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Accelerator and Fusion Research Division

1987

Summary of Activities

**Lawrence Berkeley Laboratory
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Berkeley, California 94720**

April 1988

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Foreword

During the past year, the Advanced Light Source (ALS) became a reality: Funding was modest in 1987, but the year was marked by formal construction authorization for the \$100 million project. Scheduled for completion in 1992, the ALS is the largest construction project undertaken at LBL since the Bevatron was built in the mid-1950s as a proton accelerator for high-energy physics research. In contrast to the older machine, the ALS—an electron storage ring optimized to produce ultrabright synchrotron radiation—is a facility for a multidisciplinary community of users. Significantly, these two machines bracket a period of transition for LBL, from a single-program high-energy physics laboratory to a multiprogram laboratory encompassing diverse research activities. Likewise, this division, which still operates the Bevatron (now Bevalac) as a facility for research in heavy-ion nuclear science and biomedicine, is home to a rich diversity of programs.

Apart from the ALS, one of the foremost achievements of 1987 was the delivery of over 4000 hours of beam time for research at the Bevalac, a level of productivity never before reached at that facility. Much of the reason for this record is the success of the “fast-switching” program, which allows rapid and reproducible changes to be made to beam parameters, a capability that in turn allows us to switch the beam efficiently between nuclear science and biomedical beamlines. As described in Section 3, this bounty of research time was transmuted by Bevalac users into an especially productive year of experimental science. Indeed, there is a growing realization that the energy range accessible by the Bevalac offers fertile grounds for further work. Accordingly, in the *Bevalac Upgrade Conceptual Design Report*, published in May 1987, we have proposed replacing the 30-year-old Bevatron with a modern synchrotron, thereby increasing by 100-fold the beam intensities available to researchers.

Among many others, a few additional 1987 highlights might be mentioned. Toward the end of the fiscal year, we completed the apparatus for the multiple-beam experiment MBE-4, thus setting the stage for critical experimental tests of the concept of using heavy-ion drivers for fusion. In high-energy physics, our activities continued in support of the highly visible Superconducting Super Collider project, and together with SLAC and LLNL, we made significant progress in developing the concept of a Two-Beam Accelerator driven by relativistic klystrons, for the era of colliders *beyond* the SSC. The Center for X-Ray Optics likewise continued its record of successes, both in the design of optical components and systems, and in their use in experimental science. And in our magnetic fusion energy group, further advances in the technology of ion sources and accelerators now look to have possible application to major new projects, including the International Thermonuclear Experimental Reactor.

The most significant development, however, has unquestionably been the ALS. As 1988 progresses and as the pace of construction increases, we feel a continuing pride to be a part of this landmark activity in the history of the Lawrence Berkeley Laboratory.

Klaus H. Berkner
Associate Director and Division Head
April 6, 1988

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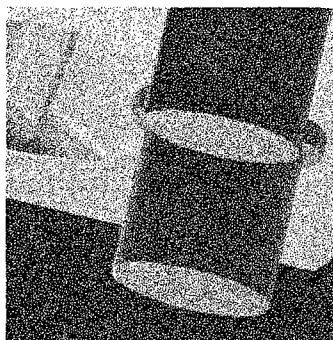
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1.

ADVANCED LIGHT SOURCE

*... a source of
synchrotron radiation
in the ultraviolet and
soft x-ray regions, now
anticipated with great
interest by a diverse
group of scientists ...*

IN DECEMBER 1986, WORK COMMENCED on the architectural and engineering design for the Advanced Light Source (ALS), a national user facility based on a 1- to 2-GeV electron storage ring, optimized to produce synchrotron radiation in the ultraviolet and soft x-ray regions of the spectrum. This activity officially marked the beginning of a project to construct the storage ring and its injector, to design and fabricate the insertion devices that would generate light of unprecedented brightness, and to build the beamlines that would link light source with user. This official beginning was, at the same time, a fitting culmination of a five-year period during which the original ALS proposal was carefully studied by a broad community of potential users, and during which the virtues of such a machine became increasingly well-understood.

As a source of radiation with extremely high spectral brightness and considerable coherent power, the ALS is now anticipated with great interest by a diverse group of scientists. The ultraviolet region is particularly interesting to such groups as chemists and surface scientists, and the soft x-ray region, containing the primary (*K*-shell) resonances of the lower-*Z* elements and the *L*-shell resonances of intermediate-*Z* elements, is of special interest for thin-film and interface studies, atomic physics research, studies of living biological systems, and various industrial applications, including high-resolution lithography. During the past year, workshops and colloquia were held in several of these areas, the focus in each case being the science to be done with the unique capabilities soon to become available.

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In 1987 specific emphasis was put on the overall facility layout and the design of the facility control system, the aim being to ensure that all technical systems can be properly integrated. Design activities also included so-called Title I design (or preliminary engineering design) of the dipole and quadrupole magnets for both the booster synchrotron and the storage ring, the storage ring and booster vacuum systems, and the main power supply systems. Of perhaps equal significance were the organizational and administrative steps taken in 1987 to lay a firm foundation for the major construction activities planned for fiscal 1988. A detailed management plan was drafted, all key personnel were in place by year's end, an architectural-engineering firm was contracted, and formal approval of the building plan was secured from the Regents of the University of California.

The activities of the past year have resulted in refinements to the conceptual design of the ALS. As described in the conceptual design report (CDR) of July 1986, and as shown in Fig. 1, the ALS consists of an injection system (comprising a 50-MeV linac and a 1.5-GeV booster synchrotron); a low-emittance storage ring that includes 12 straight sections and is optimized at 1.5 GeV; five periodic magnetic structures—so-called insertion devices—for generating synchrotron radiation; five insertion device beamlines; and front-end components for two bending magnet beamlines. Ultimately, we anticipate construction of 11 insertion devices to feed high-brightness beamlines, and 48 ports will be available for bending magnet beamlines. The essential performance goals remain unchanged: a very low electron beam emittance (a measure of the beam's transverse dimensions and its divergence), high beam stability and a long beam lifetime, and a short bunch length. Coupled with the properties of insertion devices, especially those known as undulators, the low emittance translates directly into tunable emitted radiation of high brightness and narrow bandwidth. During the past year, activity has focused on refining the designs of high-priority systems and on detailed studies of beam dynamics.

Technical Design Activities

During 1987 mechanical design efforts focused on the storage ring magnets and vacuum chamber, and as a result, the conceptual designs of 1986 evolved into so-called preliminary engineering designs—designs of sufficient detail to allow materials to be ordered for components with the longest lead times. For the magnets, magnetostatic calculations were completed for all but the storage ring dipole/gradient magnets, and formal preliminary design reviews were held (or were imminent at year's end). A detailed cross section of the storage ring dipole/gradient magnet is shown in Fig. 2. For the booster dipole magnets, conductor and iron were ordered, and a requisition was issued for the magnet laminations. (This reflects the fact that the injection systems will be commissioned about a year earlier than the storage ring.)

Engineering Design

Before its design was frozen during the past year, the vacuum chamber was modified slightly, as shown in Fig. 3. As a result, front-end components of the beamlines are now outside the vacuum chamber, thus allowing independent design decisions to be made for the two systems. The new design also demands less material, less machining, and less welding. The result is a simpler and less costly component. Of even greater import, we conducted experiments at Brookhaven's National Synchrotron Light Source (NSLS) aimed at validating one

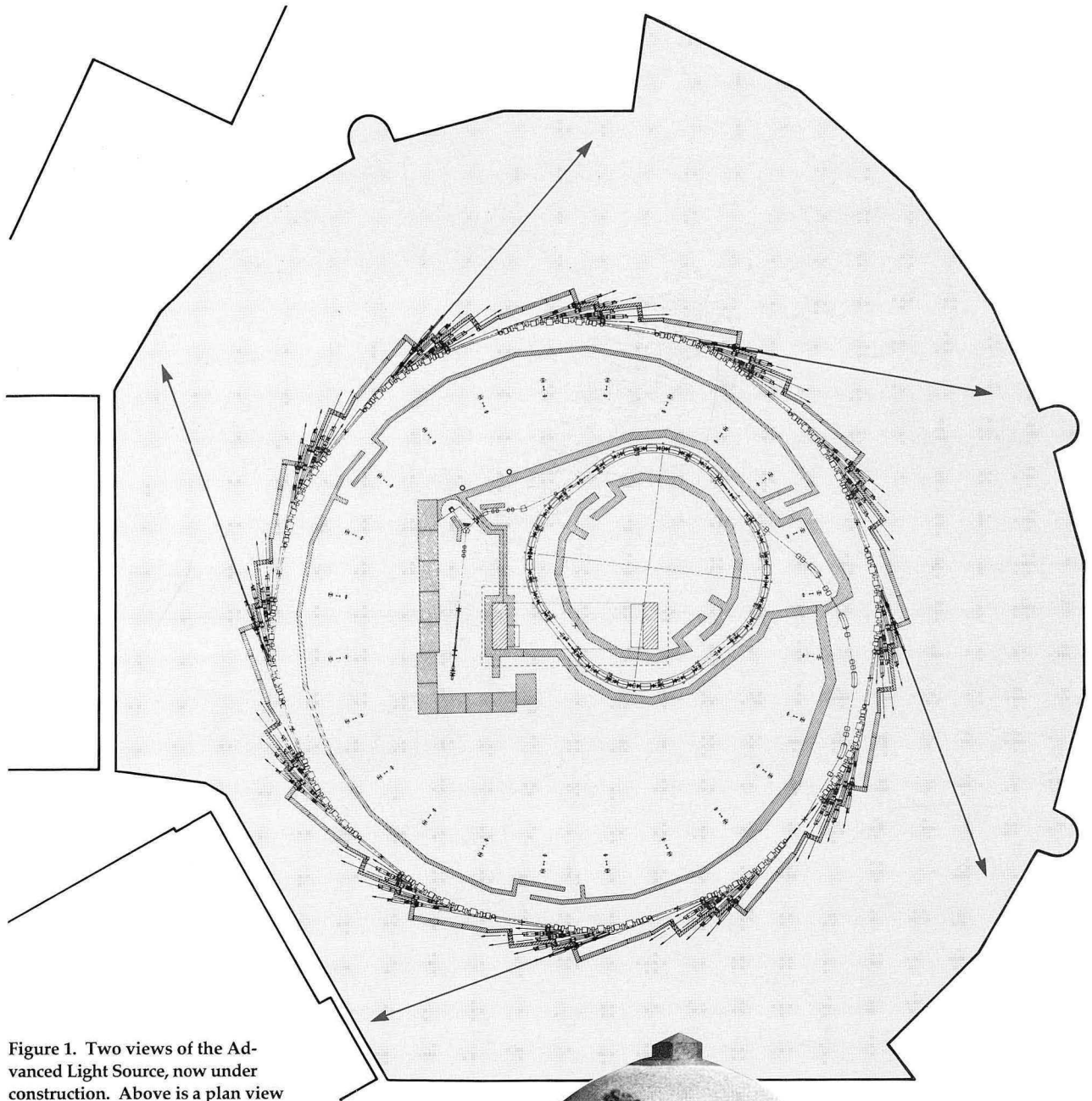
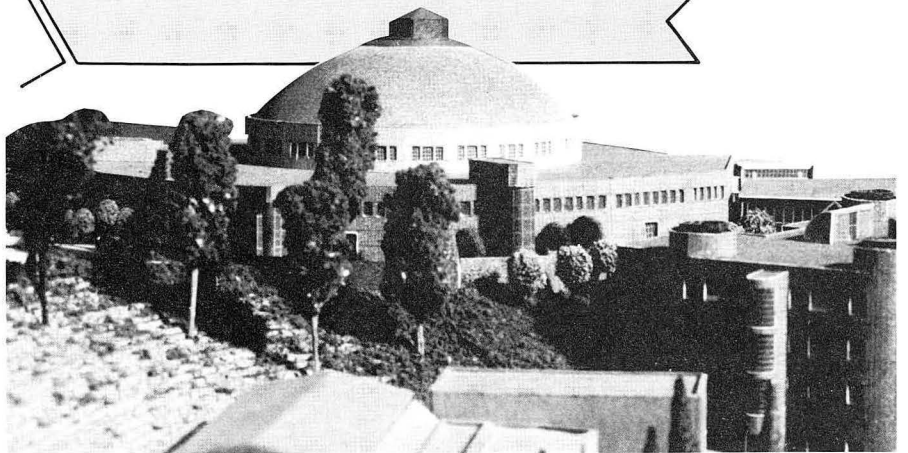


Figure 1. Two views of the Advanced Light Source, now under construction. Above is a plan view of the ALS, showing an initial complement of insertion devices and beamlines, as well as the envisioned full set of 60 beamlines. The size of the existing building is shown by the circle of I-beams well inside the storage ring. The lower illustration is a photograph of a detailed architectural model of the ALS building, showing in particular the success of the design in preserving the character of the historic 184-Inch Synchrocyclotron building.



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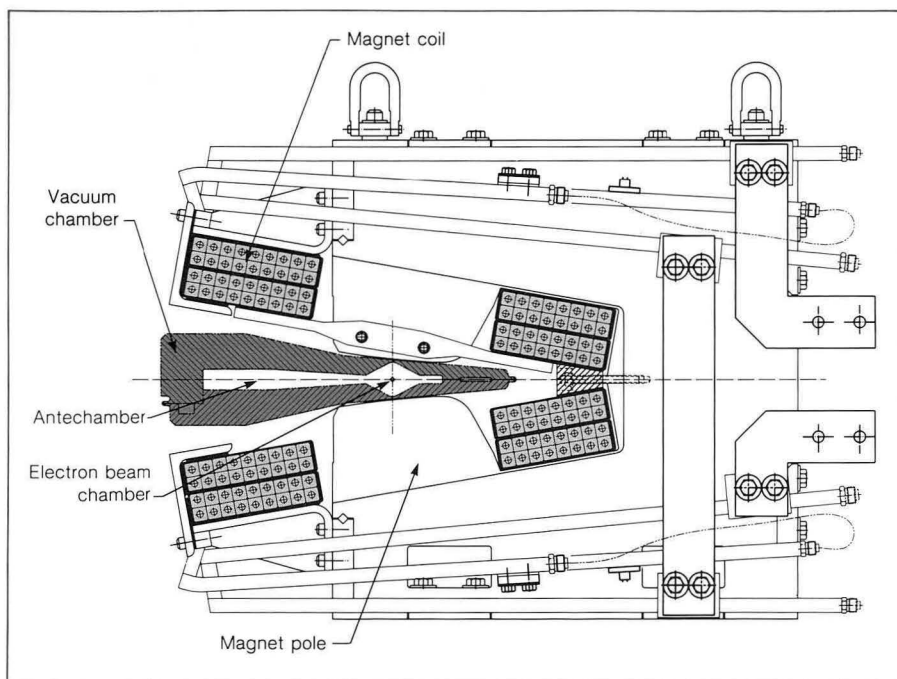
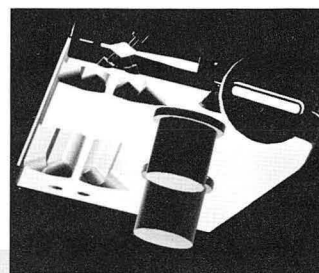


Figure 2. A detailed cross section of the storage ring dipole/gradient magnet.



1986 DESIGN

CURRENT DESIGN

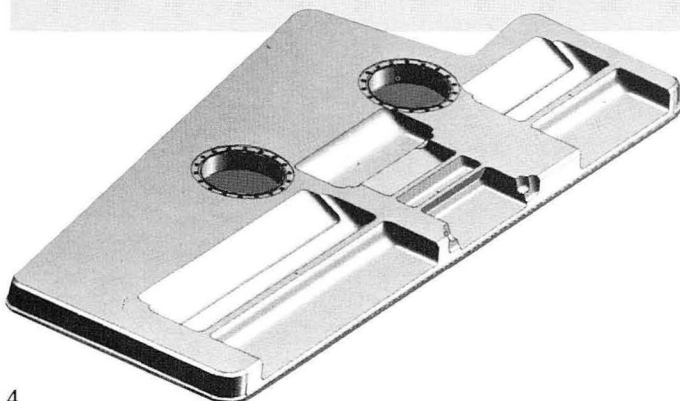
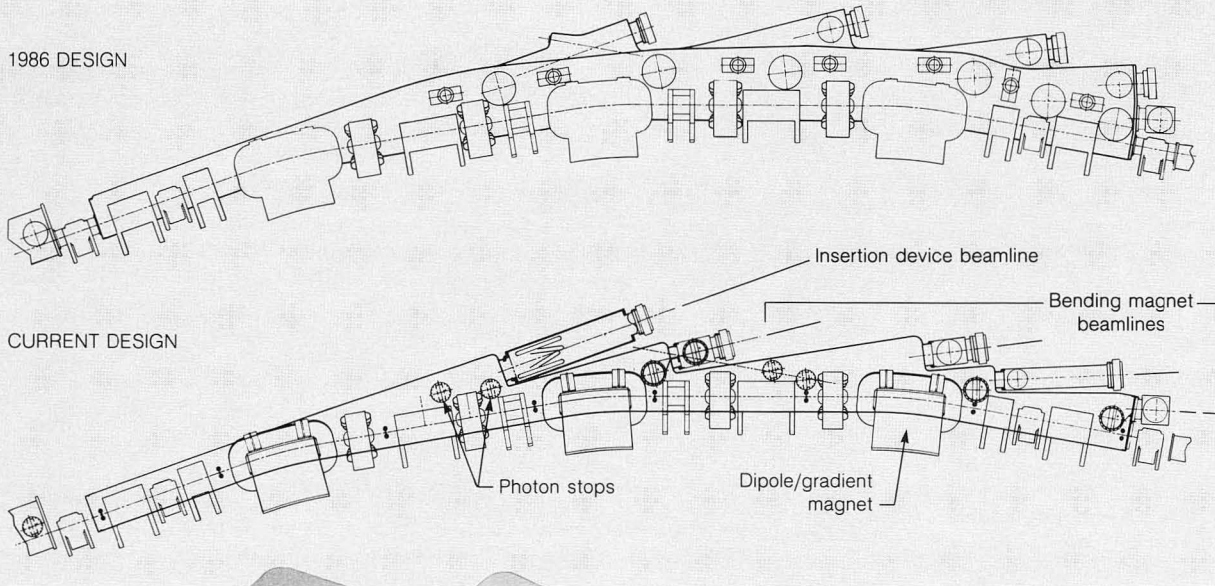


Figure 3. A comparison of the vacuum chamber conceptual design of 1986 and the current design. The present design "decouples" design decisions affecting front-end components of the beamlines, now outside the vacuum chamber, and those affecting the storage ring itself. The new design also reduces the complexity of machining and the number of welds required. The photographs show computer-generated three-dimensional images of a portion of the vacuum chamber; images such as these are used to confirm final design details.

