittance electron beam; the bend magnets also produce useful synchrotron light.

Construction Progress

After three years of construction, the ALS building is complete (Figure 3-2). As later sections describe, progress within has also been noteworthy. In May 1991, electrons were injected into the recently completed booster synchrotron and circulated without acceleration for 400 turns; acceleration tests are now under way. Meanwhile, the storage ring is being assembled, the first insertion device is being fabricated, and two insertion-device beamlines are being designed.

Throughout these activities, extensive testing and verification work was performed under the comprehensive quality-assurance policies of the ALS project. ALS environment, safety, and health personnel are also overseeing the commissioning process and gearing up for user-facility operations.

Figure 3-2. A sequence of photos shows the Building 6 area during and after conventional construction of the ALS. The injection complex, including the booster synchrotron, is under the dome—a Berkeley landmark preserved in the ALS design. The storage ring is being 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.



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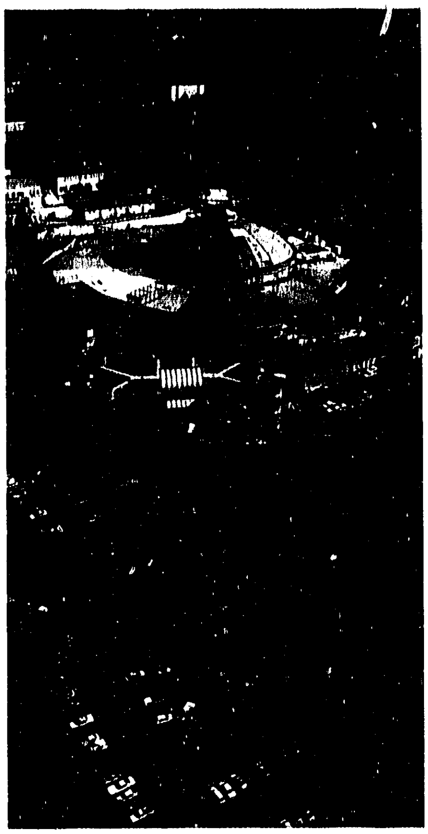

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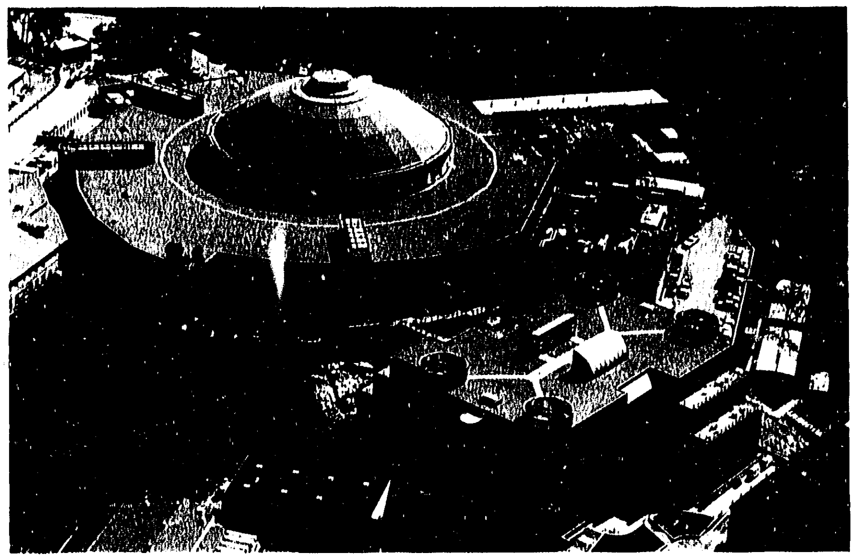

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Conventional Construction and Shielding

In March 1991, the conventional-facilities contractor turned over the 61 000-square-foot addition to LBL. The 20 000-square-foot central portion (beneath the dome) had been made available to us a year earlier. Most major conventional-construction activities are now finished. As of September 1991, all conventional construction was accepted as complete; the only portion of the building that is not finished is the inside of the mezzanine, which is beyond the scope of the currently funded ALS project. Work has commenced on thermal stabilization systems for the building. These should be complete by December 1992.

The concrete inner shielding wall for the storage ring was cast in three pours in 1990. The conceptual design for the precast outer wall has been reviewed and approved for seismic safety, and detailed design of the last blocks is nearing completion. The first precast shielding blocks for the wall have been ordered, and delivery is expected in December 1991. All the precast shielding is expected to be in place by mid-1992.

Accelerator Assembly and Commissioning

The ALS injection complex, consisting of a 50-MeV linac and a 1.5-GeV booster synchrotron, is now complete, and commissioning is in progress. Meanwhile, the storage ring is being assembled.

Linac

The 3-GHz (S-band) linac, shown in Figure 3-3, was completed by the end of 1990. Linac commissioning began in February 1991 after extensive preparation, and on February 20, on the first try, we accelerated a beam to 35 MeV. This prompt success is a testimony to the craftsmanship that went into the construction, assembly, installation, and alignment of the accelerator's complex components. In March 1991, after conditioning of the accelerator guides, adjustment of the phases between the two independent sections of the linac, and completion of the safety system for the entire injection complex, the linac was tested at the full beam energy of 50 MeV.

Booster

Meanwhile, installation of the booster proceeded. All magnets, vacuum chambers, and instrumentation in the bend sections were preassembled on 12 girders in the mechanical shops. There the magnets were prealigned on the girders, which were then transported to the ALS building. Figure 3-4 shows a completed girder assembly being lifted into the booster's concrete shielding tunnel. The considerable increase in assembly and installation activity required a major effort in survey and alignment that is expected to

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Figure 3-3. The 50-MeV linac was installed in its tunnel at the ALS site in 1990 and is now providing a beam for commissioning of the booster. The major systems are a 120-kV electron gun, an S-band (3-GHz) buncher, and two accelerator cavities totaling 4 m in length. This view follows the beam from the electron gun (at far left) to the transfer line that leads to the booster. The linac has been tested at its full energy, and work is under way to increase the beam current to the design value.

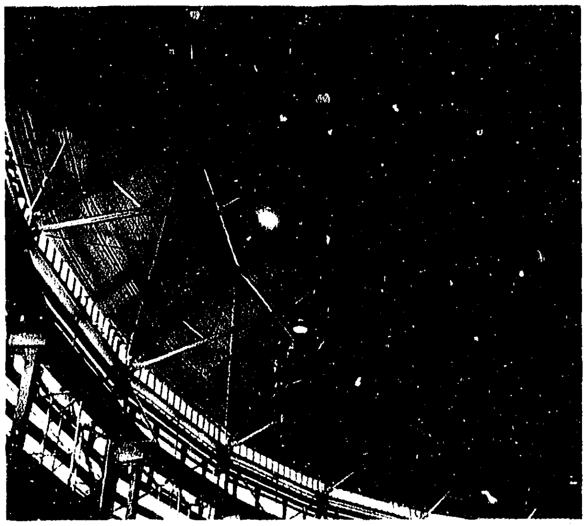

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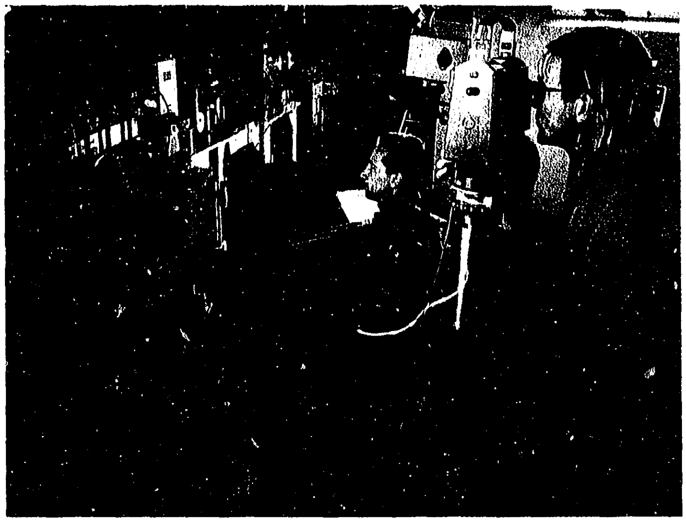
Figure 3-4. The completed girder assemblies for the booster were lifted by crane into the booster's concrete shielding tunnel. After utility connections were made in the tunnel, the magnets were aligned to tolerances better than ±200 μm. The booster is now complete and is being commissioned with beam and rf power.



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continue throughout the construction project and remain significant during operations. By April 1991, all mechanical elements of the injection complex were installed. After utility connections were made in the booster's concrete shielding tunnel, the magnets were aligned again, this time to tolerances of better than ±200 μm.

After another period of intense preparation, we were ready to start commissioning of the booster. All the necessary hardware, the personnel safety system, and the required procedures were in place by May 3, 1991, when we turned on the equipment and, within two hours, successfully injected a 50-MeV beam into the booster. Soon thereafter we circulated the beam for more than 400 turns without acceleration. Since that date, the circulating beam in the booster has reached 2 mA; we expect to reach the design value of 16 mA as the accelerator is conditioned (that is, when outgassing induced by synchrotron radiation and by particle loss has dwindled). Much of our commissioning activity since May 1991 has focused on four areas:

- Consolidating our earlier successes.
- Incorporating and enhancing the computer control system.
- Commissioning diagnostic devices.
- Improving the reliability and stability of the accelerator systems.

These activities have enhanced our understanding of these complicated systems. The knowledge will have continuing benefits, especially during the beginning of the operations phase.

Other Commisioning Activities

One of the especially noteworthy improvements is a virtual revolution in the control system. Early in 1991, most activity in this area was concerned with switching devices on and off and providing a user-friendly environment in which to do so. Since then, the system has blossomed with applications that can visually monitor the electron beam, auto-calibrate the beam-position monitors, take turn-by-turn beam-position data, analyze such data through fast Fourier transform techniques, and measure, analyze, and correct closed orbits.

Another example of our commissioning activities is the study of beam properties, such as the horizontal and vertical tunes and the synchrotron-oscillation frequency, which are being measured and compared with theoretical calculations. Orbit distortions were measured using the 32 beam-position monitors, and orbit correction schemes using the 32 steering magnets are being implemented. At the end of a commissioning shift, all beam parameters are saved in the computer to be restored for continuation the next day. Beam restorability is important in a user facility, and because of the high beam quality needed, stability is paramount in both the long and the short term. Any possible source of jitter, either in hardware or software, must be tracked down and corrected.

Checking and troubleshooting of the hardware also figures importantly in commissioning, as does developing and debugging the control-system software. Each component must be fine-tuned to meet the design specifications.

Beam acceleration in the booster to 1.5 GeV is scheduled to begin late in 1991 when the pulsed power supplies for the injection and extraction kicker magnets become operational. The 500-MHz rf acceleration system is routinely running at the maximum design power of 15 kW. The extraction system, consisting of bump magnets, extraction kicker magnets, and thick- and thin-septum magnets, along with their technically challenging high-powered, fast-responding power supplies, has been installed.

By December 1991, the section of the booster-to-storage ring transport line leading to the beam dump was installed in preparation for booster extraction studies. The extraction timing system, consisting of a coincidence clock, must be added to the existing timing system in order to make possible any fill pattern that users may require. The injection system will be ready for the commissioning of the storage ring, which is expected to start in the summer of 1992.

Storage Ring

While the injection complex was being commissioned, fabrication and installation of storage-ring components continued apace. By autumn 1991, all the 204 major magnets for the storage ring (quadrupole, sextupole, and combined-function dipole/gradient) had been fabricated, and quality-assurance characterization of them was in progress. To date, with more than half the magnets of each type measured, their quality exceeds the tight specifications, so special schemes for magnet placement have not been invoked. In other words, any dipole can be used at any dipole position in the lattice—the individual variation is so small that magnets of a given type are interchangeable.

Testing of the storage-ring vacuum vessels, which began in parallel with magnet production, is in progress. Scenarios for system bakeout and pumpdown have been developed and explored; the results confirmed that the vacuum specifications for the ALS will be achieved. The current effort is directed toward vacuum-testing the sector vacuum chambers and approving them for the LBL mechanical shops to install on the girders that hold the storage-ring components. Installation of girders and other storage-ring items in the ALS building began in June 1991 (Figure 3-5), and 10 of the 12 girders were in place by November. As with the booster, the storage-ring girders and vacuum vessels have to be surveyed into position precisely, an activity that involves cooperative efforts by the accelerator group and the survey-and-alignment team.

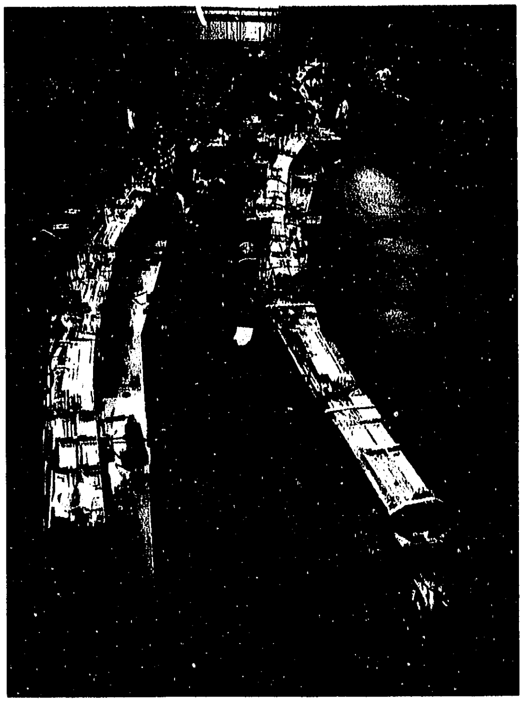

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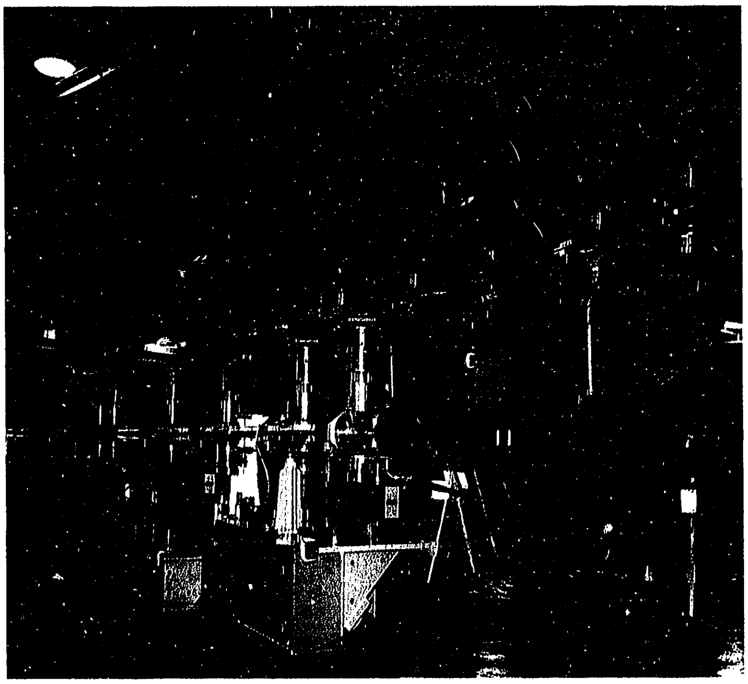
Figure 3-5. Girders for the arcs of the storage ring are currently being supplied by the mechanical shops and installed in the ALS building. Note the antivibration floor mounts, which are necessary for the high degree of beam stability implicit in the photon-beam requirements of ALS users.



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Supporting Technical Facilities

Few aspects of a modern accelerator are untouched by electronic systems for measurement, control, and power. In 1990 and 1991, as the injection complex was assembled and commissioned, electronics work at the ALS expanded greatly, as described here and in other sections. Another important technical project—a system for thermal stabilization—got under way in 1991.

Electronics

The ALS accelerator control room has been built, and components of the control system, which is based on distributed intelligent local controllers connected by a fiber-optic network to easy-to-use workstations, continue to be installed. Portions of the system are in use for linac and booster commissioning (Figure 3-6).

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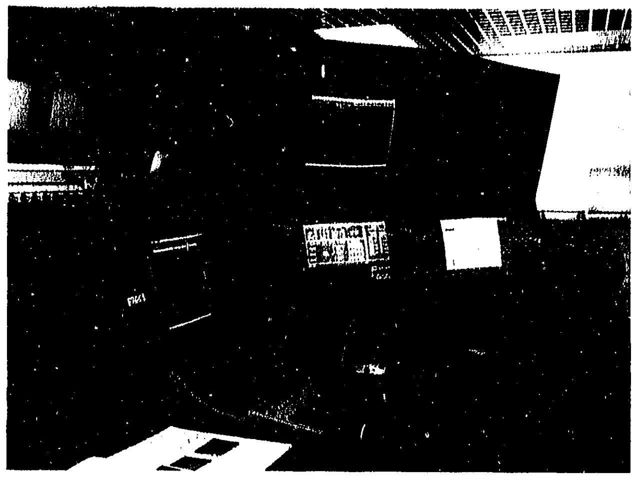

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Figure 3-6. Subsets of the computerized control system for the ALS were used from the early stages of linac and booster commissioning. As shown in these views of the control room at progressive stages, the system can provide a wide variety of operator displays, including a TV-monitor image of the linac beam and schematic displays of measurements and control parameters at various points along the injector chain and the storage ring. The complete system will include a network of more than 600 intelligent local controllers directed by central computers operated from the control room.

A workstation originally meant primarily for free-standing use in software development has instead been incorporated into the control system. This enables new procedures to be fully tested and debugged at the workstation before they are included in the library of procedures that run directly on the control computers.

The ALS will have an elaborate beam-position monitoring system to provide high-quality data concerning the position of the electron beam. In addition to the numerous beam-position monitors, the linac and booster require several other types of beam instrumentation. Completing these scintillators, collimators, tune-measuring electrodes, and beam-intensity monitors has been a significant ongoing effort. These instruments are used to characterize the beam size and emittance, the beam energy, and the transport efficiency. They also provide data to help verify the accelerator-modeling equations used by the control system.

The 15-kW rf system for the booster is being used for commissioning. Currently, the different parts of the storage ring's high-power 500-MHz rf system are also being fabricated or tested.

Thermal Stabilization

Construction has now started on a thermal stabilization system for the building. This system will provide an air-conditioned environment for the storage-ring tunnel and the experimental beamline areas. Earlier, in the first-ever systematic analysis of how thermal instabilities would affect the performance of a synchrotron light source, we had determined that stabilization to ±1° C would be required in order to prevent expansion or contraction of ALS components due to temperature variations. Such changes in the physical dimensions of components can cause shifts in beam position. Work on the thermal stabilization system includes the construction of a new cooling tower, the installation of chilled- and hot-water piping, and numerous changes in the ALS ductwork. Completion is expected by December 1992.

Experimental Systems

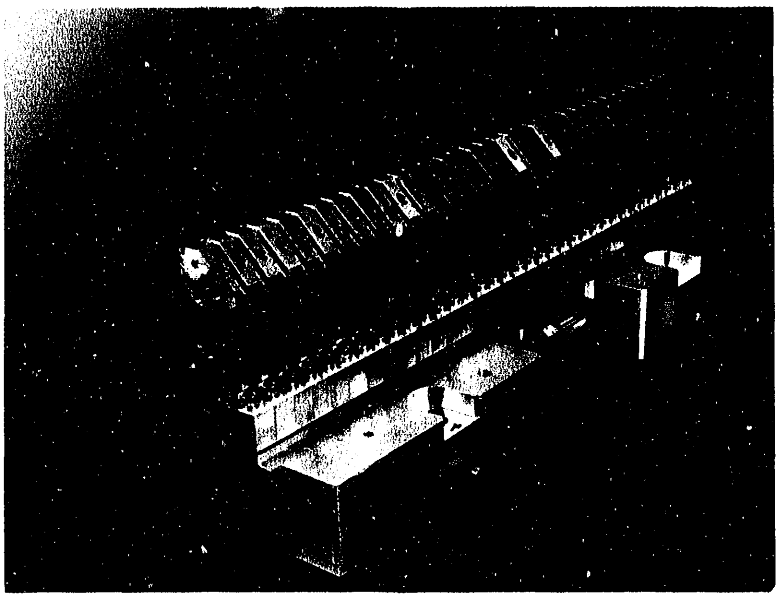
This area has been increasng in importance as the ALS progresses toward completion. Insertion devices—the key to producing small, intense, tunable beams of synchrotron light—have moved from design into fabrication. Also critical are high-performance beamlines that convey the photon beams to the users' experimental stations without compromising the brightness of the beams; the components of these systems must maintain precision even under high heat loads. With the user program less than two years away, the experimental-systems group has ramped up its efforts considerably, building upon several years of research and development.

Insertion Devices

In 1990, generic designs were developed, reviewed, and approved for the undulator support and drive systems, as well as for the magnetic structures. Since then, fabrication of the three undulators currently being funded by the ALS project has begun. Two undulators designated U5.0 (for their 5.0-cm magnetic periods) are well under way, and fabrication of U8.0 began recently.

Figure 3-7 shows the first pole section, which confirmed that the design would achieve the tight positional tolerances needed to fulfill the stringent magnetic-field specifications. Although they are based on earlier devices constructed by LBL for operation at the Stanford Synchrotron Radiation Laboratory (SSRL), these undulators are subject to far more stringent mechanical and magnetic-error tolerances. Tighter tolerances are required to achieve the photon-beam brightness made possible by the much smaller emittance of the electron beam in the ALS. Typical tolerances for the placement of magnetic materials are 12-50 µm, and gap motion must be controlled and reproducible to about 1 µm. Fabrication of pole assemblies for the first U5.0 is nearly complete. The pole assemblies will be mounted on the backing beams, which are being assembled in the LBL mechanical shops, and initial magnetic field measurements will begin early in 1992.

Figure 3-7. A pole assembly section of the U5.0 magnetic structure (right), using production components, confirmed that the stringent positional accuracy requirements could be achieved in practice. The two ALS-built U5.0 undulators are well into assembly, and fabrication of U8.0 has begun. Shown below is the mechanical superstructure, a support and drive system that must provide 0.1-µm gap reproducibility while resisting as much as 42 tons of force as the arrays of permanent-magnet blocks attract each other.



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The 4.5-m-long undulators will generate high-brightness radiation at photon energies from less than 10 eV to more than 2 keV (that is, in the ultraviolet and soft-x-ray regions of the spectrum). The tuning range is determined by the length of the magnetic period, the peak magnetic field achievable, and the electron beam energy. This radiation will be more than 10 times brighter than radiation from the brightest existing sources. Within this range, the photon energy will be tuned by varying the magnetic field, which changes as the gap between the magnetic poles is widened or narrowed.

The undulators are known as hybrids because the magnetic fields are produced by a high-strength permanent-magnet material, neodymium-iron-boron, and the field seen by the electron beam is shaped by a ferromagnetic material, vanadium permendur. Each U5.0 has 181 pole pairs and requires about 2100 magnetic blocks. The U8.0 has 113 pole pairs and requires about 1400 blocks. The magnetic blocks for all three undulators have been delivered, inspected, and precisely measured to determine the magnetic-field characteristics. These characteristics determine the ideal location for each block in the insertion device. Because of the large number of blocks, we developed a semiautomatic magnetic-moment measuring facility based on a Helmholtz coil (Figure 3-8). This facility has been able to measure the three

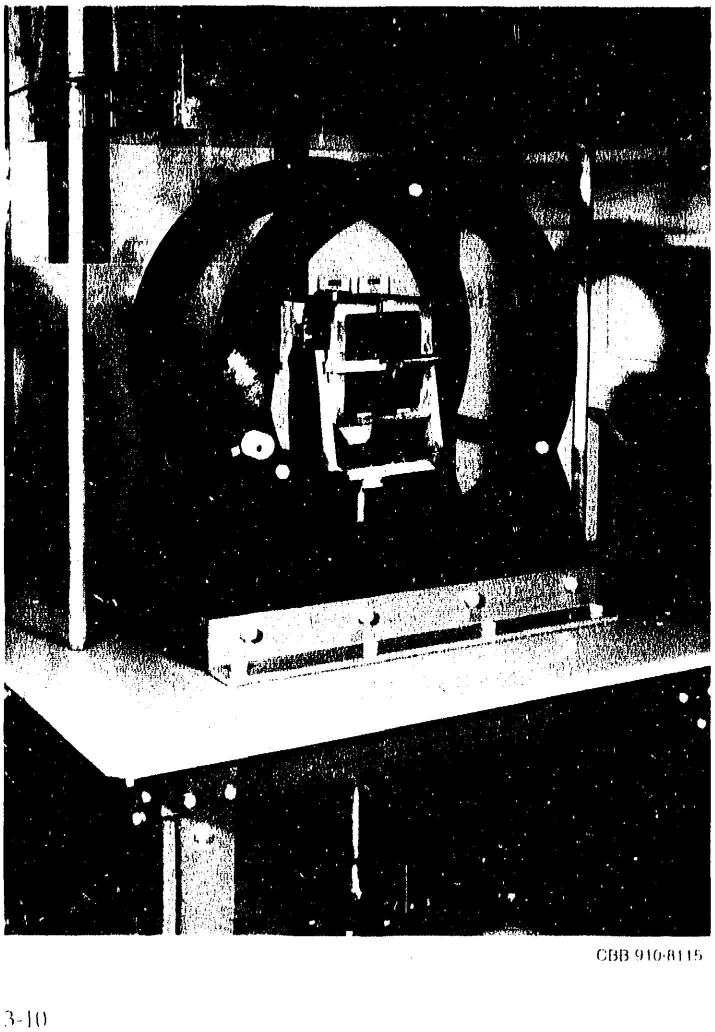

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Figure 3-8. The individual blocks of permanent-magnet material used in ALS undulators have individual variations; they must be characterized so that their ideal positions in the magnetic structure can be found. This semiautomatic device can measure up to 200 blocks per day.

components of the magnetic moment for more than 200 blocks per day. 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 Chemical Dynamics Research Laboratory, as described in Chapter 5, "Exploratory Studies."

User Beamlines

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.) Engineering efforts for the ALS beamlines increased during 1990 and 1991, and procurement of components began. Design work involved major front-end and mirror-system components, including photon shutters, horizontal beam-defining apertures, personnel safety shutters, fast-valve systems, and aperture plates. Generic design concepts were developed for actuators and in-vacuum assemblies, and test hardware was assembled to verify that the designs would meet the operational requirements. Assembly of front-end components began in October 1991. Figure 3-9 shows a typical beamline.

We conducted an R&D program at the National Synchrotron Light Source at Brookhaven National Laboratory. This program produced conceptual designs for photon-position monitors, which are critical to the operation of the beamlines. At LBL, we studied the passive stability of optical components and of active stabilization systems. These studies focused on three areas: agile mirrors to compensate thermal drift and vibration; feedback

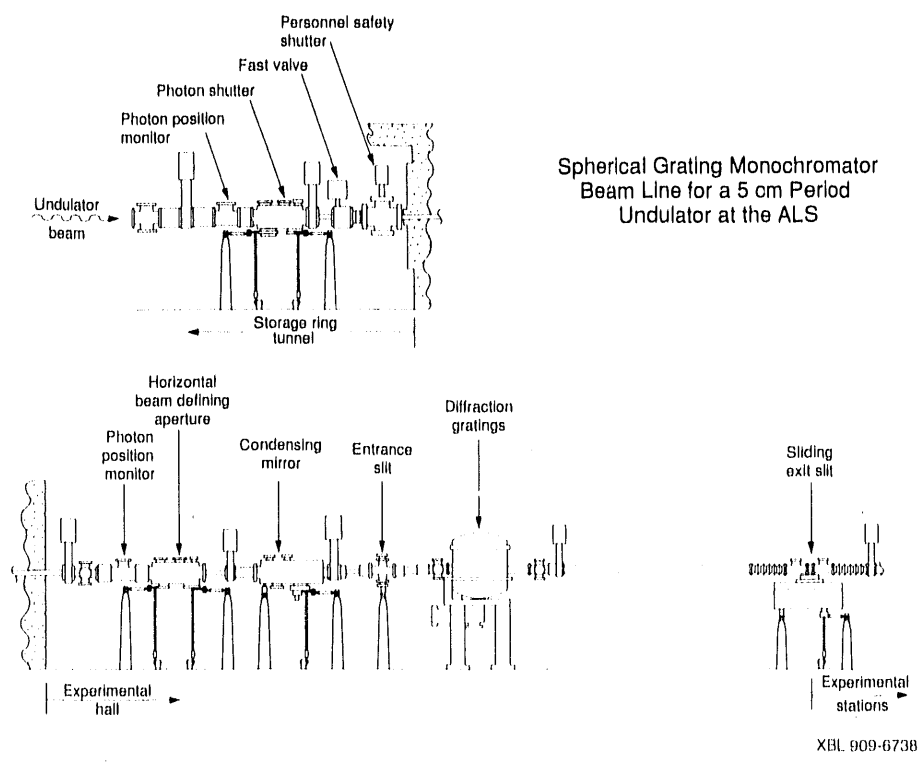

Figure 3-9. Two illustrations of a typical ALS insertion-device beamline show components before (*top left*) and beyond the storage-ring shielding wall. The user's experimental station would be beyond the exit slit of the monochromator.

* The U8.0 beamline will be used for studying photoprocesses in atoms, molecules, and ions. This U5.0 beamline will be used for spatially resolved spectroscopy of surfaces, interfaces, and other physical systems.

loops to local bump magnets in the storage ring straight section that will stabilize the motion of the electron beam; and the thermal and vibrational stability characteristics of an LBL-developed prototype spherical-grating monochromator installed in 1987 at the Stanford Synchrotron Light Source.

The small size of the ALS photon beams creates new challenges for beamline designers, as does the emphasis on insertion devices. First, the source size and divergence have become very small. For undulators at the high-photon-energy end of the spectral range, the rms photon-beam size is typically 330 µm horizontal by 65 µm vertical, and the rms divergence is typically 40 µm horizontal by 30 µm vertical. To avoid loss of light from this small source, tighter tolerances are needed for the figure and finish of relay optics and monochromator components.* Further, it is now practical to achieve higher resolution by the use of narrower monochromator slits; therefore monochromator components need tighter tolerances to avoid loss of resolution. Finally, the photon-beam power has increased to several kilowatts per square centimeter. The resulting requirement for control of thermal distortion and stress complicates the design.