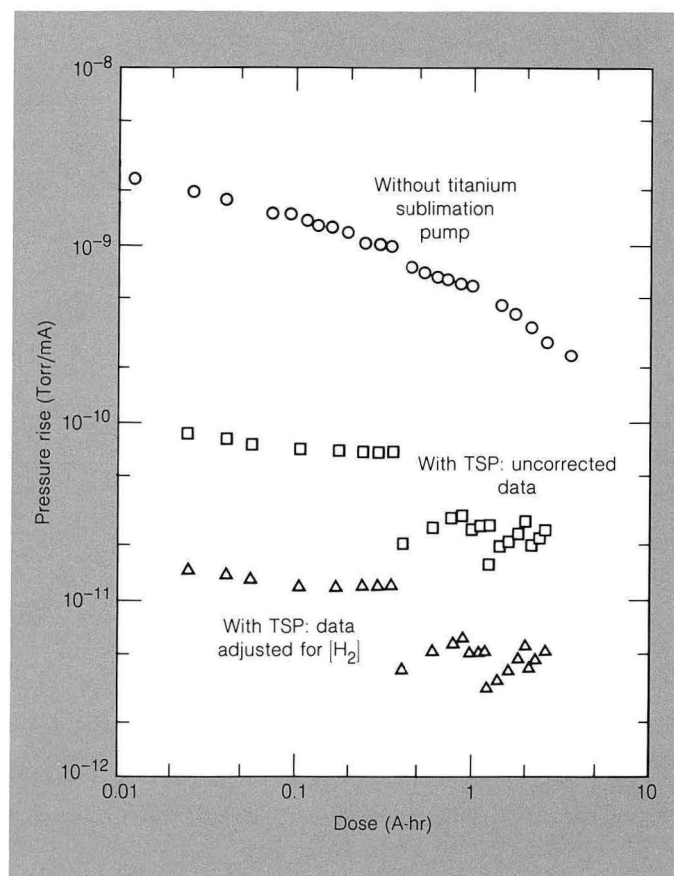
of the fundamental concepts underlying the design of the ALS vacuum system. This basic concept is to have all photons, except those directed toward experimental areas, strike photon stops in an antechamber to the main beam tube (see Fig. 3). There, local sublimation pumps will remove gases desorbed by the photons. In the NSLS experiments, the results of which are summarized in Fig. 4, the efficiency of this scheme was fully confirmed. We now confidently expect to meet the vacuum design goal of 1 nTorr.

Less intensive mechanical design efforts, but efforts consistent with our construction schedule nonetheless, were devoted to issues related to the interfaces between storage ring and beamlines, and to survey and alignment.

The past year also saw a great deal of emphasis on refining and optimizing the design of the injection system for the ALS. Work on the electron gun, bunchers, and linac has been viewed as especially important, since these components will be the first to be commissioned. Working with the Stanford Linear Accelerator Center (SLAC), we have now designed a 3-GHz linac structure, fabricated prototype components, and made frequency measurements. Building on SLAC's experience with such systems, we have also worked out new fabrication techniques (see Fig. 5) that make use of the precision milling machines now available and that allow us to achieve tolerances of a fraction of a mil.

We also completed preliminary tests on a model rf cavity and waveguide, and demonstrated significant higher-order mode damping. Effort is now turning to fabrication of full-scale prototypes of critical components. Beam-position monitors were another component that received considerable attention during 1987. We developed practical physical and electrical mounting designs, measured electrical signals from a beam pickup in a model beam chamber, and

Figure 4. A summary of the data obtained during experiments with a mockup of the ALS vacuum pumping system, conducted at the National Synchrotron Light Source. Each point represents the pressure rise observed in the chamber when the electron beam in the storage ring was turned on; the dose reflects prior conditioning (the product of current and time) before turn-on. The adjusted data take account of the fact that the sublimation pumps are inefficient in removing hydrogen, whereby the residual gas is dominated by this relatively innocuous species. Therefore, with sublimation pumps in use, the pressure attained is operationally equivalent to a lower pressure in a conventionally pumped storage ring. These results confirm the adequacy of the photon stop-sublimation pump concept. The discontinuities in the lower sets of data resulted from regeneration of the sublimation pumps.



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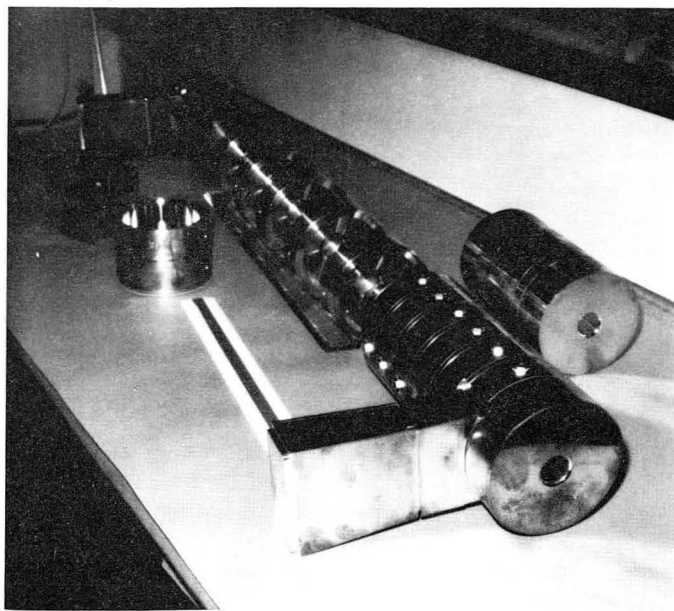


Figure 5. Components for a model of the ALS linac structure, fabricated and assembled at the Stanford Linear Accelerator Center. Precision milling of the cuplike components results in tolerances of a fraction of a mil.

developed prototypes for the signal-processing electronics. And finally, we evaluated hardware and software options for several elements of the ALS control system, and kept pace with the magnet designers in specifying power supply requirements and testing commercially available components.

The most visible achievement in terms of conventional facilities design during 1987 was the completion of a schematic design for the ALS building, which was then approved by the Regents of the University of California. The first steps toward this design included a Site Development Study by the architectural-engineering firm, Keller & Gannon-Tudor, supplemented by a report on the historical and architectural significance of the 184-Inch Synchrocyclotron building, prepared by David Gebhard of the University of California at Santa Barbara. The approved design fully conforms to the recommendations in the Site Development Study and the historical report; in particular, it preserves the character of the original building, which will appear largely unchanged to off-site observers.

During the past year, we also devoted considerable effort to shielding design and to schemes for the removal of existing shielding around the cyclotron, which must be dismantled to make room for the ALS. Shielding design focused on radiation safety, but also took account of machine-clearance and line-of-sight requirements. Revised plans for shielding removal will realize significant savings over the plan in the CDR. Some of the existing blocks will be reused for the new linac injector and at the Bevatron, while others will be disposed of at a nearby landfill, subject to the approval of the State of California.

With the engineering design of many ALS subsystems well-advanced, a major effort has been devoted to understanding in detail the behavior of the electron beam at different points in the injector accelerators and the storage ring. We have therefore accurately modeled the channels in which the beam must travel, taking into account all significant deleterious factors. For the storage ring, the model included the effects of random errors in the main field components of the magnets, higher-order field components, magnet displacements and misalignments, closed-orbit corrections, and insertion devices. Each of these "imperfections" caused a deterioration of the dynamic aperture (the cross-

Conventional Facilities Design

Accelerator Systems Studies

sectional area within which the beam is stable), but the reduced aperture was found to be fully adequate for storage ring operation. At injection it may be necessary to limit the perturbing effects of the insertion devices by increasing the gaps. (A more detailed discussion of these and other accelerator physics studies can be found in Section 7.)

The injection system has likewise undergone careful scrutiny. A study of beam dynamics in the booster, for example, has shown that, even in the event of beam blowup soon after injection, and in the worst-case scenario, the important characteristics of the beam are not compromised. Also, the operation of the subharmonic bunchers at the linac entrance has been simulated and shown to be highly effective in delivering a bunched beam to the linac.

Two other significant advances lay in the area of electronics research. Kicker magnets that inject and extract the beam from the booster ring must turn on or off in 100 nsec. We developed a simplified circuit for pulsing these magnets that operates at a reduced voltage of less than 20 kV. Each magnet is made as a simple lumped inductor, with each half of a one-turn coil energized from a charged capacitor through thyatron switches. The second development was a response to the requirement for unprecedented beam stability and positional reproducibility. A scheme for calibrating the position-monitoring electrodes was devised and tested on model systems (see also page 21). The beam position is obtained by comparing signals from electrodes mounted in the walls of the vacuum chamber. However, small variations in the geometries of the electrodes and in the electrical characteristics of the feedthroughs and cables introduce offsets in the signal amplitudes. By making a set of measurements in which signals from three of the electrodes are observed when the fourth is excited from the control room, these offsets may be calculated, thus allowing correction of the beam-position signals. This convenient scheme eliminates the need to insert calibration devices into the chamber and may be repeated as desired on the operating machine.

Interactions with the Community of Users

In concert with the increasing construction activity on the ALS, efforts to raise and resolve issues related to potential users of the facility have likewise intensified. Perhaps the foremost among these issues is the matter of insertion device specifications, which will depend ultimately on which regions of the electromagnetic spectrum appear to offer the greatest promise for the first few years of ALS operation. Pertinent to this question is a series of workshops and colloquia that began in 1987, the collective aim of which is to highlight the scientific goals of several research communities and to consider the corresponding impact on the ALS design. Another broad question that must be answered in parallel with the early phases of construction is, What will be the nature of the facility's user policy? The clear commitment is to ensure optimum scientific productivity from this forefront user facility and to assure the broadest possible access. During the past year, a mechanism was set in motion, involving members of the Users Executive Committee, as well as ALS project leaders, to draft a policy consonant with this commitment.

ALS Workshops and Colloquia

Scientific meetings held in fiscal 1987 that were pertinent to future research activities at the ALS included a symposium on soft x-ray near-threshold phenomena, a workshop on chemical applications of undulator radiation, and the International Symposium on X-Ray Microscopy. In addition, an optical systems workshop was held at LBL, not to assess scientific opportunities, but rather to explore innovations in beamline design—a necessary precursor to the science itself.

At the chemical applications workshop, held in May at the University of California at Berkeley, chemists expressed an especially strong interest in the possibility of two-photon pump-probe experiments, in which the picosecond pulses of the ALS would be synchronized with radiation from a second source. They envisioned an extensive facility comprising lasers and molecular beams, built near or around an ALS beamline. During the international microscopy meeting in August, an evening session was devoted to early planning for advanced synchrotron radiation facilities, thus providing a forum for discussing research possibilities at the ALS. Those making presentations stressed the need for a permanent scanning x-ray microscopy facility that can exploit the high brightness of the ALS in the energy range between 200 and 1000 eV. An integrated biology facility was also described, with a capability for cell culturing, light and scanning electron microscopy, and sample preparation and analysis.

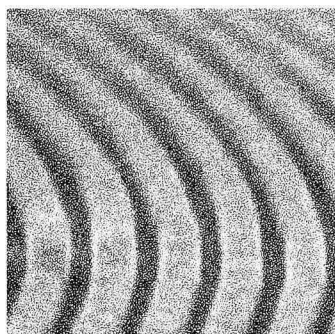
A host of issues must be confronted if the ALS is to function successfully not merely as a user facility, but, in current parlance, as a "user-friendly" facility. These issues include the provision of adequate nearby office space and supporting laboratories, the allotment of sufficient parking, and the handling of hazardous materials. All such identified issues are under discussion by the Users Executive Committee (whose members are identified in Table 1), ALS project management, and Laboratory management. Perhaps the paramount issue is the matter of a user policy governing the allocation of beam time. As a starting point, a subcommittee of the Users Executive Committee has reviewed the policy at NSLS and has used it as the basis for a draft policy for ongoing discussion. A final policy, to be defined by ALS management, should be in place by the spring of 1988. A call for letters of intent from parties interested in developing beamlines or experimental facilities is also planned for early 1988. We expect these letters to lead eventually to the formation of insertion device teams (IDTs) and participating research teams (PRTs), which would enjoy priority of use at their designated beamlines.

Along similar lines, a first annual general users meeting has been scheduled for June 1988. Likely agenda items would include discussion of ALS user policy and a constitution for a broad-based users' organization.

The Making of a User Facility

Bernd Crasemann, University of Oregon (chair through Dec. 1987)
 Stephen Kevan, University of Oregon (chair, effective Jan. 1988)
 Tomas Baer, University of North Carolina
 John Browne, Los Alamos National Laboratory
 Wolfgang Eberhardt, Exxon Corporation
 Charles Fadley, University of Hawaii
 Warren Grobman, IBM
 Allen Hartford, Los Alamos National Laboratory
 Franz Himpsel, IBM
 Janos Kirz, State University of New York at Stony Brook
 Yuan Lee, University of California at Berkeley
 Carl Poppe, Lawrence Livermore National Laboratory
 Stephen Rothman, University of California at San Francisco
 Neville Smith, AT&T
 Joachim Stöhr, IBM
 Richard Stulen, Sandia National Laboratories

Table 1. Members of the Advanced Light Source Users Executive Committee.



2.

CENTER FOR X-RAY OPTICS

*... making x-rays more
scientifically accessible
by developing
technologies for their
generation,
manipulation, and
detection ...*

IN LINE WITH ITS BROAD CHARTER to make the x-ray region of the electromagnetic spectrum more scientifically accessible, the Center for X-Ray Optics made substantial progress during the past year in the development of technologies for the generation, manipulation, and detection of x-rays, and it embarked on several scientific investigations made possible only with these new technologies. We continued to interact with scientists outside Berkeley, largely through our affiliates program, and participated in several projects at other institutions. Training of students remained an important part of our effort, as reflected by the large number of student researchers supported under our University Research Initiative contract and by the continued offering of the course "Introduction to X-Ray Physics" in the UC Berkeley Department of Physics.

X-ray imaging and its application to real scientific problems, especially in biology, has been a major focus of activity. A significant accomplishment in advanced instrumentation was the fabrication and testing, in collaboration with IBM, of Fresnel zone plates for the focusing of soft x-rays. These lenses are also a key ingredient in a collaborative x-ray microscopic investigation of protein transport in secretory cells. A second, closely related imaging project has succeeded in reconstructing images from holograms of zymogen granules, an intracellular structure associated with protein transport.

For the more difficult task of focusing hard x-rays, we concentrated our efforts on multilayer coatings on mirrors. In addition to basic structural studies of multilayers, we have learned how to make uniform, large-area coatings, and during the past year, we installed a multilayer-coated

D. Attwood
(director)
P. Batson
D. Bradley
J. Brown
A. Catalano
J. Chin
R. Delano
R. Digennaro
R. Edwards
W. Edwards
B. Gee
J. Guigli
E. Gullikson
K. Halbach
B. Henke
M. Hettrick

H. Hogrefe
M. Howells
E. Hoyer
D. Humphries
P. Jaanimagi
J. Kerner
K.-J. Kim
J. Kortright
T. Lauritzen
S. Marks
W. McKinney
J. Meneghetti
E. Okoye
R. Perera
D. Plate
A. Robinson
L. Sasaki

D. Shuman
R. Srinivasan
R. Tackaberry
A. Thompson
J. Thompson
J. Uejio
J. Underwood
Y. Vladimirovsky
R. Weidenbach

Students

D. Berkeland
E. Bollt
K. Cherry
J. Davis
J. Denlinger

C. Frieber
M. Fryer
C. Gross
G. Guttman
N. Iskander
C. Lee
R. Lefstin
D. Liedahl
C. Mulder
T. Nguyen
A. Oren
G. Paap
P. Plag
A. Renema
S. Turek
D. Walrod
N. Wang

B. Wargelin
A. Weissburg
Y. Wu
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Administrative Support

P. Butler
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D. Nanod
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Affiliate Members

T. Barbee, LLNL
F. Cerrina, University of Wisconsin
T.H.P. Chang, IBM
R. Deslattes, NBS
C. Dittmore, LLNL
R. Feder, IBM
D. Kern, IBM
B. Kincaid, AT&T Bell Laboratories
J. Kirz, SUNY at Stony Brook
M. Richardson, University of Rochester
S. Rothman, U.C. San Francisco
G. Sommargren, Zygo Corporation
G. Stradling, Los Alamos National Laboratory
D. Sweeney, Sandia National Laboratories
R. Tatchyn, Stanford University

“premirror” in a beamline at the National Synchrotron Light Source.

We also have a broad interest in the generation and detection of x-rays. In addition to our continuing work on insertion devices (wigglers and undulators) for the Advanced Light Source (ALS), we updated our comparisons of high-brightness, partially coherent x-ray sources, including x-ray lasers. And at year’s end, we were at work on an advanced solid-state position-sensitive detector for a high-resolution synchrotron radiation-based coronary angiography system.

In the areas of x-ray scattering and x-ray spectroscopy, we have now designed, built, and characterized an ultrahigh-resolution spectrometer that uses advanced diffraction gratings with variably spaced grooves to give a measured spectral resolving power of 35,000 in the extreme ultraviolet. And we applied the technique of grazing-incidence x-ray scattering to the problem of quantitatively characterizing defects in heteroepitaxial semiconductor systems.

Also during 1987 our synchrotron radiation projects group completed the construction of an advanced wiggler that uses the new neodymium-iron-boron permanent-magnet material. The wiggler was installed at the Stanford Synchrotron Radiation Laboratory, where it will generate high-flux beams of x-rays. We also developed a theory for the accurate calculation of the position of the beam in a particle accelerator, such as an electron storage ring, from the signals picked up by a beam-position monitor. Accurately knowing and then controlling the beam position is essential for efficient use of the radiation from high-brightness synchrotron radiation sources such as the ALS.

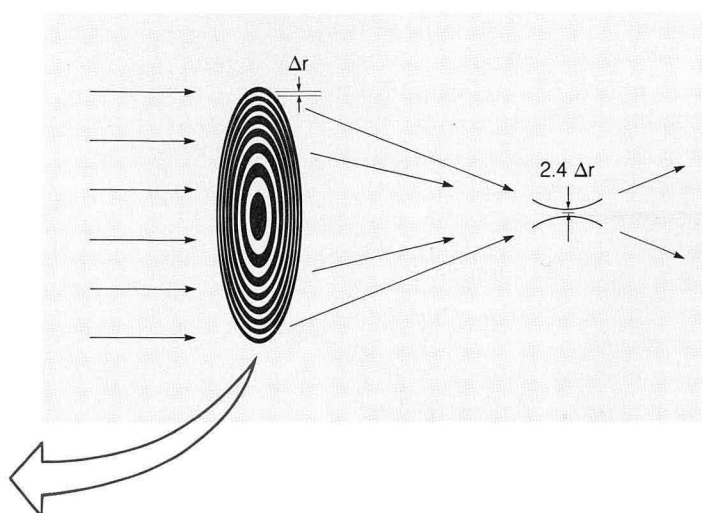
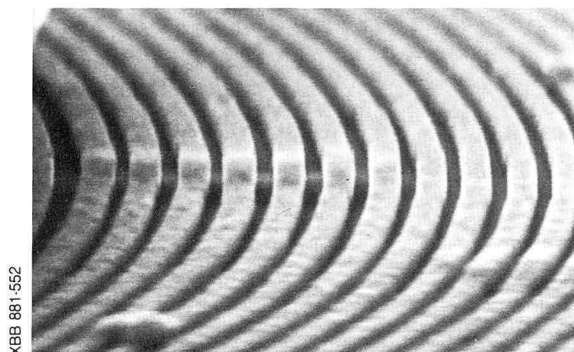
X-rays pose special problems for optics designers, because image formation with conventional refractive lenses is not possible and because specular reflectivity from mirrors at near-normal incidence is negligible. Fortunately, several other methods are available for manipulating short-wavelength radiation. For example, Fresnel zone plates are circular structures whose alternating opaque and transparent concentric rings can focus low-energy, or soft, x-rays by diffraction. Alternatively, holography provides a means of imaging with soft x-rays that does not require focusing optics at all. During the past year, we made significant advances in developing both of these imaging techniques and successfully applied them to practical problems in experimental science.

Circular diffractive structures known as Fresnel zone plates can focus soft x-rays with wavelengths between 10 and 100 angstroms. When used with a suitable source of collimated x-rays, a zone plate can focus radiation to a spot with a radius somewhat larger than the width of the outer zone (see Fig. 6). In collaboration with colleagues at the IBM Thomas J. Watson Research Center, we have been fabricating gold zone plates of ever-improving quality and resolution for the past several years, using the technique of electron-beam lithography. Most recently, we completed fabrication and testing of a zone plate 62 μm in diameter (comparable to the diameter of a human hair), with an outer zone width of 500 angstroms. Consisting of x-ray-absorbing gold rings 1200 angstroms thick on a transparent silicon nitride substrate 1000 angstroms thick, the lens has a focal length of 1 mm at a wavelength of 31 angstroms and a demonstrated resolution of 750 angstroms. Another measure of lens quality is the diffraction efficiency, which was measured to be 1.3%, considerably lower than the 5.2% of an earlier lens with a 1000-angstrom outer zone width. We are now working to improve the efficiency.

X-Ray Imaging

Fresnel Zone Plate Lenses

Figure 6. A schematic diagram of a Fresnel zone plate lens for diffractive focusing of x-rays, together with a close-up of an actual lens with an outer zone width of 500 angstroms. Gold zone plates such as this have been successfully used to image biological material with a resolution close to the outer zone spacing.



XBL 842-9405C

Soft X-Ray Microscopy

The ability to focus soft x-rays makes it reasonable to contemplate a microscope with which to study both biological and inorganic materials at a spatial resolution of better than 1000 angstroms and with elemental specificity. In materials science, for example, a focused beam of x-rays could be used to investigate such technologically important surface processes as the formation and coalescence of islands of new material on a substrate during the growth of epitaxial layers on electronic and opto-electronic devices. Such studies, in fact, are being planned. In biology, our efforts have focused on the use of such a microscope to overcome important limitations of existing imaging techniques. The ultimate goal is the realization of the biologist's dream: to view the interior of an unaltered living cell and to understand quantitatively the physics and chemistry of cellular structure and cellular processes.

To this end, we have begun a study of a small intracellular structure called the zymogen granule, which is associated with the secretion of some 20 different digestive enzymes from pancreatic cells and is a model system for the investigation of secretion. The evidence for existing models of secretion is weak and indirect, largely because the electron microscope cannot follow secretory processes in real time and because the light microscope cannot resolve the details of the structures involved, such as the 1- μm -diameter granules. Accordingly, experiments to test models of cellular secretion have begun with the scanning x-ray microscope at the National Synchrotron Light Source (NSLS) at the Brookhaven National Laboratory. The initial experiments, organized by the Center and done in collaboration with researchers from UC San Francisco, SUNY Stony Brook, and IBM, produced the first views of the interior of such a small intracellular structure as the zymogen granule in its natural aqueous environment. With zone plate lenses having 500- to 700-angstrom outer zone widths, the microscope generated images with a resolution of better than 1000 angstroms.

Physical and chemical studies had suggested that the zymogen granule is organized internally, whereas electron micrographs showed a relatively fine-grain interior with no clearly evident ultrastructure. The preliminary x-ray microscope results are inconsistent with the model of a uniform sphere of protein. However, estimates of protein concentration within the granule, based on quantitative measurements of x-ray absorption by the carbon atoms in the protein, are consistent with published chemical estimates of the net content. These observations show the promise of using element-specific x-ray absorption to quantitatively measure the concentrations of substances within intracellular objects. Future experiments will jump from visualizing intracellular structures to

watching the dynamics of processes in real time by following changes in the structure of the granules during a graded release of protein.

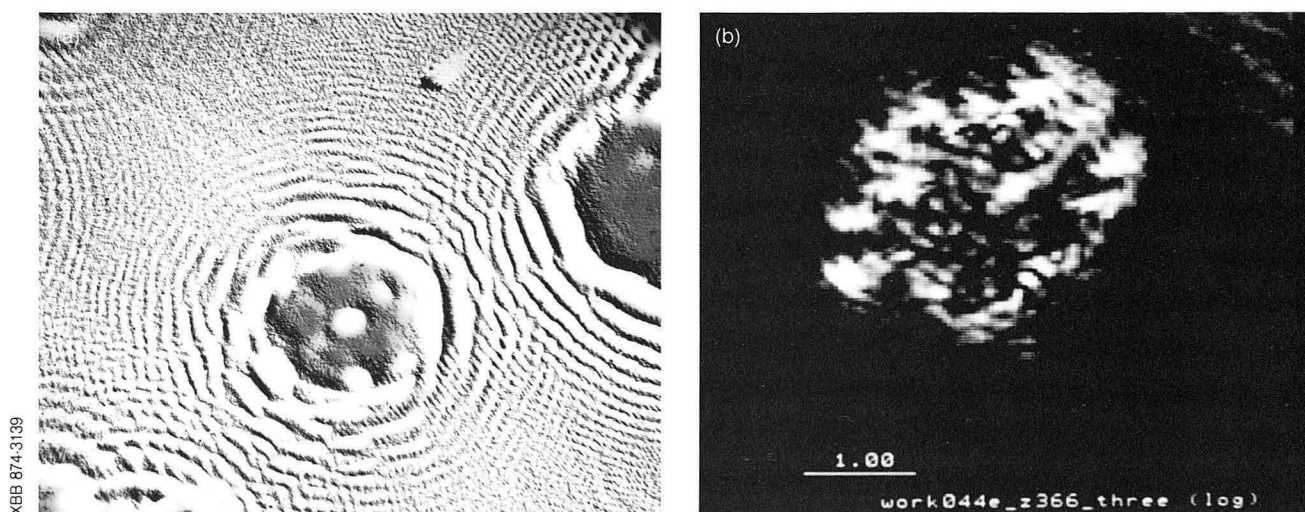
In previous years, we successfully demonstrated that the holographic methods used with visible light could also be applied to soft x-rays by recording holograms on photographic film exposed to 31-angstrom x-rays from a bending magnet beamline at NSLS. Images with a resolution of about $1\ \mu\text{m}$ were reconstructed with a visible-light laser. During 1987 we made two further advances, both aimed at achieving significantly better resolution and thereby bringing x-ray holography closer to real scientific applicability. First, we shifted from a silver halide film detector to a high-resolution x-ray resist. And second, to compensate for the much lower "speed" of the resist, we used a much brighter undulator source on NSLS's X-17T beamline, in place of the bending magnet source.

About 100 holograms, including some of zymogen granules, were made, with typical exposure times of approximately 1 hour. The holograms were recorded on copolymer resist layers about 2000 angstroms thick on a silicon nitride substrate, using 24.7-angstrom x-rays. After exposure, the resist was developed and then shadowed with metal to enhance the relief image, which consisted of an interference pattern formed by coherent superposition of scattered and unscattered x-rays. Transmission electron micrographs of the metallized holograms indicated that the minimum fringe period was about 400 angstroms (see Fig. 7). This pointed directly to the possibility of reconstructing images of like resolution.

The holograms themselves served as an important proof that a major obstacle to the use of x-ray holography as a high-resolution method of imaging could be overcome, but it still remained to reconstruct images from the holograms. To take this next step, we have concentrated on the use of numerical reconstruction from a digitized hologram. Our approach has been to calculate the signal propagated forward from the hologram that encodes the amplitude and phase of the wave. The reconstructed images shown in Fig. 7 show small discrete objects and are similar to the granule images obtained with the scanning x-ray microscope. However, the halos visible in the reconstructions make it difficult to interpret features in the image with complete confidence. Present efforts are directed toward the study of these halos, along with further refinement of the model for correcting nonlinearities (an important advantage of reconstruction from digital holograms) and evaluation of the ultimate resolution that can be obtained in reconstructed images from the present holograms.

Holographic Microscopy

Figure 7. A hologram (a) and a reconstructed image (b) of a zymogen granule. The minimum fringe period in the hologram is about 400 angstroms; efforts to attain this resolution in the reconstructed images continue.



XBB 874-3139

CBB 881-596

Multilayer Mirror Technology

As photon energies increase, Fresnel zone plates become progressively more transparent and, consequently, less effective. Fortunately, in the hard x-ray region, mirrors can be used to focus x-rays that are incident at a grazing angle. In this configuration, coating the mirror with multiple ultrathin layers of alternating high- and low-atomic-number materials provides several advantages over uncoated optics. For example, the mirrors operate at larger-than-usual glancing angles, set by the Bragg condition for the x-ray wavelength and the multilayer spacing. Consequently, multilayer coatings cause only a narrow band of wavelengths to be reflected. In addition, the larger glancing angles increase the size of the solid angle of collected light and significantly reduce aberrations. Over the past year, we continued to make significant progress in understanding the materials science of multilayers, in learning how to fabricate high-quality mirrors, and in applying them to real scientific problems. We deposited and characterized many materials in a search for improved material combinations for x-ray optical multilayers. And we successfully coated multilayers onto areas as large as 3×6 inches with a uniformity near 1%.

X-Ray Analysis of Mirrors

Tungsten-carbon multilayer structures were among the first with demonstrated utility as x-ray optical devices. Even so, little is known about the local interatomic arrangements in the ultrathin layers, although these arrangements strongly influence optical performance and stability. To learn more about in-plane atomic arrangements and how they change with layer thickness and with heat treatment, we have studied the W-C system by using the technique of grazing-incidence x-ray scattering. When close to the critical angle for total external reflection, the grazing angle limits the penetration depth of the x-rays into a sample, making the technique ideal for probing the structure of thin layers near the surface. When applied to a series of W-C multilayers with periods ranging from 8.3 to 109 angstroms, grazing-incidence scattering revealed an increase in the mixing of tungsten and carbon with decreasing layer thickness. Annealing the thinner layers also caused mixing of the elements. These and other changes in interatomic arrangements with thickness and annealing are in qualitative agreement with the x-ray optical performance of the multilayer mirrors, which diminishes as the layers lose their identity because of the mixing.

Multilayer Mirror Prefilter

Because of the wavelength selectivity of multilayer mirrors, they can be used on synchrotron radiation beamlines to reduce the power at unwanted photon energies that is incident upon downstream optical elements. If the multilayer is sufficiently reflective, the power reduction can be achieved without significant loss in efficiency over the limited bandpass of the multilayer. Accordingly, multilayer "premirrors" may be used in situations where thermal loading due to the excess radiation on the optical elements might impair the spectral resolution of a beamline.

During the past year, we installed a multilayer premirror on the X-24 bending magnet beamline at NSLS, as the first step toward the use of such mirrors in place of conventional mirrors. The system comprises a cooled metal substrate, coated with a multilayer designed specifically for the geometry and photon energy range of the beamline (800 to 4000 eV). Many factors led to the selection of vanadium and amorphous silicon carbide, layered in a relatively large-period structure comprising 17 layer pairs with a period of 147 angstroms. These material and parameter choices provide for a narrower passband and better isolation of the Bragg reflection from the specular reflection, as compared to a conventional combination of high- and low-atomic-number materials.

As shown in Fig. 8, the calculated reflectivity of the vanadium-silicon carbide multilayer mirror shows that the multilayer can reduce the reflected power to a

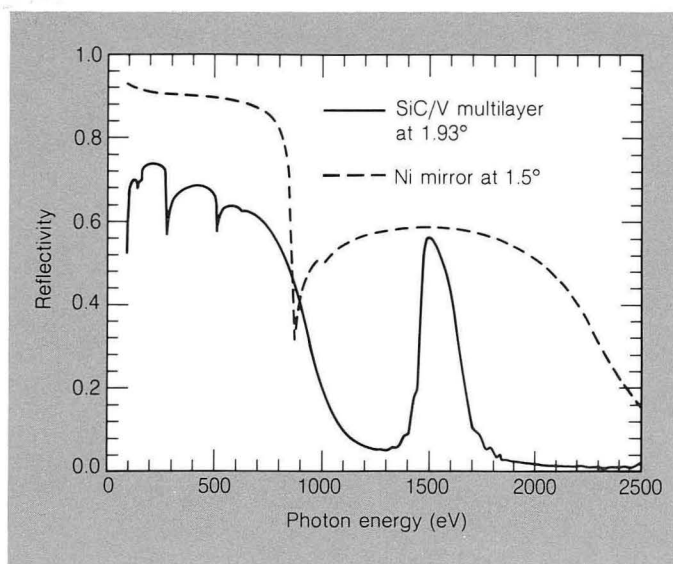


Figure 8. A plot showing reflectivities of a conventional nickel mirror and a vanadium-silicon carbide multilayer, as functions of photon energy. The region of interest on NSLS's Beamline X-24 is between 800 and 4000 eV. The Bragg peak at about 1500 eV can be moved by varying the glancing angle of incidence on the multilayer-coated mirror. The narrow reflectivity band significantly reduces the unwanted power transmitted to radiation-sensitive optical elements downstream.

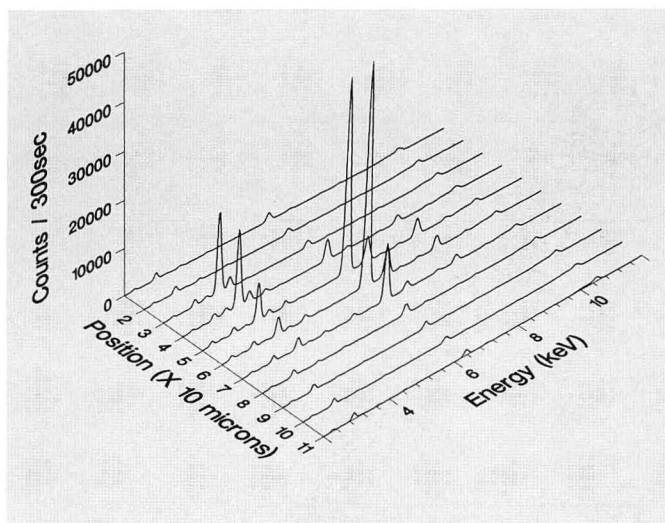
quarter of that reflected by a conventional mirror. Furthermore, the experimentally measured reflectivity profile on the NSLS beamline was reasonably close to that calculated from a model for an ideal multilayer. The close agreement between the experimental and theoretical widths of the second-order Bragg peak for the multilayer is an indication of the uniformity of the multilayer coating over the area of the mirror. Finally, heating of the multilayer in the photon beam did not cause any degradation after one month of exposure at storage ring currents as high as 230 mA, while the temperature of the first silicon monochromator crystal in the beamline was significantly reduced.

Until recently, the nondestructive measurement of trace-element concentrations in small sample areas was difficult, as was the microanalysis of materials that could not be placed in a vacuum. Now we have developed an x-ray microprobe that can quickly measure the concentration and spatial distribution of many elements, using a beam of synchrotron radiation focused to a spot less than $10 \times 10 \mu\text{m}$ square. This fine spot size, achieved at both the Stanford Synchrotron Radiation Laboratory (SSRL) and NSLS, was obtained by using a pair of concave spherical mirrors with tungsten-carbon multilayers. The Kirkpatrick-Baez geometry of the two mirrors eliminates the severe astigmatic aberration associated with a single grazing-incidence reflector. At NSLS the microprobe accepts a broad radiation spectrum, then selects and focuses a 1-keV-wide slice of the spectrum near 10 keV. Focused on a sample, these x-rays excite fluorescence at wavelengths characteristic of the atomic elements in the sample. A lithium-drifted silicon detector analyzes the photon energies and the intensities of peaks in the fluorescence spectrum to reveal the elements and their concentrations. One- or two-dimensional maps of elemental concentration are obtained by scanning the sample past the focused x-ray beam in a raster pattern. The microprobe has a sensitivity of femtograms for elements from potassium to zinc, with a counting time of 60 seconds.

During the past year, we analyzed a variety of samples with the microprobe, including ceramics, red blood cells, blue-green algae, and thin sections of cancerous rat tissue. We also investigated thinned coal sections to map their heterogeneity. Figure 9 shows the elemental spectra that were obtained at several points on a 50- μm -thick coal sample. The figure graphically portrays the very large variations in the trace-element concentrations in this sample. We also analyzed a series of simulated quartz samples containing fluid inclusions and obtained

Hard X-Ray Microprobe

Figure 9. A perspective plot of x-ray microprobe spectra from a coal sample. The photon energies of spectral peaks identify the elements present in the sample, while the peak heights represent their concentrations. The third axis gives the distance along a linear scan through the sample. This plot graphically illustrates the spatial inhomogeneity of coal, with concentrations of impurity elements being highly localized. The prominent peaks near 3.7 and 6.4 keV are due to calcium and iron, respectively.



XBL 881-8815

contour maps for the elements of the inclusions, clearly showing their extent. These initial results vividly demonstrate the high elemental and spatial sensitivity of the x-ray microprobe and demonstrate its promise as a nondestructive probe for trace-element analysis. We plan to upgrade the performance of the microprobe with a pair of improved mirrors that will permit elemental concentrations to be mapped within structures as small as a single biological cell.