The procurement of optical elements for the ALS beamlines was started, since these items take a long time to obtain. Three water-cooled mirror substrates are being fabricated; one of them was finished by the polishing vendor and returned to us in May 1991. This met the first critical milestone for fabrication of mechanical components for the ALS beamlines. The other is being polished.

One of the most important areas of beamline R&D has been characterization of optical surfaces. The typical quality of optical components for use in synchrotron-radiation beamlines had been sub-optimal for many years. Our requirements are stringent (slope errors in the range of 0.1 second of arc, for example), so optical metrology plays a key role. To this end, the ALS project funded the construction of two long-trace profilers (Figure 3-10) based on an advanced surface-profiling instrument developed at Brookhaven National Laboratory. One is operating in the new ALS Optical Metrology Laboratory, where it is housed in a class-10 000 cleanroom to avoid contamination of optical surfaces. The other is installed at Tucson Optical Research Corporation (TORC), a private company with which we are cooperating to develop manufacturing techniques for water-cooled metal beamline optics. These surface profilers make it possible for us to obtain the best beamline optics available while making significant contributions to state-of-the-art surface profiling.

To date, the profilers can measure surface slope error to better than 1 microradian rms. With the help of these instruments, water-cooled metal optics at least as good as the best glass optical components have been fabricated for the ALS. Surface microroughness figures of 2 Å rms—five times better than previously achievable—have been obtained on 15-inch-long copper alloy mirrors coated with electroless nickel. Currently we are working with TORC to achieve this microroughness on metal surfaces that also have a slope error of only 0.5 microradian rms; the project is proceeding well. In addition, we developed, in collaboration with industry, a completely new

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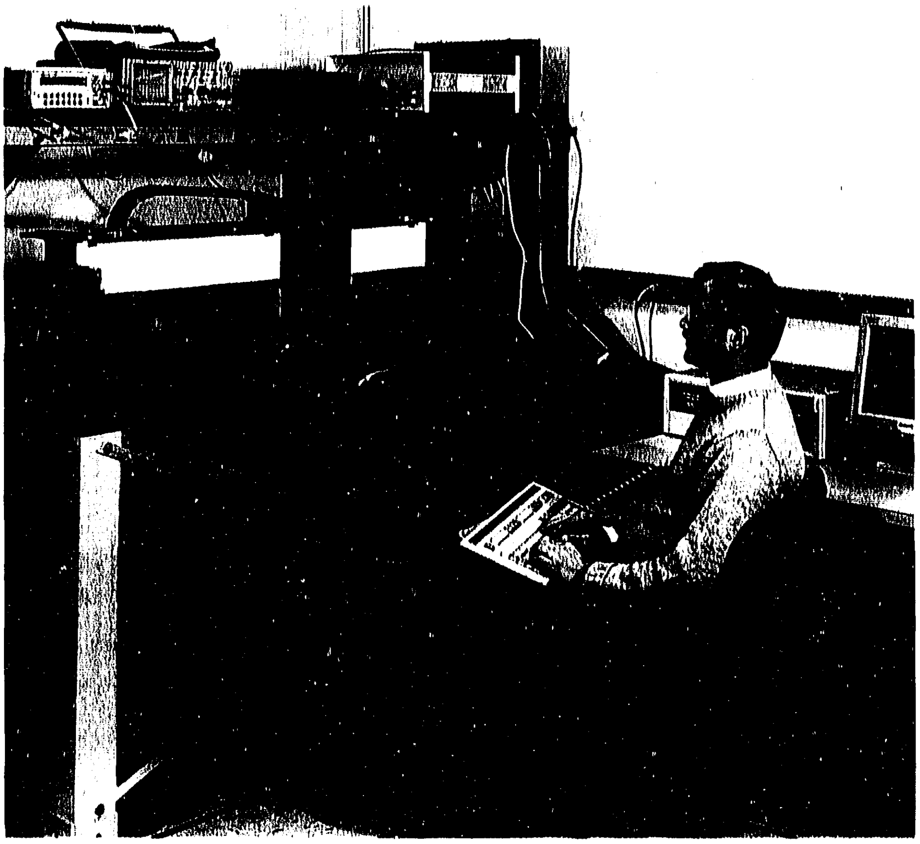
* Surface figure refers to the accuracy of the profile at low spatial frequencies or long periods, whereas surface finish refers to the smoothness of the profile at high spatial frequencies or short periods.

Figure 3-10. Because the figure and finish of optical components can be no better than the available measurement instruments, we worked with Tucson Optical Research Corporation, Continental Optical, and other private-sector vendors to develop this long-trace surface profiler, based on a concept from Brookhaven National Laboratory. Thus far, using these instruments, slope errors as small as 1 microradian rms and surface microroughness errors as small as 2 Å rms have been measured.



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method of making toroidal mirrors to a slope tolerance of 5 microradians rms. These developments have opened a new era in the availability of high-quality grazing-incidence optical elements for the synchrotron radiation community.

Diagnostic Beamline

In addition to building the two user beamlines, we plan to install a diagnostic beamline with which we can use synchrotron radiation for precision imaging and transverse measurement of the electron beam in the storage ring. This system will also provide information about the positional stability and length of the bunch. These measurements are essential for optimizing the operation of the storage ring, insertion devices, and monochromators. The diagnostic beamline will be installed at the first bend magnet following the straight section used for acceleration. This constricted area of the experimental floor is the least desirable for user beamlines.

The ALS has a natural emittance of 3.4×10^{-9} m-rad and, in the first bending magnet, has horizontal and vertical beam sizes σ_h and σ_v of 44 μm and 83 μm, respectively (assuming a 9:1 ratio of vertical to horizontal emittance). Simple diffractive optical calculations show that it is not feasible to image this beam with visible-light optics; imaging must be performed using photon energies greater than 50 eV.

The beamline will have an imaging system for 200-eV photons and a "white beam" port (i.e., a port with no monochromator, passing the full spectrum of bend-magnet radiation) with a streak camera to obtain timing information. The imaging system will employ two crossed, spherical mirrors in a Kirkpatrick-Baez configuration to eliminate astigmatism. Use of 1:1 imaging will eliminate coma, thereby producing an image of the source limited only by the residual aberrations of the optics. Real-time imaging of the beam should be feasible with the use of a high-resolution charge-coupled device.

The design of the diagnostic-beamline imaging system for the ALS was implemented with an eye toward application in other third-generation synchrotron radiation sources, all of which will present challenges similar to those outlined above. This beamline is scheduled to be in operation by July 1992 to facilitate the commissioning of the storage ring.

Environment, Health, and Safety

Both in construction and in the planning of the user program, we have placed great emphasis on health, safety, and environmental protection. Commissioning activities have been paced not only by the installation of the mechanical and electrical hardware, but also by installation of the safety systems deemed necessary for a particular activity. For example, operating the 120-kV electron gun system with only the linac tunnel secured was acceptable, whereas it was necessary to implement the full personnel safety system for the injection complex before a beam could be accelerated to 50 MeV. Commissioning activities are limited to the evenings because of ALS construction and installation activities during normal working hours. In late afternoon the linac and booster tunnels are searched and secured according to the established procedure. The accelerator building is also locked, although measurements have shown that the radiation level outside the tunnels is well below the safety limit. Only then does commissioning begin.

Radiation safety is one of our major concerns. The linac and the booster generate high levels of radiation (x-rays, gamma rays, and neutrons), confined inside the accelerator tunnels. We surveyed the radiation around the interlocked high-radiation areas under nominal operating conditions and under abnormal conditions in which beam has been lost deliberately to simulate accidents. In all but one situation, the radiation shielding proved to be highly effective, reducing the radiation fields to less than 1 millirem per hour at the outside surface of the shield wall. In the one exceptional case, a transport-line switching magnet was turned off and a narrow beam of radiation at 15 millirem per hour was observed at the inside of the shielding wall. While this level is within the allowed limits for this controlled area, extra local shielding was added inside the enclosure for even greater safety assurance. In the experimental area, the radiation level is expected to be well within the levels that are considered safe. The radiation level in the accelerator building is re-measured every time commissioning reaches a milestone that is relevant to radiation.

During two annual safety reviews by the Department of Energy, participants from the DOE and from other national laboratories evaluated the facility and presented action items, recommendations, and suggestions. The 1991 review stressed the need to establish policies and procedures to ensure the safety of ALS users when the facility becomes operational.

Toward this end, a November 1991 workshop for the user community was jointly planned by the ALS Operations Safety Officer and the chairperson of the ALS Users' Executive Committee. The workshop agenda covered chemical, radiation, electrical, mechanical, vacuum, and seismic safety, along with training requirements in these areas. It also included a joint planning session in which ALS staff and prospective users addressed these goals:

- Ensuring effective communication with regard to health and safety between the ALS organization and the user community.
- Gaining a better understanding of users' health and safety concerns.
- Establishing a joint user-ALS safety committee to formulate plans and guidelines.
- Initiating plans for a jointly developed user safety manual.

The 1991 review also produced recommendations pertaining to the fire and life-safety codes, now under consideration by the LBL Fire Department.

Interaction with the User Community

When one examines the complexities and lead times involved in 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. 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.*

Eight insertion-device PRTs and six bend-magnet PRTs have been approved. The strong response confirms the user demand for the ALS and bodes well for an active scientific future at the facility.

Scientific Program Development

The initial scientific program emphasizes the high brightness of soft-x-ray and extreme-ultraviolet (XUV) light available from the ALS. The experiments will be conducted by PRTs, which comprise investigators with related research interests from one or more institutions. The primary responsibility for experimental apparatus rests with the PRTs; the responsibility for the beamlines and insertion devices will be shared by the ALS and the PRTs. In return for its commitment, each PRT receives a guaranteed fraction of the ALS operating time at its beamline. Through a proposal process, a substantial fraction of running time at each beamline will also be made available to independent investigators not affiliated with a PRT.

Eight insertion-device PRTs were approved by the Program Review Committee in December 1989. (Originally nine teams were approved; two of them have since joined forces.) The panel reviewed bend-magnet proposals at its June 1990 and May 1991 meetings; six teams have been approved. Some of the PRTs already have funding in place.

Nine of the 24 available "prime" bend-magnet ports have been allocated: six to these bend-magnet PRTs and three to insertion-device PRTs. An advertisement for additional bend-magnet teams was published to encourage use of bend-magnet radiation.

Some of these teams are expected to use the high brightness of the ALS undulators (*sidebar*) to open new areas of research in the materials sciences, such as spatially resolved photon and photoelectron spectroscopy (spectromicroscopy). Biological applications will include x-ray microscopy with element-specific sensitivity in the "water window" of the spectrum, the 2.3-4.4 nm region where water is much more transparent than protein. The ALS will also be an excellent research tool for atomic physics and chemistry because the high flux will allow measurements to be made with tenuous gas-phase targets. The short pulse width (30-50 ps) will facilitate time-resolved experiments.

Other research areas planned for ALS undulator beamlines include high-resolution soft-x-ray spectroscopy of materials and surfaces, spin-polarized photoemission spectroscopy of magnetic materials, and experiments that exploit the polarization of undulator radiation. A future option is the construction of special devices to generate radiation with a controlled elliptical polarization. Wiggler-based x-ray studies will include spectroscopy of atoms both in the gas phase and in condensed matter; spatially resolved elemental analysis with an x-ray microprobe; grazing-incidence x-ray scattering from surfaces; and x-ray diffraction of large biological molecules (that is, protein crystallography). Research planned by bend-magnet teams includes studies of physical and biological systems with polarized radiation, as well as infrared absorption spectroscopy of solids, surfaces, and gases.

The scientific potential of the ALS encouraged more than 200 people, mostly from universities and Federal laboratories, to respond to the first call for PRT proposals. Additional participation by the private sector would be desirable, so an effort to broaden the ALS user community by including more industrial participation is underway, as described later in this chapter.

Benefits of Brightness

Spectral brightness is in general the most prized virtue of XUV light from the ALS. The rays of light occupy a small cross-sectional area and can be focused onto a small spot (or, in more-technical terms, a high photon flux per unit source area and per unit solid angle into which the source radiates). The source radiates into a narrow cone with an opening angle of a few hundredths of a milliradian or less for undulators, or a few tenths of a milliradian for bend magnets. Spectral brightness is the same quantity per unit spectral bandwidth. Brightness is conserved as light travels through an ideal optical system. in other words, it cannot be improved by focusing or other means; it is limited by the quality of the source.

Experiments with synchrotron light tend to fall into three categories. Spectroscopy provides information about quantum states; elastic scattering (such as x-ray diffraction) locates the position of atoms and molecules; and imaging provides a view of microstructures and nanostructures. Brightness brings distinct advantages to each of these experimental groupings.

The most direct beneficiaries are researchers in the physical and life sciences who hope to achieve enhanced spatial resolution down to distance scales of about 100 Å in x-ray microscopy, or who plan to pursue spatially resolved ultraviolet and x-ray spectroscopy. A typical benefit accrues to the study of solid surfaces, which are mostly heterogeneous, making interpretation of spectroscopic data obtained from illuminating the entire surface difficult. With spatial resolution, spectral features could be directly associated with specific surface areas and structures.

For the spectroscopist, brightness allows high spectral resolution without the usual penalty of reduction in signal and increase in measuring time. Experiments whose measuring times were once impractically long, perhaps because of inherently weak signals, become reasonable to contemplate.

Finally, brightness and the pulsed nature of synchrotron radiation bring another opportunity: the ability to observe short-lived or transient systems by means of time-resolved spectroscopic, scattering, and imaging experiments. The ultimate time resolution, made possible because there are enough photons in a single pulse of bright synchrotron light to generate a useful signal, would be to follow events in real time on a sub-nanosecond time scale.

Workshops and ALS Science

Several workshops have helped highlight the wide variety of scientific opportunities for high-brightness XUV light and further broaden the participation by all segments of the potential user community.

Soft X-Ray Lithography. The ALS and LBL in general, the adjacent University of California campus, and nearby Silicon Valley constitute a unique combination of resources for the development and exploitation of x-ray lithography technology. To acquaint the semiconductor lithography community with the capabilities and availability of the ALS, a workshop entitled "Soft X-ray Lithography at Berkeley's Advanced Light Source" was held at LBL in January 1991 under the auspices of the Center for X-Ray Optics (see Chapter 4). In addition to informing the community about the ALS, an equally important objective was to learn about the community's needs. The ongoing goal is to work together to fashion an effective strategy for developing advanced circuit-manufacturing technology.

Three major conclusions emerged. The high brightness of the ALS in the soft x-ray spectrum will be particularly useful for characterization of optics and coatings and for metrology and registration. Initiation of ALS operations in 1993 is well matched to industrial needs for advanced pattern transfer below 0.15 µm in the year 2000 and beyond. Finally, development of production technology will require a supporting infrastructure for masks, optical coatings, resists, synthesis, and processing. This infrastructure should be available to the community in a location contiguous to the x-ray test facilities.

Photon-In Photon-Out Spectroscopy. A one-day workshop on "Applications of Photon-In/Photon-Out Spectroscopy with Third-Generation Synchrotron-Radiation Sources" was held in April 1991 in Washington, DC. The workshop focused on photon-induced fluorescence, which is recognized not only as a powerful technique in atomic and molecular physics, chemistry, materials science, and imaging, but as a tool offering expanded opportunities with the arrival of a new generation of high-brightness vacuum-ultraviolet and x-ray synchrotron-radiation sources, such as the ALS, the Advanced Photon Source, and the European Synchrotron Radiation Facility.

Circularly Polarized Photons. Bend-magnet synchrotron radiation has natural polarization properties, being linearly polarized in the plane of the orbiting electrons and elliptically polarized out of the plane. By selecting the angle of observation out of the plane, researchers have access to an x-ray source with a high degree of circular polarization. To focus attention on and to stimulate the scientific exploitation of the natural polarization properties of bend-magnet radiation, a "Workshop on Circularly Polarized Photons from a Bend-Magnet Source at the ALS" was held at LBL in June 1991. The magnetic properties of materials and differential scattering from and absorption by chiral molecules were among several topics in biology, materials science, physics, and chemistry addressed at the workshop.

Spectroscopic Imaging. In conjunction with the ALS Users' Association fourth annual meeting, there was a workshop on "Spectroscopic Imaging, Diffraction, and Holography with X-rays" in August 1991 at LBL. Several x-ray techniques share a common goal of combining a capability for structure determination with chemical-state specificity over length scales from about 1 µm down to atomic dimensions. The image-formation methods, chemical-state sensitivities, and spatial resolutions of these techniques can be very different. Examples include photoemission microscopy, energy-dependent photoemission diffraction, photoelectron holography, x-ray absorption microspectroscopy, x-ray microscopy, and x-ray holography. This workshop addressed recent theoretical and experimental advances in holographic, diffraction, and direct imaging techniques.

Earth Sciences. Synchrotron radiation has numerous current and potential applications in geochemistry, mineralogy, and other geological disciplines. In December 1991, in conjunction with the San Francisco meeting of the American Geophysical Union, a workshop was held on "Applications of the Advanced Light Source to Problems in the Earth, Soil, and Environmental Sciences." Topics will include x-ray microprobe analysis, x-ray spectroscopy, and surveys of current applications.

Industrial Applications. To help the industrial research community to become better acquainted with the ALS, a brochure entitled "Putting Synchrotron Radiation to Work: New Opportunities for Industrial Research" has been mailed to more than 3000 scientists in industrial laboratories. The brochure describes some of the ways that XUV radiation from synchrotron sources have already been put to beneficial use by industrial scientists, who are invited to investigate the research opportunities at the ALS. The brochure emphasizes that the ALS will be a highly reliable, full-time source of XUV radiation for proven experimental techniques of demonstrated value to industrial R&D. A workshop will be held at LBL in January 1992 to showcase the ways in which synchrotron radiation can help solve problems faced in industrial laboratories.

ALS Advisory Panels

Two committees provide advice on ALS planning and operation to the LBL Director. The Science Policy Board (see Table 3-1) provides advice on high-level policy issues affecting the ALS. At its second annual meeting, held in July 1990, it gave the ALS excellent marks for its scientific program policies and approved the ALS strategy for allocating available resources. It also noted that these resources are limited and suggested ways to address the resulting issues.

The Program Review Panel (Table 3-2) gives advice on the scientific program through the ALS Director. Until the ALS is commissioned in spring 1993, this panel's main task will be evaluation of PRT proposals. The panel devoted its November 1989 meeting to proposals from insertion-device teams and the June 1990 and March 1991 meetings to proposals from bend-magnet teams. As the PRTs become established, the scope of the Program Review Panel's activity has been broadening to include reviews of their performance. Evaluation of beamtime proposals from independent users will be added to the Panel's agenda once the ALS becomes operational.

ALS Users' Association

The ALS Users' Association held its third and fourth annual meetings in August 1990 and 1991 at LBL. The programs featured (among other topics) DOE's view of funding prospects for experimental facilities (insertion devices, beamlines, and end stations). Other highlights included projections of scientific opportunities at the ALS based on work now in progress elsewhere.

At both meetings, new members were nominated to the Users' Executive Committee, which serves as the voice of the user community in communicating its needs to the ALS staff. The 1990 election marked the completion of the committee's three-year transition to a fully elected body (initially, members had been appointed rather than elected). Table 3-3 lists the 1990-1992 Users' Executive Committee members.

Table 3-1. ALS Science Policy Board, 1990 and 1991

Dean E. Eastman, IBM Thomas J. Watson Research Center (chair)
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
J. McEwan Paterson, Stanford Linear Accelerator Center

Table 3-2. ALS Program Review Panel, 1990 and 1991

Neville V. Smith, AT&T Bell Laboratories (chair)
C. Richard Brundle, IBM Almaden Research Center*
Sheldon Datz, Oak Ridge National Laboratory
John W. Hepburn, University of Waterloo, Ontario, Canada†
Franz J. Himpsel, IBM Thomas J. Watson Research Center†
Michael L. Knotek, Battelle Pacific Northwest Laboratories
Gerald J. Lapeyre, Montana State University†
Robert I. Macey, University of California at Berkeley*
Giorgio Margaritondo, Ecole Polytechnique Federale (Lausanne, Switzerland)
Keith Moffat, University of Chicago
William Orme-Johnson, Massachusetts Institute of Technology†
J. Michael White, University of Texas at Austin*
Joe Wong, Lawrence Livermore National Laboratory*

* Through 1990.
† New member for 1991.

Table 3-3. ALS Users' Executive Committee, 1990-1992

Tomas Baer, University of North Carolina at Chapel Hill *
C. Denise Caldwell, University of Central Florida**
George Castro, IBM Almaden Research Center**
Stephen P. Cramer, University of California at Davis
Wolfgang Eberhardt, Exxon Research and Engineering Co.*
David L. Ederer, National Institute of Standards and Technology
Charles S. Fadley, University of Hawaii (1990 chair)†
Cynthia Friend, Harvard University
T. Kenneth Gustafson, University of California at Berkeley†
Stephen D. Kevan, University of Oregon*
Melvin P. Klein, Lawrence Berkeley Laboratory†
Manfred O. Krause, Oak Ridge National Laboratory†
Dennis W. Lindle, University of Nevada at Las Vegas (1991 chair)
Rupert C. Perera, Lawrence Berkeley Laboratory
Piero Pianetta, Stanford Synchrotron Radiation Laboratory (1992 chair)
Stephen S. Rothman, University of California at San Francisco*
James G. Tobin, Lawrence Livermore National Laboratory**
Brian P. Tonner, University of Wisconsin at Milwaukee and Synchrotron Radiation Center, University of Wisconsin at Madison**
Michael G. White, Brookhaven National Laboratory

* Through 1990.
† Through 1991.
**New member for 1992.

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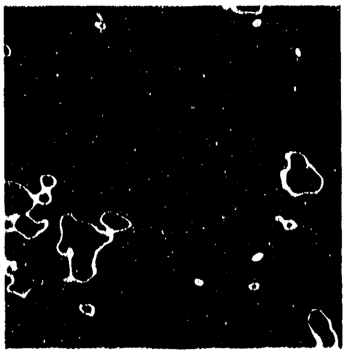

4.

CENTER FOR X-RAY OPTICS

IN 1990 AND 1991, THE CENTER FOR X-RAY OPTICS (CXRO) 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.

High-resolution x-ray microscopy continues to be prominent among our activities. Soft-x-ray microscopy based on Fresnel zone-plate lenses has provided images of features as small as 300 Å in experiments at the Berlin Electron Synchrotron (BESSY). In the hard-x-ray regime, our microprobe, based on multilayer-coated reflective optics, has achieved 2-μm spatial resolution at the National Synchrotron Light Source (NSLS) and has been used in a large number of applications in the life and physical sciences.

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 continued investigating the structure and stability of various multilayer pairs and developed a new, highly versatile reflectometer based on a laser-plasma x-ray source and a high-throughput monochromator.

These ongoing efforts in soft-x-ray imaging led to the initial funding of an Advanced Light Source/CXRO program in projection lithography. This joint initiative brings researchers from CXRO and the University of California at Berkeley campus together with representatives of the semiconductor industry. The goal is to further the use of x-rays in the fabrication of computer chips with feature sizes of order 0.1 μm. The photon beams from the ALS are well suited to this research.

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CXRO won two 1990 R&D 100 awards from *Research and Development Magazine* and one 1991 award—the group's fourth and fifth consecutive years of winning in this contest. One award was for a CXRO-developed apparatus that uses soft-x-ray scattering for various applications. Another award recognized a high-fluence X-ray source, developed in a joint project with Sandia National Laboratories at Livermore. The third was for a scanning photoelectron microscope, developed jointly by several collaborators. Also, we tested a new, more portable version of our X-ray microprobe, a previous R&D 100 winner.

Soft-X-Ray Imaging with Zone-Plate Lenses

Extending high-resolution visible-light and ultraviolet imaging techniques into the soft-x-ray region of the spectrum offers several special advantages. The relatively short wavelengths, ranging from several angstroms to perhaps one hundred angstroms, permit users to both "see" and "write" smaller patterns. Furthermore, the associated photon energies, ranging from approximately one hundred to several thousand electron volts (eV), span the primary resonances of many elements. Resonances constitute a sensitive mechanism for element identification, for elemental mapping, and, in some cases, for the determination of chemical bonding. During 1990 and 1991 we advanced the technology of soft-x-ray imaging and demonstrated some potential applications in the physical and life sciences. Features as small as 300 Å may be seen in our best images.

One of these lenses is at the heart of the High-Resolution Scanning Photoelectron Microscope at Brookhaven National Laboratory's National Synchrotron Light Source (NSLS). The microscope, installed in the X1A beamline at the NSLS, was developed by a collaboration involving the State University of New York at Stony Brook, BNL/NSLS, IBM, and CXRO. It won an R&D 100 award in 1991. It currently offers a peak two-dimensional resolution of 0.4 μm; upgraded beamline optics and improved nickel zone plates may improve resolution to about 50 nm.

Development of Fresnel Zone-Plate Lenses

In microscopy with soft x-rays, the key optical component that ultimately determines performance is the objective lens. Ordinary refractive lenses like those used for visible light, which transform the phase of a wavefront 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 part of the soft-x-ray region (≈ 100 eV), where efficient high-reflectivity multilayer coatings can be fabricated. To date, however, their resolution in this spectral region has not been as high as that of Fresnel zone plates. Zone plates are thus the lenses of choice for the highest spatial resolution, particularly for energies greater than 200 eV.

Accordingly, one of our major areas of research has been the development of zone plates that have smaller and more-accurately located zones. We are also pursuing the use of materials such as nickel to achieve greater diffraction efficiency. The lenses are fabricated by means of electron-beam writing techniques.

In pressing toward the fundamental diffraction limit of lens performance, accurate placement of the zones (alternate circular bands of transmissive and opaque material) is important. The maximum placement error should be less than a small fraction—25% or so—of the smallest zone width on the lens. This is a formidable challenge, since our highest-resolution lenses, like the one shown in Figure 4-1, have zone widths of 300 Å. Achievement of the required accuracy at these dimensions, especially across large (50-μm-diameter) lenses, is at the frontier of microfabrication. One of our current efforts is aimed at characterizing and reducing placement errors.

In collaboration with researchers from the University of Göttingen, we have been using and characterizing the 300-Å zone plates in the Göttingen x-ray microscope at the Berlin Electron Synchrotron Facility (BESSY). Although measurements of the microscope's optical performance indicate that the diffraction limit has not been reached, images of test patterns show that features as small as 300 Å are visible. Because of our efforts to reduce errors in the placement of the zones, our newest set of 300-Å nickel zone plates should be even better in both spatial resolution and diffractive efficiency.

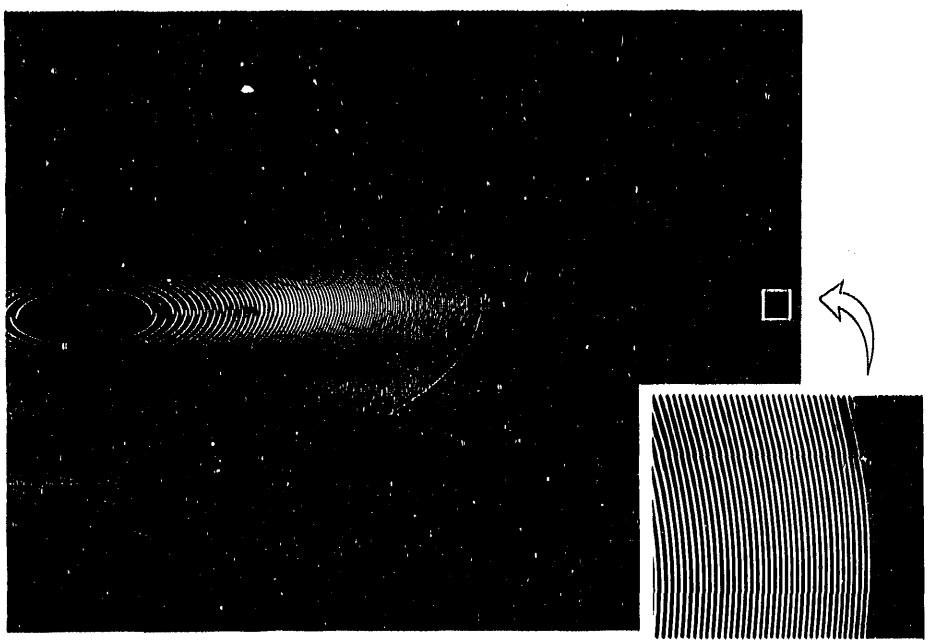


Figure 4-1. A high-resolution Fresnel zone-plate lens is shown during processing. The tri-level resist has been etched and is ready for electroplating with nickel. The smallest zone width is 300 Å. The lenses are produced in an ongoing collaboration in which a CXRO scientist works in IBM's Nanostructure Technology Group at the Thomas J. Watson Research Center in Yorktown Heights, New York.

XBB 910-8000A

CXRO-ALS X-Ray Lithography Program

The attempt to "write" ever-smaller patterns on silicon chips has been a natural application for x-ray techniques and technologies, such as those developed by CXRO. As research and applications start to converge toward industrially useful x-ray projection lithography (*sidebar*), a unique environment for collaboration is emerging. CXRO, the University of California at Berkeley, LLNL, and Silicon Valley semiconductor companies are working together toward an advanced lithography R&D program at the ALS. A large measure of impetus came from successful projection printing of features smaller than 0.1 μm by an AT&T group working at Brookhaven National Laboratory's National Synchrotron Light Source. This early success, combined with the realization that the brightness and spectral properties of ALS radiation would be ideally suited for testing techniques and optics for lithography, led to this initiative.