X-Ray Sources and Detectors

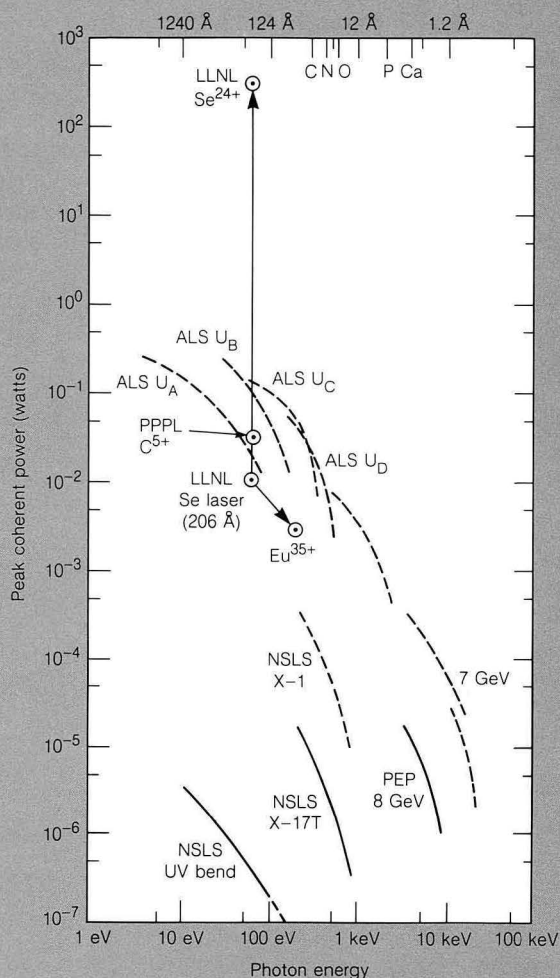
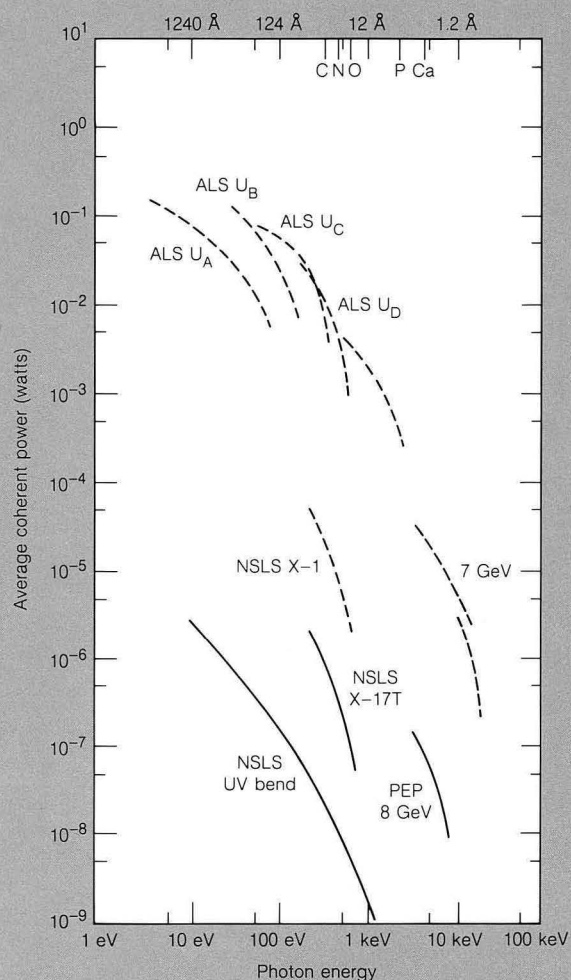
Our broad interest in sources of x-rays has been reflected in past comparative studies of generators of high-brightness x-ray beams, including x-ray lasers, high-temperature plasmas, and undulators in electron storage rings. We have also investigated the relative merits of compact storage rings and laser-produced plasmas, two candidate sources for manufacturing integrated circuits by x-ray lithography. More recently, we have concentrated our efforts on the theoretical understanding and design of periodic magnet structures known as insertion devices (wigglers and undulators). This work is particularly relevant to the ALS (see pages 1–8). We are also interested in the other end of any experimental setup. For example, we are developing an efficient position-sensitive x-ray detector for use in synchrotron radiation-based coronary angiography.

High Brightness and Coherence

We continue to update our comparisons of sources of high-brightness, partially coherent laserlike radiation at ultraviolet and x-ray photon energies. We have now included new results obtained with undulators at NSLS, and at SSRL beamlines on the PEP high-energy physics storage ring. We have also included results from the x-ray laser at the Princeton Plasma Physics Laboratory, which radiates at 182 angstroms. And we have included new data from the x-ray laser at the Lawrence Livermore National Laboratory (LLNL). The first Livermore experiments used neonlike selenium ions to generate radiation at 206 angstroms, but more recent work has extended to shorter wavelengths, including the 71-angstrom emission obtained from nickellike europium ions. Earlier versions of these comparisons were widely distributed in the synchrotron radiation, x-ray laser, and plasma communities.

Comparisons of the various radiation sources depend sensitively on the intended applications. Figure 10 shows how the choice of a basis of comparison can affect the relative "merit" of different radiation sources. Depending on the experiment, the most appropriate figure of merit could be the peak spectral

Figure 10. Plots of average (a) and peak (b) coherent power as functions of photon energy for a variety of radiation sources. The peak coherent power is given for a 100- μm coherence length; the average coherent power for a 1- μm coherence length.



brightness of a single pulse, the time-averaged spectral brightness, the peak coherent power, or the time-averaged coherent power. Peak brightness is an appropriate figure of merit for time-resolved experiments requiring high spectral purity, especially in the sub-nanosecond time regime, whereas time-averaged power is relevant when longer exposures are either acceptable or necessary. Coherent power is taken here to mean that portion of the radiation that is diffraction limited and has a longitudinal coherence length of 1 μm or more. It is important in experiments where phase is important, such as holography. Note that the undulators dominate in the x-ray region near 10 angstroms for both peak and average coherent power, whereas the lasers dominate only for peak power at wavelengths longer than 100 angstroms. Tunability, polarization control, and megahertz repetition rates are additional advantages of undulator sources.

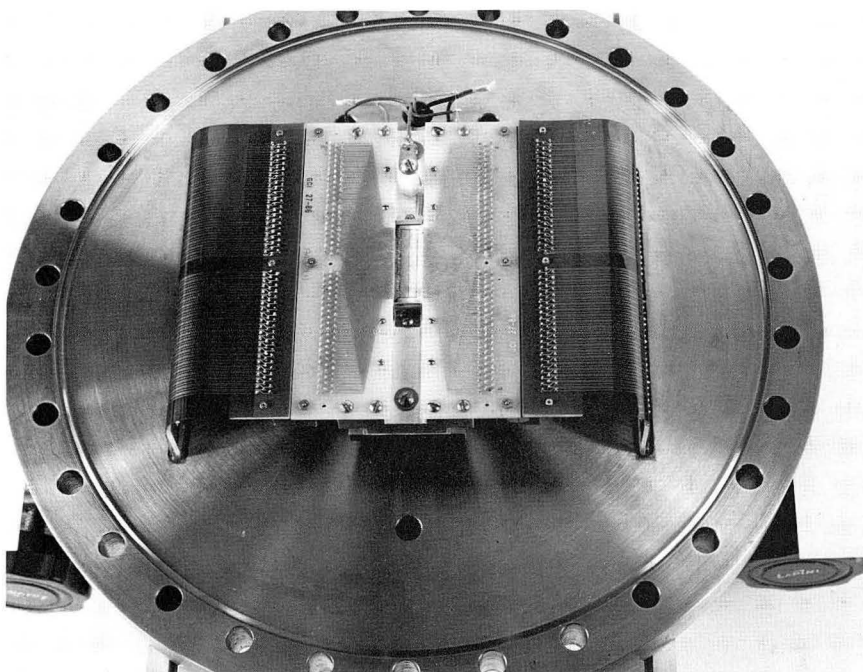
Position-Sensitive Detector

Transvenous coronary angiography with synchrotron radiation is a promising alternative to the widely practiced conventional x-ray technique for imaging the coronary arteries. Partially occluded arteries are easily detected by the conventional method, but arterial catheterization poses a significant risk to the patient. Consequently, we have been collaborating with researchers from Stanford University, the Stanford Medical School, SSRL, and NSLS on the synchrotron radiation-based alternative, a less invasive method in which the contrast agent is injected into the venous system. The high x-ray intensity of a synchrotron radiation source makes the method work. After several years of effort, we can now image coronary arteries in humans using synchrotron radiation, but with less than clinical-quality fidelity. The principal limitation is the x-ray flux reaching the patient, which needs to be increased by a factor of eight or so.

The present x-ray detector is a linear array of 300 lithium-drifted silicon elements, spaced to give a spatial resolution of 0.5 mm. As the patient is moved vertically through a horizontal fan of radiation, the detector alternately records x-ray intensities at two photon energies, one just above and one just below the absorption edge of the iodine in the injected contrast agent. One pair of intensity measurements constitutes data for a single "line" of the final image. It takes two seconds to record an entire angiogram. A computer then calculates the difference between the two intensities for each line in the frame and constructs the image from the differential absorption due to the contrast agent in the coronary arteries. However, the mechanical system that alternately passes x-rays of one, then the other, photon energy also limits the x-ray flux. An improved system is under development that will pass both beams simultaneously.

Concurrently, we have been developing a new position-sensitive detector that will record simultaneously the x-ray intensities at both photon energies. The dual detector, to be integrated on a single silicon chip, will have two rows of elements. A test version, shown in Fig. 11, with a reduced number of elements spaced to give a resolution of 0.25 mm, was built and operated during the past year. On test objects, the detector can detect simulated arterial openings 0.25 mm in diameter. A full-scale detector containing 600 elements spaced 0.5 mm apart in each row is under construction.

Figure 11. A photomicrograph of a prototype high-resolution position-sensitive x-ray detector designed for use in synchrotron radiation-based transvenous coronary angiography. An angiogram is recorded one line at a time as the patient is moved vertically through a horizontal fan of x-rays. For each line, two rows of 128 lithium-drifted silicon elements simultaneously register the intensities of transmitted x-rays at two photon energies. The final image, which arises from x-ray absorption by the injected contrast agent in the patient's coronary arteries, is built up line by line from the differences in the measured intensities at the two energies.



The development of tools for high-resolution x-ray spectroscopy and scattering and the application of these tools to real scientific problems are major parts of the Center's effort. In the past year, for example, we built and tested a high-resolution spectrometer suitable for a wide variety of applications, including materials studies at the ALS and time-resolved measurements of x-ray laser line widths. We also used grazing-incidence x-ray scattering to investigate defects due to lattice mismatch in heteroepitaxial semiconductor systems. And finally, we continued our progress along several fronts in an effort to develop the means for absolute x-ray spectrometry; for example, we updated our tables of basic atomic interaction coefficients for x-rays and continued development of high-efficiency x-ray photocathodes based on thin films of condensed rare gases.

The increased interest in intense coherent sources of soft x-ray and extreme ultraviolet (collectively, XUV) radiation is motivating the development of new spectroscopic instruments operating in the grazing-incidence region from 10 to 500 angstroms. X-ray holography, photoelectron spectroscopy, and grating spectroscopy all require monochromators with a spectral resolving power ($\lambda/\Delta\lambda$) of 10,000 or higher. Until now spectroscopic instruments have been incapable of this performance without severe compromises in other areas and could not simultaneously achieve high resolution, freedom from astigmatism, and the erect focal plane necessary for a simple wavelength-scanning motion. But recent advances in grating fabrication techniques now make it possible to vary the groove spacing continuously across the surface. This allows precise correction of the optical aberrations that limit spectral resolution and makes it possible to construct monochromators and spectrometers that are free from astigmatism and have a flat focal plane. Moreover, the surfaces of the mirrors and gratings in these instruments can be easily fabricated planes and spheres. The technology for gratings with variable groove spacing has already been exploited in space-borne astrophysical instrumentation and in instruments for laboratory plasma spectroscopy.

In the past year, we completed the mechanical design of a grazing-incidence ultrahigh-resolution XUV spectrometer and built a prototype instrument (Fig. 12).

Spectroscopy and Scattering

High-Resolution XUV Spectrometer

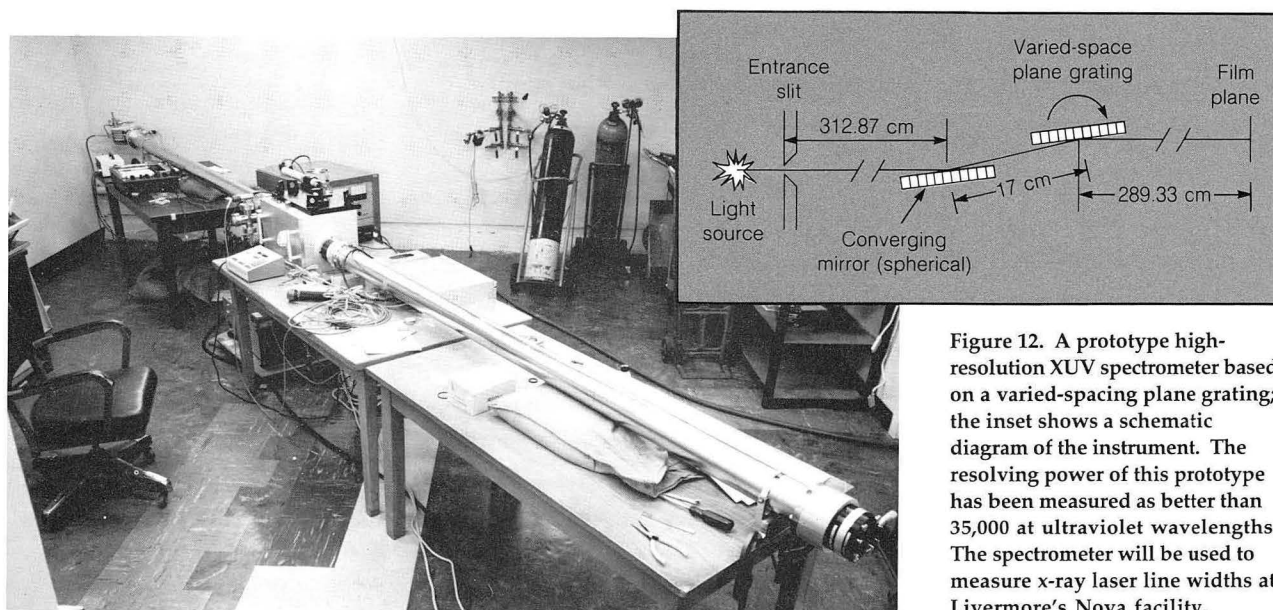


Figure 12. A prototype high-resolution XUV spectrometer based on a varied-spacing plane grating; the inset shows a schematic diagram of the instrument. The resolving power of this prototype has been measured as better than 35,000 at ultraviolet wavelengths. The spectrometer will be used to measure x-ray laser line widths at Livermore's Nova facility.

At year's end, the spectrometer was being aligned and tested at LBL before being moved to LLNL for installation at the Nova laser facility, where it will be used for the time-resolved measurement of line widths of the LLNL x-ray laser. The essential features of the optical system include a spherical mirror, which converts the incoming divergent light to a convergent beam, and the varied-groove-spacing grating. The spacings between adjacent grooves are calculated to introduce minimum defocusing at the fixed position of the detector as the grating rotates about its central groove during wavelength scanning. Alignment is by means of a laser that is an integral part of the instrument.

We tested the spectrometer with a Penning discharge source, whose cool discharge produces narrow spectral lines of ionized aluminum and neon. Microdensitometer tracings of spectra recorded on film indicate resolutions of 4 to 13 milliangstroms for spectral lines at 130 to 208 angstroms. These resolutions correspond to spectral resolving powers as high as 35,600 (at 160 angstroms), demonstrating that the instrument is clearly suitable for the line width measurements for which it was designed. Moreover, the possibility of obtaining such high resolution in the XUV with a simple and easy-to-use instrument also opens up new possibilities for a variety of materials, surface, and chemical science experiments in conjunction with a high-brightness synchrotron radiation source, such as the ALS.

X-Ray Emission Spectroscopy

X-ray emission spectroscopy gives direct information about the energies, widths, and populations of the quantum states of "outer" electrons, such as those in molecular orbitals and in the valence bands of a solid. In solids, it complements photoelectron and Auger electron spectroscopy in that it is less surface sensitive, hence more closely related to bulk properties. Moreover, with the coming availability of high-resolution spectrometers and high-brightness synchrotron light sources, x-ray emission spectroscopy will have the capability of unraveling spectral details that are otherwise beyond its reach.

One of our ongoing studies illustrates the twin virtues of synchrotron radiation sources, namely, high intensity and tunability. The intensity can be translated into high resolution, while the tunability allows unoccupied molecular orbitals below the ionization energy to be selectively populated, thereby producing highly excited neutral molecules. During the past year, we continued to use the X-24 beamline at NSLS to obtain x-ray fluorescence spectra from molecules excited below the ionization threshold.

Grazing-Incidence Scattering

In a recent collaboration with scientists from Hewlett-Packard Laboratories, we applied the technique of grazing-incidence x-ray scattering to the investigation of structural defects in thin gallium arsenide films grown on silicon substrates by various methods, including molecular-beam epitaxy and metallo-organic chemical vapor deposition. Such systems are of intense technological interest: If electrically active defects can be minimized, heteroepitaxy is likely to become a means of obtaining high-quality, large-area gallium arsenide substrates for electronic and opto-electronic devices, and it may also be a means of monolithically integrating gallium arsenide and silicon devices on a single chip.

Grazing-incidence scattering is a powerful tool for investigating the distribution of defects with depth between the thin-film surface and the substrate and for measuring the volume fraction of "defected" material. The tool's particular advantages stem from its ability to do depth profiling nondestructively, to sample relatively large volumes of material, to allow different specimen orientations, and to distinguish between different types of defects. Our experiments were performed at SSRL on the 54-pole wiggler beamline (Beamline VI) and on wiggler Beamline VII-2. The initial results demonstrate that quantitative information can be obtained about twins, stacking faults, interface strain, and dislocations in the buried buffer layer of gallium arsenide (see Fig. 13).

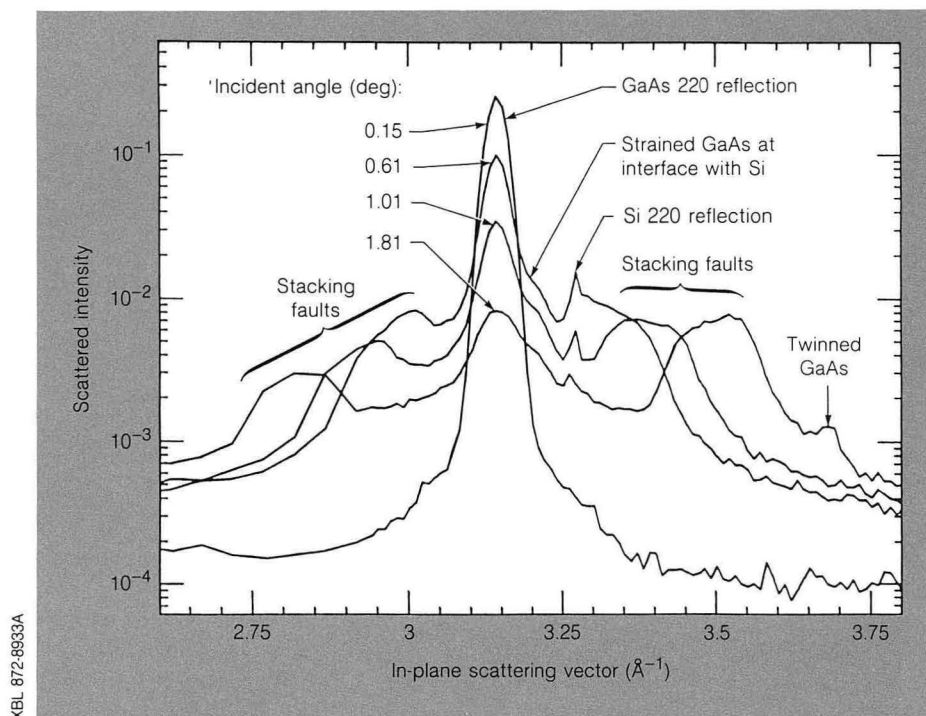


Figure 13. Plots of the intensity of x-rays scattered from a system of gallium arsenide layers on a silicon substrate. Such plots reveal the presence of structural imperfections in the gallium arsenide, and often yield quantitative information as well. The distribution of scattered intensity in "reciprocal space" (where the scattering vector resides) is a clue to the type of imperfection, such as the crystalline twins, stacking faults, interface strain, and dislocations indicated in the plot. Because the x-rays penetrate to a greater depth at larger grazing angles, the growing prominence of structural imperfections with incident angle indicates that the defects are primarily below the surface—a reasonable finding, since the imperfections are caused largely by the mismatch between the gallium arsenide lattice and that of the silicon.

Ultimately, the performance of x-ray optical components, including multilayer-coated mirrors and wavelength filters, depends on the coefficients that describe the interaction between atoms and x-rays, that is, on the atomic scattering factors. These coefficients are obtained from measurements of the absorption cross section as a function of photon energy. From these data, the atomic scattering factors are extracted by applying the Kramers-Kronig dispersion relations. The tables that we have generated in the past, covering photon energies from 30 eV to 10 keV, are currently the best available in the low-energy x-ray region. We are in the process of updating the tables to include the most recent cross section measurements and to extend the lower photon energy to 10 eV.

Well-characterized x-ray photocathodes are another aspect of absolute x-ray spectrometry. They are important for detectors that must have high spatial or temporal resolution at photon energies between 100 eV and 10 keV, but they are not sufficiently sensitive to record low x-ray intensities. Recently, we collaborated with researchers at AT&T Bell Laboratories in the discovery that condensed rare gases, such as xenon and argon, have secondary electron yields about ten times that of cesium iodide, which we had earlier demonstrated to be a highly efficient and stable photocathode material at room temperature. We are continuing to explore the properties of these materials and their suitability for working photocathodes.

Absolute X-Ray Spectrometry

Synchrotron Radiation Projects

The Center for X-Ray Optics is also host to LBL's program in synchrotron radiation optical systems. As part of this program, we design and fabricate state-of-the-art engineering systems—beamlines and beamline components—for high-brightness synchrotron radiation sources, both those now operating and those under construction, including the ALS. In the past, we have focused considerable activity on the design and testing of components that can withstand x-ray fluxes high enough to melt or badly distort common mirrors and crystals. As part of this activity, we have designed water-cooled mirrors for beamlines at both NSLS and SSRL. This past year, we built on our prior experience with the SSRL Beamline VI wiggler to design and construct a next-generation wiggler that has now been installed on Beamline X at SSRL. We have also developed the theory for a method aimed at accurately monitoring the position of the electron beam in a storage ring.

Water-Cooled Optics

During the past year, we installed and tested a water-cooled x-ray mirror system on the X-17T miniundulator beamline at NSLS, in preparation for its final installation on Beamline X-1. No measurable surface distortion associated with the relatively low thermal loads was detected, and overall system performance exceeded requirements. At the end of the year, a similar mirror system was ready for installation on the VUV branch of Beamline VI at SSRL, where the thermal load may be as high as 5.2 W/mm^2 . Both the NSLS and the SSRL systems were fabricated with a dispersion-strengthened copper alloy for high strength and high thermal conductivity. The optical surfaces are polished electroless nickel plating with gold and beryllium coatings.

We are also investigating the extension of the successful water-cooled mirror technology to diffraction gratings. No industrial technology exists for applying grating grooves to large water-cooled substrates. The best approach at present may be direct mechanical ruling of the grooves. A demonstration project using electroforming technology is planned.

Beamline X Wiggler

The August 1987 installation of the Beamline X wiggler on the SPEAR storage ring at SSRL marked the completion of LBL's design and fabrication effort on this advanced insertion device. This wiggler will now become the high-intensity source for a hard x-ray beamline fabricated by LLNL, to be operated jointly by the University of California, LLNL, the Los Alamos National Laboratory, and Sandia National Laboratories as a facility for general research and for x-ray calibration and standards. The design of this wiggler is considerably simplified, as compared to that of its predecessor, the 54-pole wiggler on Beamline VI. Featuring the new neodymium-iron-boron permanent-magnet material in a steel-hybrid configuration, the wiggler consists of 31 poles with a period of 12.85 cm. The magnetic field is adjusted by opening and closing the gap between the poles; the peak field at the midplane is 1.44 T at the minimum operating gap of 21 mm. Future low-emittance storage rings will permit even smaller gaps, so it is of interest that a peak midplane field of 2.37 T was measured with a gap of 8 mm. A maximum variation in the peak field of only 0.0031 T (0.22%) was measured at 1.44 T for the central 25 poles of the wiggler. It was also demonstrated that, by adjusting tuning studs incorporated into the structure, this variation could be reduced to 0.06%.

Electron-Beam Monitoring

In most particle accelerators, it is critical to be able to measure the position of the beam accurately. In a low-emittance electron storage ring that generates high-brightness synchrotron radiation, for example, a wandering electron beam results in a photon beam that misses the entrance slit of the user's instrumentation. Only if the beam position can be monitored can appropriate measures be taken to

restore it to its proper location. For a large class of accelerators, the most frequently used nonintrusive monitor senses the beam position by means of electric or magnetic signals. But the extraction of the beam position from such signals is usually difficult because of an unknown longitudinal charge distribution in the particle bunches making up the beam, the generation of wake fields, and so on. As a consequence, we have developed a new and rigorous theory that allows the straightforward calculation of the beam position from the signals, provided that an appropriate analog signal-processing system is also used. Moreover, the theory shows that some types of beam-position monitors can give erroneous information about large beams, and it shows how to design the system to avoid this problem (see also page 7).

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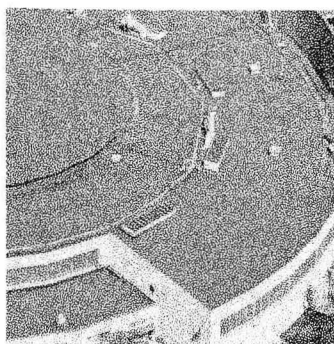
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3.

ACCELERATOR OPERATIONS

*... a record 4023 hours
of research time
for use in rich and
diversified programs in
nuclear science and
biomedicine ...*

IN 1974 A NEW AND FRUITFUL AREA of scientific study was opened when two neighboring accelerators at LBL were linked by means of an evacuated "transfer line." The accelerators were the SuperHILAC, a linac capable of accelerating all elements to energies as high as 8.5 MeV/amu, and the Bevatron, a venerable proton synchrotron with a history of pioneering discoveries in high-energy physics. The combination of the two, the Bevalac, in effect established a pair of new scientific disciplines, relativistic heavy-ion physics and heavy-ion biomedicine. Fifteen years later, the Bevalac continues to play a unique role as a national research facility for studies in nuclear and atomic physics, nuclear chemistry, and biomedicine.

The mating of the SuperHILAC and the Bevatron provided the synchrotron with a source of heavy ions that could subsequently be accelerated to relativistic energies. Today, the SuperHILAC generates up to 36 ion pulses per second, two of which are sent down the transfer line while 34 pulses (usually of a second ion species, from a second SuperHILAC injector) are used "locally," often for two independent experiments. Every six sec-

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J. Krupnick
P. LaPlant
J. Lax
D. Leneman
R. Leres
S. Lewis
A. Lindner
A. Loop
F.H. Lothrop
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B. Ludewigt
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H. Matis
M.A. McCloud
R. McDonald
M. McEvoy
M. McMahan
D. Meaney
S. Meaney

J. Milburn
R.A. Miller
R.M. Miller
E. Moldenhauer
M. Monroy
D. Morris
M. Morrison
M. Nyman
H. Oakley
E. Parker
J.M. Parker
C. Pascale
S.L. Patterson
M. Payne
E. Perry
R.E. Photos
D.D. Pohl
J.L. Pusina
H.H. Quach
J.F. Quan
B. Rathbon
J. Redding
D.E. Reimers
R. Reimers
T. Renner
R.M. Richter
W.L. Ridgeway
G. Ritscher
A. Ritchie
F. Rogers
S. Rogoff

B. Rude
S.E. Ryce
T.C. Sampson
B.C. Samuelson
R. Sanders
D.W. Schmeyer
F. Selph
L. Shalz
C.R. Siero
K.H. Sihler
R.P. Singh
L. Skvarla
J.F. Smith
R. Sorenson
J.W. Staples
L.L. Stout
G. Stover
S.A. Stricklin
J. Swepp
D.L. Syversrud
H.K. Syversrud
R.L. Tafelski
J. Tanabe
M.M. Tekawa
R.K. Thatcher
J.R. Thomas
C.W. Thornton
C.A. Timossi
P. Torres
J.C. Walling
C.J. Wang

H. Wieman
O.S. Wiggins
M.D. Wolfe
N. Wong
K. Woolfe
H. Wozniak
R.T. Wright
A. Wydler
S. Yashita
G. Yuen
E. Zajec
R.C. Zink

184-Inch Synchrocyclotron

G. Hampton
(in charge)
S.L. Baba
L. Kanstein
H.E. Ketchum
C.R. Siero

Administrative Support

P. Bullocks
S. Fujimura
K.E. Williams

onds, one of the pulses sent to the Bevatron is captured and further accelerated—to energies as high as 2.1 GeV/amu for light nuclei or 960 MeV/amu for uranium.

During fiscal 1987, twenty different ion species, from protons to uranium, were delivered to experimenters. The standard repertoire of ions comprises neon, carbon, iron, niobium, lanthanum, gold, and uranium, but essentially all ions are available upon request. For all elements, both partially and fully stripped ions can be delivered. In addition to stable isotopes, we have also generated and delivered short-lived radioactive isotopes by letting accelerated ions impinge on targets at the first external beam focal point, then collimating and focusing the desired product.

Also during 1987, improvement projects at the SuperHILAC designed to increase the intensity of heavy ions were essentially completed, and improvements were confirmed during the preliminary runs that followed the usual summer shutdown. Aimed at much greater intensity increases has been a conceptual design effort focused on an upgrade of the Bevalac, a project that would entail replacing the 30-year-old Bevatron with a modern, strong-focusing synchrotron. The culmination of this design effort was marked in May 1987 with the publication of the *Bevalac Upgrade Conceptual Design Report*.

During fiscal 1987, we delivered 4023 hours of beam time for nuclear science and biomedical experiments at the Bevalac and another 2160 hours of beam to SuperHILAC users. Nearly 200 scientists, representing 45 institutions both here and abroad, participated in 51 different experiments. About one-third of the beam time at the Bevalac was devoted to research in biology and medicine. As national facilities, both the Bevalac and the SuperHILAC are available to qualified researchers from around the world; accordingly, about half of the available research time is used by scientists not affiliated with LBL. Beam time is apportioned by Program Advisory Committees, which review submitted proposals twice each year. In addition, the users have formed users' associations for the purpose of exchanging information and recommending operational and procedural improvements.

Operations Summary

Table 2 summarizes Bevalac operations during fiscal 1987 and compares them with operations during 1986 and with projections for fiscal 1988. The record 4023 hours of research time delivered in 1987, a 25% increase over the year before, can be attributed in part to the lower-than-expected costs of electrical power (which allowed us, in turn, to run longer before shutting down for the summer) and in part to improvements in operating efficiency, notably the full implementation of the "fast-switching" program. The so-called Local Injector now routinely delivers neon and silicon beams intense enough for all radiotherapeutic needs, thus freeing the SuperHILAC to deliver only the heavier nuclei usually required for nuclear science experiments. Of paramount importance, however, has been the success achieved in switching rapidly between these two injectors, which entails a complete retuning of machine parameters. The switch between, say, 500-MeV/amu neon and 1200-MeV/amu niobium can now be done in less than two minutes. The half-hour intervals between typically brief patient treatments is now used productively.

The focus of support for the Bevalac user community is the Accelerator Research Coordination (ARC) Office, which supports the researchers at all stages, from proposal submission through the actual running of experiments. In addition,

Table 2. Operating summary for the Bevalac facility for fiscal 1986, 1987, and 1988 (projected).

	Fiscal year		
	1986	1987	1988
Bevalac operations (hours)			
Research	3011	4023	4000
Tuning	968	867	850
Machine studies	215	225	300
Unscheduled maintenance	642	751	750
Scheduled shutdowns	3923	2894	2884
Total	8760	8760	8784
Beam utilization for research (hours)			
Bevalac nuclear science	2044	2784	2667
Bevalac biology/medicine	968	1239	1333
SuperHILAC	1754	2173	2160
Total	4766	6196	6160
Number of Bevalac and SuperHILAC experiments receiving beam	52	51	51
Number of participating scientists	195	189	190
Institutions represented			
Universities	26	26	26
National laboratories	5	5	5
Other	15	15	15
Total	46	46	46
Users of beam time (%)			
LBL	50	50	50
Universities	35	35	35
Other national labs	5	5	5
Other institutions	10	10	10

researchers at the Bevalac and SuperHILAC have formed users' associations that meet periodically to exchange scientific information and to convey their views to LBL management. The members of the executive committees of the two users' associations for fiscal 1987 are listed in Table 3. Proposals for research time are submitted twice each year to Program Advisory Committees (PACs), one each for the Bevalac nuclear science program, the Bevalac biomedical program, and the SuperHILAC program. These expert panels, whose members' names also appear in Table 3, recommend research time allocations to the Laboratory Director. In addition, the LBL scientific director of each program may allocate about 10% of the available time on a discretionary basis.

Bevalac Physical Sciences Users' Association Executive Committee

A. Mignerey, University of Maryland (chair)
 D. Beavis, Brookhaven National Laboratory
 H. Britt, Lawrence Livermore National Laboratory
 S. Fung, University of California at Riverside
 J. Wefel, Louisiana State University
 H. Wieman, LBL

SuperHILAC Users' Association Executive Committee

J. Alexander, State University of New York
 at Stony Brook (chair)
 R. M. Diamond, LBL
 D. Dietrich, Lawrence Livermore National Laboratory
 K. Toth, Oak Ridge National Laboratory
 G. Wozniak, LBL

Bevalac Nuclear Science PAC

H. Gutbrod, GSI (chair)
 D. H. Boal, Simon Fraser University
 P. Braun-Munzinger, State University of New York
 at Stony Brook
 J. I. Kapusta, University of Minnesota
 G. Westfall, Michigan State University
 G. Young, Oak Ridge National Laboratory

Bevalac Biomedical PAC

K. Clifton, University of Wisconsin (chair)
 M. Elkind, Colorado State University
 J. Lyman, LBL
 P. Todd, University City Science Center, Philadelphia
 R. Urtasun, University of Alberta

SuperHILAC PAC

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

Table 3. Membership lists for the Users' Association Executive Committees and the three Program Advisory Committees (PACs) for fiscal 1987.

Research by Accelerator Users: Highlights

The heavy-ion program at the Bevalac continues to emphasize "extreme conditions" in nuclear matter, but apart from this common focus, the experimental and theoretical investigations are exceedingly diverse. They include, for example, studies of the nuclear matter equation of state at high temperatures (typically 30–100 MeV) and densities (two to four times normal density); the production of rare and often exotic nuclear species, some near the very limits of nuclear stability; searches for new phases of matter, such as might be found at the liquid-gas phase transition, which should occur at low temperature and nuclear density; and new tests of quantum electrodynamics, made possible by the ability to produce and deliver hydrogen- and heliumlike uranium ions. At the SuperHILAC, beam time was devoted almost equally to studies of nuclear reactions, nuclear structure, exotic nuclei, and atomic physics. Particularly exciting was the use of the High-Energy-Resolution Array in a search for a two-photon decay mode of a possible new neutral particle. Sharing time with nuclear science, biomedical researchers at the Bevalac continued to pursue both a cancer radiotherapy program and a basic research effort aimed at a more complete understanding of radiation biophysics and radiobiology.

Nuclear Physics

The nuclear matter equation of state at high temperature and density is best probed with head-on collisions between nuclei. By increasing the mass of the target and projectile, one naturally enhances the number of participating nucleons, a necessary condition for producing the desired extremes of temperature and density. Because many particles are produced in these head-on or central collisions, severe constraints are placed on the granularity and dynamic range of the detectors. These requirements have thus spawned a new generation of detectors, known generically as " 4π detectors." Examples include the Streamer Chamber (a 4π visual detector) and the Plastic Ball (a 4π electronic detector now at CERN).

At the other extreme are grazing or peripheral collisions between nuclei, which produce secondary fragments by projectile fragmentation. These secondary fragments often contain extreme numbers of protons and neutrons, and they can be either studied directly or used as secondary beams for nuclear reaction studies. Because of the strong forward focusing of these high-energy fragments, often referred to as "kinematic focusing," detectors can be much more compact. Between these two "impact parameter" extremes lie many possibilities. The more central the collision, however, the more particles are expected in the final state. Thus, multiplicity detectors have become an integral and necessary part of most Bevalac experiments. Selection of events on the basis of their multiplicities allows us to choose nuclear collisions suitable for study and thus to isolate the most interesting physics.

The Year in Review. Because of the extremely successful operation of the Bevalac in fiscal 1987, a truly rich and diversified program was carried out. Highlights included:

- A maturing program to study the transition in physics as one goes from the low-energy region (typically 10–20 MeV/amu), characterized by compound nucleus formation and dinuclear breakup, to intermediate energies (50–100 MeV/amu), where the process of multifragmentation and the possible formation of a liquid-gaseous phase should occur.
- Continuation of the pioneering work by scientists from Japan and LBL to exploit the projectile fragmentation process to produce exotic secondary

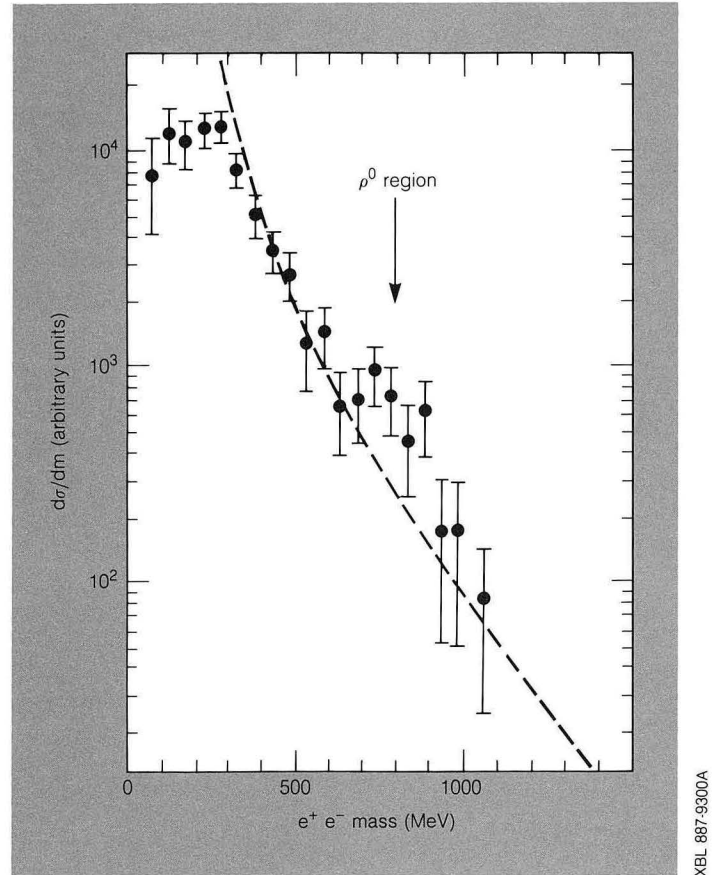
beams (e.g., ^{11}Li), both for fundamental nuclear physics studies and to further develop a program to measure the magnetic moments of mirror nuclei.