A formative workshop was held in January 1991 to help researchers in government and industry work together toward a strategy for developing an advanced manufacturing capability in the U.S. It familiarized researchers from the semiconductor lithography industry with the capabilities of the ALS and user access to it, and also helped us to understand industry's needs. Technical discussions resulted in consensus on three key issues:

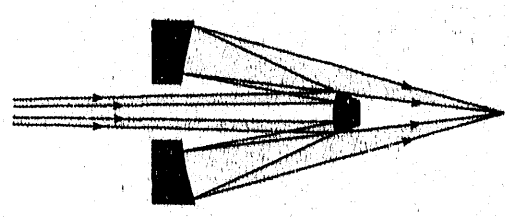
- The x-ray lithography community would benefit from ALS beams from both a bending magnet and a high-brightness undulator. This combination could supply a registration and metrology station and an easily accessible facility for basic testing of components, resists, and masks. There would also be sophisticated testing capabilities for optical elements, optical systems, and various projection technologies that have yet to be developed.
- The time frame for research activities at the ALS (that is, beginning in 1993) is well-matched to industry's needs for pattern transfer below 0.15 µm in the year 2000 and beyond.
- Development of production technologies for structures of these dimensions will require a nearby supporting infrastructure for nanostructure pattern generation, masks, optical coatings, resists, and the requisite synthesis and processing operations.

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 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 (see the illustration *below*). 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 sufficient resolution and breadth of field, corresponding to a small, uniformly good pattern across a large chip.

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. (Multilayer-coated optics are described in the next section.) The experimental work will use a Schwarzschild objective, coated with Mo/Si multilayers by CXRO. Optics suitable for manufacturing will be far more complex and demanding.



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An advisory group including industry, university, and national-laboratory representatives met six times in 1991 to develop the specific focus of the program. Their efforts culminated in a "white paper" that calls for a major investment in specialized facilities and infrastructure at LBL. These efforts recently resulted in a notice of initial funding from the Defense Advanced Research Projects Agency.

Multilayer Reflective Optics

Multilayer coatings are good reflectors of x-rays over a broad wavelength range. 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 to elucidate their performance limits.

Multilayer-coated mirrors fabricated in our laboratory have been incorporated into a wide variety of x-ray optical systems in the U.S. and abroad, operating at photon energies ranging from the XUV to the hard-x-ray regions of the spectrum. Our long-wavelength multilayer characterization capabilities were recently enhanced by the development of a self-contained XUV reflectometer. The innovative device is based on a broadband laser-plasma x-ray source and a high-throughput, easily tunable monochromator.

Improving Multilayer Reflectance

Multilayer-coated optics have high reflectance at near-normal incidence, leading to proven and potential applications that range from x-ray astronomy to nanoelectronics. 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 exceeding 50% for a limited range of wavelengths longer than 124 Å, which corresponds to the $L_{2,3}$ edges of silicon. Mo/Si multilayers reflect well in this range, partly because Si is relatively transparent at energies below its absorption edge. At shorter wavelengths, multilayer normal-incidence reflection falls rapidly, presumably because the wavelengths are closer to the size of structural imperfections associated with the layers and interfaces, and the reflectance diminishes.

We are pursuing several means of improving multilayer reflectance at shorter wavelengths. One of them is an ongoing earch for new material combinations; we are experimenting with multilayers that alternate ruthenium with carbon, boron, or boron carbide. Near the boron edge, Ru/B_4C multilayers hold great promise as normal-incidence reflectors; multilayers grown and measured in our labs have shown reflectance in excess of 15% at a wavelength of 70 Å. In addition to measuring the normal-incidence reflectance of these structures, we use techniques such as transmission electron microscopy and nonspecular x-ray scattering to study the structural imperfections that are thought to reduce reflectance.

Multilayer Phase Retarders for the Extreme Ultraviolet

Many techniques for examining samples with x-rays call for optical elements that have specific polarization properties, such as linear polarizers and phase retarders. Such optical elements can also be used to generate beams with specific polarization states and to modulate those states. Multilayer phase-manipulating optics are important recent subjects of investigation for CXRO. Developing such optics is a great challenge, but it holds the potential for providing a simple, inexpensive route to polarization control with existing sources.

The physical basis for these devices is the polarization dependence of electromagnetic scattering, combined with the geometry-dependent reflectance of multilayers. When the Bragg reflectance peak is very close to 45° (for a total scattering angle near 90°, as shown in Figure 4-2), the component of the radiation that has an electric vector in the scattering plane is extinguished by the extremely small reflectance at that angle. The result is a linear polarizer. Such devices have been investigated by a number of groups.

A differential phase change between two polarization components of a radiation beam upon interaction with a material can be achieved with a multilayer by using either the reflected or the transmitted beam. Calculations show that such a phase retardation can approach 90° at an energy of 100 eV in the case of the molybdenum-silicon multilayers we are studying. Such a device could be used as a quarter-wave plate to convert linear polarization to circular polarization and *vice versa*. The major challenge is the development of high-quality free-standing multilayers* that can work in the transmission geometry as well as in the reflection geometry. Recent collaborative measurements with the group at Tohoku University, using free-standing multilayers made at CXRO, confirmed the theoretical predictions. As the multilayers were not ideal, improvements in performance can be expected.

At shorter wavelengths, the magnitude of phase retardation in the transmission mode decreases along with the optical constants of the materials and the quality of the multilayers. These limits have not yet been established. From 300 to at least 3000 eV, no optical means of achieving significant phase retardation have been demonstrated.

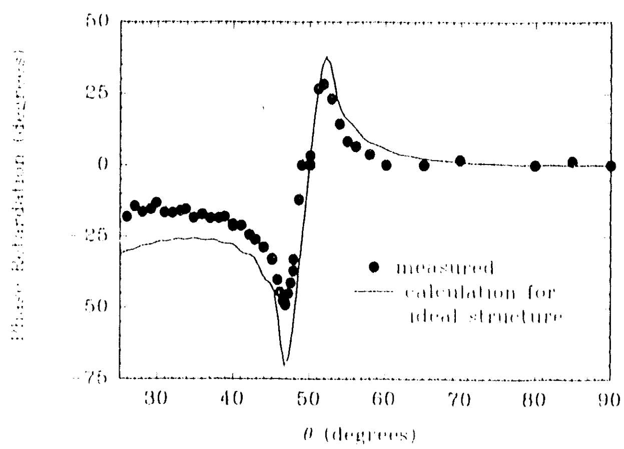

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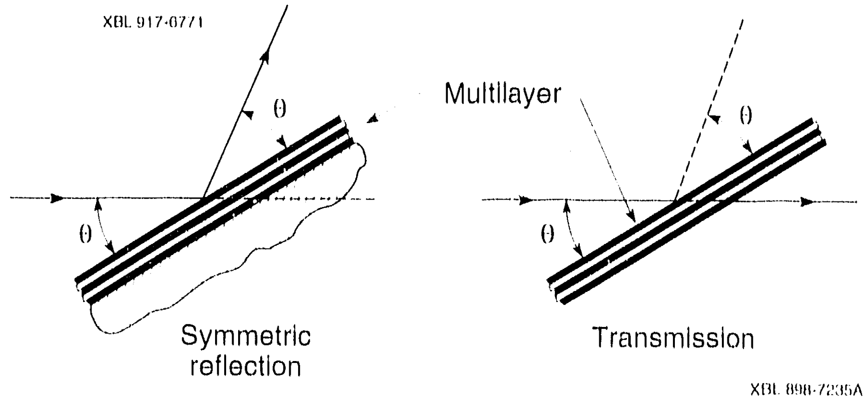
Figure 4-2. Phase retardation of soft x-rays can be obtained in both the reflection and the transmission geometries when the Bragg peak is near 45° (total scattering angle near 90°). The graph shows data from the first measurement of soft-x-ray phase retardation. The experiment used a free-standing Mo/Si multilayer at 97 eV. Also shown is the retardation predicted for an ideal multilayer structure with the same parameters. These measurements were made at Tohoku University.



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* The multilayer *mirrors* used in some of CXRO's other programs are made up of multilayers on a substrate.

XUV Reflectometer

Development of means for characterizing optical elements must go hand in hand with the development of the optics themselves. We recently completed a soft-x-ray/extreme-ultraviolet reflectometer based on laser-induced x-ray emission from a plasma. The plasma is generated by a neodymium:yttrium-aluminum-garnet (Nd:YAG) laser, as diagrammed in Figure 4-3. The reflectometer uses a unique high-throughput monochromator designed and built at CXRO that varies the wavelength transmitted to the optical element being tested. (A monochromator of the same design was used in the High Fluence Laboratory XUV Source that we developed together with Sandia National Laboratories in Livermore, a 1990 R&D 100 award winner.) One of the immediate applications of our new reflectometer will be characterization of our short-wavelength multilayer optics. A recent measurement of the Ru/B_4C multilayer's reflectance is shown in Figure 4-4.

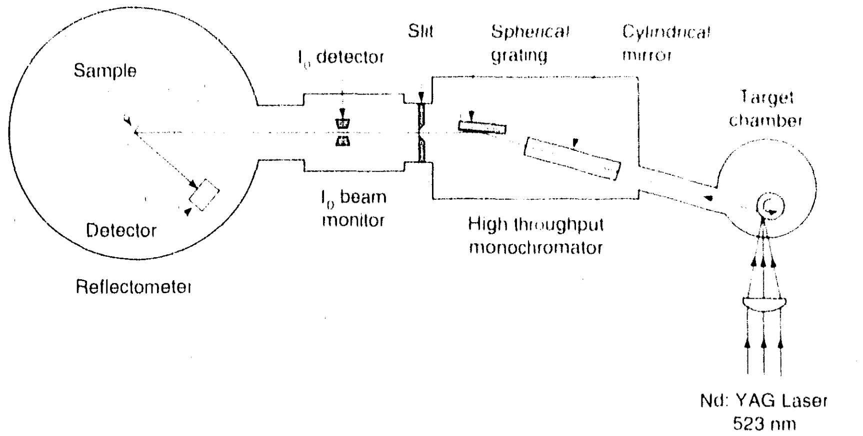


Figure 4-3. The new CXRO extreme-ultraviolet reflectometer uses a laser-produced plasma; the desired wavelength is selected from its broadband x-ray output with a unique high-throughput monochromator designed and built at LBL. (Conventional reflectometers use an x-ray tube of fixed wavelength.) The wavelength range extends from about 30 to 400 Å. One of the immediate applications is characterization of our short-wavelength multilayer optics, such as the Ru/B_4C multilayer.

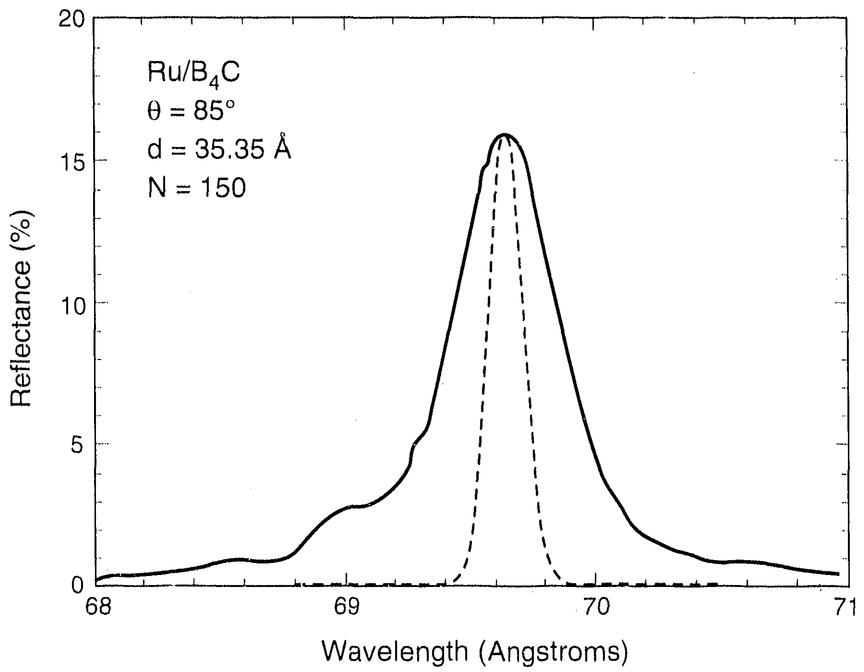


Figure 4-4. With our new XUV reflectometer, we measured this reflectance profile for a Ru/B_4C multilayer designed to reflect at a wavelength of about 70 Å. The dashed curve shows the resolution of the monochromator at these wavelengths.

Soft-X-Ray Small-Angle Scattering

Another application of multilayer-coated optics may fill a significant gap in the coverage of present-day techniques for small-angle soft-x-ray scattering measurements. The SXSA-447 is a combination sample chamber, focusing apparatus, and detector for analyzing particulates and thin films with small-angle diffraction of soft x rays. Through mathematical analysis of the interference patterns that result from scattering of x rays by the sample, a variety of characteristics of the sample can be determined, including the sizes of micrometer and submicrometer particles within it, the structure of the particles (solids, hollow shells, and so forth), and, in the case of thin films, periodic or nonperiodic structures. The incident beam is gathered and focused with one of the periodic multilayer-coated mirrors that are among CXRO's specialties. The apparatus won a [illegible] R&D 100 award, given annually by *[illegible] Magazine* to recognize the year's 100 most significant technical innovations.

Hard-X-Ray Microprobe

The latest development of our hard-x-ray microprobe (Figure 4-5) is a portable version that can be readily moved from one synchrotron-light source to another. It is similar in operating principles to its predecessor, and appears to be comparable in performance as well, providing both micrometer spatial resolution and femtogram elemental resolution with 30-second exposures. The data the microprobe provides — what elements a sample contains and where they are concentrated — are useful in many scientific disciplines.

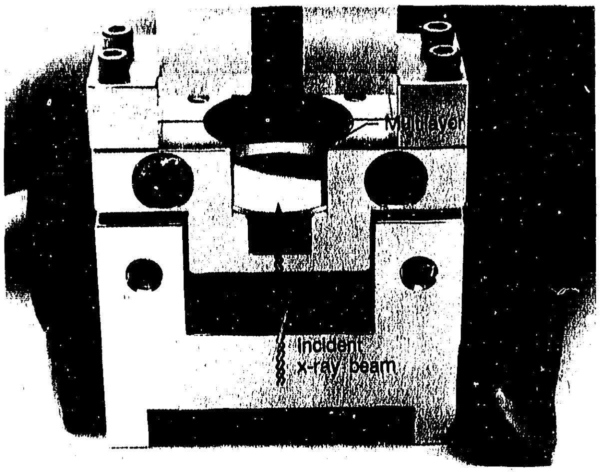
The new microprobe is based on a pair of concave, spherical multilayer-coated mirrors that serve both as focusing elements and as monochromators for the incoming x-ray beam. Following the mirrors, we have a scanning stage to raster-scan the sample; an optical microscope for prealignment of the sample; an x-ray fluorescence detector; and a beam-intensity monitor. A computer controls the system and provides rapid analysis and display of the recorded data on elemental concentrations. Figure 4-6 shows a typical set of data: the concentration of titanium in a silicon carbide ceramic. The false-color display makes it easy to visualize complicated quantitative data.

The portable microprobe has thus far achieved a spot size of 2 μm × 2 μm at a bending-magnet beamline at the NSLS. By tuning the mirrors to energies just below the K absorption edge of major elements in a sample, the elemental sensitivity for lighter trace elements is greatly improved, as compared to electron-stimulated techniques.

Recently we used our system on a high-energy x-ray undulator beamline at the Cornell High Energy Synchrotron Source (CHESS). In this collaborative experiment with Oak Ridge National Laboratory, the University of Chicago, Argonne National Laboratory, and Cornell University, we studied different x-ray optical elements for potential use on microprobe beamlines at the new third-generation x-ray facilities. Our multilayer mirrors were able to provide the best focus of a 250 μm × 250 μm undulator beam, achieving a 4 μm × 8 μm spot. Working with several user groups, we are currently developing plans for dedicated microprobe beamlines that use focusing optics on the NSLS, the ALS, and the Advanced Photon Source (APS).* With the lower emittance of the ALS and APS, we will be able to achieve a beam spot size of 1 μm × 1 μm. The APS, where we will have access to a hard-x-ray

* A 7-GeV "third-generation" synchrotron-radiation source being built at Argonne National Laboratory.

Figure 4-5. The hard-x-ray microprobe has been used to achieve 2-μm spatial resolution, along with femtogram elemental sensitivity, at Beamline X26 of 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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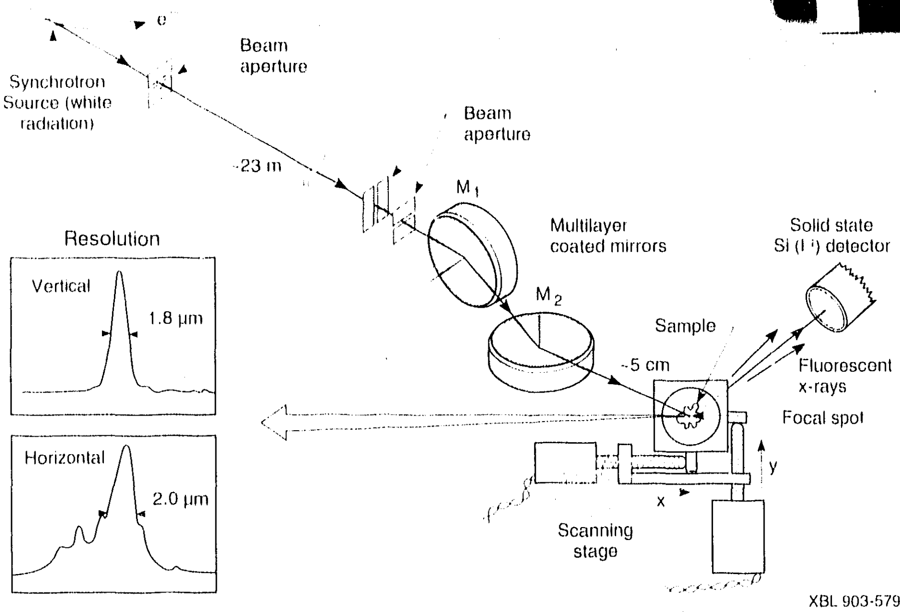

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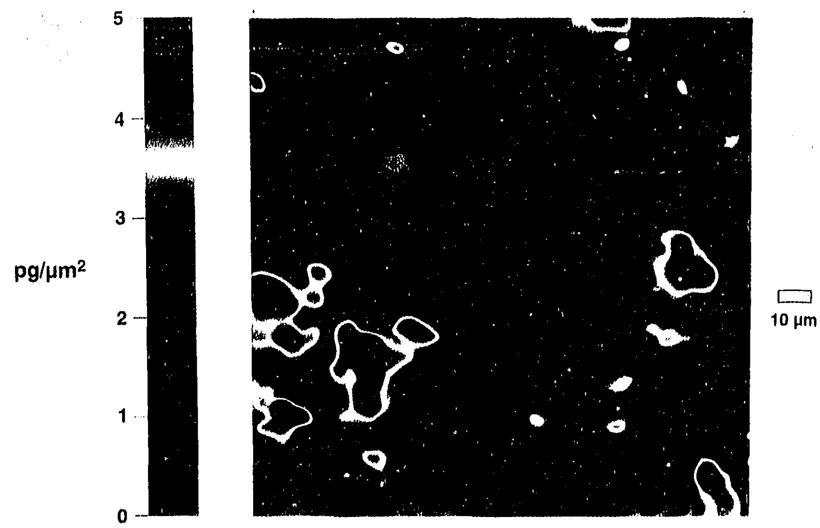
Figure 4-6. Data from the hard-x-ray microprobe shows the concentration of dilute amounts of titanium in a silicon carbide ceramic. In this false-color plot (rendered here in black and white), the color bar quantifies the range of concentrations. Such ceramics exhibit characteristic tensile and fractile strengths based on the uniformity of titanium through the ceramic. This can be controlled by the temperature of the material during the sintering process. The measurements were made at the NSLS.



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undulator, will also provide higher intensity. The microprobes at these facilities will use elliptically curved multilayer mirrors to improve the focus, and will scan the beam instead of the sample for greater experimental flexibility.

Spectroscopy with X-Rays

The Center for X-ray Optics has always been 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. 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

To achieve high spectral resolution without compromising throughput, 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 used for x-ray-laser studies at Lawrence Livermore National Laboratory's Nova facility. In addition, we have continued our studies of advanced monochromator and spectrometer designs for several synchrotron-radiation applications.

Earlier studies established that the varied-line-spacing designs can achieve resolution at least as high as conventional designs with the same tuning range. Recently we have developed computer codes that use ray-tracing techniques to simulate synchrotron radiation and estimate grating efficiency. In a theoretical study of such a monochromator for a U5.0 beamline at the ALS, we confirmed that it would provide high spectral resolution, high throughput, and small spot size with a simpler and less-costly tuning mechanism. To verify these results experimentally, we are planning to build a new varied-line-spacing plane-grating monochromator for use at BESSY.

In another application-oriented program, we are investigating design options for dividing a soft-x-ray beam among several users. This is challenging, because an undulator source in a modern, low-emittance storage ring puts out a very thin, quasi-monochromatic beam that does not lend itself readily to either spatial or spectral beamsplitting. The possibilities that we are examining include wavefront splitting, high-efficiency timesharing, and splitting according to diffraction-grating order. The findings will be especially relevant for beamlines at third-generation synchrotron-light sources. Present studies are focused on the ALS U3.9 undulator beamline, which is intended for biological microscopy and research in coherent optics.

A high-throughput, high-resolution spectrograph based on varied-line-space gratings, designed and built by CXRO, is installed on the two-beam x-ray laser chamber at Nova. The instrument continues to provide time-resolved spectral profiles for x-ray emissions in the wavelength range of 155-210 Å, as illustrated in Figure 4-7. It is now fully operational and achieves a spectral resolving power ($\lambda/\Delta\lambda$) in excess of 20 000. The line-profile data have proved to be invaluable for understanding physical processes in the Nova x-ray laser facility and are in demand for diagnostic measurements of other kinds of laser-produced plasmas. CXRO is involved

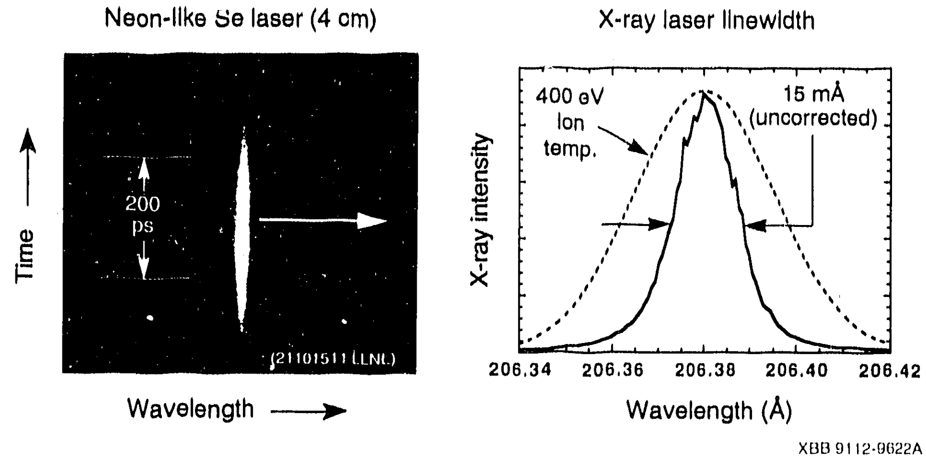


Figure 4-7. Using the CXRO time-resolved high-resolution spectrometer, x-ray-laser line narrowing has been measured for several lasing lines at LLNL's Nova facility. Shown here is the 206.38-Å line of neon-like selenium from a target 4 cm long. The line width is 15 mÅ full width at half maximum. Though not yet corrected for instrumental broadening, this is significantly narrower than the 36 mÅ that would correspond to a 400-eV Doppler-broadened emission line in the same plasma.

in design studies for a new instrument that will operate at 44.83 Å, which is the wavelength of the Ni-like-tantalum laser, and is considered ideal for holographic imaging of biological material.

Coronary Angiography

X-ray beams from a synchrotron source—monochromatic, well-collimated, and intense—provide unique opportunities for medical imaging. One of them is a new method of coronary angiography that uses venous injection of contrast agent, as opposed to arterial injection. For several years we have collaborated with colleagues from Stanford, Brookhaven and elsewhere who are working on this new, safer method. A new step toward large-scale tests of clinical applicability was taken in 1990 with the completion of a dedicated medical-imaging facility on a special wiggler beamline at the NSLS. Three patients' hearts have been imaged there; the results are not yet equivalent to conventional angiograms, but they are approaching clinical usefulness, and the technique is dramatically easier and safer for the patients.

Progress toward Clinical Quality

Using an upgraded imaging system previously tested at the Stanford Synchrotron Radiation Laboratory, three patients were examined in late 1990 and early 1991. Figure 4-8 shows the resulting image from one of the patients. Shown next to it is an earlier angiogram from the same patient, taken with the conventional, highly invasive, and somewhat risky technique of x-ray angiography using arterial injection of contrast agent.

The images obtained thus far clearly indicate that large portions of both the left anterior and the right coronary arteries can be examined with this method. Various changes are now underway to further improve the image quality. Later, a medical research team will begin to use this technique on a large group of patients, comparing the new method to standard coronary angiography and also studying the effect of various medical treatments on the progression of coronary artery disease.

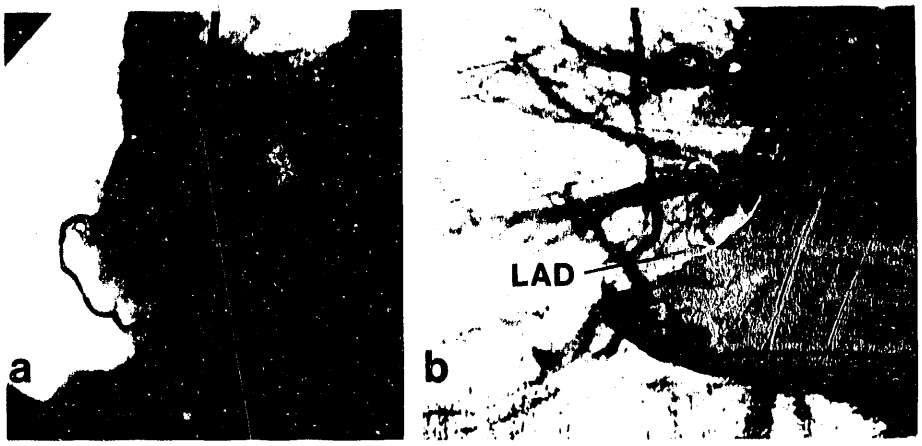
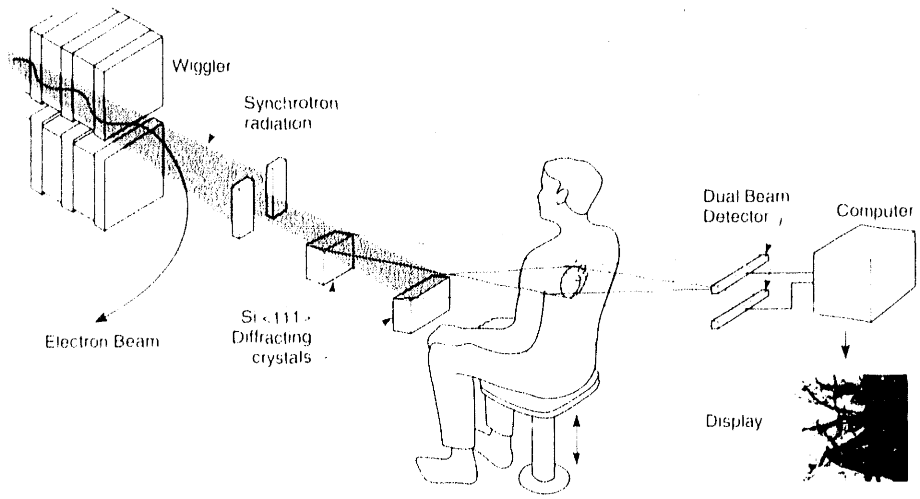


Figure 4-8. An angiogram made with arterial injection of contrast agent, an invasive and risky procedure, is shown at *left*. At *right* is an angiogram of the same patient taken with the synchrotron-radiation method, which uses venous injection. Clearly visible in both images is a total occlusion of the right coronary artery. The patient attended a Broadway musical the evening after the synchrotron angiogram—a recovery time unheard of with arterial angiography. This work is part of a long-term collaboration with Stanford University; Brookhaven National Laboratory; the North Shore Hospital on Long Island, NY; the Veterans Administration hospital in Palo Alto, CA; and the University of Tennessee. The images were obtained on the X17 beamline at the NSLS.



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5. EXPLORATORY STUDIES

THE TWO MAJOR ACCELERATOR-BASED INITIATIVES launched in 1989 with the support of the Exploratory Studies Group continued their progress. PEP-II, a proposed energy-asymmetric B-meson "factory" based on the PEP (Positron-Electron Project) ring at the Stanford Linear Accelerator Center (SLAC), has been the subject of ongoing research, design, and development and has stimulated great interest in the worldwide high-energy physics community. Meanwhile, 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).

Other topics of special relevance to various research communities are important in our work. We continue to search for and explore techniques for generating ultrashort bursts of x-rays lasting tens to hundreds of femtoseconds. Members of our group have played major roles in the initial commissioning of the Advanced Light Source injection complex (see Chapter 3 of the *AFRD Summary of Activities*), and we are studying ideas for an experimental facility that would use the ALS linac during the considerable

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spans of time between the ALS injection cycles. Work continues in accelerator theory and nonlinear dynamics. The Collider Physics section has continued its long-range Two-Beam Accelerator research. And the Beam Control Electronics section, in addition to contributing to and supervising the multilaboratory B-factory rf and feedback design efforts, worked on beam-cooling improvements for the Tevatron's antiproton source and is supporting the rf, impedance, and feedback aspects of the ALS.

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 charge-parity (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. In collaboration with the Stanford Linear Accelerator Center (SLAC), Lawrence Livermore National Laboratory (LLNL), and the California Institute of Technology, we are designing a facility based on one of the most promising schemes: PEP-II, a collider with one high-energy ring and one low-energy ring, built in the PEP tunnel at SLAC and re-using many PEP components. Such a collider would be scientifically and economically attractive.