- Construction and successful operation of the Dilepton Spectrometer (DLS), providing a new probe of the hot, dense phase of the collision process; electron-positron pairs were observed during both proton-nucleus and nucleus-nucleus collisions.
- Measurement of the size of the pion-emitting source for heavy systems ($\text{La} + \text{La}$), using the technique of like-pion interferometry (so-called Hanbury-Brown/Twiss effect) and a search for an exotic bound state between neutrons and negative pions, called "pineuts."
- Determination of the excitation function and angular distribution of subthreshold negatively charged kaons and a search for far-subthreshold antiproton production in nucleus-nucleus collisions; the aim is to establish whether cooperative effects play a significant role in nucleus-nucleus collisions at Bevalac energies.
- Use of the revitalized HISS system to measure the production of mid-rapidity light nuclear fragments to determine entropy production and to study multipion correlations for heavy systems ($\text{La} + \text{La}$, with $\text{Au} + \text{Au}$ planned) to learn about the space-time extent of the pion source with good statistics.
- A very high statistics run with krypton and lanthanum beams at intermediate energies, using the streamer chamber to study the flow of nuclear matter, to learn about the nuclear matter equation of state.
- Measurement of high-energy photons produced by bremsstrahlung processes in $\text{La} + \text{La}$ collisions at 150 MeV/amu.
- The first measurement of reaction cross sections for exotic nuclei, as well as for normal nuclei of particular interest in nuclear physics and astrophysics.
- Improved instrumentation at the DLS, HISS, and the streamer chamber; design of a time-projection chamber (TPC), which would be placed inside the HISS magnet as the next 4π detector for the Bevalac; and the implementation of a new VME-based data acquisition system.
- The first observation of the channeling of uranium ions through crystals, a result that may open up new opportunities in both atomic and nuclear physics research.
- Exposure of a variety of targets to study inclusive mass yields and the energy dependence of electromagnetic dissociation processes for the heaviest beams.
- The continuation of programs for the calibration of detectors to be flown in balloons or on the space shuttle.

A few of these topics are expanded upon below.

Probing Nuclear Matter with Rare Processes. Rare events can often provide considerable insight into differing aspects of reaction dynamics. For example, it is generally acknowledged that dileptons, because they interact only weakly, are a useful probe of the hot, compressed phase of the collision process. By contrast, pions and nucleons, which interact strongly with matter, suffer considerable scattering before being detected. Since dileptons are expected to be extremely rare, special detection techniques are required to sort them out from the myriad other particles produced by the collision. The DLS was constructed to detect electron-positron pairs in proton-nucleus and nucleus-nucleus collisions, thus to provide a new way of probing nuclear matter. Initial operation with 2.1- and 4.9-GeV protons and with 1.95-GeV/amu calcium beams clearly established the existence of such pairs; a preliminary effective-mass spectrum for 4.9-GeV p -Be collisions is shown in Fig. 14. The general shape of this distribution is roughly consistent with dilepton spectra at higher energies, where the bump near 775 MeV

Figure 14. The e^+e^- mass spectrum from the reaction $p + \text{Be} \rightarrow e^+e^- + X$ at 4.9 GeV. This is a preliminary result, since only a rough acceptance calculation for the dilepton spectrometer was used in determining the cross section, but the general shape of the distribution is consistent with dilepton spectra obtained at higher energies.



is identified as the decay of the ρ^0 meson. At Bevalac energies, two sources of pairs are expected: (i) production (virtual bremsstrahlung $\rightarrow e^+e^-$) by cascading baryons in the hot, compressed phase and (ii) pionic annihilation ($\pi + \pi \rightarrow e^+e^-$). Further analysis and additional data are required to firmly establish the role of dileptons in studying nuclear collisions at Bevalac energies. But the observation of direct pairs in the first round of experiments with the DLS makes this approach look promising.

Subthreshold production of particles is also a way of probing collective features in nucleus-nucleus collisions at the Bevalac. Negative kaons and, in particular, antiprotons cannot be produced in normal nucleon-nucleon binary collisions at the Bevalac. Thus, a recent experiment was conducted on Beamline 44 to look for the production of these particles as a potential indicator of interesting new phenomena. Substantial production of negative kaons and a handful of "candidate antiprotons" were found. Studies of such rare processes provide valuable data in our attempt to isolate cooperative features in these collisions at Bevalac energies. To push these studies to even lower energies will require the enhanced beam currents expected from the Bevalac Upgrade.

Studies at Low to Intermediate Energies. A growing program at the Bevalac focuses on the question, How much energy can a nucleus actually hold before it explodes into its constituent parts? One such limit is realized when the excitation energy of a nucleus equals or exceeds its binding energy per nucleon, where a nucleus might be expected to spontaneously decay into nucleons and/or light nuclear fragments.

The low-energy beamlines (39 and 44) are hosts to two ongoing experiments that seek to measure these limits of nuclear excitation. Experiments with relatively heavy beams ($A > 100$) in the 30- to 100-MeV/amu range are being performed. Reverse kinematics is employed on Beamline 44 to produce very hot compound nuclei that can decay by emitting a wide range of intermediate-mass fragments, whereas normal kinematics is used in the Beamline 39 experiment to detect intermediate-mass fragments (down to alphas), primarily from the target nucleus. Correlation studies of the reaction products in each experiment are being analyzed to gain insight about the excitation energy required for the onset of multifragmentation. These studies are now being upgraded by the addition of more detector elements, and they will be part of the experimental arsenal used to search for a liquid-gas phase transition, which is speculated to exist at low temperature and nuclear density.

New Results from Projectile Fragmentation. The earliest inclusive experiments at the Bevalac studied how incident projectiles break up as a result of their interactions with target nuclei. It was soon learned that this process of projectile fragmentation was dominated by peripheral collisions between projectile and target nuclei. In such collisions, relatively little energy and momentum need be transferred between the reaction partners for fragmentation or breakup to occur. Thus, this type of interaction can be viewed as a "gentle process," one that can be exploited to study the detailed structure of the incident projectile. By fragmenting high-intensity beams (10^9 – 10^{10} particles per pulse), secondary beams of exotic nuclei such as ^{11}Li can be created.

A recent experiment used such a beam to measure the fragmentation products of the secondary beam itself. Figure 15 shows the transverse momentum distribution for the reaction $^{11}\text{Li} + \text{C} \rightarrow ^9\text{Li} + \text{X}$. In addition to the broad Gaussian distribution peaked around $p_{\perp} = 0$, a sharp peak is observed. The broad component is understood in terms of the normal systematics of the fragmentation process and involves the intrinsic Fermi momenta known to exist in light nuclei. The narrow distribution can possibly be understood in terms of a model in which the incident ^{11}Li is viewed as comprising a core ^9Li with two loosely bound neutrons. Although this interpretation certainly requires more study before it can

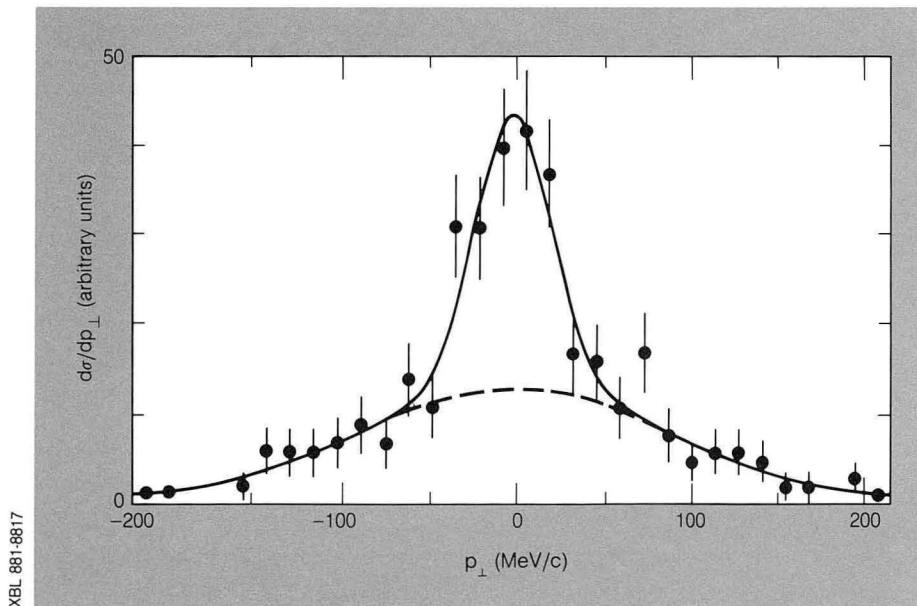


Figure 15. The transverse momentum distribution of ^9Li fragments from the reaction $^{11}\text{Li} + \text{C} \rightarrow ^9\text{Li} + \text{X}$ at 800 MeV/amu. The broad distribution is understood in terms of normal fragmentation systematics; the existence of a narrow distribution superimposed on it suggests a "neutron halo" in the ^{11}Li nucleus.

be accepted, it is clear that studying the fragmentation of exotic nuclei may provide us with a very powerful tool for investigating the details of their structure. This has the added potential of opening up a new field of experimental investigation with beams of exotic nuclei.

Research at the SuperHILAC. Intense beams of very heavy ions, at energies up to 8.5 MeV/amu, are the basis for nuclear and atomic physics research at the SuperHILAC, which remains the only accelerator facility in the U.S. where microampere beams of xenon, gold, lead, uranium, and the rare earths are available at energies above the Coulomb barrier. Beam time is devoted in almost equal portions to studies of nuclear reactions, nuclear structure, exotic nuclei, and atomic physics. Over the years, the relative proportion of these activities has changed, but the nearly equal division between inside and outside users (often working collaboratively) has remained roughly constant.

During the past year, the High-Energy-Resolution Array (HERA) was installed at the SuperHILAC for a multicomponent experimental program. This array of 21 Compton-suppressed germanium detectors is one of the premier instruments of its type in the world. Experiments included investigations of superdeformed bands, studies involving Coulomb excitation with neutron transfer, and a search for a two-photon decay mode of a possible neutral particle believed responsible for the electron and positron peaks observed at GSI over the last several years. In this last study, a Stanford-LBL collaboration looked for 180°-correlated, equal-energy photons from a ^{238}U irradiation of ^{232}Th targets, as an alternate decay mode to the back-to-back, equal-energy e^+e^- pairs observed at GSI. A possible explanation for the origin of the three e^+e^- peaks seen there is that they come from the decay of excited states (having energies of 1646 ± 10 , 1782 ± 20 , and 1837 ± 10 keV) of a new neutral particle, created in the reaction and moving with the center of mass. After more than 150 hours of running time at the SuperHILAC, a statistically significant sum-energy γ -ray peak was seen at 1062 ± 1 keV, with a width (3 keV) comparable to the intrinsic width of the germanium detectors. If this is a lower-energy (ground?) state of a neutral particle, it would not have been seen at GSI, as its energy is too close to the threshold for pair production. A longer, more complete experiment aimed at resolving this very interesting problem is planned for the coming year.

In the field of exotic nuclei, the OASIS facility continues to be very productive: Twenty-six new β -delayed proton precursors and several new β -delayed γ -emitters have been identified. Most of these are located in the region $56 < Z < 72$ and $N < 82$, and they include spherical, transitional, and well-deformed nuclei. In a collaboration with theorists from the Lawrence Livermore National Laboratory, statistical-model calculations were carried out using GT β -strength functions obtained from RPA calculations with Nilsson-model wave functions. These are among the most accurate β -strength functions yet calculated, and their form is critical in reproducing the observed proton spectra. The pronounced structure in the proton spectra of the $N = 81$ precursors ^{151}Yb , ^{149}Er , and ^{147}Dy described last year can now be understood in the framework of an "intermediate structure" based on two-particle, one-hole "doorway states." A new total-absorption spectrometer is being added to the OASIS detector system, which will allow the measurement of masses and improve the determination of the β -strength functions. But the most important development is that the OASIS beamline has been rebuilt to provide full-rigidity beams to the isotope separator. This marks the beginning of a program to produce and study neutron-rich isotopes; the first examples will be ^{174}Er and ^{171}Ho , utilizing beams of ^{176}Yb or ^{186}W and deep-inelastic nuclear reactions.

The number of atomic physics studies has increased over the past couple of years, owing to the great interest in the properties of highly charged ions in

plasmas and to the importance of highly charged heavy ions for fundamental QED tests. An example of work performed this past year is an extension to heavier targets (such as neon, argon, and krypton) of resonant electron transfer studies of highly charged ions, previously done with H₂ and helium targets. Using beams of 1.2-MeV/amu Ca¹⁷⁺ ions, a group of scientists from Western Michigan University, LBL, and six other universities found unexpectedly that three- and four-electron capture was more likely than single-electron capture in K-shell excitation events (close collisions). The increasing use by atomic physicists of sophisticated coincidence experiments seems likely to produce many more surprises.

Also in atomic physics, a new Oxford University–Livermore program will involve the installation of a new ultraviolet spectrometer that will look along the beam direction (and therefore perpendicular to the average scattered particle direction) to do high-precision Doppler-free spectroscopy. The uranium beams of the SuperHILAC will be used to generate slow recoils of gas atoms in very highly excited states; first examples will be hydrogenlike and heliumlike argon ions, with the possibility for the first time of few-parts-per-million accuracy for wavelength measurements in these systems.

In the field of heavy-ion nuclear reaction mechanisms, a number of nagging, but fundamental, problems—such as the equilibration of energy, mass, and charge in deep-inelastic reactions—are now showing signs of yielding answers. Good examples are furnished by the work of a group from the University of Rochester. In one study, the effective balance between the static and dynamic forces driving mass and charge transfer was probed, using reactions between ²³⁸U targets and ⁴⁰Ca and ⁴⁸Ca projectiles at 8.5 MeV/amu. Because of the additional neutrons in ⁴⁸Ca, its entry point on the nuclear potential energy surface is quite different from that of ⁴⁰Ca, hence quite different A and Z distributions are predicted qualitatively (from the different static driving forces). These differences are indeed observed. However, the experimental first and second moments of these distributions show large discrepancies with the predictions of the one-body transport model, reflecting our present lack of understanding. In another set of experiments, a large neutron multiplicity meter (or ball) was used to study energy equilibration in the damped reactions ⁵⁶Fe + ¹⁶⁵Ho and ⁵⁶Fe + ²⁰⁹Bi. For the first time, multiplicity distributions of neutrons emitted from either the projectilelike or targetlike fragment were measured individually. First results indicate that the average neutron energies and fluctuations do not correspond to thermal (equilibrium) distribution values. A second neutron ball is being prepared to extend these measurements to neutron correlations by using the two multiplicity meters in coincidence.

Finally, it should be mentioned that development of the data-acquisition system utilizing the STARBURST pre-processor has continued with the implementation of the CDAS code for data acquisition and monitoring. This code uses the EVA program developed at the Niels Bohr Institute for high-speed sorting, but we can still use our older software (CHAOS) when needed. Our experience with STARBURST has been outstanding. In nearly two years of operation, we have yet to have a hardware failure, and the software has been equally reliable.

Like the nuclear physics program at the Bevalac, the biomedical research effort exploits the uniqueness of the facility as a source of energetic heavy-ion beams. This program is at the forefront of radiation biophysics, especially in understanding the relationships between charged-particle energy absorption and biological effects. Most prominently, an ongoing cancer radiotherapy program uses the heavy ions from the Bevalac to deliver therapeutically useful doses to

Biology and Medicine

deep-seated malignant tumors. The continuing aim is to compare the effectiveness of this heavy-ion therapy with more routine modalities. Another component of the biology and medicine program is a broad research effort aimed at a fuller understanding of radiation biophysics and radiobiology. In addition, along lines similar to the Bevalac radiotherapy program, the 230-MeV/amu helium-ion beam of the 184-Inch Synchrocyclotron was used both in cancer therapy trials and in the radiosurgical treatment of inoperable pathologies, especially intracranial arteriovenous malformations.

Medical Programs. In distinct contrast to x-rays, heavy ions and neutrons are especially effective in killing typically oxygen-deficient cancer cells. In addition, ions can penetrate deeply into the body, then deposit their energy abruptly at the end of their path. Furthermore, this so-called Bragg peak of delivered dose can be manipulated in three dimensions, so that a well-defined volume of tissue is irradiated. As a consequence, the radiotherapy program at LBL has been able to demonstrate unequivocally that superior local cancer control can be achieved with ions for small tumors of the eye and near the spinal cord or the base of the brain. The most definitive medical results have been achieved with helium, but there is good reason to believe that heavier ions—carbon, neon, silicon, perhaps argon—would perform still better, especially in treating deep-seated tumors.

In an effort to demonstrate the therapeutic value of these heavier ions, randomized trials continued at the Bevalac during 1987, in which neon ions were used to treat locally advanced carcinomas of the prostate and inoperable carcinomas of the lung. At the same time, helium-ion therapy trials were under way at the 184-Inch Synchrocyclotron, both to study dose localization in tumors of the head and neck and to compare the effectiveness of helium ions with that of ^{125}I in treating uveal melanomas. The dose-localization studies are being conducted in conjunction with the Department of Radiation Medicine of the Massachusetts General Hospital and with the Harvard Cyclotron Laboratory.

In 1988 the 184-Inch will be shut down and dismantled, in preparation for construction of the Advanced Light Source (see pages 1–8). A new treatment room has therefore been prepared at the Bevalac, which will allow the helium-ion radiosurgery and radiotherapy programs to continue with only a brief interruption, following the move of the patient positioner (ISAH) from the cyclotron.

Biophysics Programs. The scope of the biophysics programs encompasses radiological physics, radiation chemistry, cellular and molecular biology, experimental tumor radiobiology, studies of the responses of various animal tissues, and radiation carcinogenesis.