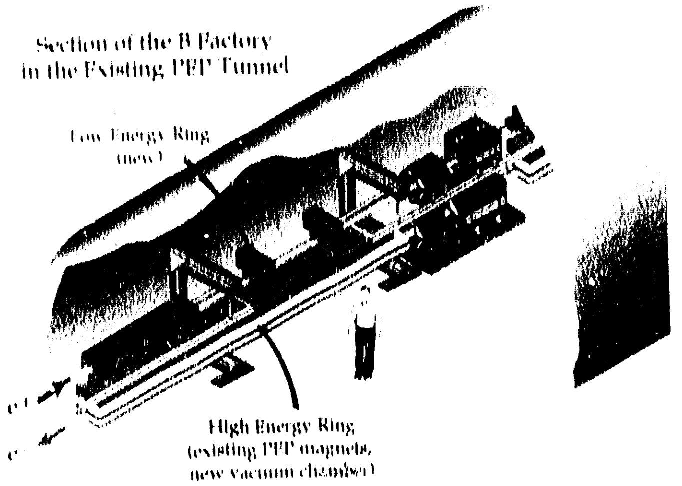
Conceptual Design

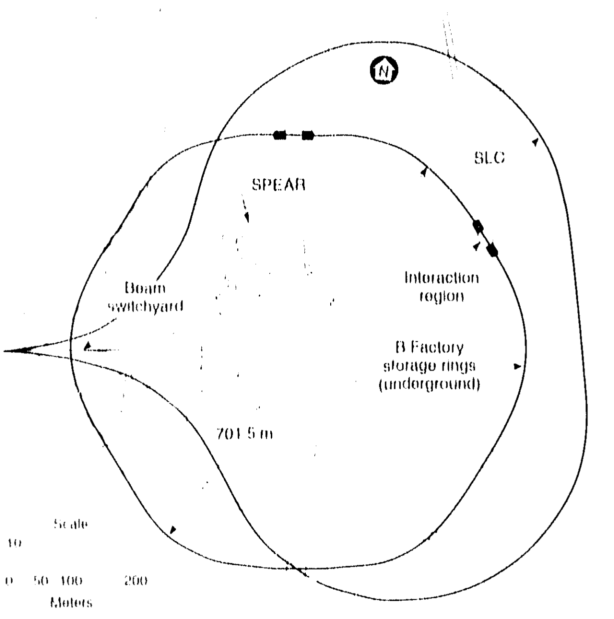
During 1990 and 1991 the collaboration continued refining the design of a B factory in which a 9-GeV electron beam in PEP collides with a 3.1-GeV positron beam circulating in a new storage ring. The new low-energy ring will be the same circumference as PEP and will be mounted above it in the existing tunnel, as shown in Figure 5-1. Using the same circumference permits equal numbers of bunches in the two rings, even if a gap in the bunch train is left in the high-energy ring to combat ion trapping. Moreover, a large low-energy ring provides a long luminosity lifetime (the relative loss in luminosity from beam-beam collisions scales inversely with ring circumference). The chosen energy combination reach the Upsilon (4S) resonance, at which $B\bar{B}$ pairs are produced in the abundance required for the study of CP violation. The challenge in the design of a B factory is to reach an initial luminosity of 3×10^{33} cm^{-2} s^{-1}, more than an order of magnitude beyond the luminosities achieved to date in electron-positron colliders.

In principle, all of the relevant parameters—the ratio of the cross sections of the two beams, the beam current, the beam-beam tune shift, the beam energy, and the vertical beta function at the interaction point—are adjustable. In practice, however, the beam-beam tune shift cannot be increased beyond a certain value, which has been determined experimentally in many colliders to lie in the range of 0.02–0.06. Similarly, a collision energy at the Upsilon (4S) resonance implies that the product of the beam energies must be 28 GeV^2. Thus, only three parameters—the beam-size ratio, the beam current, and the vertical beta function at the interaction point—are fully at the disposal of the accelerator designer.

The chosen luminosity, 3×10^{33} cm^{-2} s^{-1}, has been shown to be adequate for beginning the study of the key physics issue, CP violation. However, if more-detailed measurements are subsequently desired, additional development work should permit the design to reach even higher luminosities. Given the limitations caused by the beam-beam interaction—which we take for our design to correspond to a maximum tune shift of 0.03—a great increase in luminosity implies that the high-current beam must be separated

Figure 5-1. The proposed asymmetric B factory, PEP-II, would be built in the Positron-Electron Project tunnel and would use a substantial amount of the existing hardware for the PEP collider. (Artist's impression courtesy SLAC)





into a large number of individual bunches (1658 in our design). This approach involves a design in which the single-bunch parameters (emittances, bunch lengths, currents, tune shifts, etc.) are well within present practice for colliders. Our choice does not exacerbate problems with coupled-bunch instabilities, yet avoids problems from single-bunch effects.

Since the beginning of the conceptual-design phase of the project, a number of design issues have been clarified, and most of the design choices have been made. Particular topics that have been investigated include:

- Heat load on the vacuum chamber wall from the synchrotron radiation, which can reach 10 kW/m at maximum beam current in the high-energy ring.
- Gas load from the synchrotron-radiation photodesorption in the high-energy ring.
- Damping of the higher-order-mode impedance of the rf system, which drives strong coupled-bunch instabilities.
- Separation of the closely spaced beam bunches near the interaction point while minimizing detector backgrounds.

For PEP to serve as the high-energy ring, several of its systems must be significantly upgraded to deal with the issues listed above. Foremost among these are the rf and vacuum systems. The rf system for the B factory will consist of 20 single-cell cavities, operating at a frequency of 476 MHz in order to phase-lock the storage ring rf system to that of the 2856-MHz injector (the "two-mile linac" also used to inject the Stanford Linear Collider). This choice of frequency minimizes injection phase errors, which contribute significantly to the power demands of the multibunch feedback system. The cavity design itself is aimed at minimizing the higher-order-mode impedance contribution of the rf system.

To handle the high synchrotron radiation power and to minimize photodesorption of gas, copper was chosen as the vacuum-chamber material. A number of experimental studies confirmed that a desorption coefficient of roughly 2×10^{-6} will be achievable for copper after proper pretreatment and conditioning with a beam. A copper chamber has the additional benefit of being self-shielding against the synchrotron radiation produced by the beam.

After a number of detailed studies, we have decided to utilize a conventional "flat-beam" configuration for the rings. This choice was dictated primarily by the desire to reduce the synchrotron radiation produced near the interaction point to a more-manageable level. With optics designed to focus a round beam at the interaction point, approximately 750 kW of synchrotron radiation would be produced in this region; the use of flat-beam optics reduces this by about an order of magnitude. Furthermore, using flat beams makes it possible to lower the vertical beta functions at the interaction point by a factor of 2 compared to the round-beam case, and thus to retain essentially a constant luminosity at a given beam current. (There is some

B Decays and CPT Symmetry

Judging particle interactions by the standards of the familiar, macroscopic world, one would think that if a process and the participating objects were replaced either by their antimatter equivalents or by versions of themselves as seen in a mirror, the rate of the process would remain the same. It seems equally intuitive that reversing a process would yield the original participants, much as though one were running a movie in reverse and watching the actors run backwards in their own footprints.

But on the scale of subatomic particles and the quarks that make them up—a scale where the "weak interaction" becomes the strongest of forces—the first two rules, called "conservation of parity" and "charge conjugation," are not necessarily obeyed. Not even CP symmetry, which combines both rules, necessarily holds true. The remaining variable is time; we are left with CPT symmetry—a scheme in which C, P, and CP symmetry violations can occur, but only if the arrow of time is allowed to take a different course when reversed, going back to a different beginning.

Thus far, CP violation has been observed through asymmetries in the decay modes of the neutral K meson and its antiparticle. The K^0 and $\bar{K}^0$ contain an unusual quark, the "strange" quark, which is not found in the group of quarks that make up ordinary matter. The K decays in a wide variety of fashions (it is axiomatic that every decay mode not explicitly forbidden must eventually occur). In a few of these modes, the K^0 decays a few tenths of a percent differently than the $\bar{K}^0$, a sign of CP violation. But studies of the K system have left a great many questions unanswered about the mechanisms and magnitude of CP violation.

The B meson, which contains a different unusual quark ("bottom" as opposed to "strange"), is predicted by the Standard Model of Particles and Interactions to have asymmetries as great as 30% in some rare decay modes. This makes it a very promising candidate for CP-violation studies. However, the branching fraction—the proportion of $B\bar{B}$ pairs that will not only decay through the unusual modes but also violate CP symmetry in doing so—is only about 10^{-4} to 10^{-5}. Therefore, about 10^7 to 10^8 $B\bar{B}$ pairs will have to be produced in order to get good CP-violation statistics. This requirement, implying the need for a great many e^+e^- collisions, brings us to the luminosity frontier of accelerator physics, whose technical challenges are described elsewhere in this chapter.

The ultimate goal of this research is to enhance the Standard Model—today's partial theory of the building blocks of nature and how they interact—or replace it with a new, more-satisfactory theory. In either case, CP violation will have to be better quantified, and its origins will have to be explained. The present Standard Model does not disallow CP viola ion but does not explain it either. These studies also have ramifications beyond particle physics.

In 1967, not long after the discovery of CP violation, Andrei Sakharov pointed out that it might explain one of the longstanding riddles of cosmology: why the universe was not born with equal, evenly distributed quantities of matter and antimatter that would annihilate each other whenever they interacted. For some reason, the laws of nature appear to prefer matter over antimatter—a phenomenon that makes possible the physical universe we see every day. Such will be the implications of the research at PEP-II.

suggestion from simulations that round beams may permit a greater beam-beam tune shift. However, it does not seem likely that such a tune-shift increase would permit a reduction in beam current sufficient to obtain a reasonable decrease in the synchrotron-radiation power near the IP.)

For the initial collider configuration, we intend to employ head-on collisions, using the S-bend geometry illustrated schematically in Figure 5-2. An alternative scheme, involving a non-zero collision angle along with tilted bunches ("crab crossing"), offers the potential advantage of reduced background at higher luminosities, but will require significant R&D effort to verify its performance. Although we do not think it prudent to adopt this scheme immediately, the possible benefits have convinced us to retain crab crossing as a possibility for a future upgrade.

At present, most of the problems have been addressed in a satisfactory manner and technical solutions are in hand. We are now involved in the detailed engineering design of the various components. A conceptual design report was submitted to the Department of Energy in February 1991 and was successfully reviewed that March.

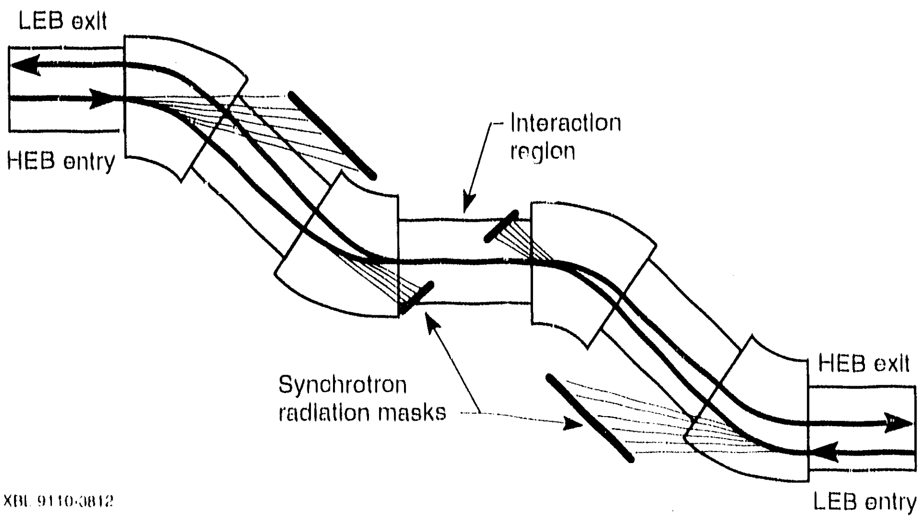


Figure 5-2. An S-bend design for a head-on collision configuration was chosen for the interaction region of the initial PEP-based B factory. This layout does not rule out a possible future upgrade in which flattened beams would cross "crabwise" at a finite angle.

Chemical Dynamics Research Laboratory

The Chemical Dynamics Research Laboratory (CDRL) is a key new facility in the multi-laboratory Combustion Dynamics Initiative (CDI). The CDI is being put forward by the DOE's Division of Chemical Sciences to provide a foundation in chemistry and combustion science and technology for enhancing energy and environmental efficiency, securing future energy supplies, and enhancing environmental quality—all key parts of the National Energy Strategy. The focus of the CDI is on cleaner, more efficient combustion of fossil fuels. They account for more than 90 percent of U.S. energy consumption, a situation that will continue well into the next century. Even an increase in combustion efficiency or pollution reduction of a few percent would have tremendous payback. Such improvements might be achieved by starting with a systematic understanding of the fundamental chemistry of combustion and related industrial processes.

The research proposed for the CDRL (sidebar) is aimed at gaining a rigorous, molecular-level understanding of the chemistry of the combustion process. This understanding will lead to enhanced combustion efficiency and reduced production of pollutants. Success in these areas is of critical importance to the nation's environmental quality and economic competitiveness.

The CDRL is proposed for LBL with significant participation by Sandia National Laboratories (SNL). Because of the complementary research capabilities of the two laboratories, this partnership will enable progress that would be beyond the reach of either laboratory acting alone. SNL researchers will be responsible for the construction and operation of some of the experimental equipment, and will play a key role in the scientific program and the transfer of combustion technology to industry.

CDRL: A Unique Combination of User Facilities

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. At its heart is the infrared free-electron laser (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 machines, will enable research that will have a great impact on our understanding of chemical dynamics and combustion chemistry.

The IRFEL will be installed in a new building adjacent to the ALS (Figure 5-3) so that photon beams from both facilities can be delivered to the experimental stations. The ALS beamlines have been another area of study and development by our group, in collaboration with the ALS staff and the Center for X-Ray Optics. Advanced optical lasers are being designed by

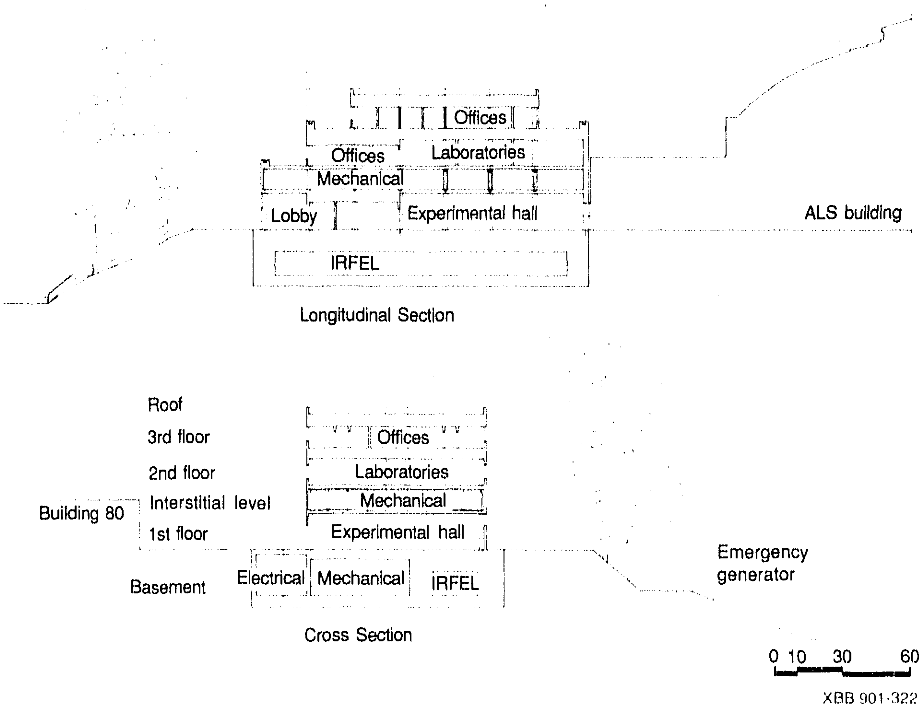


Figure 5-3. The four-story CDRL building will be located adjacent to the ALS so that the IRFEL and conventional-laser beams can be brought together with UV and soft-x-ray beams from the ALS. The CDRL main experimental hall, on the first floor, will be served by one bending-magnet beamline and one insertion-device 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.

colleagues from both the University of California at Berkeley Chemistry Department and Sandia National Laboratories. These collaborators have been deeply involved in the design of experimental facilities and in the development of the research program.

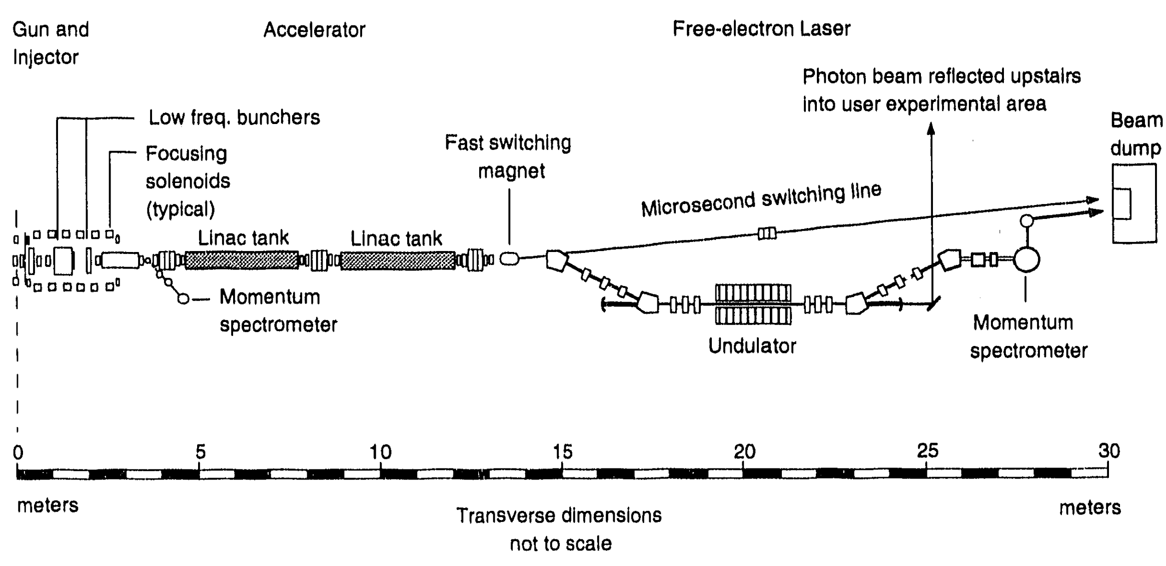
IRFEL Design Progress

A conceptual design of a room-temperature IRFEL was completed in February 1990. The FEL can operate in synchronization with the ALS and produce intense (up to 100 μJ per micropulse), narrow-band (< 0.1 %) radiation with wavelengths tunable in the 3–50 μm range. The design, shown in Figure 5-4, uses two sections of standing-wave L-band linac to accelerate electrons up to 50 MeV. The sequence of a thermionic gun, two low-frequency bunchers, and an L-band buncher establishes a micropulse width that can be varied in the 10–20 ps range. The system operates in a pulsed mode, with a macropulse duration of 100 μsec, repeating at a rate of 60 Hz. Infrared radiation is produced with a variable-gap undulator and an 8.2-m-long optical cavity with a broadly tunable outcoupling scheme.

Particular attention was paid to stability and tunability, which are crucial for the users' needs. A detailed analysis of the response of the electron beam fluctuation on the FEL characteristics was carried out through analytic calculation and numerical simulation. Also studied were various sources of fluctuations in the gun, bunchers, and accelerating sections, as well as feedback and feedforward schemes to reduce these fluctuations. Our studies show that the FEL spectrum can be stabilized to about 0.1% using this approach.

A standing-wave structure was chosen for the linac because of the need for electron-beam stability. Spectral stability could be further improved to about 0.01% by introducing a grating into the optical cavity, but at the price of reduced tunability. Various schemes to couple out the optical beam over the entire wavelength range were evaluated. Hole coupling with metallic optical components appears to be the most promising of these approaches in terms of power handling and bandwidth capability. With a new computer

Figure 5-4. The room-temperature IRFEL design uses 1300-MHz side-coupled standing-wave linacs. Two sections of standing-wave L-band linac accelerate electrons up to 50 MeV. The sequence of a thermionic gun, two low-frequency bunchers, and an L-band buncher establishes a micropulse width that can be varied in the 10–20 ps range. The system operates in a pulsed mode, with a macropulse duration of 100 μs, repeating at a rate of 60 Hz. Coherent infrared radiation is produced with a variable-gap undulator and an 8.2-m-long optical cavity with a broadly tunable outcoupling scheme.



code, the performance of the hole-coupling resonator was analyzed.

An alternate technical approach has been explored that takes advantage of recent developments in the technology of superconducting rf linacs. An FEL based on superconducting accelerating cavities could be operated in the continuous-wave (cw) mode instead of in a pulsed mode, providing an opportunity to reduce the wavelength fluctuations to 0.01% and to operate with significantly increased average output power.

A preliminary design has been developed using 500-MHz rf cavities operating at 4 K, as shown in Figure 5-5. The gun and low-frequency bunchers are similar to those in the room-temperature design, but the three L-band accelerating structures are replaced with superconducting structures. The accelerating gradient is 5 MV/m, so a single pass will accelerate the beam to ~30 MeV, corresponding to an infrared wavelength of 10 μm. A recirculation loop (*sidebar*) could be used to further accelerate the beam to 50 MeV, needed to reach 3 μm. Such a structure could be operated with a continuous-wave (cw) electron beam rather than a pulsed beam, which

Research Prospects

The CDRL, with its IRFEL and advanced lasers, will complement the ALS, which upon completion will be the world's brightest source of soft x-rays for basic and applied research. Collaborative CDRL researchers from industry, universities, and national laboratories will use the unique features of ALS x-ray beams—high spectral brightness and very short pulse length (nominally tens of picoseconds). Undulators in the storage ring will provide somewhat spatially coherent radiation—sometimes referred to as "laserlike"—that is broadly tunable across the soft-x-ray to ultraviolet regions of the electromagnetic spectrum.

The CDRL experimental systems will be used by collaborative researchers for dynamic, spectroscopic, and structural studies of highly reactive molecules. Many of these are created during the early stages of combustion. These studies will take place in an experimental hall where light from the IRFEL, the ALS, and advanced conventional lasers (Figure 5-6) can be directed into experiment stations to study the dynamics of fast-moving chemical processes in detail. Such fundamental knowledge—which is beyond the reach of existing experimental facilities—is crucial for improving the efficiency of combustion and controlling the formation of pollutants.

Other LBL divisions, the University of California at Berkeley, and Sandia National Laboratory-Livermore are prominent among the organizations whose scientists are developing the CDRL research program. Research results will feed directly into U.S. industries concerned with cleaner combustion, alternative fuel supplies, reduced pollution, and improved industrial processes. Many regions of the nation face significant economic curtailment during the coming decades if air pollution from mobile and stationary sources is not controlled more effectively. The CDRL can provide a foundation of fundamental understanding that will enable long-term success in solving these problems.

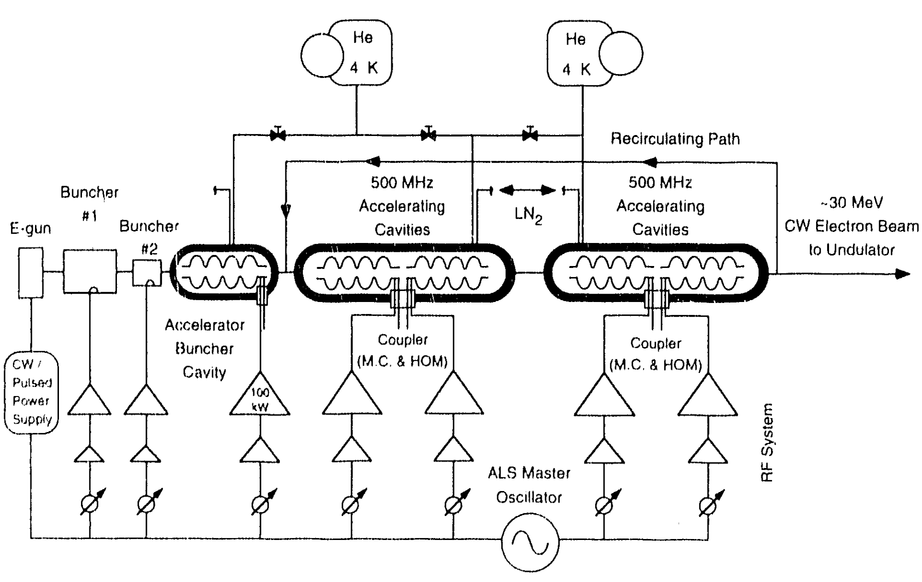
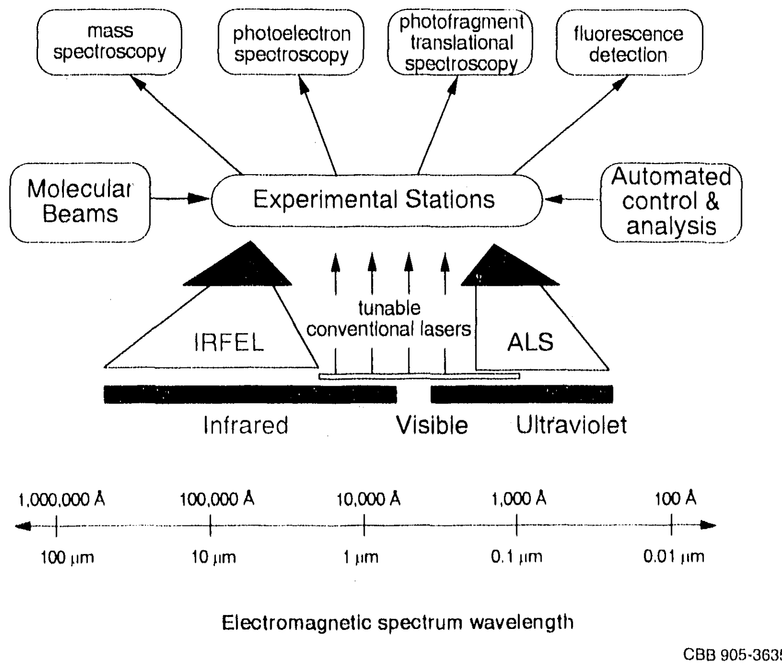


Figure 5-5. This IRFEL, based on 500-MHz niobium-titanium superconducting linacs, is being studied. A superconducting linac would allow continuous rather than pulsed beams and would lend itself to various recirculator options.

Figure 5-6. A key to the scientific potential of the CDRL is the unprecedented integration of several technologies over a wide spectral range. Tunability, synchronization capabilities, and time resolution on the order of picoseconds are among the other important features of the proposed facilities.



An Advanced IRFEL Option

We have speculated extensively on future possibilities that could be implemented either in a CDRL upgrade or in some other facility. One of them is a recirculating, superconducting accelerator.

In the present design, as in nearly all linacs, the electron beam makes a single pass through the accelerating cavities. But a number of laboratories have been examining superconducting, recirculating linacs. (The concept is, in fact, at the heart of the Continuous Electron Beam Accelerator Facility, which is being built in Newport News, Virginia.) Although complicated and not without technical risk, recirculating linacs offer great promise for achieving high beam energies and intensities in relatively short accelerators.

With an extra, in-phase pass through the accelerating cavities, the beam could reach an energy of 50 MeV, greatly extending the short-wavelength capability of the IRFEL. In another operational mode, the recirculated beam could instead be introduced into the cavities 180° out of phase with the rf. This would decelerate the beam, putting its power back into the rf cavities in a sort of flywheel effect for use on the next pulse. The electron beam, and hence the optical beam, would be quite powerful.

Our work on the recirculation scheme is only beginning to address such important issues as isochronous beam transport and safe dumping of energetic, intense beams. Nor has it examined in detail the physical logistics of building the system (with, possibly, a longer lasing cavity) in the CDRL shielding vault. However, these speculative, long-range studies point the way to the future of the CDRL and help us avoid inadvertently making decisions (such as the placement of thick concrete shielding walls) that would lock out future options.

implies a time-averaged optical power in excess of 600 W. We continue to study the technological and scientific implications of operation at this high power. Table 5-1 compares this option with the room-temperature design. Note especially the tremendous increase in average optical power, achieved without sacrificing beam quality.

Table 5-1. Proposed IRFEL Characteristics

	Room Temp	Superconducting
Accelerator		
Type	SW side-coupled	SCA
RF frequency (MHz)	1300	500
Maximum energy (MeV)	56	~ 50
General properties		
Wavelength λ (μm)	3–50	3–50
Linewidth	transform-limited	transform-limited
Bandwidth stability δλ/λ	10^{-3}	10^{-4}
Intensity stability δI/I	0.1	≤ 0.1
Average power (W)	≤ 20	≤ 600
Micropulse		
Energy (μJ)	100 at 50 MeV	50–100 at 50 MeV
Duration (ps)	10–25	≈ 30
Repetition rate (MHz)	36.6	6.1–12.3
Macropulse		
Energy (J)	0.36	
Duration (ms)	0.1	> 10
Repetition rate (Hz)	60	flexible to cw

ALS Beam Physics Facility

In the ALS, the site of photon-beam generation is an electron storage ring with a predicted useful beam lifetime of several hours. The injection linac will be idle for several-hour stretches between injection cycles. A variety of interesting experiments, including plasma focusing, tests of accelerator structures, and generation of "chirped" photon pulses, could be conducted with that high-quality 50-MeV electron beam. We have proposed an initiative that would use the linac's "dead time" for a highly productive and cost-effective program in beam physics with minimal disruption to ALS operations. Currently, both the facility itself and the possible research program are being examined in more detail in the wake of encouraging comments from LBL's 1991 DOE High Energy Physics Review.