One of the highlights of the past year was further development of diagnostic techniques based on high-energy radioactive beams. Radioactive secondary beams are produced at the Bevalac by letting the primary beam strike a target upstream of the experimental areas; ^{19}Ne , for example, can be readily produced from a beam of stable ^{20}Ne . During the subsequent decay of the radioactive particles, γ -rays produced during positron annihilation are emitted in opposite directions, allowing one to determine exactly the position of the decaying particle. Therefore, by irradiating a patient with a radioactive beam of low intensity, one can accurately determine the region in which the more intense therapeutic beam will deposit its energy. About 20 cancer patients have now undergone these diagnostic procedures with ^{19}Ne . In each patient, information was obtained on the “water-equivalent thickness” of the air, bone, blood, and other tissue the beam must penetrate before reaching the region of the tumor. As a result, it is possible to localize the Bragg peak on the tumor volume with an accuracy of ± 1 mm.

The most significant outcome of this study has been the difference uncovered between results based on computed tomography (CT) and those based on

positron emission from radioactive beams. Significant differences in estimated water-equivalent thicknesses have been found, sometimes as large as 1 cm.

Another phenomenon of interest is multiple Coulomb scattering of heavy charged particles. In radiotherapy at the Bevalac, the rapid fall-off of dose at the end of the particle range is used to advantage to spare critical structures just beyond the target volume. On the other hand, the multiple scattering suffered by particles before they reach the treatment volume can affect the depth-dose characteristics of the beam and can destroy this advantage. To assess the importance of this effect, we have initiated a systematic experimental study of multiple Coulomb scattering of heavy ions. A quantitative understanding of the scattering is also of importance for the design of beams and beam delivery systems utilizing these particles.

To investigate the effect of ion mass on the scattering, we have studied uranium, the heaviest particles accelerated at the Bevalac. The experimental method makes use of position-sensitive detectors, developed at LBL, to determine the spatial trajectories of individual particles, before and after scattering in a target. This method avoids physical collimation of the beam; collimation edge scattering and particle fragmentation effects are therefore eliminated. In addition, the method is independent of beam divergence. Using Monte Carlo techniques, the experiment can be simulated by computer and the results compared to actual experimental findings. Results so far indicate that the standard description of multiple scattering, developed for elementary particles, is adequate to describe the multiple scattering of uranium ions as well.

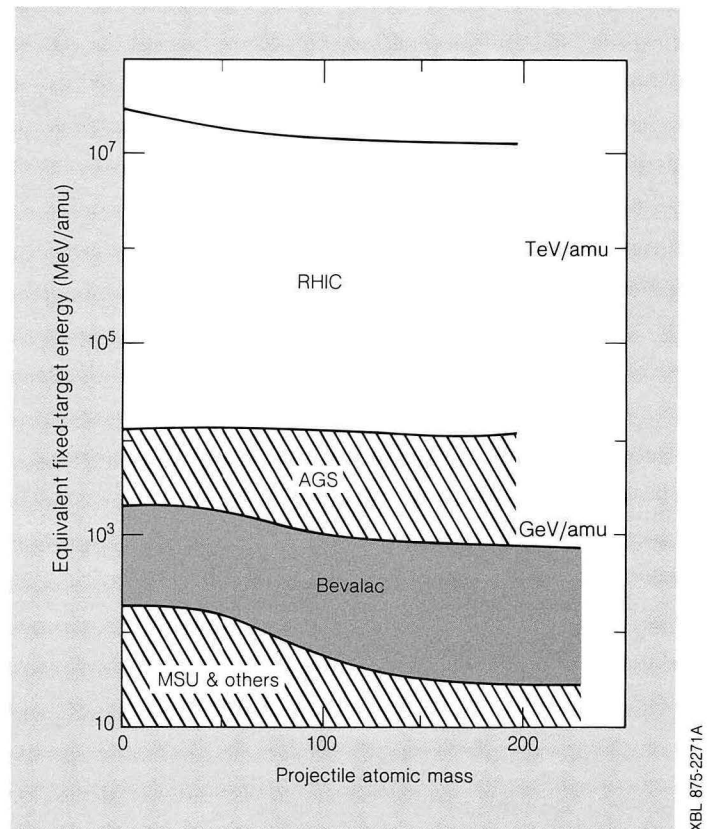
The current level of interest in relativistic heavy-ion physics is reflected in active research programs at CERN and GSI in Europe and in the high priority assigned by the U.S. nuclear science community to a relativistic heavy-ion collider at the Brookhaven National Laboratory. As suggested in Fig. 16, however, a balanced national program requires continuing research in the energy range accessible by the Bevalac, the facility that has pioneered the entire field over the past few years. A proposal for an upgraded Bevalac answers this need. This upgrade, documented in the Bevalac Upgrade Conceptual Design Report, would involve replacement of the 30-year-old Bevatron with a modern, strong-focusing synchrotron, at the same time making cost-effective use of existing injectors, shielding, experimental areas, and detectors. The conceptual design report documents a cost estimate of \$34.1 million (in FY 1987 dollars). More immediate improvement efforts were also on track (or completed) in 1987, including significant intensity upgrades at the SuperHILAC and computer control system upgrades.

Bevalac Upgrade and Other Activities

Two recent achievements at the Bevalac—the acceleration of uranium to relativistic velocities in 1982 and the creation of hot, dense nuclear matter two years later—were news-making milestones in the infant field of relativistic heavy-ion physics. The impact of these successes is reflected in the sudden flurry of activity in this field and, especially, in the great interest in producing and observing the postulated quark-gluon plasma. The surest route to this yet-unseen, highly energetic state of matter is a collider providing heavy-ion beams at extreme relativistic energies. Such a machine has already been proposed for construction at the Brookhaven National Laboratory. However, if the U.S. is to maintain its current preeminence in the field, a new and complementary facility is required that will deliver ions at energies in the range of 1 to 2 GeV/amu, at much higher

Bevalac Upgrade

Figure 16. Plot of the capabilities of heavy-ion accelerator facilities in the U.S., in terms of equivalent fixed-target energies and projectile masses.



intensities than those now available. Such a machine is the upgraded Bevalac, shown in Fig. 17, a fixed-target synchrotron operating in the energy range of today's Bevalac but embodying significant improvements in duty factor, injection and extraction efficiency, and operational flexibility.

Machine Design. In May 1987, the *Bevalac Upgrade Conceptual Design Report* was published, in which a self-consistent design was laid out that would increase the available ion intensities at the Bevalac by 100-fold. The improvements that underlie this intensity increase are summarized in Table 4. The essential elements that contribute to this central design goal are a modern, strong-focusing synchrotron within the existing Bevatron shielding, a redesigned injection channel, and a slightly modified extraction channel. Little or no modifications would be required to the SuperHILAC, the transfer line, the experimental areas, or the conventional facilities.

The principal design consideration was the circumference of the accelerator. Locating the synchrotron inside the present Bevatron shielding uses existing facilities to best advantage and also provides a convenient match to existing injection and extraction channels. Most of the existing Bevatron will therefore be removed, allowing construction of a new ring with the largest diameter permitted by the present shielding. Accordingly, the new ring has a circumference of 136 meters.

Consistent with this circumference, the design rigidity was chosen to be 17 T-m. This value makes available fully stripped ions across the entire mass spectrum, at intensities and energies consonant with the facility's scientific objectives. The guide field in the dipoles was chosen in turn to minimize the total dipole length, consistent with a tolerable hysteresis loss. To circulate an ion with a rigidity of 17 T-m, the accelerator ring must have a total integrated magnetic field

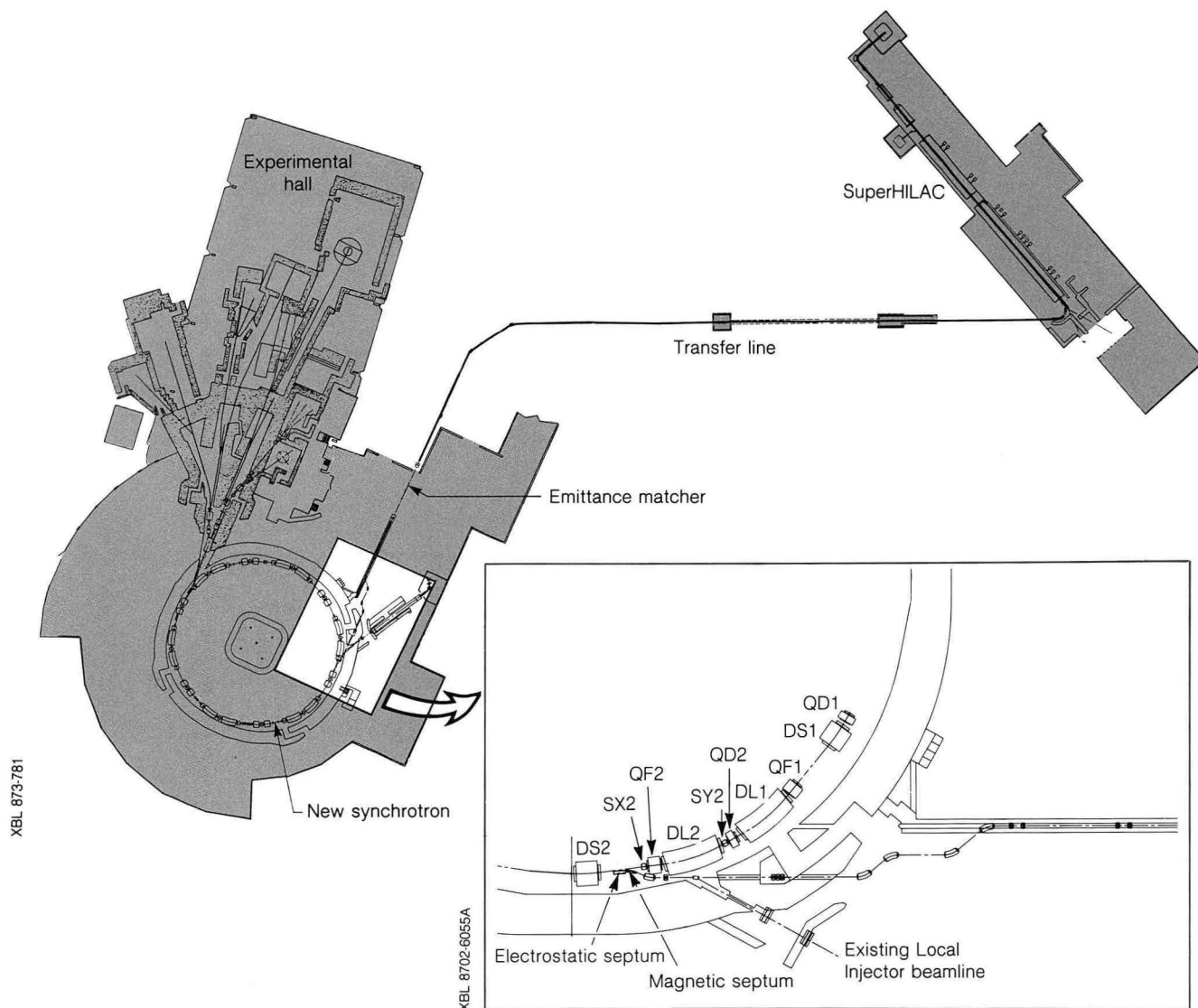


Figure 17. Plan view of the upgraded Bevalac, including the unmodified SuperHILAC, transfer line, Local Injector, and experimental facilities. The enlarged insets show one period of the new synchrotron and the re-designed injection channel.

Source	Present Bevalac	Upgraded Bevalac	Gain
Transport and inflection efficiency	30%	90%	$\times 3.0$
Injection stacking	80 turns	69 turns	$\times 0.85$
Circumference	120 m	136 m	$\times 1.14$
RF capture	40%	90%	$\times 2.25$
Extraction efficiency	30%	90%	$\times 3.0$
Minimum cycle time (at full field)	6 sec	1.15 sec	$\times 5.2$
Total			$\times 102$

Table 4. Sources of intensity improvements in the upgraded Bevalac. Most of the improvements are direct consequences of the differences between the weak-focusing synchrotrons of 30 years ago, with their massive magnets and poorly controlled beam dynamics, and modern strong-focusing synchrotrons.

equal to 107 T-m. The chosen peak dipole field of 1.72 T gives a total magnet length of 62 meters, or 46% of the circumference.

To minimize the total length of quadrupole magnets in the lattice, we chose a FODO design, which makes the most effective use of the quadrupoles. The machine comprises 12 FODO cells, with two cells forming a period. The 24 bending magnets provide a good-field aperture of $22\text{ cm} \times 7\text{ cm}$ (in contrast to the $120\text{ cm} \times 30\text{ cm}$ aperture of the weak-focusing Bevatron), with sufficient clearance for a cryogenic vacuum chamber. The maximum cycle rate to full field is 1 Hz.

Because partially stripped circulating ions are extremely vulnerable to loss by collision with residual gas molecules, the vacuum requirements are stringent. A guard vacuum-high vacuum system has thus been modeled after the successful Bevatron design to assure a maximum pressure of 10^{-10} Torr.

The upgrade also entails modest changes to the present injection and extraction channels. Meeting the multiturn-injection requirements of the new synchrotron requires that the horizontal emittance of the beam from the SuperHILAC be as small as possible. An emittance matcher, to be located near the foot of the transfer line, was therefore designed that reduces the mean horizontal emittance of the SuperHILAC beam, simultaneously increasing the vertical emittance. In addition, the optics of the injection channel was redesigned, primarily to assure zero dispersion at the inflection point, with minimum sensitivity to beamline tuning. On the extraction side, the only major new component is a fast-pulse dipole, required by the new pulse-to-pulse switching capability.

A final crucial element in the proposed upgrade is an improved control system. Flexibility in meeting the needs of several experimenters, for example, will depend on the ability to switch rapidly among several users. The present successful time-sharing operation of the SuperHILAC serves as a model for the future operation of the upgraded Bevalac.

Research Opportunities. Accelerator-based heavy-ion physics has significantly advanced our understanding of nuclear and biomedical science. Foremost among the many new research avenues it has opened to the nuclear scientist is that of creating and investigating various extraordinary forms of nuclear matter, such as those associated with high temperatures and densities, high spin states, and highly unstable compositions. During the past decade, pioneering studies with heavy-ion beams have revealed many novel features of nuclear dynamics, in both low- and high-energy regimes. At the same time, the scope of nuclear physics has been greatly enlarged by the production of several new heavy elements and of many new isotopes (both light and heavy) far from stability. Studies such as these have revealed a wealth of research opportunities, both experimental and theoretical, which in turn have stimulated a vigorous interest in heavy-ion physics in the nuclear science community worldwide.

Extraordinary forms of nuclear matter are revealed, for the most part, by penetrating into previously inaccessible regions of the nuclear matter phase diagram (Fig. 18), on the one hand, and the chart of nuclides, on the other. Until the Bevalac gave birth to the field of accelerator-based relativistic heavy-ion physics in the mid-seventies, virtually the entire body of knowledge of nuclear physics, gained during the preceding six decades, pertained to the tiny region of the phase diagram representing cold nuclear matter at saturation density. Great strides have been made in experiment and theory during the past decade, but they represent only the first small steps into the broad domain of nuclear matter beyond these narrow confines.

Like the phase diagram, the chart of nuclides is still largely terra incognita: Thousands of nuclides that are predicted to be observable have not yet been observed. The production of nuclei far from the line of β -stability makes it possible to study systematically the response of nuclei to large variations in the nuclear

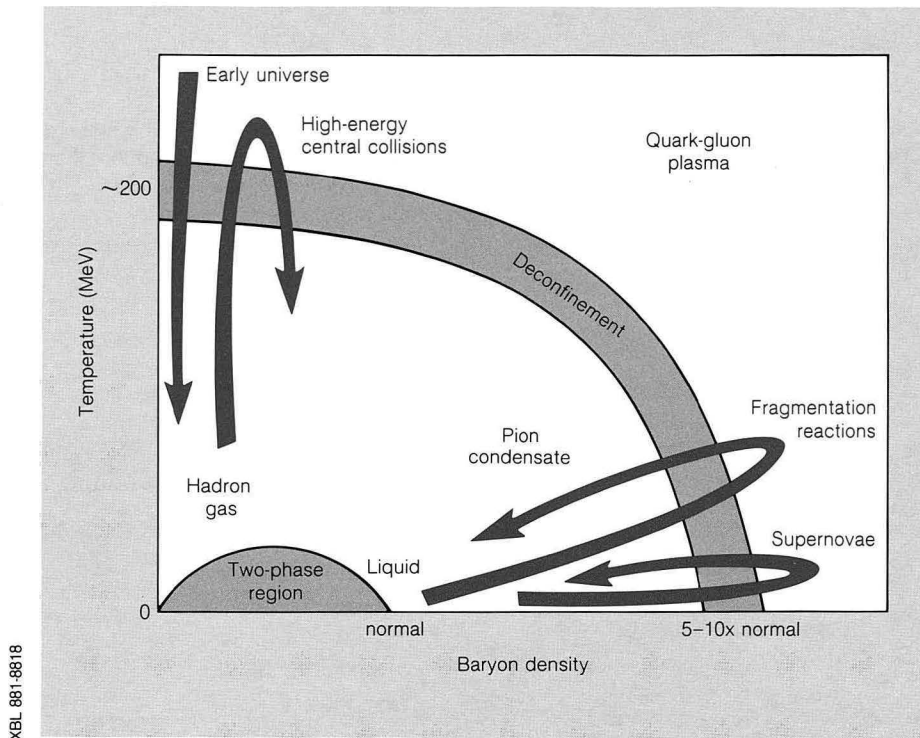


Figure 18. A schematic phase diagram for nuclear matter, showing some of the states and transformations predicted by various theories. The normal state of nuclear matter can be characterized as a liquid, which may undergo phase transitions to a hadron gas (at relatively low densities) or to some condensed phase, perhaps the so-called pion condensate or superdense nuclei containing thousands of nucleons. Under more extreme conditions, the constituent hadrons of nuclear matter are themselves expected to break down into "deconfined" quarks and gluons. Central collisions between nuclei at extreme relativistic energies are predicted to approximate the high-temperature, low-density conditions of the early universe, whereas the dense matter produced during fragmentation reactions at lower energies may yield clues about the states of matter inside supernovae and neutron stars.

isospin degree of freedom. Furthermore, many such unstable nuclei are important in astrophysical nucleosynthesis.

The most productive scientific advances often result from going beyond the mere observation and analysis of what already exists, to the *creation* of novel systems and processes that are otherwise unavailable for study. Accordingly, many of the research goals for the upgraded Bevalac concern phenomena that do not normally occur in our local environment. Some of them probably exist at distant stellar sites; other may have existed only at the birth of the universe; and still others may be entirely novel in the universe. As the opportunities for nuclear physics to explore exciting new realms present themselves, it is surely worthwhile to exploit them, above all for the scientific advances to be made, but also for the possibilities of eventual technological benefits.

In the decade and a half since the Bevalac began operations, and especially in the five years since beams of the heaviest ions became available, substantial progress has been made toward a realization of the promise of relativistic heavy-ion physics. We have begun to explore the nuclear phase diagram, at least in a tentative way. Hot, dense nuclear matter has been created, and the idea of nuclear matter under extraordinary conditions has assumed major importance in the conceptual foundations of nuclear physics. Our quest to understand nuclear matter is well-begun; the upgraded Bevalac is a logical vehicle for pursuing it further.