Facility and Operations

Figure 5-7 shows the proposed facility. Most of the focusing magnets for the beamline, which takes a 180° bend into the new cave, appear to be already on hand, left over from decommissioned caves at the SuperHILAC.* An effort is underway to evaluate the supply of salvaged magnets for appropriateness.

We anticipate that most experiments would be entirely transparent to ALS operations, involving no changes in the electron-gun and linac settings. Some special experiments might call for temporarily changing the relative

* A heavy-ion linear accelerator at LBL that formerly supported its own experimental program in nuclear chemistry but is now used only as an injector for the Bevatron. For more information see Chapter 7, "Bevalac Operations," of the *AFRD Summary of Activities*.

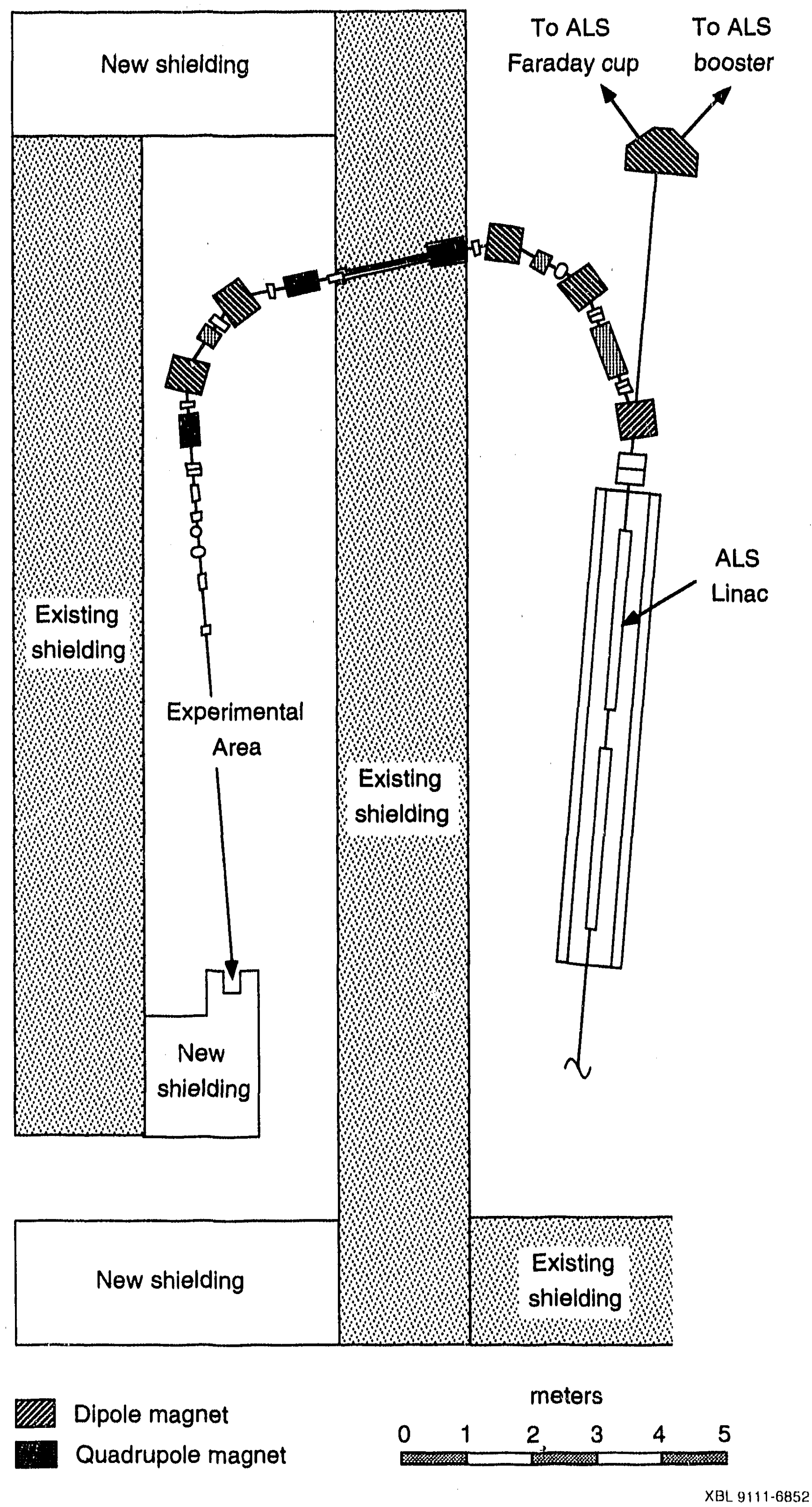


Figure 5-7. Because the ALS is based on a storage ring, the injector linac will be idle much of the time. This affords a highly cost-effective opportunity to develop a facility for beam-physics research.

amplitude and phase settings of the two linac tanks; others might require the gun pulser and the grid voltage to be turned up to their maximum capacity in terms of charge extraction and pulse-train length. The linac would remain under the overall control of the ALS throughout.

Research Program

Many interesting experiments could be performed with this conveniently available, short-pulsed, low-emittance electron beam. These four candidates appear especially attractive.

Beam-Structure Interaction Studies. Several kinds of special-purpose structures interrupt the smooth beampipe of an accelerator, including rf cavities, pickups and monitoring devices, and beam-manipulation devices such as kickers. These structures interact with the electron beam electromagnetically, limiting the maximum current which can be stored. Usually, electromagnetic characterization of such devices can be performed only through indirect strategies such as launching microwaves down the device or running rf along a wire stretched through it. The new facility would make it easy to measure a test object's response to an actual electron beam.

FEL Beam-Conditioning Cavities. The gain of a free-electron laser is limited by the energy spread and emittance, in three dimensions, of an electron beam. In principle, special rf cavities could be built that would couple these parameters, allowing one to respond to changes in the other and preserving the best possible combination. The facility would allow us to examine various candidates for beam-conditioning cavities and determine whether the idea can be realized in practice. (See "Beam Conditioning" in the Collider Physics section of this chapter.)

Chirped Radiation. Today, the shortness of synchrotron photon pulses is limited by, and comparable with, the shortness of electron pulses. An idea has evolved in our group for chirping* conveniently long (10-ps) electron-beam bunches to produce photon pulses that are much shorter. To chirp the electron bunch, that is, to give it a systematic energy tilt in phase space of 5–10%, we would "slide" it along the rf waveform of the linac by differentially phasing the two sections of the linac. Then photons would be produced, either magnetically in an undulator or through Compton scattering against a powerful laser beam. Since the head and tail of the bunch would have different energies, they would radiate at different wavelengths. A spectroscopic grating could then be used to select only one narrow slice from this band of wavelengths. Because the photons would come from a pulse rather than a continuous beam, a narrow slice of wavelengths would also mean a narrow slice of time. Applications include the many potential uses of sub-picosecond x-ray bursts, as well as, possibly, diagnostics for linear electron colliders.

Plasma Focus. When a relativistic electron beam passes through a plasma, electromagnetic interactions focus the beam. To date, most work with the plasma-focus concept has involved thin "lenses." Continuous plasma focusing holds the promise of overcoming the so-called Oide limit—a fundamental limit of focusability arising from statistical emission of high-energy photons in a sharp focusing bend. Our plans for the proposed facility include a proof-of-principle test of an idea from our group's Collider Physics section. The idea is a long, continuous plasma focus in which diaphragms

* A term for a small, rapid change in energy during a pulse, historically based in radio transmission of Morse code.

and differential pumping combine to taper the plasma density. The density would be tapered from about 1×10^{10} to 5×10^{12} cm^{-3} over a length of 0.5 m. We hypothesize that, at 5 MeV, such a device could focus a beam with a 3-mm cross section into a 400-μm spot.

Accelerator Physics for the ALS

Members of the Exploratory Studies Group have been involved in the Advanced Light Source from the outset, 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.

Beam Lifetime

One of the significant achievement of the ALS-support effort 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 oscillations were taken into account. As shown in Figure 5-8, 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 in greater depth.

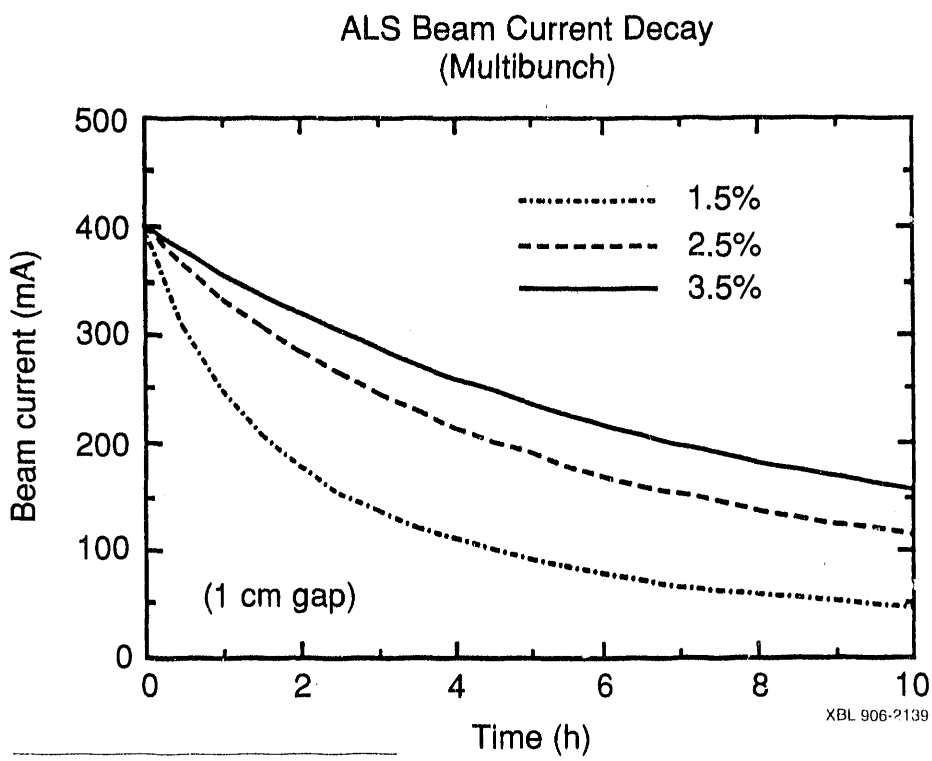


Figure 5-8. A combination of several resonance effects limits the dynamic aperture of the ALS storage ring for off-momentum particles. This reduces the beam lifetime, as shown in this plot of beam current vs. time for various degradations (1.5%, 2.5%, and 3.5%) of the energy aperture of the storage ring. The plot assumes a 1-cm (worst-case) gap at the insertion devices and realistic errors in magnetic fields.

* 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.

Control System

We modeled the behavior of the ALS to first order, and the information was applied by the ALS project in the development of the control system, which is now being implemented and used for commissioning. Figure 5-9 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.

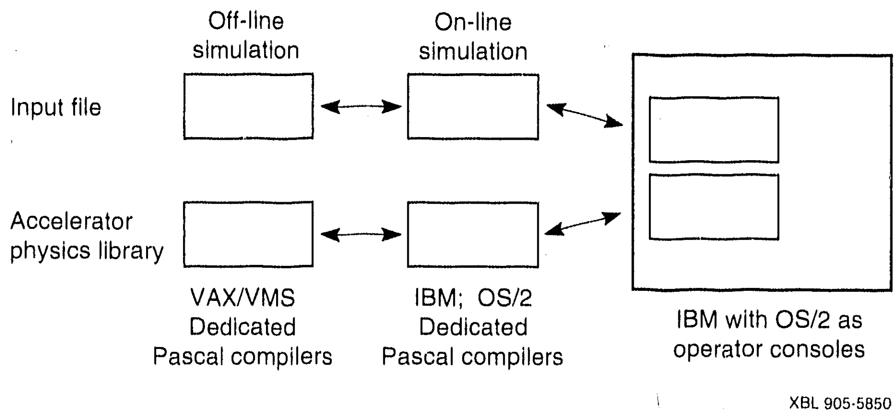


Figure 5-9. The accelerator analysis and simulation code TRACY2 can be used as an integrated environment for developing model-based control algorithms. Off-line activities can be performed under the VMS operating system on a VAX computer or under OS/2 on an IBM desktop computer. Then, given a control system using IBM computers like that of the ALS, testing with actual accelerator hardware can be performed.

Injector Commissioning Experience

Members of our group working on the ALS project have been closely involved in the commissioning of the 50-MeV injection linac and the 1.5-GeV booster synchrotron. Linac commissioning is well under way; the present efforts are directed toward maximizing the intensity and the phase and energy stability of the beam. The beam supplied by the linac has been circulated for many thousands of turns in the booster without acceleration. Soon we will begin commissioning the booster with rf, learning how to ramp up the magnetic fields and the rf power to accelerate the beam instead of merely storing it at the injection energy.

Nonlinear Dynamics and Mathematical Physics

In 1990 and 1991, we continued our theoretical investigation of nonlinear dynamics, exploring the outer limits of perturbation theory as applied to nonlinear dynamical maps. In particular, we have 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 (SLAC), and to some extent, the work of F. Willeke (DESY) and F. Schmidt (CERN). We collaborated with J. Irwin (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 technique, which involves fitted maps on an action-angle grid, has 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.

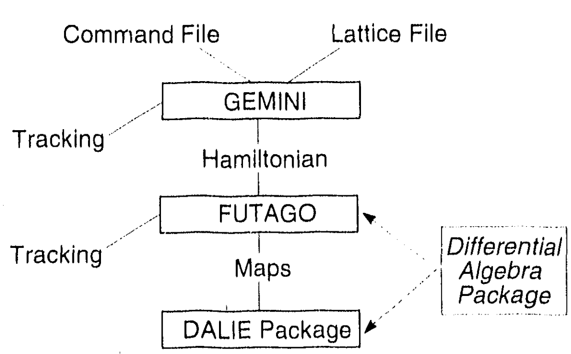
Code Development

We 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 5-10.

With applications to compact storage rings and fringe-field-dominated transport lines in mind, we 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.

Most of the existing tracking codes have been written for modeling of large accelerators that have separated-function bend magnets. These codes use particle-dynamics approximations that render them inappropriate for tracking in compact storage rings such as the SXLS at Brookhaven National Laboratory. These compact rings are becoming increasingly important, largely because of the widespread scientific and industrial interest in synchrotron radiation. To better accommodate compact storage rings and fringe-field-dominated transport lines, we have developed new tools for studying the dynamics of these systems. This effort has resulted in a new tracking code called KRACKPOT.

Essentially a "kick" code based on the symplectic-integrator concept of Forest and Ruth rather than on maps, KRACKPOT includes a tracker linked to the differential-algebra package. KRACKPOT can generate arbitrary-order Taylor series or Lie polynomial maps from which information such as tunes, chromaticity, and geometric tune shifts with betatron amplitude can be extracted. One of KRACKPOT's primary advantages over existing codes is the way it properly addresses isomagnetic combined-function bend magnets that have nonlinearities of arbitrary order. The code is being upgraded to include the effects of nonisomagnetic fringe fields.



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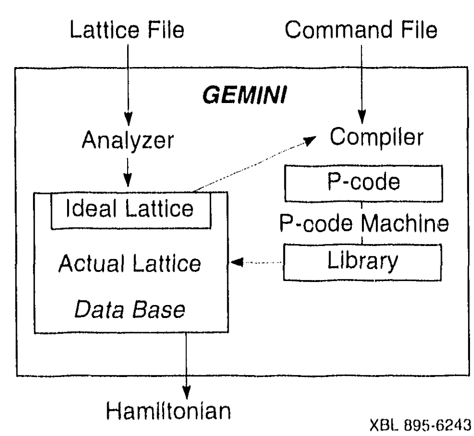


Figure 5-10. The GEMINI and FUTAGO programs can be used independently or together. The diagram at left shows their relationship; the diagram at right illustrates the interworkings of the various components of GEMINI.

* 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.

Collider Physics

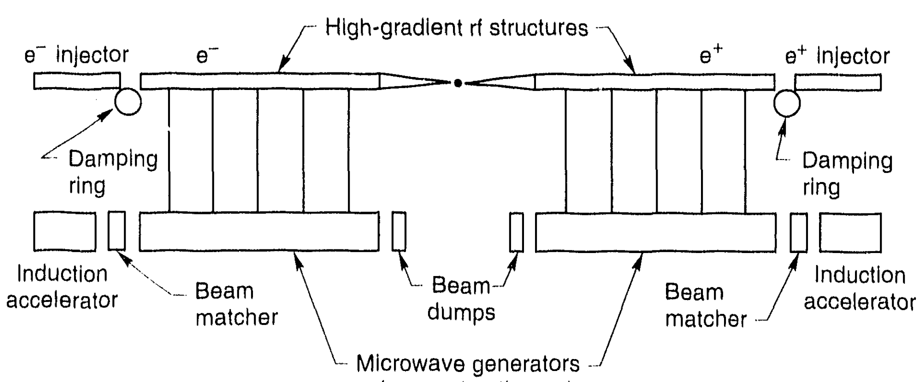
Of the many ideas that have been proposed for the electron-positron colliders of the next century, the two-beam accelerator, or TBA, appears to be one of the more promising. Conceived at LBL, it is now being investigated, in several configurations, for research programs at many of the world's accelerator 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 while in collaboration with colleagues from LLNL and SLAC, the basic components of a TBA are being developed and tested. We have continued work on the relativistic klystron (RK) as a power source for the TBA and on high-gradient linac structures.

High-Gradient Accelerator Structure

The latest of several high-gradient acceleration structures is the 10-cm-long, 34-cavity unit that was fabricated to LBL specifications by the Haimson Research Corporation. We are preparing to test it at the Massachusetts Institute of Technology, using as the power source an FEL that has already produced 50 MW. These tests will probe the breakdown threshold of the high-gradient acceleration structure at 33.31 GHz and at power levels of 20–50 MW. Acceleration gradients of 200–300 MeV/m are expected.



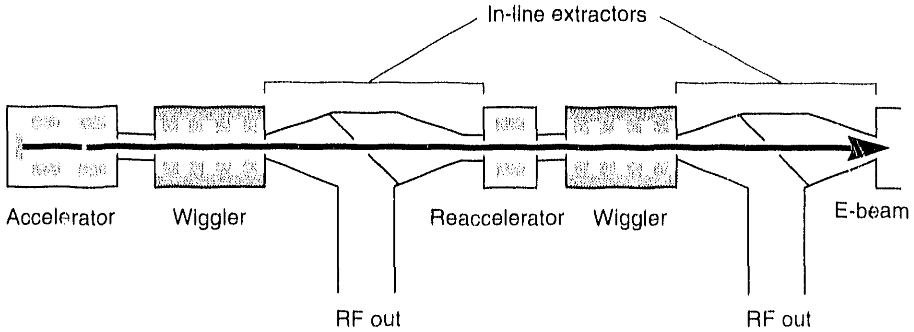


Figure 5-11. As shown in the TBA sketch *above*, a high-current, low-energy drive beam is used for generating rf power that is applied to a high-gradient acceleration structure, where a low-current load beam is accelerated to high energy. The diagram at *left* shows the progress of the drive beam through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

Transversely Modulated RK

All of the TBA/RK work performed thus far has used longitudinal bunching of the drive beam. This is adequate for low energies, but at moderate energies (greater than 3 MeV or so) it becomes less effective. To extend our work to higher energies, we experimented with a transverse chopper cavity or "choppertron," also built according to our designs by Haimson Research. We demonstrated in 1991 that the choppertron works—the peak power was hundreds of megawatts—but the pulses were short. We determined that the problem is a beam break-up mode generated in the output structure. The solution apparently lies in lengthening the beam pulse and thus reducing the peak current; we plan to accomplish this with a new rf extraction structure, which has been fabricated and will be tested in 1992.

Standing-Wave FEL

Although in recent years we have focused primarily upon the RK as a source of rf power, the FEL, explored in our original TBA research, remains a proven candidate with great potential. We are developing a new idea, called the "standing-wave FEL," in which the radiation is trapped in a standing-wave rf cavity and beat-coupled to a nearby high-gradient acceleration structure.

Horizons for the TBA

The work done on the TBA since we first conceived of it 10 years ago has validated the basic concept and the use of either an RK or an FEL as the source of rf power. However, there remains a vast amount of research and development before the concept can be put to use in high-energy physics. Here are some of the planned near-term investigations.

- Re-acceleration of the "spent" drive beam (useful for economic reasons) will be examined in a planned experiment at LLNL; preliminary work was done in 1990.
- There is much theoretical and experimental work to be done in extraction of microwaves from the power source. A demonstration of repeated extraction is being studied at LLNL. A Department of Energy Small Business Incentive Research contract is enabling DULY Associates to participate in the theoretical study.
- Sensitivity studies to determine the importance of various parameters will be important. A great deal of theoretical work has been done; coming years will see more studies on real apparatus.
- Economic issues will be significant in the eventual decision on whether to build a full-scale TBA and also in the technological choices within such a project. LLNL, with DOE support, is working on these issues.

Additionally a collaboration with the Japanese high-energy physics laboratory KEK is under way, using an FEL from which up to 30 MW of rf power has been extracted at 8.6 GHz.

Beam Conditioning

The gain of a free-electron laser or other resonant electron-beam device is limited by the energy spread and emittance of a three-dimensional beam. The electron-beam emittance must be less than the wavelength of the radiation from the device, reduced by 2π. In principle, special cavities could be built that would use the TM_{210} mode to couple the energy spread and the emittance, allowing one to respond to changes in the other and preserving the best possible combination. We have analyzed this idea with a simple numerical model for beam transport, assuming ideal rf cavities. We have also analyzed an FEL to evaluate its performance with reduced axial-velocity spread; these studies lead us to expect distinct improvements from beam conditioning. Experiments to test the feasibility of a beam-conditioning cavity are being planned for the ALS Beam Physics Facility (described in a previous section of this chapter) or the Accelerator Test Facility at Brookhaven National Laboratory. Such a facility would allow us to examine various candidates for beam-conditioning cavities and determine whether the idea can be realized in practice.

Beam Control Electronics

As greater demands are made on the performance of accelerators—such as increased luminosity, as in the proposed B factory PEP-II, or lower emittance, as in the ALS—it becomes ever more important to understand potentially disruptive rf phenomena within the beam chamber and to perform various rf "gymnastics" to monitor and control the beam. This is the work of the Beam Control Electronics group within Exploratory Studies. We have recently contributed to the B factory by leading the design of rf and feedback systems, and have also continued our history of contribution to the Tevatron by designing a beam-cooling upgrade for its antiproton source.

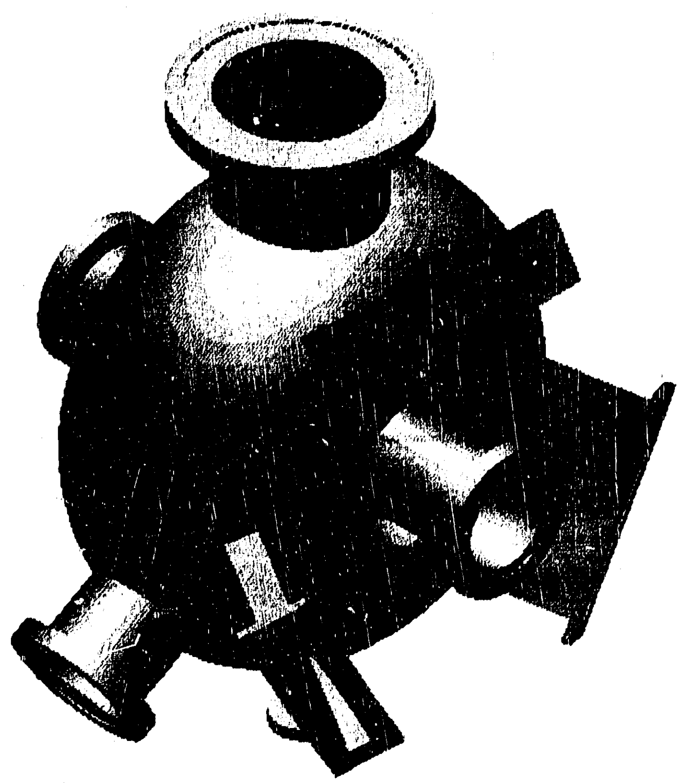
B-Factory Contributions

The major rf-design challenge posed by PEP-II is control of coupled-bunch motions. In each of the three directions (horizontal, vertical, and longitudinal) these motions have 1658 modes that may be driven strongly by the higher-order resonant modes of the rf cavities. Each higher-order cavity mode can drive a hundred or so of these motions at a growth rate thousands of times stronger than would be tolerable. The first step toward stabilization is to reduce the shunt impedances of the higher-order modes by as much as a factor of 500. Control of the remaining instabilities will then be within the reach of a practical feedback system. To reduce the shunt impedance of the higher-order modes, we attach waveguides to the cavity to couple these modes to an external resistor.

Figure 5-12 shows a possible design for such a cavity, designed and analyzed with the aid of the MAFIA code and Kroll-Yu processing of the output. Tests conducted with a simple pillbox cavity were encouraging. A low-power test cavity is now being designed so that we can make measurements. The experiments will examine which modes are damped and whether there is interference with the fundamental mode. Waveguide-load designs for removing and dissipating the higher-order-mode power will be studied as well.

Coupled-bunch modes that fall within the width of the fundamental resonance give rise to an additional driving impedance. This problem, endemic to large-circumference rings, must be addressed with active rf feedback around the cavity and its driver, a problem that we are now studying in collaboration with SLAC and LLNL. It appears that the problem of suppressing coupled-bunch modes, although difficult, can indeed be solved.

Figure 5-12. This design for the B-factory rf cavities is being built in low-power prototype form.



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Fermilab Antiproton Cooling System

The latest achievement in our ongoing collaboration with Fermilab is the design of a biplanar electrode system for cooling the beam of the antiproton source. (LBL was involved in the initial design of pickup and kicker electrodes for the source and has been continually engaged in analyzing the performance of the cooling system and seeking ways of improving it.) Earlier, we demonstrated that, for power-limited cooling systems, it is more efficient and cost-effective to double the number of cooling electrodes than to double the operating frequency.

Building upon that finding, we developed biplanar electrodes that could effectively double the number of electrodes without using any more space. This scheme, with the existing 2–4 GHz electronics, should yield better results than would a system with uniplanar electrodes and completely reworked 4–8 GHz electronics. Calculations indicate that the resulting performance would exceed the needs of any anticipated upgrade to the Tevatron complex, including the proposed new main injector.

In the past year, we confirmed the validity of our beam-cooling calculations by comparison with newly available cooling data from Fermilab. We also refined the prototype design and modified it so that its action would follow the contour of the beam envelope. Currently we are beginning to make detailed design drawings and cost estimates. (Performance measurements on a prototype were successful enough to indicate that we were ready to design a production model.) We will soon build an eight-element prototype module and measure its performance. Full production awaits a go-ahead decision by Fermilab.

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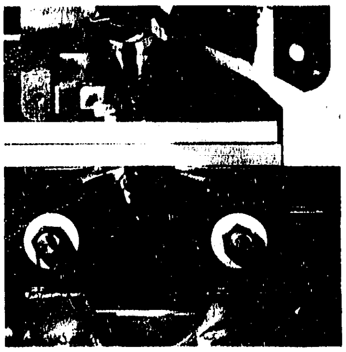

6. SUPERCONDUCTING MAGNETS

THE LARGEST SCIENTIFIC INSTRUMENT that man has ever attempted to build, the Superconducting Super Collider (SSC), draws upon resources throughout the U.S. high-energy physics community. LBL's contributions include design and development of 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. In 1991 we began the Magnet Industrialization Program, in which industry representatives from Babcock and Wilcox and from Siemens are working alongside LBL engineers and technicians to learn how to build these technically challenging magnets. Earlier, we had specified and designed a cabling machine that can make the appropriate type of cable with sufficient speed and quality for the SSC. The machine is now commercially available from two companies, Dour Metal and AFA Development. We are continuing to explore cabling technologies, anticipating the need for additional cable designs for various magnet windings.

Superconducting Magnets

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R. Lafever*
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R. Meuser**
K. Mirk*
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Our recent technical achievements have been highlighted by fabrication and test of the first full-scale collider quadrupole magnets. We continue pursuing our wide-ranging interests in superconducting magnets and materials. In successful ongoing programs, we strive to upgrade our R&D cabling machine, investigate ways of making magnets that are easier to assemble and have stronger, more-uniform magnetic fields, and explore a promising new line of research that uses "artificial flux pinning" to anchor magnetic lines of flux in the superconducting material.

SSC Magnet Development

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 that we could concentrate on the dipole.

Because the SSC design called for dipoles 17 m long, which was 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 could be examined in this scaled fashion. But the full-length quadrupoles are only 5 m long, so we took on the entire effort, including fabrication and testing of full-sized prototype magnets and subsequent transfer of the technology to industry.

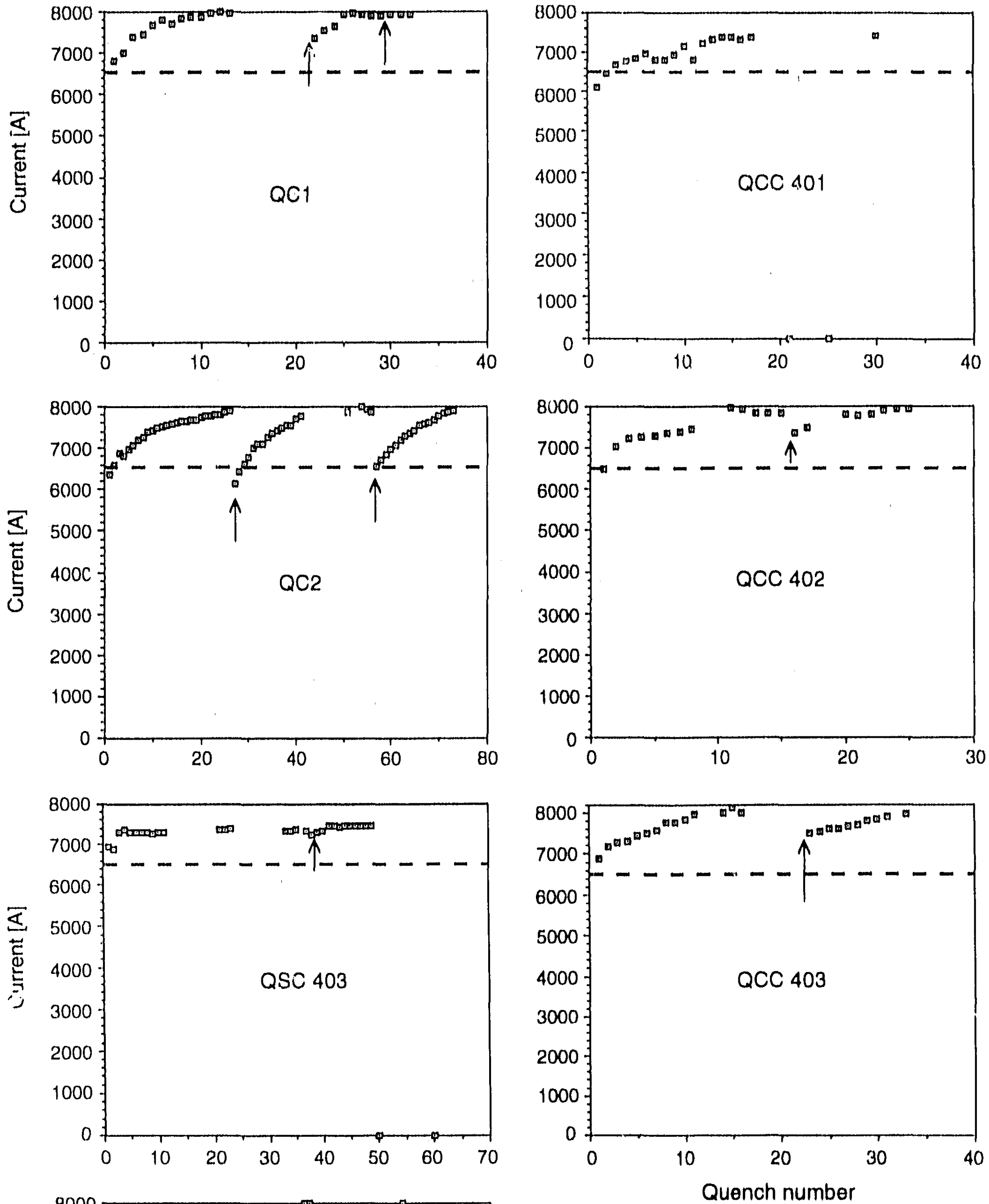
During 1991, we successfully tested the first four full-length quadrupole prototypes. In August, this work led into the start of the Magnet Industrialization Program, in which industry representatives are working alongside LBL engineers and technicians to learn how to build and test these magnets.

Quadrupole Development

The results of "training" the first four of the 5-m quadrupoles (we plan to build two more) are shown in Figure 6-1. All but the first of the 5-m prototypes met the SSC's specification for quadrupole training behavior, which requires that the magnet exceed the operating current of 6560 A by 5% after no more than three quenches and subsequently reach the operating current without quenching. Most of the magnets achieved 6560 A, corresponding to a field gradient of 211 T/m across the 4-cm bore,* on or by the second quench. After a moderate amount of training, they far exceeded the design requirements. However, it is desirable to eventually achieve even better performance. Toward this end, we are continually working to identify the causes of quenching and to develop techniques for minimizing them.

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

* The collider dipoles in the original SSC design had a 4-cm bore; this was changed to 5 cm to ensure a sufficient transverse "good-field" region. The concerns were not applicable to the much shorter collider quadrupoles, so there the less-costly 4-cm design remains in use.



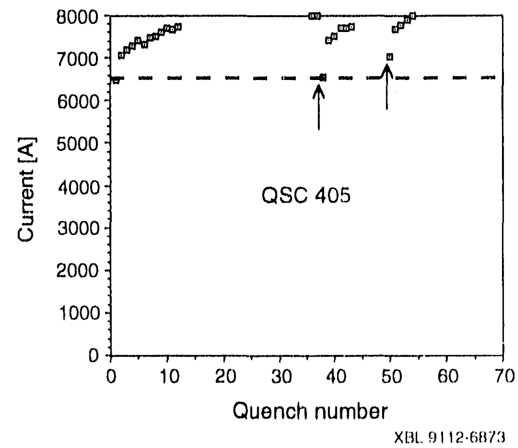
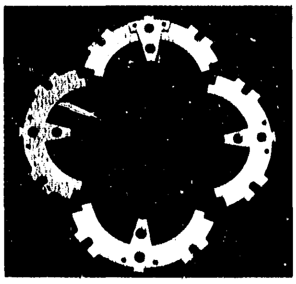


Figure 6-1. Training results at 4.3 K for full-scale SSC collider quadrupole prototypes and 1-m quadrupole models show that the desired field (dashed line) was usually achieved on the second quench or sooner, with subsequent performance well in excess of requirements. They also show considerable variability, including one case (QC02) where repeated, low-current quenches and lack of lasting "training" indicate a defect near the leads. The arrows indicate experiment interruptions during which the magnet was brought back up to room temperature. QC1, QC2, QSC403, and QSC405 *(left column)* are 1-m models. QCC401, QCC402, and QCC403 *(right column)* are 5-m prototypes.



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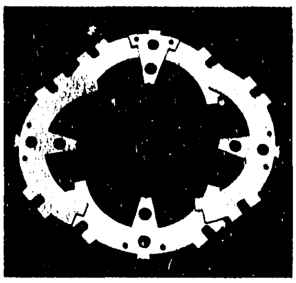

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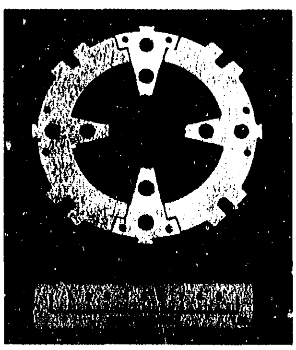

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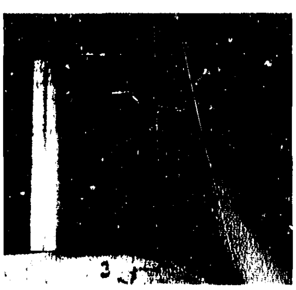

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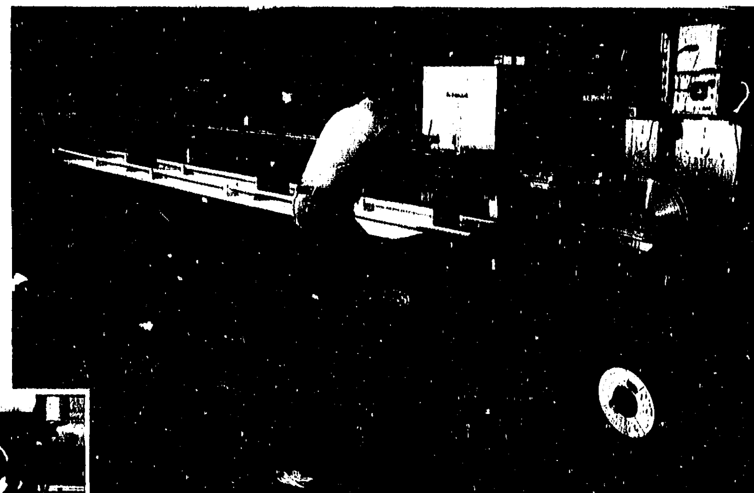

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Figure 6-2. Stages in the assembly of a magnet include *(counterclockwise from top right)* winding the layers of superconducting cable on a mandrel, compressing and heating this assembly inside a precision mold, installing collars, and finally applying and welding the stainless-steel jacket at the outer edge of the cold mass. 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.

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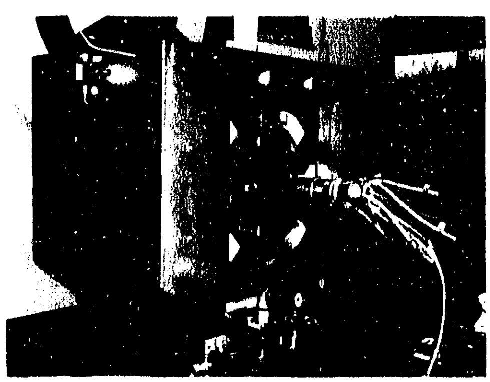

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while the cable spool travels around in a "racetrack" path.) The cable and mandrel are inserted in a precisely machined molding cavity where heat is applied. A heat-activated B-stage epoxy on the windings holds them in place until laminated-metal collars 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. Finally, iron yokes and a welded stainless-steel jacket are applied.

Each of these magnets is slightly different, for engineering them is an iterative process. Although physicists and engineers understand quite well how to build adequate magnets of this type, a great many potentially beneficial innovations have yet to be tested. (After our research ends, the final design will be determined by the industrial companies, which will mass-produce the 1664 collider quadrupoles.) Each magnet incorporates some feature that we think will improve performance, reliability, or manufacturability.

After the magnet has been fabricated, it is operated 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. This information can be used to improve design and fabrication in the search for greater reliability and predictability.

Until fairly recently, we worked with 1-m functional "models" of the SSC quadrupole as well as the 5-m prototypes. The 1-m models, which are quicker and cheaper to make, were useful for many of our research activities. Recently, though, the need for additional 1-m models of SSC collider quadrupoles has diminished. We now build 1-m quadrupole models only to find the answers to specific technical questions from the SSC Laboratory and are concentrating our SSC-quadrupole efforts on the 5-m prototypes. Our own program of non-SSC magnet research is performed mainly with short dipoles, though.

"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 mechanism of training is not definitively understood. The predominant hypothesis centers on small, unavoidable mechanical instabilities in the windings. 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 a small 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. Nonetheless, we continue 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.

The SSC is planning to use conditioning if necessary. However, our unconditioned SSC collider quadrupole prototypes have recently been consistently reaching the field strengths required by the SSC after, at most, one or two quenches. Full-length dipole prototypes built at Brookhaven National Laboratory and Fermilab (a different design with 20% lower current density) have recently achieved their design current without quenching at all.

In keeping with the highly applied nature of the SSC program, quality assurance and quality control are carried to great lengths. The emphasis begins in engineering, where we strive to create designs and procedures that reduce the need for skilled craftsmanship and the variability it entails. Precision tooling is another key feature. Coils are wound to a uniformity of ± 0.001 to 0.0015 inch (azimuthal) over the 5-m length of each magnet, and similar degrees of reproducibility from one magnet to another are sought. Each of the major manufacturing fixtures—the molding, collaring, skinning, and yoking presses—is built to close tolerances, and automated, numerically controlled processes are used whenever possible. The result is a final assembly that is true to within ± 0.005 inch in straightness and ± 0.25 milliradian in twist.

Each coil is measured at 20 locations along its length, using a semi-automated, numerically controlled measuring machine. Figure 6-3 is a typical plot of the azimuthal size variation of the two sides of a 5-m quadrupole's inner winding. The measurements were made with an azimuthal load of 10 000 psi, applied by the measuring machine. The small variations are similar for all coils made with the same tooling, and are well within the quality requirements for SSC magnets.

Measurement and documentation are also important factors in quality. Each magnet is made according to standard procedures and is accompanied by a logbook where some 1000 electrical and mechanical measurements are recorded. This kind of information will build a knowledge base of normal readings and critical parameters that will be useful during mass production of these highly precise magnets.

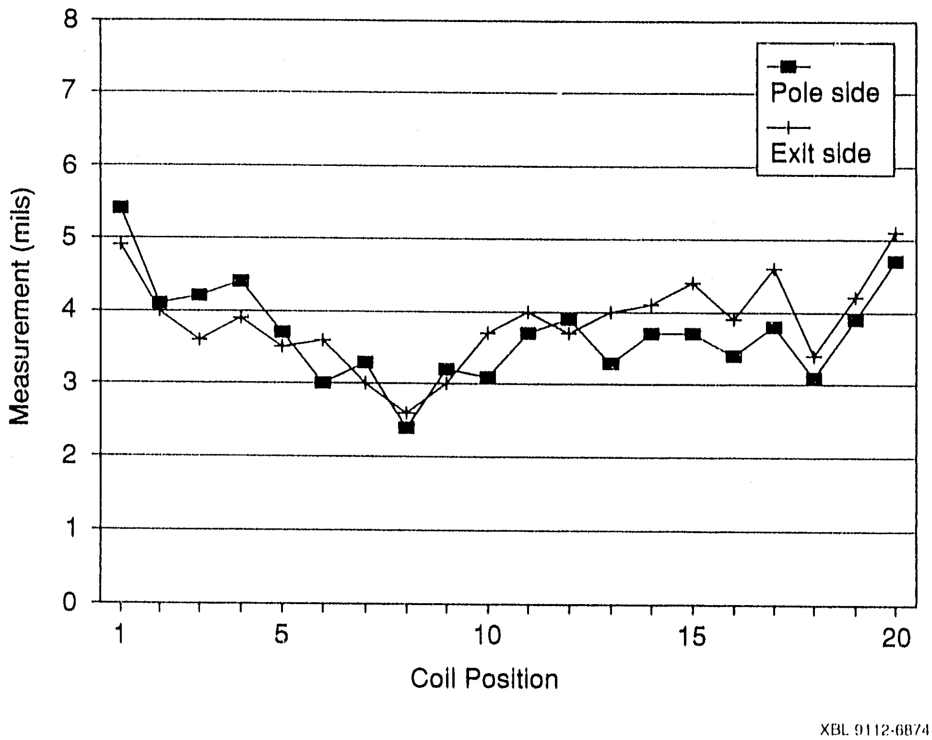


Figure 6-3. This plot shows the azimuthal size variation of one side of a 5-m quadrupole's inner winding under an azimuthal load of 10 000 psi. The small variations are similar for all coils made with the same tooling and are well within the quality requirements for SSC magnets.

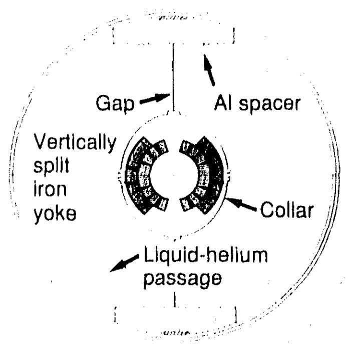
Advanced Technology Development

Although goal-oriented development work for the SSC has dominated our activities in recent years, we have continued to investigate other aspects of superconducting-magnet science and technology. The findings will be relevant to accelerators other than the SSC and to superconducting-magnet applications other than accelerators.

These efforts also represent the future of our program, as our SSC work has reached a climax and will ramp down as the magnet technology is transferred and private industry begins mass production. Our future directions include specialty magnets such as interaction-region focusing quadrupoles for colliders; advances in cablemaking and in superconducting-materials R&D; and ongoing efforts to build magnets that are stronger, more reliable, and easier to assemble.

High-Field Test Magnets

To advance the state of the art in magnets and to support our development of superconducting cables and of machines to make them, we build experimental magnets comparable in size and shape to those actually used in accelerators. One of the latest is D19, a high-field dipole which is closer in design to an accelerator magnet than was the earlier D16B1, which it superficially resembles. D19, shown in Figure 6-4 in an early stage of assembly, uses the same niobium-titanium cable as the SSC dipole magnets. However, because the design is more efficient, we can operate it at 5800 A, as opposed to the 6500 A that an earlier design such as the SSC collider dipoles would require for the same field.* The cross section in Figure 6-4 reveals the noncircular inner profile of the iron yoke. This shape maximizes the magnetic-field contribution of the iron while keeping high-field saturation effects down to manageable levels.



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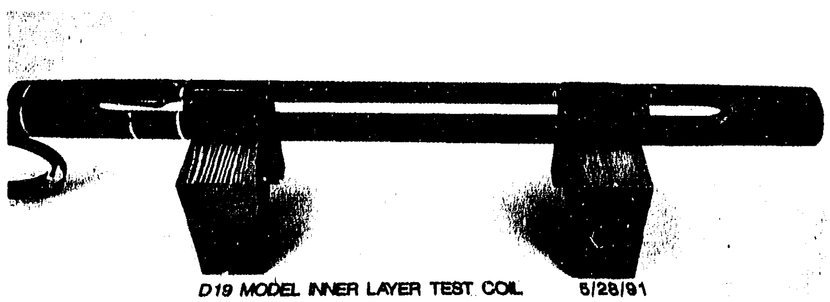

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Figure 6-4. Dipole D19, shown here at an early, partial stage of assembly, is similar in overall configuration to a magnet for the SSC, but is actually an advanced experimental unit designed to achieve fields of 10 T, very high for this type of magnet. The design is more efficient than that of the SSC magnets because of the noncircular inner profile of the iron yoke. This shape maximizes the magnetic-field contribution of the iron while keeping high-field saturation effects down to manageable levels. Another interesting feature is the vertically split iron yoke with aluminum-alloy spacers between the halves. The spacers maintain a predetermined gap between the halves at room temperature but allows them to shrink together tightly at cryogenic temperatures. This maintains the high compressive load on the coils and prevents the windings from shrinking faster than the iron yoke during cooldown. Such differential contraction would relieve the compression of the windings and thus undo the "training" process that allows the ultimate magnetic field to be reached.

* 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 has become more and more stringent as the project progresses and components move toward mass production.

Another advanced magnet, D20, uses niobium-tin superconductor. In its finished form, capable of superconductivity, niobium-tin is much more brittle that the widely used niobium-titanium and cannot be wound into cable. Instead, cable containing the ingredients is wound onto magnet forms and then heated to 700° C to make its ingredients react (which also embrittles it). All of these high-field magnets use superconductors other than niobium-titanium that require similar heating after winding; therefore, the techniques developed for D20 will be needed for further R&D using any of the high-field materials. D20, now being fabricated, is meant to push the capabilities of our technology, with a goal of 13 T at a temperature of 1.8 K, whereas a predecessor, D16B1, was designed for a maximum field of 9.5 T, which it has achieved.

Cable and Cabling-Machine Development

A longtime goal of our superconductor R&D program has been to develop improved techniques and tooling for the fabrication of Rutherford-style cable. The R&D cabling machine we developed to meet the needs of the SSC, and which is now available in a commercial version, continues to serve our R&D needs. In 1991 we upgraded it with a new spool and Turk's-head (Figure 6-5) so that it could fabricate cables with as many as 48 strands of

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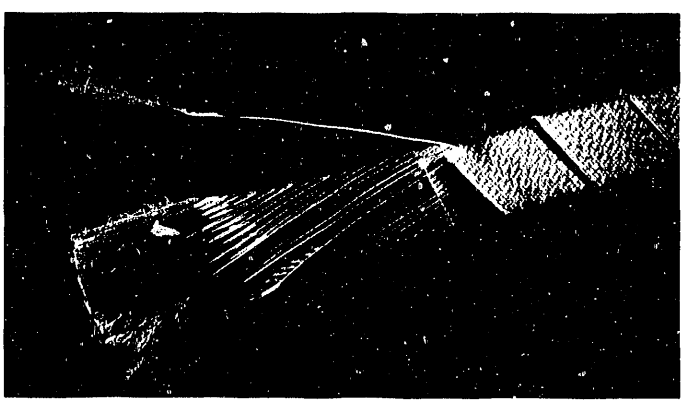

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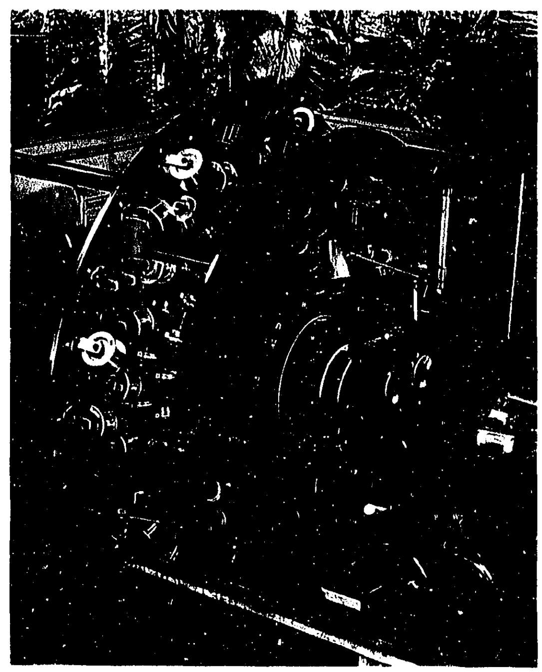
Figure 6-5. The R&D cabling machine, originally a prototype for an SSC cabling machine that is now com-mercially available, remains an important tool in our magnet-experimentation program. With recent improvements, including the new Turk's-head (*left*) and spool (*below*), it can weave high-quality cables with as many as 48 strands of superconducting wire. Also shown is a close-up of a typical piece of "Rutherford-style" cable. Thousands of fine filaments, made of superconductor such as niobium-titanium in a copper matrix, are braided into strands of wire, which are then formed into a flattened, keystoned cable in the cabling machine.



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superconducting wire. With this new equipment, we have been able to fabricate cables that are 30% wider and contain 25% more strands than the cable we developed in the late 1980s for the SSC dipole magnets. In addition to furthering cable manufacturing, this upgrade will provide our magnet designers with additional flexibility in their choice of superconducting materials and cable designs.

The easy in-house availability of this machine, along with the expert assistance of its operators, has also paved the way for innovative materials experiments. We recently made a 48-strand cable out of niobium-tin wire that was reacted after cabling to form it into a superconductor. Brittleness makes Nb_3Sn much more challenging to work with than NbTi, but it offers great opportunities for future high-field magnets. (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." Critical field and temperature can be limited by fundamental phenomena; critical current can be affected significantly by fabrication processes.) Recent tests indicated very good results, and our magnet designers are now using this cable in their efforts to design a high-field dipole magnet.

Materials Development

As we look toward the future of superconducting-magnet development, we realize that materials-science research plays a key role in achieving higher, more-uniform, and more-predictable magnetic fields. A promising recent line of inquiry involves the "artificial pinning center" (APC) concept. In APC superconductors, the random distribution of pinning centers, which ordinarily arise from precipitation, is replaced with a more-precise distribution that matches the magnetic fluxoid lattice for a given field strength.

A fluxoid is the site of one quantum of magnetic effect, and may be thought of as the place where a line of magnetic flux penetrates the superconducting wire. Ordinarily, fluxoids can move through the superconductor in response to an applied magnetic field, and energy is dissipated. In artificial flux pinning, a material (niobium in the case of our niobium-titanium wire) is introduced as a normal-conducting phase in the superconducting material. The flux lines are localized to these regions. Artificial flux pinning allows some measure of control over the final microstructure of the superconducting material—an intrinsic characteristic that cannot be altered by the way the superconducting material is formed into wires. (The significant intrinsic factors are filament microstructure and composition. Extrinsic factors, such as the cross-sectional area, integrity, and uniformity of the superconductor, are also important.)

The ultimate application of this research is to enable the fabrication of multifilamentary superconducting wire that has higher critical-current density (J_c) and is more economical to produce. We are examining niobium distribution and pinning strength as key intrinsic factors that may offer opportunities for further understanding and progress. We are also working with several industrial companies on ways of producing APC superconductor by the strictly mechanical means of cold-working, rather than the time-consuming and expensive heat-treatment technique that is presently used. Figure 6-6 shows the microscopic structure of samples produced by this new technique.

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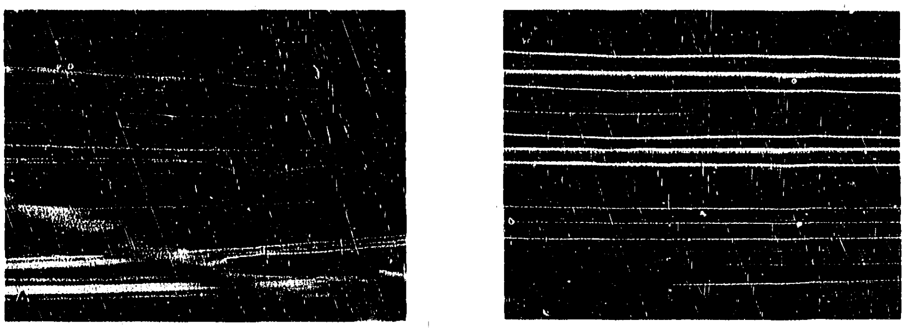

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Figure 6-6. Scanning electron micrographs of filaments of artificially pinned NbTi superconductor show differences between hot-extruded wire (*A, above center*) and bundle-and-draw wire (*B, above right*). Recently, in conjunction with LBL, Supercon, Inc., has improved upon the bundle-and-draw technique. Details of a sample of their new APC material are shown at *left*. The dark areas are the normal-conducting substances, including the pinning centers; the white ones are NbTi superconductor. Note the nonrandomness of the pinning centers even at the nanometer scale.

The solenoid shown in Figure 6-7 allowed a simple test of this wire; it has achieved an 8-T magnetic field across its 45-mm bore diameter. The solenoid was built with NbTi APC wire made by Supercon, Inc., under contract to LBL. The 8-T field has been achieved not only in a continually driven mode, but also in a persistent-current mode. In persistent-current mode, the coil is cut off from the power supply after being energized and the leads are shorted with a piece of superconductor, so a supercurrent circulates through it almost indefinitely. (This effect should not be confused with the undesirable, small-scale persistent eddy currents that can occur when the field strength is varied at low field and current.) This test provides an important confirmation of the uniformity of the APC wire. As a result of this successful demonstration, we have ordered enough of the APC wire to fabricate cable and build a 1-m-long dipole that will give us further information on the performance, reliability, and cost-effectiveness of this type of material.

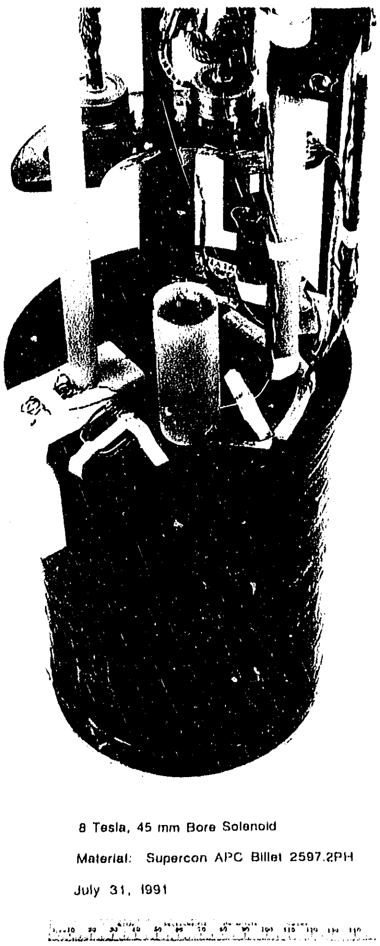

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Figure 6-7. This 8-T solenoid was built as a simple test of the new wire from Supercon, Inc., shown in Figure 6-6. Tests with persistent current (continuing circulation of a current after the power supply was disconnected) provided an important confirmation of the uniformity of the APC wire. As a result of this successful demonstration, we have ordered enough of the APC wire to fabricate cable and build a 1-m-long dipole that will give us further information on the performance, reliability, and cost-effectiveness of this type of material.

Publications and Presentations

S. Caspi, M. Helm, and L.J. Laslett, "Magnetic field in the end regions of the SSC quadrupole magnets," in *Proceedings* of the 12th International Magnetic Technology Conference (Leningrad, USSR, 1991); Lawrence Berkeley Laboratory report LBL-29819 (1991).

S. Caspi, M. Helm, and L.J. Laslett, "Magnetic field in the SSC quad," Lawrence Berkeley Laboratory report LBL-30668 (1991).

S. Caspi, M. Helm, and L.J. Laslett, "3D field harmonics," Lawrence Berkeley Laboratory report LBL-30313 (1991).

S. Caspi, M. Helm, and L.J. Laslett, "The use of a relaxation method to calculate the 3D magnetic field contribution of an iron yoke," 1991 Conference on the Computation of Electromagnetic Fields, COMPUMAG (Sorrento, Italy, 1991); Lawrence Berkeley Laboratory report LBL-29826 (1991).

D.R. Dietderich and R.M. Scanlan, "Characterization of NbTi superconductors with artificial pinning structures," in *Proceedings* of the 1991 Cryogenic Engineering Conference/International Cryogenic Materials Conference (Huntsville, AL, 1991); Lawrence Berkeley Laboratory report LBL-30063 (1991).

M.A. Green, "Correction of magnetization sextupole and decapole in a 5 centimeter bore SSC dipole using passive superconductor," Lawrence Berkeley Laboratory report LBL-30702 (May 1991).

M.A. Green, "Estimating the cost of superconducting magnets and the refrigerators needed to keep them cold," in *Proceedings* of the 1991 Cryogenic Engineering Conference/International Cryogenic Materials Conference (Huntsville, AL, 1991); Lawrence Berkeley Laboratory report LBL-30824 (1991).

M.A. Green, "Ferromagnetic material in the superconductor and its effect on the sextupole and decapole in the SSC dipoles at injection," in *Proceedings* of the 1991 Cryogenic Engineering Conference/International Cryogenic Materials Conference (Huntsville, AL, 1991); Lawrence Berkeley Laboratory report LBL-30403 (1991).

M.A. Green, "Measurements of magnetization multipoles in four centimeter quadrupoles for the SSC," in *Proceedings* of the 1991 Cryogenic Engineering Conference/International Cryogenic Materials Conference (Huntsville, AL, 1991); Lawrence Berkeley Laboratory report LBL-30811 (1991).

M.A. Green and L. Hansen, "Proposal for a cryogenic magnetic field measurement system for SSC dipole magnets," in *Proceedings* of the Third Annual International Industrial Symposium on the Super Collider (Atlanta, GA, 1991); Lawrence Berkeley Laboratory report LBL-29596a (1991).

L.J. Laslett, S. Caspi, M. Helm, and V. Brady, "Calculation of 3D field components of high permeability circular iron," in *Proceedings* of the 12th International Magnetic Technology Conference (Leningrad, USSR, 1991); Lawrence Berkeley Laboratory report LBL-29810 (1991).

R. Meuser, "Shell hoop prestress generated by welding and shell-to-yoke friction," in *Proceedings* of the Third Annual International Industrial Symposium on the Super Collider (Atlanta, GA, 1991); Lawrence Berkeley Laboratory report LBL-29702 (1991).

R.M. Scanlan and J.M. Royet, "Recent improvements in superconducting cable for accelerator dipole magnets," in *Proceedings* of the IEEE Particle Accelerator Conference (San Francisco, CA, 1991).

C.E. Taylor, P. Barale, R. Benjergerdes, S. Caspi, D. Dell'Orco, D. Fritz, W. Gilbert, A. Lietzke, K. Mirk, C. Peters, R. Scanlan, and A. Wandesforde, "Quadrupole magnets for the SSC collider," in *Proceedings* of the 12th International Magnetic Technology Conference (Leningrad, USSR, 1991); Lawrence Berkeley Laboratory report LBL-29971 (1991).

7.

BEVALAC OPERATIONS

ASTRONAUTS ON LONG MISSIONS BEYOND EARTH'S MAGNETIC field will be exposed to cosmic rays to an extent whose effects are unknown. As we plan for the phaseout of the Bevalac's nuclear-science program sometime in the mid-1990s, other researchers are poised to use it in support of future space exploration, building a data base on the biological and physical effects of heavy ions.

Meanwhile, the Bevalac, guided by its advisory committees (Tables 7-1 and 7-2), continues its traditional mission of serving nuclear science, radiation biology, and clinical radiation treatment. A major effort to prepare for the early-1991 DOE Tiger Team inspection has left it in a strong position both physically and procedurally. Management formalisms, employee attitudes, and facility and equipment improvements combine to ensure protection of safety, health, and environmental quality.

B. Feinberg (*operations manager; head of planning and development*)
G.F. Krebs (*head of research coordination*)
R.M. Miller (*head of operations*)
R. Stevenson (*head of safety and administrative services*)
J.B. Abenojar*
S. Abbott**
R.V. Aita
D.P. Almeida*
J.F. Althar
D. Anderson**
R.L. Anderson§
L. Archambault**
J.J. Ayers**
B.J. Bailey**
M.O. Balagot**
K.M. Baptiste**
R. Barr
D. Beck**
G. Behrsing**
M. Bennett**
D.A. Bentsen
R. Berninzoni*
J. Bercovitz**
R.L. Bisbee**
J. Bishop**
M. Bordua**
H. Bowman†† §
G.S. Boyle
J.P. Brannigan
M.J. Bricker, Jr.*
R.W. Brokloff
J. Brown
W.L. Bruemmer*
L.A. Brusse**
J.P. Burch**
G.M. Byer§
W.E. Byrne
R.L. Callaway
J. Calvert**
G. Carmignani**
C. Celata
H.J. Chambers**
H. Chew**
W.T. Chu†
R. Coates
K. Connelly**
D.N. Cowles
H. Crawford (*guest*)†††
A.W. Cutt*
S.L. Daly
M.R. Dickinson**
R.L. Doty*
J.R. Dougherty**
R. Dwinell**
J.A. Elkins**
H.M. Ellison
R.S. Everett
W.L. Everette§
W. Faust**
M. Felix*
K. Fetters**
K. Finegan**
L. Finsch**
I. Flores**
E. Fong** §
R. Force
K. Fowler**
P. Freda††
R. Frias** §
D.S. Garfield*
B. Gavin
F.E. Geisler**
T.L. Gimpel
S. Graham**
D. Greaves
J.D. Gregor**
J.R. Guggemos§
A.P. Guy
G.F. Hartley**
J. Henderson**
E. Henson**
D. Howard**
P.M. Howell§
M. Hui**
D. Hunt**
R.E. Jahnigen
O. Jones
J.G. Kalnins
N. Kellogg**
R. Kerns**
G.H. Kleist**
P. LaPlant**
J. Lax** §
S. Lewis**
A. Lindner**
A. Loop**
E.H. Lothrop
D. Lozano
B. Ludewigt†
R. MacGill**
C. Marks**
M.A. McCloud**
R. McDonald
M. McEvoy**
M. McMahan
S. Meaney
R.A. Miller
E. Moldenhauer*
E.K. Moller*
M. Monroy
D. Morris**
M. Morrison**
R. Mueller**
M. Nyman**
H. Oakley**
E. Parker§
J.M. Parker*
S.L. Patterson**
M. Payne**
E. Perry**
M.R. Photos**
D.D. Pohl
J.L. Pusina
J.F. Quan**
D.F. Reimers*
R. Reimers**
T. Renner
R.M. Richter
W.L. Ridgeway**
S. Rogoff**
B. Rude**
S.E. Ryce**
T.C. Sampson*
B.C. Samuelson**
D.W. Schmeyer§
L. Shalz**
C.R. Siero
K.H. Sihler**
R.P. Singh**
L. Skvarla
R. Sorensen** §
J.W. Staples
L.L. Stout**
G. Stover**
S.A. Stricklin**
D.L. Syversrud**
H.K. Syversrud
R.L. Tafelski**
M.M. Tekawa
R.K. Thatcher
D. Thewlis**
J.R. Thomas**
C.W. Thornton**
P. Torres*
J.C. Walling*
H. Wieman††
K. Williams§
O.S. Wiggins
N. Wong
K. Woolfe**
M.D. Woolfe
E. Zajec

Administrative Support
P. Bullocks
S. Fujimura
C. Gardener
K.E. Williams§

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* Plant Engineering and Construction and Maintenance Departments
** Engineering Division
† Research Medicine and Radiation Biology Division
†† Nuclear Science Division
††† University of California Space Sciences Laboratory
§ Retired

A proton-therapy project being considered by the University of California at Davis would also draw heavily upon the body of expertise associated with the Bevalac. The accelerator, built at their cancer center in Sacramento, would be designed in a cooperative effort involving oversight from LBL scientists and engineers and strong industrial participation.

Table 7-1. Program Advisory Committees (PACs) for 1990 and 1991.

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.

Bevalac Nuclear Science PAC

J. Carroll, University of California at Los Angeles, users' representative*
S. Datz, Oak Ridge National Laboratory
B. Feinberg, LBL, operations manager
C. Gelbke, Michigan State University
F. Goldhaber, State University of New York at Stony Brook
M. Gyulassy, LBL†
W. Henning, GSI, Darmstadt, Germany
G. Krebs, LBL research coordinator
F. Lothrop, LBL scheduling coordinator
P. McMahan, LBL executive secretary
F. Plasil, Oak Ridge National Laboratory
R. Scharenberg, Notre Dame University, users' representative*
L. Schroeder, LBL, scientific director
V. Viola, Indiana University, chair

Bevalac Biomedical PAC

S.J. Adelstein, Harvard Medical School, chair
Eleanor A. Blakely, LBL, deputy executive secretary
J.D. Chapman, Cross Cancer Institute
William T. Chu, LBL, executive secretary
Edward R. Epp, Massachusetts General Hospital
B. Feinberg, Bevalac operations manager (*ex officio*)
Robert J. Michael Fry, Oak Ridge National Laboratory
David J. Grdina, Argonne National Laboratory
G.F. Krebs, Bevalac research coordinator (*ex officio*)
Robert E. Krisch, University of Pennsylvania
Amy Kronenberg, LBL
F. Lothrop, LBL, scheduling coordinator
Bernhard Ludewigt, LBL, biomedical experiment liaison
Lester J. Peters, University of Texas System Cancer Center

Table 7-2. Nuclear Science Users' Association Executive Committees for 1990 and 1991.

W. Benenson, Michigan State University†
P. Brady, University of California at Davis
J. Carroll, University of California at Los Angeles, 1991 chair†
S.Y. Fung, University of California at Riverside
R. Madey, Kent State University†
M. McMahan, LBL, executive secretary
D. Olson, LBL*
R. Scharenberg, Notre Dame University, chair-elect
L. Schroeder, LBL, scientific director
K. Toth, Oak Ridge National Laboratory
H. Wieman, LBL

* Beginning in 1991.
† Through 1990.

Accelerator Technology and Operations Summary

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 a long-term trend of decreasing budgets coupled with inflationary erosion. Budget restrictions brought the Bevalac down to 3689 hours of experimental beamtime in 1990, followed by 2975 hours in 1991, after three consecutive years of record-breaking, 4000-hour-plus operation.

1990 and 1991 Performance Statistics

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.

Table 7-3. Operating summary by fiscal year.

	1990 actual	1991 actual	1992 projected	1993 projected
Bevalac Operation (*hours*)				
Research	3689	2975	2800	2800
Machine Studies	243	225	187	187
Tuning	987	706	653	653
Total Operation	4919	3906	3640	3640
Unscheduled maintenance	671	459	535	535
Scheduled shutdowns	3170	4395	4609	4609
Total Downtime	3841	4854	5184	5184
Beam Use for Research (*hours*)*				
Nuclear Science	2535	2034	1867	1867
Life Sciences	1153	941	933	933
SuperHILAC	728	400	0	0
Total	4416	3375	2800	2800
Number of nuclear-science experiments receiving beam	25	6	12	12
Number of participating scientists	189	64	64	64
Institutions represented				
Universities	33	15	18	18
National laboratories	5	3	5	5
Other	7	2	3	3
Total	45	20	26	26
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

* These figures include the SuperHILAC parasitic program and therefore may exceed the research beamtime reported for the Bevalac alone.

Facility Development Projects

The Bevalac (Figure 7-1) has an ongoing program of technology upgrades designed to increase efficiency, improve user service, and ensure safety. A multiyear project to modernize the Bevalac's control systems and extend modern computer systems throughout the facility saw additional progress in 1990 and 1991. The computer control system has been extended to the local injector's rf system and drift-tube-magnet power supplies and to the beam transport and diagnostic devices in all beamlines. Conversion from the obsolete ModComp computer control system to the new system, which is based on networked Sun workstations, also progressed.

Our 1991 accelerator-improvement projects were directed toward modernizing the power-distribution system in the beamline areas and bringing it up to today's standards. Another significant improvement,

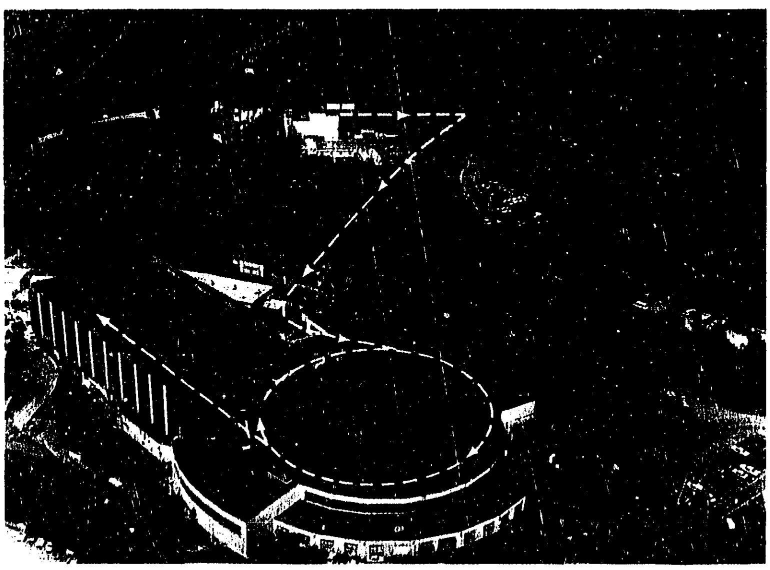

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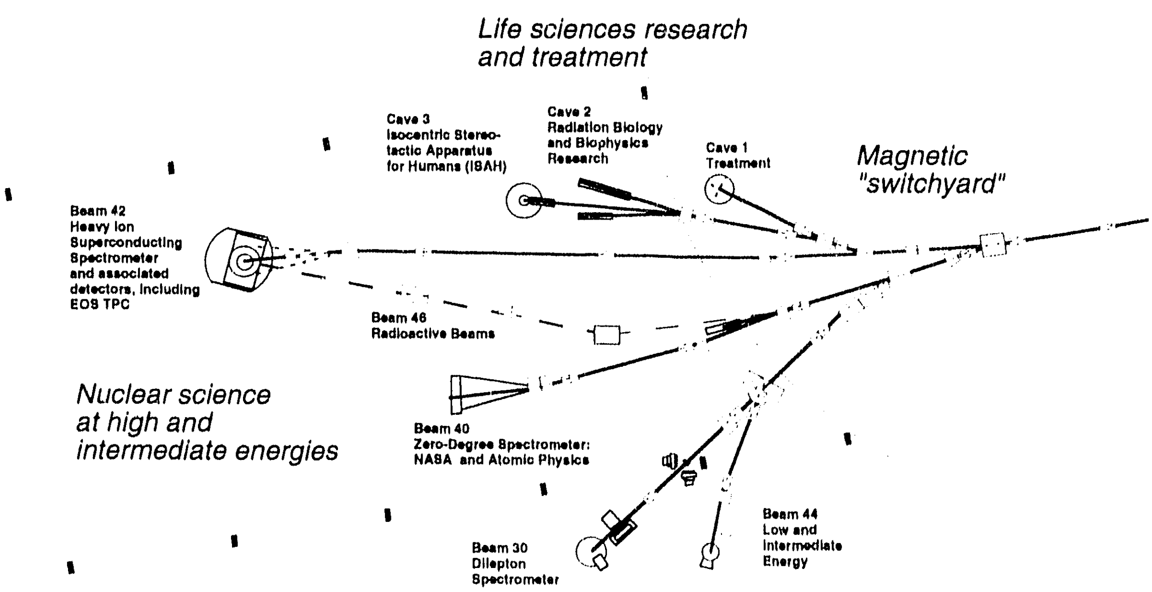
Figure 7-1. The Bevatron, a synchrotron, accelerates beams from either its local injector or the SuperHILAC heavy-ion linear accelerator. The dotted lines in the picture show the beam path from the SuperHILAC through the Bevatron. The SuperHILAC, which has three complementary ion sources, is used when higher energies and heavier ions are needed, as 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.



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planned for 1992, will raise the maximum "flat-top" time of the main guide-field magnet's power supply, and therefore the maximum beam spill time, from 1 second to as much as 4 or 5 seconds. This project requires R&D for new measures to stabilize the magnetic field and to substantially reduce power-supply ripple. This will allow the Bevalac to greatly increase the overall duty cycle, thus providing service that better matches today's emphasis on high-statistics investigations rather than survey experiments.

Improvements to the control of the main guide-field magnet also yielded advantages to the users. After a prolonged search for proper corrections to the field shape at the very low field (about 250 gauss) used at injection, we have achieved very good proton intensities, being able to deliver about 10^{10} particles per second.

In recent months, equipment refinements aimed at improving the optical quality of extracted beams have been getting under way. Major goals are to reduce beam halo (thus cutting the rate of unwanted background events) and to provide feedback instrumentation to aid precision tunings for specific targets.

Support for Space Exploration

The Bevalac presents unique opportunities to NASA because its energetic beams of heavy ions can realistically simulate most of the cosmic-ray spectrum in a laboratory environment. NASA has taken advantage of this capability for many years by conducting materials studies, calibrating detectors, and performing basic space-science research. In support of manned planetary missions beyond the magnetosphere, the program would be expanded greatly into three main areas:

- *Radiation biology, studying the effects of heavy-ion irradiation on cell cultures and animals.*
- *Materials science, characterizing the effectiveness of shielding materials and the radiation resistance of equipment.*
- *Space physics, a basic-science corollary of the manned-mission research, seeking to understand the interactions of cosmic rays with, for example, interstellar gas clouds.*

This pure and applied research builds not only upon the technical capabilities of the Bevalac, but also upon its existing research program.

NASA and the Bevalac

Under this proposal as it currently stands, NASA would significantly increase its current low level of Bevalac usage beginning in fiscal year 1993, sponsoring additional operation on nights and weekends during the 22 weeks per year in which the Bevalac is used solely for the therapy program. The total NASA program would ramp up from its current level of about 300 hours of research beamtime per year to 1000-plus hours. Meanwhile, the current nuclear-science and biomedical programs would continue.

After FY 1994, NASA-supported research would comprise the entire base program at the Bevalac. Other agencies might purchase additional beamtime. It is likely that some present users of the facility, from LBL and elsewhere, would be among the scientists proposing research within the NASA program. The section on "Biomedical Research," presented later in this chapter, gives further details on the some of these research challenges associated with space exploration.

Proton Medical Accelerator

The use of accelerated ion beams to reach tumors precisely in three dimensions is deeply rooted in the history of LBL. Over four and a half decades, radiotherapy with heavy, charged particles has become widely accepted for the treatment of an ever-increasing variety of tumors. Meanwhile, LBL accelerator scientists and their life-sciences colleagues have been thinking from time to time about special-purpose accelerators dedicated to medical use. Now these two lines of inquiry are coming together in a proton-therapy initiative planned for the University of California at Davis Cancer Center, located in Sacramento. This facility, to be built with privately raised funds, will be the second dedicated, hospital-based, clinical charged-particle treatment facility in the world, following the lead of the Loma Linda University Medical Center.

The Davis Initiative

The Davis facility—formally, the University of California at Davis Proton Therapy Center—will be a 250-MeV proton accelerator optimized for medical treatment. Specifications and design decisions for the Davis facility are being developed with the aid of grants from the National Cancer Institute.

In 1991, under the first-year grant, an analysis of the current state of technologies applicable to proton therapy was completed. The synchrotron emerged as the leading candidate, with a conventional (that is, non-superconducting) cyclotron as a close runner-up. (Proton therapy is currently performed or planned worldwide at more than a dozen accelerators, all of which are cyclotrons and synchrotrons.) Specifications for accelerator performance have been developed, and comparisons have been made among the various techniques for creating large radiation fields suitable for therapy, along with isocentric gantry delivery of the beam.

The second year of NCI funding is being used to address a specific design for the Davis site. The Proton Therapy Facility, to be located in a new structure adjoining the recently completed Cancer Center, is currently envisioned as a 250-MeV proton accelerator, probably a synchrotron, delivering beam to three treatment rooms, two of which are equipped with rotary gantries capable of bringing the treatment beam into a supine patient from any angle. Several specific areas are being addressed in this segment of the project:

- Detailed specifications for all parameters of both technical and conventional facilities.
- Conceptual designs covering all elements of the project.
- Cost estimates to provide fund-raising targets for UC-Davis.
- Technical issues identified from the operation of the Loma Linda facility, as well as other medical charged-particle programs around the world. These are recently identified problems that prevent the full implementation of many of the recent innovations in beam delivery. By solving these problems, true "second-generation" performance can be obtained at the Davis facility.

Close collaboration with industry is planned throughout this portion of the project. Conceptual designs and cost estimates will be performed by the private sector once the detailed specifications have been developed. The technical issues will also be addressed primarily by industry, with assistance from LBL. One of the principal goals of this process is to transfer technology to industry, as advanced systems for charged-particle therapy could eventually emerge as a significant market.

Nuclear Science

The Bevalac's ability to provide beams of the heaviest of ions in the GeV/nucleon range gives it a unique role in the U.S. nuclear-science program. The anticipated phaseout of the program in the mid-1990s has led researchers to concentrate upon the experiments that can provide the most-decisive results in the remaining years. They are focusing upon the study of extreme conditions in nuclear matter, the thermodynamic and transport properties of nuclear matter, and the nuclear equation of state (EOS). The prominent achievements of 1990 and 1991 include important new data from the Dilepton Spectrometer and the ongoing preparation of a Time Projection Chamber.

EOS Studies and the Time Projection Chamber

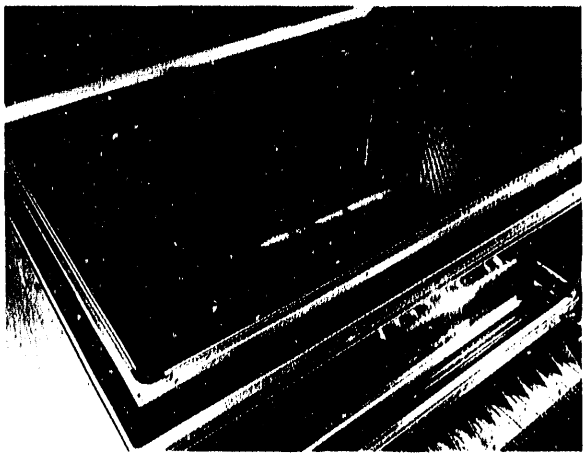
The running theme of the Bevalac's nuclear science program has been the production and examination of extreme conditions in nuclear matter. Early Bevalac experiments, using the Streamer Chamber and Plastic Ball detectors, established that central collisions* between nuclei could create high temperatures (50-100 MeV) and high densities (two to four times normal). The first evidence for "collective flow" in nuclear matter was obtained in these experiments. Such studies reveal the thermodynamic and transport properties of nuclear matter, and thus the equation of state (EOS), as described in the sidebar.

The experimental observables of the EOS are now clear; they include, for example, the dependence of "collective flow" on fragment mass, as well as the correlation of flow with reaction plane, etc. 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. What is required is a 4π detector capable of analyzing all the particles produced in a central collision between the heaviest nuclei. At the same time, this detector must be able to collect a large statistical sample of such events and study them on an event-by-event basis. At the Bevalac, this next-generation detector will be the EOS TPC (time projection chamber).

The EOS TPC (Figure 7-2), installed and undergoing tests and electronics completion, is an electronic 4π detector that fits inside the Heavy Ion Superconducting Spectrometer (HISS) magnet. The EOS 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, ^{3}He and ^{4}He nuclei, and pi mesons) that are produced when heavy nuclei such as gold collide at Bevalac energies. In the HISS dipole, its functions will be complemented by a variety of existing detectors.

Nuclear multifragmentation will be studied through exclusive experiments (that is, experiments that do not account "inclusively" for all particles and phenomena) using the technique of reverse kinematics. This work will involve heavy beams such as krypton, lanthanum, and gold upon lighter targets such as beryllium and carbon. Flow effects will be studied as a function of mass and energy, and other experiments below 200 MeV/n will

* Central, head-on collisions, as opposed to "grazing" or peripheral collisions.



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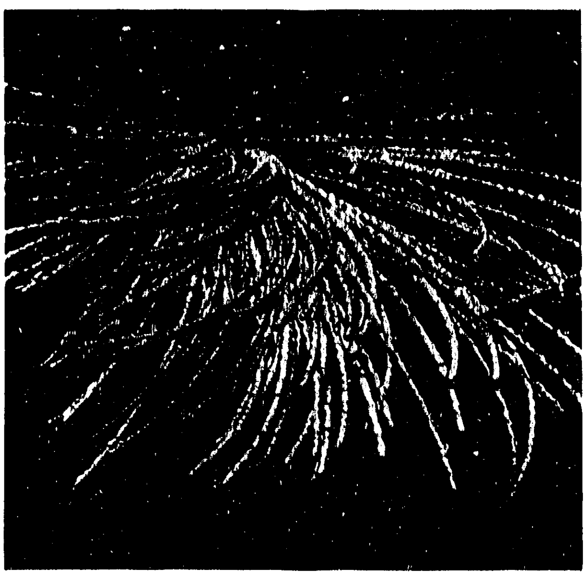

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Figure 7-2. The Equation of State Time Projection Chamber (EOS TPC) will play a key role in optimizing scientific progress during the remaining years of the Bevalac nuclear-science program. The detector system was tested in scaled prototype form in 1988 and installed in 1991; it is scheduled to come fully on-line early in 1992. The TPC, a full-solid-angle detector in the Heavy Ion Superconducting Spectrometer (HISS) magnet, 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, ^{3}He and ^{4}He nuclei, and pi mesons) that are produced when heavy nuclei such as those of gold collide at Bevalac energies. Here an illustration of the EOS TPC concept is shown alongside part of the apparatus *(top left)* and a computer-modeled result of a simulated 800-MeV Au + Au central collision.

search for their decrease and presumed eventual disappearance as incident-projectile energy decreases. Experimental operations will begin in 1992, with 1000 hours of beamtime approved for these initial experiments, and will continue until the termination of the nuclear-science program at the Bevalac.

Pumping and Compressing the Nuclear Fluid

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 one sees in everyday, macroscopic matter. (An example of such behavior is collective flow, which was first observed in the Plastic Ball and Streamer Chamb r detectors at the Bevalac.) Nuclear matter can be thought of as a solid, liquid, gas, or plasma, depending on temperature and pressure, as shown in Figure 7-3. The equation of state (EOS) mathematically describes the balance among these phases and the borderlines of the phase transitions. 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 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 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.

Dilepton Spectrometry

Another important detector is designed to provide an especially clear view of certain reactions. The Dilepton Spectrometer (DLS), shown in Figure 7-4, is a unique detector that was installed at the Bevalac in 1986. It 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.

Dilepton emission 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

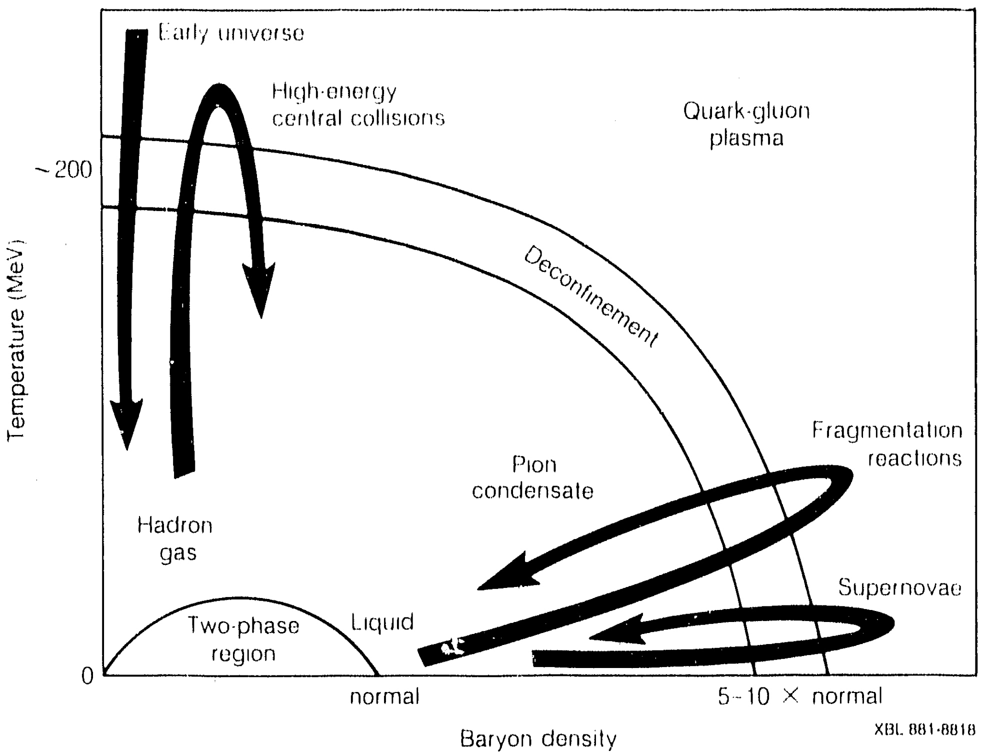


Figure 7-3. A schematic phase diagram for nuclear matter shows some of the states and transformations predicted by various theories. The normal state of nuclear matter can be characterized as liquid. It may undergo phase transitions to a hadron gas at relatively low densities or, at higher densities, 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 supernovae. Such extreme conditions can be re-created at a laboratory scale through central collisions between nuclei at extreme relativistic energies.

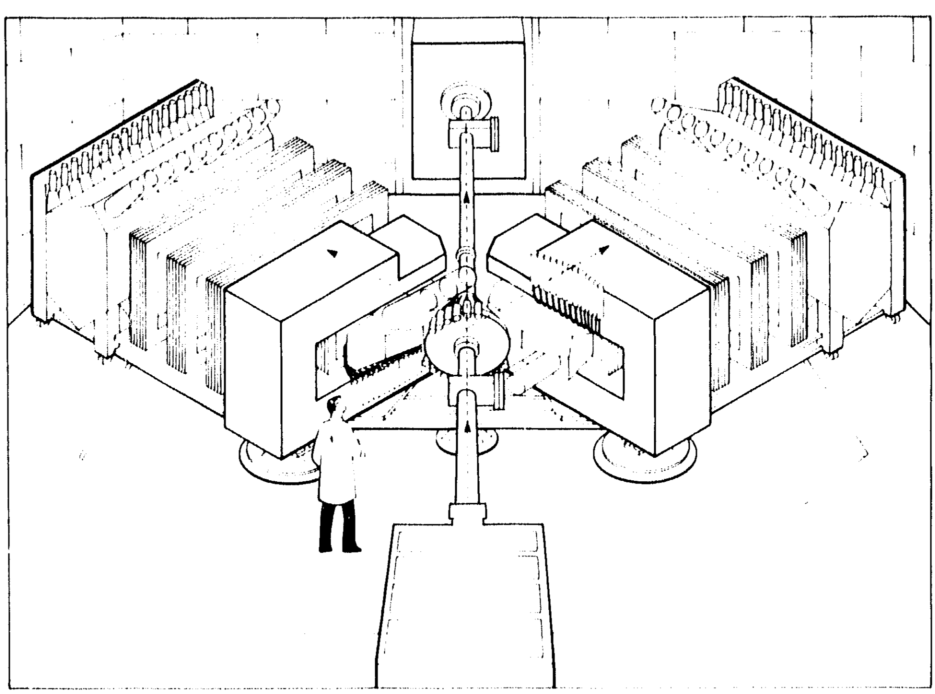


Figure 7-4. An artist's rendering shows the major elements of the Dilepton Spectrometer (DLS), which in its completed and installed form is difficult to photograph. Electron-positron pairs are detected in the two arms, each of which has a three-cell Cerenkov gas counter, a 16-element scintillation hodoscope, drift chambers and a magnetic dipole, a 20-cell Cerenkov gas counter, and a large 16-element scintillation hodoscope. In 1989, an additional multiplicity detector was added: a 96-element hodoscope configured as a cone surrounding the target chamber. This hodoscope detects charged particles and gives information about the centrality of the event.

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 $p+{}^{9}Be$ collisions, and to some extent in 1.95-GeV/n ${}^{40}Ca+{}^{40}Ca$ 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 preliminary interpretations of these DLS data, it was essential to measure the dilepton spectrum for the elementary nucleon-nucleon case. A liquid hydrogen/deuterium target was added to the DLS. In these collisions, which involve elementary nucleons rather than nuclei with a collective "mean field," the sharp peak was expected to disappear, providing 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.

In fall 1990 a one-month run studying dilepton production in p-p and p-d collisions at 1 and 4.9 GeV was conducted. Several thousand direct pairs were obtained at 4.9 GeV. Even though the production cross section decreased by a factor of more than 50 at 1.05 GeV, a few hundred direct pairs were detected at that energy. The fall 1990 work increased the total DLS sample of direct pairs more than fivefold; the substantial data set is being analyzed to see if the previous structure observed earlier in p-Be is also present in p-p and p-d. The future DLS program will use long blocks of beamtime to finish a high-statistics p-p and p-d study. Then the group will bring back its solid-target scattering chamber for a series of high-statistics experiments on dilepton production in nucleus-nucleus collisions. This will reveal whether the structure observed in the data truly reflects a property of the nuclear medium.

Subthreshold Production

Collective features of heavy-ion collisions can be highlighted through the study of particle production below the free nucleon-nucleon threshold. To test various theoretical models predicting the yields and distributions of antiprotons, substantially improved data are required.

Subthreshold pions in Au + Au collisions have been observed, for the first time, at energies of 180-240 MeV/n. Analysis is in progress to determine if the yield of subthreshold pions has a larger-than-expected dependence on projectile/target mass, indicative of a highly cooperative production mechanism. Other subthreshold-production experiments, such as Si + Si, have also been conducted recently. A new experiment will provide such data and will extend the subthreshold antiproton measurements to lower energies. At the same time, an interesting scaling hypothesis will be tested in which all particle production below threshold, be it production of pions, kaons, or antiprotons, falls on a single curve.

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.

Earlier comparisons between the shapes of pion spectra and the predictions of various models suggested that pions are sensitive to the EOS. The systematic study of two-pion interferometry with the JANUS spectrometer was completed as results came in from La + La studies (with multiplicity selection to aid in determining the degree to which the ions collided head-on rather than grazing each other). Systematic measurements of the size, shape, lifetime, and coherence of the pion source have played a valuable role in our understanding of the dynamics of heavy-ion collisions at Bevalac energies.

Neutrons and Light Charged Particles

Recent theoretical speculation suggests that collective flow should set in at energies as low as 50-100 MeV/n. Earlier data from a Streamer Chamber experiment carried out by researchers from Michigan State University apparently show a disappearance of flow at energies below 70 MeV/n. In 1991, a group from Kent State University began an extensive set of measurements of the triple differential cross section for neutrons produced in the collisions of the heaviest systems, attempting to ascertain the energy at which flow disappears.

Inclusive charged-particle experiments, carried out using the two single-arm spectrometers at the end of Beam 30, are in the final stages of analysis using new data sets. These data, taken with high precision, should be sensitive to effects of the nuclear medium and should also serve as a testing ground for theoretical models of central nucleus-nucleus collisions for heavy systems.

Intermediate-Mass Fragments

An active collaboration exploits reverse kinematics to measure the interaction between substantial currents of heavy projectiles (with atomic number in the range of 100) and lighter targets. These collisions, in the 30-150 MeV/n energy range, produce nuclear matter at intermediate temperatures, but at below-normal densities in the area of the liquid-gas phase transition. The sources and characteristics of complex fragment emission are being studied as functions of mass and energy. The measurements are compared with dynamic calculations of the interactions, followed by examination of the statistical decay of the hot matter to ascertain whether multifragmentation (an instantaneous rather than sequential process) is occurring.

Grazing Collisions and Secondary Radioactive Beams

Although most Bevalac research focuses upon the extreme temperatures and pressures caused by central collisions, other extreme phenomena can be studied in "grazing" collisions. For example, nuclear fragments with extreme numbers of protons or neutrons—out to the "driplines" at the edges of the chart of the nuclides—can be created. Considerable progress continues to be made in using the projectile fragmentation processes to produce and study beams of radioactive nuclei. Initial studies with ^{11}Li showed clear evidence for a two-component structure, which has been interpreted as a sign of a diffuse neutron skin (halo). This has been followed by studying the

A-dependence of the electromagnetic-dissociation (EMD) process for ^{11}Li, an isotope for which a large EMD component was observed.

Another group is completing the measurements of the magnetic moments of polarized unstable mirror nuclei, producing polarizations as large as 5% in unstable nuclei through reaction kinematics.

Nuclear Astrophysics, Atomic Physics, and NASA Instrument Calibration

Many of the Bevalac's capabilities are relevant to astrophysics. HISS is used to study nuclear reaction mechanisms and to measure heavy-ion inclusive fragmentation cross sections. This holds particular interest for those who study cosmic-ray propagation in the interstellar medium. The group performing this research is measuring fragmentation cross sections for projectiles up to Fe on liquid hydrogen and helium (principal components of the interstellar medium).

A variety of work is done at the Bevalac in disciplines other than nuclear science. Bevalac beams are used for instrument calibration by researchers from the National Aeronautics and Space Administration (NASA) and by other cosmic-ray scientists from around the world. They use the beams to calibrate detectors that will be used on balloon, rocket, and satellite flights, and to recalibrate them after retrieval.

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 highly stripped 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.

Production of electron-positron pairs in collisions of fully stripped uranium nuclei on gold targets, with the electron captured by the outgoing nucleus, has consequences for RHIC, the Relativistic Heavy Ion Collider being built at Brookhaven National Laboratory, and is being explored in an upcoming experiment at the Bevalac. And a gas-cell target was developed at the Bevalac in order to measure charge-changing cross sections for ions that are of interest to the designers of new accelerators at CERN and Brookhaven; it also examines the role of electrons in relativistic ionizing collisions. This same gas cell was then used to study resonant transfer and excitation for U^{90+} projectiles in hydrogen. These experiments provide a test of relativistic dielectronic-recombination theory.

Biomedical Research

In addition to nuclear science, a diverse biomedical program has thrived at the Bevalac. This section describes selected 1990 and 1991 highlights in the three primary areas of Bevalac biomedical work:

- *Clinical programs in heavy-charged-particle radiation therapy and radiosurgery.*
- *Radiation biology and biophysics research.*
- *Development of equipment and techniques.*

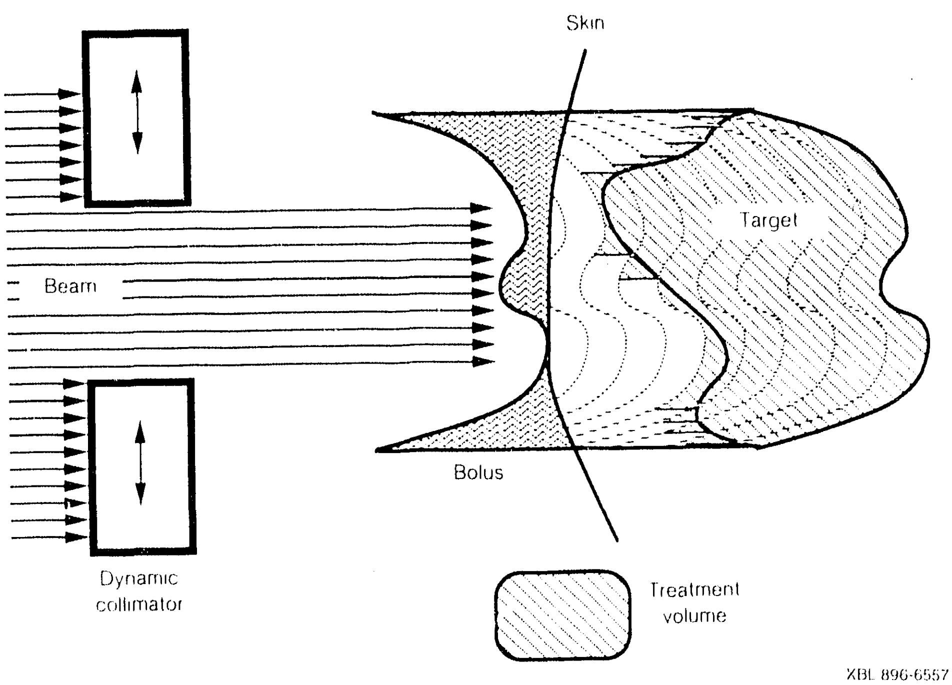
An area of life sciences research at the Bevalac accounting for about 20% of biomedical beamtime involves basic studies of the effects of radiation on both normal and abnormal cells and tissues. In vivo *and* in vitro *experiments examine such subjects as damage and repair of DNA, cell and tissue kinetics, and radiation tumorogenesis. The radiation biology and biophysics programs found their research temporarily curtailed in late 1990 and early 1991 because of the effort to prepare for and support* *the DOE Tiger Team inspection. (The clinical trials, with patients depending on the availability of treatment beamtime, proceeded as usual.) Substantial progress was nonetheless made in a variety of areas.*

A program of technology development, aimed at safer and more effective delivery of the prescribed radiation doses, has gone hand in hand with these research and treatment efforts. The major achievement of 1991 was the clinical commissioning of the Raster Scanner beam-delivery system, a significant step towards dynamic three-dimensional conformal delivery.

Heavy-Ion Radiotherapy and Radiosurgery

Clinical research medicine at the Bevalac focuses primarily on Bragg-peak radiation treatment (Figure 7-5). Two general types of treatments are carried out: radiosurgery of intracranial arteriovenous malformations (AVMs) and radiotherapy of tumors.

Over the years, more than 400 patients with symptomatic, inoperable intracranial AVMs have been treated at LBL with stereotactic Bragg peak radiosurgery in a collaborative program with area medical centers. This program, initiated at the now-decommissioned 184-Inch Synchrocyclotron, now uses helium beams at the Bevalac. A long-term dose-searching clinical-trial protocol has followed more than 250 patients for more than 2 years.



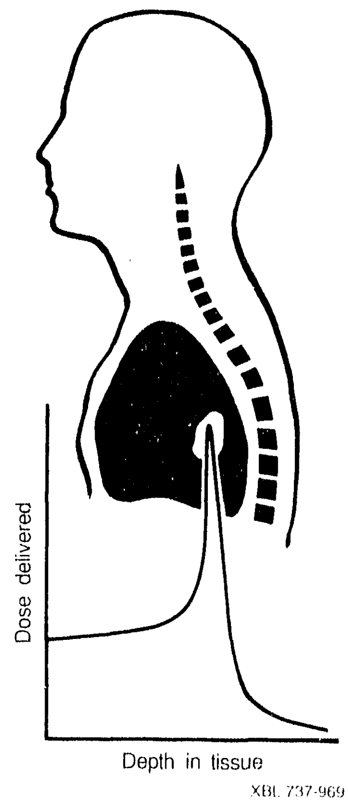


Figure 7-5. The Bragg peak gives charged particles an advantage over electromagnetic radiation (such as x-rays) for radiosurgery. Electromagnetic radiation grows weaker exponentially as it is absorbed, so delivering an effective dose to a deep tumor means considerable damage to healthy tissues in front 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 here, 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. Changing these variables can fit the treatment area to the tumor across three dimensions.

Initially, radiation doses ranged from 45 to 35 gray-equivalent (GyE)* now, doses of 25, 20, 15 and, under special circumstances, 10 GyE can be used, depending on a number of factors.

The characteristics of charged-particle beams provide a relatively homogeneous dose distribution with the 90% isodose contour to the periphery of the lesion. When the entire arterial phase of the AVM core is included in the treatment field, the rates for complete obliteration 3 years after treatment are impressive: 90-95% for volumes of 4-14 cm^3 and 60-70% for volumes greater than 14 cm^3. The total obliteration rate for all volumes up to 70 cm^3 is approximately 80-85%. For complete radiation-induced obliteration, dose is primarily related to volume, secondarily to location. The implementation of raster scanning in Cave III opens up the possibility of treating complex intracranial lesions that have previously been impossible to treat effectively, even with beams of charged particles.

A related helium-ion bioeffects research program continues to investigate the reaction to heavy-charged-particle radiation injury. Advances in dosimetry and beam-delivery technologies provide a better understanding of dose localization and dose distribution in the Bragg ionization peak at selected sites. Emphasis is placed on the cellular basis of central-nervous-system damage and repair. Research addresses the biophysical events of DNA damage and repair; oligodendrocyte, neuronal, and endothelial-cell kinetics and homeostasis; perturbations of regional blood flow dynamics and regulatory control; and cell population kinetics under heavy-ion irradiation.

In radiotherapy, more than 1200 patients have been treated in LBL clinical trials. The ongoing trial with helium continues to show excellent results for selected tumor sites, as compared to historical control data. Rates of complications are acceptably low—comparable with those of standard radiotherapy. The initial local control results with neon ion irradiation in the Phase I-II studies have been promising, with rates ranging from 50-90% for salivary gland, locally advanced prostate, advanced paranasal sinus and nasopharynx tumors, as well as for locally residual sarcoma of bone or soft tissue. We continue to search for additional evidence regarding the clinical effectiveness of high-linear-energy-transfer (high-LET)** charged particles and for improved techniques of patient selection, treatment planning, and fractionation scheduling. New randomized protocols have been opened for most of the tumor sites listed above.

We plan continued accrual in randomized Phase II and III studies, which have been established for locally advanced prostate tumors, for sarcoma, and for paranasal sinus, nasopharynx, and "radioresistant" histologies such as melanoma or renal carcinoma. For glioblastoma, a trial has been opened that compares the combination of neon ions with chemotherapy against an existing, well-characterized data base on the combination of low-LET (x-ray) irradiation plus chemotherapy. Other plans for the upcoming year include continuation of uveal-melanoma trials, a chordoma-chondrosarcoma collabo-

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* The gray is a unit of energy deposition by ionizing radiation: 1 joule per kilogram of mass. It is equivalent to 100 rads. The gray-equivalent accounts for differences in relative biological effectiveness caused by the "quality factor" of different kinds of radiation (ions, neutrons, x-rays, and so forth); the linear energy transfer (LET) of the radiation being used; and the vulnerability of the tissue being irradiated.

** LET is the energy transfer per unit length—the rate at which charged particles transfer energy as they interact with electrons when traveling through a medium. Different ions have different LETs, and many other factors come into play.

rative trial, and accrual of patients in the new randomized helium vs. neon protocol for other paraspinal and base-of-skull tumors.

The results of the study in 235 patients with uveal melanoma were excellent. A local tumor control rate of 97% has been observed in follow-up periods of 3 to 168 months (median: 62 months). Tumor control was excellent at all studied dose levels, which ranged from 50 to 80 GyE. Overall, 83% of patients have retained the affected eye. Of 181 patients who had pre-treatment visual acuity of 20/200 or better, 79 (40 %) retained this level of visual acuity. The actuarial survival rate is 80% at 5 years.

Radiation Biology and Biophysics Research

Radiation biology and biophysics research activities at the Bevalac address a broad spectrum of scientific questions. This work is relevant to the missions of several U.S. national agencies as well as to the private sector. A broad spectrum of scientific questions has been addressed by experiments employing a wide variety of beams, ranging from light ions such as helium to heavy ions such as lanthanum and even uranium.

NASA-funded biophysical research at the Bevalac has focused mainly on three space-related problems. First, an investigation is underway to assess the effects of heavy-particle fragmentation on cell killing and transformation (*sidebar*). In particular, the use of polyethylene or water-equivalent shielding material in space is under consideration, so quantitative information is necessary to determine what this material would do to the high-energy, heavy charged particles found in cosmic radiation, such as iron at 600 MeV/n. Iron fragmentation spectra under these conditions are being measured with a time-of-flight spectrometer. In addition, experiments completed to date with mouse 10T1/2 cells *in vitro* show that, in the plateau at 190 keV/μm of linear energy transfer, little change in cell killing or transformation frequency is found with up to 5 cm of polyethylene shielding.

More-fundamental work is in progress on transformation frequency in human keratinocytes subjected to iron at 600 MeV/n. The goal is quantitative assessment of the species-specific differences between rodent systems, which are readily available *in vitro*, and systems of human derivation, which are harder to develop. Assays for quantitative measurement of transformation of human mammary epithelial cells, using argon and iron, have been developed during the past year using anchorage-independent growth as a criterion. Currently in progress is a molecular analysis of the DNA of cells cloned from parent cells which were transformed by heavy ions. The goal is characterization of the kinds of genetic damage associated with the transformation process.

Experiments conducted with corn seeds conducted during space flight have spawned interest in the effects of heavy ions in producing growth inhibition, somatic mutation, and tumor induction in plants. Although the studies are limited, very interesting results have been obtained in ground-based plant studies at the Bevalac. Systematic studies with various heavy ions demonstrated that the frequency of somatic mutation in these seeds increased linearly with dose and that high-LET heavy ions were many times more effective than photons at inducing mutation.

More-recent studies with rice seeds showed significant results: both seedling survival and fertility of plants decreased with increasing doses of argon ions. Interesting mutations such as semi-dwarfism, early maturity, and large grain size were also found. These mutants demonstrate the unique potential use of heavy ions in crop improvement. In addition to the seed studies, preliminary experiments with cultured plant tissues were performed and various developmental effects of heavy ions were observed. Due to the excitement generated by these novel kinds of plant results, both basic and applied heavy-ion research with seeds and plants will surely continue.

As mentioned in an earlier section, both NASA and the Department of Defense are increasingly concerned about the loss of protection from galactic radiation provided by the magnetic field of the earth as astronauts travel deeper into space for longer periods—as in a mission to Mars, for example. Relatively little is known about the potential consequences of exposure to the types of radiation encountered in space in terms of human behavior or other effects on the brain. To reliably estimate the resulting potential for mission failure, we must understand the effects of such exposures on neurobiological systems and on behavior. Previous research showed that iron particles produce a taste aversion (a measure of behavioral toxicity) at significantly lower doses than the other types of radiation that were studied. The earlier data did not allow determination of whether the extreme behavioral toxicity of iron particles is due to their greater LET or to some other characteristics. Experiments are in progress to evaluate the LET dependence of this effect.

Another experiment, which examined mutation induction, has shown a qualitative similarity in the relationship between relative biological effectiveness (RBE) and LET at two different genetic loci (*tk* and *hprt*). The maximum RBE is achieved with ^{28}Si ions with a LET of 61 keV/μm. The *tk* locus, however, proved to be more sensitive to mutation induction for each LET. This is true whether the mutant yield is expressed as a function of dose or of particle fluence. When the mutant yield is expressed in terms of particle fluence, a qualitative difference in LET response is apparent for the two loci. This is due to the contribution of *tk-sg* (slow growth) mutants, which are induced with a vastly different LET response than either *hprt* mutants or *tk-ng* (normal growth) mutants. The spectrum of DNA structural alterations produced by high-LET radiation differs from that produced by doses of x-rays of the same toxicity. Intragenic rearrangements and allele loss are more common among mutants induced by high-LET radiations. Losses of genetic sequences associated with a linked but unselected marker locus are much more common among mutants induced by high-LET radiations.

New data have been obtained on a DOE-funded program of basic cellular and molecular effects that indicate that cellular damage caused by densely ionizing particles can be potentiated with active protein synthesis during post-irradiation heat treatment, and the radiation quality may be important to the regulation of synthesis of some specific proteins. X-rays appear to inhibit the rate of new protein synthesis, while neon ion irradiation appears to stimulate the rate of new protein synthesis post irradiation. Heat applied post-irradiation appears to amplify this response. After a treatment involving neon irradiation followed by heat, the synthesis of 70 kD, 90 kD and 110 kD proteins were enhanced while that of 100 kD protein was depressed. The differential synthesis of some proteins implies that the expression of specific gene products may be important in potentiating heavy-ion-induced radiation damage.

Further progress has been made in describing the kinetics and structures of ion-induced genetic and developmental lesions in the nematode *C. elegans*. These NASA-funded studies include lethal mutation in a 350-gene autosomal region, inactivation of both gonad and somatic blast cells, X-chromosome duplication/translocation, polycentric chromosome formation, and embryo inactivation. A set of radiation-sensitive mutants has been tested in search of specificity in the DNA-repair pathways for ion-induced lesions. Oxygen concentration and DMSO (dimethyl sulfoxide, a free-radical scavenger) were used to discriminate between direct and indirect ionization effects. The work has recently emphasized manipulation of ion-track structure by varying both charge and velocity. These experiments have shown that reducing the velocity and atomic number of the particles leads to important differences in biological effectiveness and lesion structure. This work is aimed at yielding interaction-cross-section data for multiple *in vivo* genetic and developmental endpoints, elucidating the repair pathways used for ion-induced damage, and planning for a 1992 spaceflight experiment.

DOE and NASA have supported studies during the past year directed at understanding the RBE of high-LET radiations for inducing cancer. Using the Harderian gland of the mouse as the test system, tumor prevalence data were obtained for iron (600 and 350 MeV/n), niobium (500 MeV/n), and lanthanum (693 MeV/n). These studies, together with previous results on protons (250 and 2000 MeV/n), helium (230 MeV/n), and neon (670 MeV/n), have provided enough data for regression analysis, resulting in estimates of the initial slope of the dose-versus-tumor-prevalence relationship. Contrary to data on normal tissue responses and from cell transformation studies, no convincing evidence has been found that the RBE drops at very high LET values. These data have important implications for estimating the cancer risk from heavily ionizing radiation.

In addition, dose-fractionation studies, which enable us to assess whether protracting a given particle dose reduces the hazard of tumor induction, have been completed. Early results indicate that a single dose of 40 cGy has the same effectiveness as a dose of 42 cGy given in 7 fractions of 6 cGy every two weeks. This shows that fractionation does not spare the radiogenic cancer response—in other words, that small doses of heavy ions spread out over time can be as risky as a single dose of the same size. Methods are also being developed to determine cells at risk and the transformation rate for *in vivo* irradiations.

Surviving Three Years in Space

According to the calculations for one scenario involving three years outside the magnetosphere, any given cell within an astronaut will probably be hit many times by protons and helium ions. Heavier ions (with atomic number greater than 10), though less common, would still hit one in three cell nuclei, and would have a disproportionate effect. (The calculations refer to the omnidirectional background of galactic cosmic rays. They assume that the astronauts would have a place to take shelter from the intense but short-lived and directional radiation of solar flares.)

The total dose may be as much as one sievert, or 100 rem—much more than a U.S. radiation worker would be allowed to receive in the same period. Deducing the biological effects is a complex matter. Heavy ions can damage a cell either indirectly or directly. They can produce free radicals in water and thus cause a cascade of chemical reactions. The ions can also interact directly with the DNA in the cell nucleus. A cell can be killed outright or damaged in various ways, including DNA alteration.

Radiation-induced cell transformation, one of the more worrisome biological results, begins with molecular events in the DNA, such as deletions of genes, translocations, and other genetic rearrangements. In addition to being massive and thus carrying great energy, heavy ions deposit most of that energy at the "Bragg peak," a single point at the end of their path. There, extensive cellular damage occurs, including greater potential for breaking both strands in the double helix of DNA. This compromises the cell's primary method of repairing damaged DNA, which uses an intact strand as a template.

Additional knowledge on both the physical and the biological effects of radiation will be needed for spacecraft design as well. The simplest approach would be to include massive shielding, but this could backfire, at least for the amount of overall shielding that a mechanically and financially practical spacecraft could accommodate. Naively designed shielding might make matters worse by turning the incoming particle into a shower of fragments. It would be virtually impossible to build a shielding wall that stops all these secondary particles; thus the shielding must be designed to admit the least-harmful spectrum of radiation. Clearly, a mission to Mars will require new knowledge in many fields, including the effects of heavy-ion irradiation.

Based upon an *LBL Research Review* article by Jeff Kahn of the Public Information Department.

Biomedical Operations and Quality Assurance

Procedures for safe conduct of operations in patient treatments at the Bevalac were instituted in the early stages of the clinical trials more than twelve years ago. These procedures span a wide range of activities, including treatment protocols, treatment recordkeeping, and daily calibration of dosimetry instruments. Some important procedures, such as the patient-treatment protocols, have been reviewed and approved by external committees. Our self-assessment of these procedures during the DOE Tiger Team Inspection confirmed that the procedures already in place have been satisfactory for safeguarding the patients and personnel. Our quality-assurance program, as well as the training of personnel to adhere to these safety procedures, has been also judged quite adequate.

We have also maintained sufficiently detailed documentation of the daily operations, daily calibrations, testing, and maintenance at the facility. As a result of the Tiger Team inspection, we have formalized the quality-assurance schedules and have strengthened the bookkeeping procedures for the personnel training records. We believe that these changes will improve the biomedical facility's performance, decrease its downtime, and therefore improve the patient throughput.

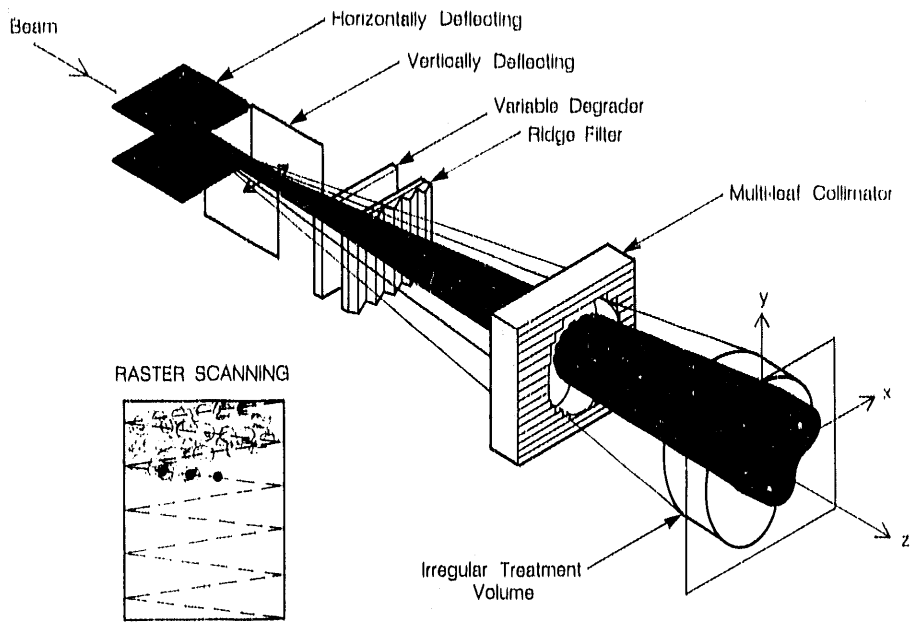
Equipment Development

The most important attribute of heavy charged-particle beams for radiotherapy is their dose-localizing property. We continue to develop the hardware necessary to achieve the optimum dose delivery—that is, delivering a uniform dose within the entire tumor volume with minimum damage to adjacent healthy tissues. The most significant advance of 1991 was commissioning of the Raster Scanner for clinical use. The Raster Scanner, commissioned in mid-1991 after extensive testing, has been shown to produce large fields with uniform dose distribution using helium and neon beams.

The Raster Scanner (Figure 7-6) represents an advance over systems currently in use, including the "wobbler" we developed in the mid-1980s. It scans the beam across the treatment area, much like the electron beam in a television's picture tube is scanned across the screen. Because the ion beams used at the Bevalac are so much more "rigid" than the low-energy electron beam in a picture tube, it was difficult to implement. Considerable effort has gone into its power supply and control system so that sharp-edged fields could be produced and the scan speed could be modulated to control the dose. Biological measurements in the proximal peak of the field, using neon ions, gave results as good as those of the wobbler.

Development of dynamic conformal treatments has continued with the construction of a multileaf collimator. We tested it with helium and neon ions for transmission through the gap between the fingers and found that leakage of the particles was suppressed sufficiently for use with patients. Other important systems currently in progress are a multi-element ionization chamber, an integrated circuit for measuring charge, and further improvements in Bevalac beam intensity control.

These results are a promising indication that the ultimate goal of implementing dynamic conformal particle therapy will be achieved. Human-use approval was very recently obtained to allow the Raster Scanner to be used with human patients in clinical trials. The therapy program at the Bevatron has already initiated a Phase I study using the Raster Scanner on selected tumor sites.



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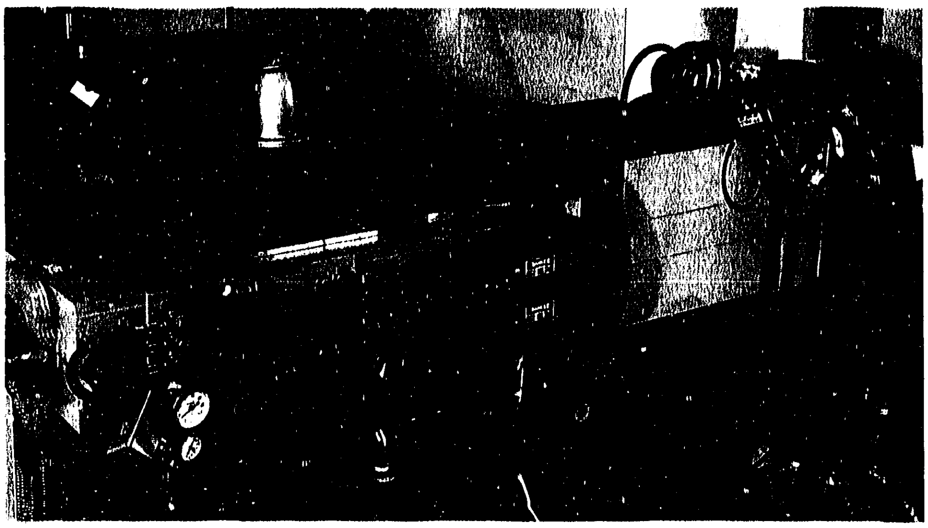

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Figure 7-6. One of the 1991 highlights in Bevalac biomedical technology development was the commissioning for clinical use of the Raster Scanner. It scans the rigid heavy-ion beam back and forth much like the electron beam in a television's picture tube. Biological measurements in the proximal peak of the field, using neon ions, have shown results as good as those of the "wobbler" beam-delivery system.

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