During 1987 all but the final phase was completed on a project to increase by fivefold the heavy-ion intensity delivered by the SuperHILAC to the Bevalac. Three new beam bunchers are now in operation, which, together with vacuum improvements, have successfully boosted intensity by a factor of three. Full commissioning, following installation of a metal-vapor vacuum arc (MEVVA) source, should follow in 1988. Along related lines, MEVVA development activities included further testing of the 16-cathode MEVVA IV and fundamental studies of

Accelerator Improvement Projects

the ion-generation process in vacuum arcs. The results of this latter study included the finding that only about 1% of the plasma generated in the arc is extracted as beam; this bodes well for further development of the MEVVA concept.

As part of a project to upgrade the drift-tube focusing magnets at the SuperHILAC, 24 damaged magnets have now been replaced with conventional tape-wound magnets, taking advantage of new insulation materials and higher-temperature epoxies. In addition, we plan to replace other magnets with permanent-magnet quadrupoles of a new design. This adjustable, hybrid iron-and-rare-earth magnet offers a greater effective field strength and adjustability over a wide range of fields. A prototype has now been subjected to 106,000 cycles, simulating ten years of normal operation, during which it showed no deterioration. In addition, in tests at the end of 67,000 cycles, the magnet still showed very low field errors. A conventional alternative to this innovative magnet has also been designed, with the space between the pole pieces laced with rare-earth permanent-magnet material to raise the saturation field. A prototype is planned.

The advantage of these new magnets will be a higher field gradient, leading to better beam transmission. Following completion of the drift-tube project, we expect intensity to improve by about a factor of two.

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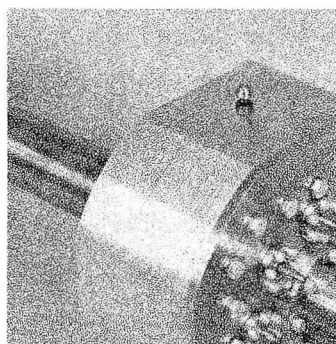
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4.

HIGH-ENERGY PHYSICS TECHNOLOGY

... building on a quarter-century-long history of magnet development, our efforts now focus on the future need to manufacture 8000 reliable SSC dipole magnets ...

HIGH-ENERGY PHYSICISTS IN THE U.S. are united in their efforts on behalf of the Superconducting Super Collider (SSC), and our research activities in this field reflect this dedication. Our long-established superconducting-magnet program, for example, focuses on the design and testing of model SSC magnets, especially the critical dipole magnets. Included in this effort is our continuing development of improved superconducting cable, as we keep always in mind the practical needs of manufacturing 8000 reliable 17-meter-long dipole magnets. In addition, AFRD accelerator physicists have been assigned to the SSC Central Design Group, where (as described on pages 90–93) their contributions have included lattice design refinements, various theoretical studies, and participation in a critical experiment at Fermilab's Tevatron.

In spite of the SSC's obvious priority, we nonetheless maintain a broad perspective on the needs of the high-energy physics community. Model magnets for the SSC, for example, embody design innovations that are likely to be applicable to any future accelerator dipole magnet. Likewise, at the same time that we are optimizing the use of niobium-titanium superconductor for the SSC, we have started a modest program to understand and improve the properties of the highly touted warm superconductors—impractical for present applications but perhaps ultimately useful. Also with an eye to the future, we continue work (described on pages 93–96) on the concept of the Two-Beam Accelerator, a futuristic high-gradient linac that would be powered by microwaves from a free-electron laser or a relativistic klystron.

During 1987 we also continued our work on stochastic antiproton-cooling systems at Fermilab's Tevatron, and we have now tested preliminary designs for Schottky monitors that could be used to actively monitor disturbances in the small random motions of beam particles in a storage ring.

Superconducting Magnets

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Our superconducting-magnet program has a quarter-century-long history of magnet development, highlighted by the achievement of record magnetic fields for accelerator-type magnets. In turning our attention to the SSC, the ultimate challenge (for us and our sister laboratories) is to show that high fields can be reliably reached in mass-produced magnets, using industrially produced superconducting cable. The past year was marked by several important achievements on the road to this goal. The dipole magnet design is generally well-established, but refinements continue, evidenced by our fabrication and testing of nine 1-meter models during 1987. One of the latest and most significant refinements has been the development of tapered-key collars, which simplify assembly on an industrial scale and eliminate overstressing the electrical insulation. Also, we designed an industrial-scale cabling machine and contracted for its fabrication. At the same time, collaborating industries met SSC specifications with production quantities of superconducting cable.

Dipole Design. The design and manufacture of the main-ring dipole magnets continue to be a major focus of the SSC research effort. The fundamental reason is clear: Nearly 8000 dipoles must be industrially produced to close tolerances, both to ensure the uniform magnetic field required for an acceptable beam lifetime and to guarantee reliability. In particular, much of the attention has turned to refinements aimed at assuring the "manufacturability" of the dipole magnets.

Along these lines, one of the principal achievements of 1987 was the development of a new collar design that uses tapered keys. As illustrated in Fig. 19, the coils of a superconducting magnet are kept in place with collars,

Superconducting Magnets

Magnet Development

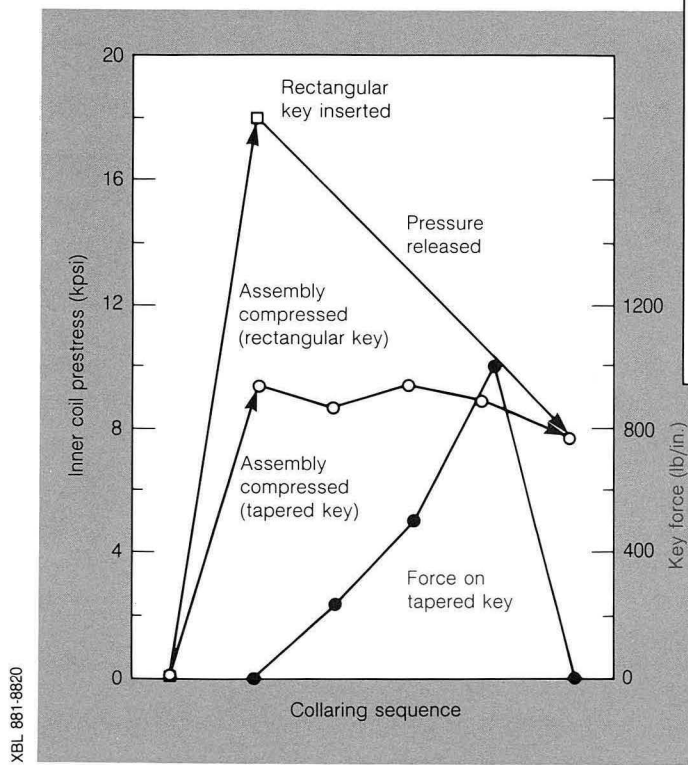


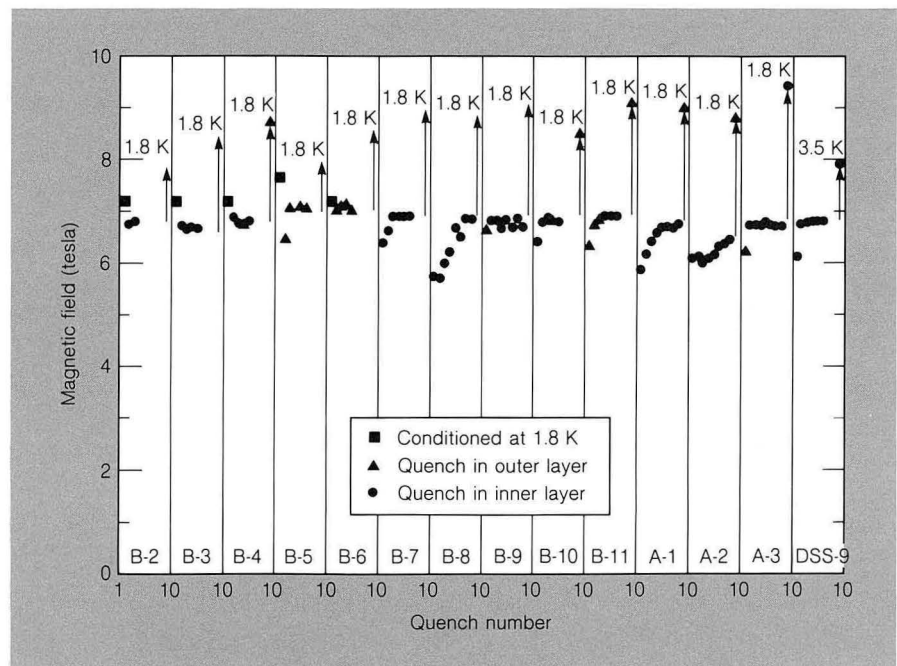
Figure 19. At left, a plot showing the coil prestress during the collaring of dipole magnets with two different collar-key designs. When a conventional rectangular key is used, the superconducting coils must be compressed with sufficient force to allow full insertion of the keys. The transient high pressure can damage the thin cable insulation used for these high-field magnets. With the tapered keys, the pressure must be sufficient only to permit the keys to be started in the keyways. The collaring sequence for the tapered design is shown schematically above. Actual collar packs typically contain about 200 of the interleaving collars shown at the left of the illustration above.

traditionally secured with "keys" having a rectangular cross section. The collar-coil assembly is compressed until the keys can be inserted, then the pressure released. About 18,000 psi is needed to permit key insertion, whereas an azimuthal pressure in the windings of only 8,000–10,000 psi is required for proper operation. Indeed, the transient high pressure can cause deterioration of the insulation between the turns of the coil and can decrease long-term reliability. Increasing the insulation thickness to get around this problem would increase the need for superconductor to achieve the same field, and hence increase the cost. (Turn-to-turn insulation in the SSC dipole consists of two layers of 0.001-inch-thick Kapton film, partially covered by a resin-impregnated fiberglass tape. The total thickness of insulation between turns is only about 0.005 inch.)

In the new design, hydraulic pressure is still needed to push the coils together, but the compression need only be great enough to allow the tapered keys to be started in the keyways. Pressure is then applied directed to the keys, pushing them the rest of the way into the keyways. Pressure peaks are thus avoided, as also shown in Fig. 19.

Magnet Testing. During the past year, we continued our program of testing 1-meter-long dipoles, the aims being to evaluate new conductor and cable designs, new collar designs, innovative coil construction procedures, and new cross section designs proposed to increase field uniformity. Figure 20 summarizes the 14 most recent tests of model magnets, including one 1.8-meter model (DSS-9) of LBL design that was fabricated and tested at the Brookhaven National Laboratory (BNL). Plotted in this figure are the magnetic fields at which successive "quenches" occurred. When a magnet is first energized, very small field-induced mechanical movements within the conductor cause frictional heating. The consequent temperature rise, exacerbated by the low heat capacity of the material at liquid-helium temperatures, can be large enough to initiate a sudden local transition from a superconducting to a normal state. The local resistance thus rises, followed by a spontaneous rapid heating, or quench, of the entire magnet. Successive quenches typically occur at increasing magnetic fields, apparently because each quench tends to stabilize the conductor mechanically.

Figure 20. Training curves for the last 13 magnets tested at LBL, along with one (DSS-9) of LBL design that was tested at the Brookhaven National Laboratory. The solid circles and triangles indicate the magnetic field at which a quench occurred (at 4.4 K unless otherwise indicated). Five of the magnets were conditioned at 1.8 K, a step that effectively eliminates training. Training in models A-3 and DSS-9 was virtually eliminated by the use of tapered collar keys.



XBL 881-8821

In 1986 we demonstrated that this "training" in our model magnets can be eliminated by initially operating the magnet at a field higher than its design field; this can be done by temporarily reducing the temperature to increase the current-carrying capacity of the cable, a procedure we call "conditioning." Nevertheless, we have not used conditioning in recent experiments, because we want to observe the nature of the training in these developmental models. The frequency and origin of training quenches can provide clues as to the adequacy of local cable support, the effect of design modifications on magnet performance, and the possibility of eliminating training without low-temperature conditioning.

As Fig. 20 shows, several 1987 models had only one training quench; those that required more training usually embodied highly experimental design or manufacturing innovations. Once trained, the magnets were usually heated to ambient temperature, recooled, and retested; training was rarely observed during the retesting. Numerous voltage taps are used during each test to determine the origins of the quenches and to follow the growth of the resistive region along the cable and onto adjacent turns.

All of the model magnets tested during the past year had aluminum collars, and the last four were constructed with tapered keys. The last two models—A-3, a 1-meter model built at LBL, and DSS-9, a 1.8-meter model built at BNL by LBL staff—were constructed without oversqueezing the coils during collaring (see Fig. 19) and performed especially well. This observation leads us to believe that training can be virtually eliminated with proper magnet design, even when the amount of stabilizing copper in the cable is low. (The copper-to-Nb-Ti ratio in the inner layer of all models was approximately 1.3:1.) We are continuing to introduce additional instrumentation into model magnets to determine the factors that influence training in these high-current-density accelerator magnets.

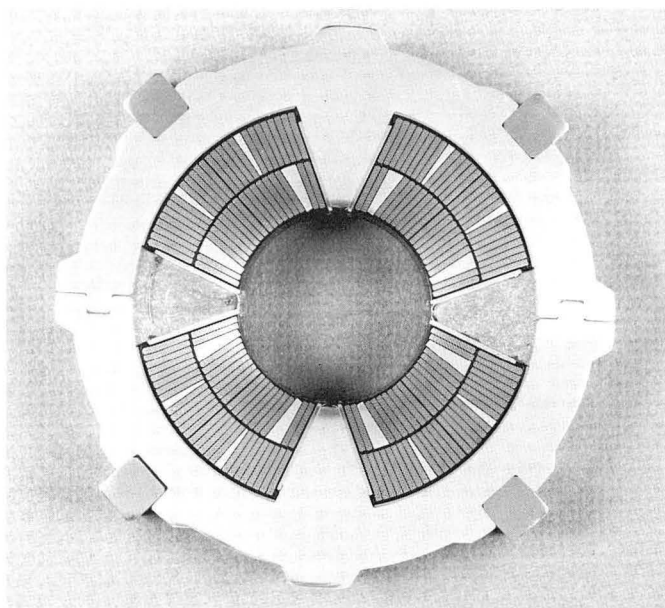
Quadrupole Design and Testing. During the last year, we built and tested the first 1-meter quadrupole model of a design suitable for the SSC. At the design current of 6600 amps, the measured gradient was 244 T/m, and a gradient of 279 T/m was reached at a critical current of 7440 amps. At a reduced temperature of 1.8 K, the maximum gradient achieved was 357 T/m. The construction method used was similar to that for the dipole models, making use of interlocking aluminum collars and tapered keys. The quadrupole, however, is self-supporting, that is, it does not depend on an iron yoke to limit deformation when energized. Figure 21 shows a cross section of the collared quadrupole coils.

In a broad sense, the making of cable for superconducting magnets involves three steps: the manufacture of the superconducting material itself (in our case, an alloy of niobium and titanium); the extrusion and drawing of this material into wire, each strand of which comprises many filaments of Nb-Ti in a copper matrix; and the weaving of this wire into cable. During fiscal 1987, our efforts in the area of superconductor and cable development for the SSC had two main objects: first, to further define SSC wire parameters, with an emphasis on the manufacturability of fine-filament wire, and second, to transfer the necessary cabling technology to industry.

Fine-Filament R&D. To establish a data base for the final optimization of wire parameters, 12 "billets" were ordered from three U.S. superconducting-wire manufacturers; at year's end, these billets, from which the manufacturers will then produce wire, were still being processed. The specifications for these billets explore two Nb-Ti filament sizes (6 and 9 μm), as well as different filament spacings and different post-extrusion "cold-working" schemes. At the same time, we have already made a change to the SSC specifications to reflect what we have learned about the importance of filament size and spacing. The specified filament size has been changed from 5 to 6 μm , and the minimum filament

Superconductor and Cable R&D

Figure 21. A cross-sectional view of the 1-meter-long model SSC quadrupole that was successfully tested during 1987.



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spacing is now 1 μm . Pending the outcome of tests on the 12 billets still being processed, these values appear to offer an optimum balance between two competing factors.

On the one hand, fine filaments offer an important advantage. With larger filaments, induced currents in the filaments produce field inhomogeneities, especially at low fields. These distortions must be corrected with auxiliary windings in each magnet. If the superconductor filaments are small enough, these field imperfections disappear. However, as filament size decreases, the filament spacing must also decrease, else the filaments lose the uniform mechanical support of the surrounding filaments. And as filament spacing is reduced, it becomes increasingly easy for superconducting electrons to pass through the copper matrix between filaments without being scattered. By coupling individual filaments, this so-called proximity effect thus increases the effective size of the filaments. As a result, the induced-current effect no longer scales with filament size, but rather can actually increase as filament size and spacing decrease.

During 1987 a number of billets were processed according to the new SSC specifications, and the results were uniformly excellent. Critical current values consistently exceeded the SSC specification of 2750 A/mm² at 5 T, and long lengths of wire were produced without the breakage that had occurred in previous fine-filament wire.

In a more exploratory vein, we also investigated a promising idea for overcoming the proximity effect, proposed by E. Collings of the Battelle Memorial Institute in Columbus, Ohio. The idea is to add a small amount of manganese to the copper matrix to increase the scattering of the superconducting electrons. In the past, nickel has been proved effective in this role, but it is necessary to add rather large amounts (10–30% by weight) to obtain the desired effects. It was argued that manganese might be much more effective than nickel, since the manganese atom should maintain its magnetic moment in a dilute copper alloy.

To test this idea, Supercon, Inc., assembled two 12-inch-diameter billets, one with a pure copper matrix and one with a copper matrix containing 0.5% manganese. Both billets were successfully processed into wire and subsequently into cable, indicating that the manganese had no detrimental effects on mechanical properties. Furthermore, measurements indicated that the added

manganese produced the predicted reduction of the proximity effect: zero-field coupling was eliminated at filament spacings greater than $0.15\text{ }\mu\text{m}$, compared to the onset of coupling at about $1.5\text{ }\mu\text{m}$ in the pure copper matrix. In addition to the obvious benefits to the high-energy physics program, this result may have important ramifications for the development of low-loss conductors for power applications. We are continuing to pursue this approach with another fine-filament billet from Supercon, this time with a final filament size of $2.5\text{ }\mu\text{m}$, half that of the first two billets.

Cable Technology Transfer. The transfer to industry of the cable fabrication technology developed at LBL over the past several years proceeded actively during 1987. We ordered a prototype production cabling machine, to be built according to specifications developed in 1986. This machine will be completed by the spring of 1988, then installed at the New England Electric Wire (NEEW) plant, where all U.S. superconducting-wire manufacturers will have access to it. At the same time, we have worked with NEEW to incorporate LBL-developed tooling and procedures into their existing cabling equipment. As a result, these machines have successfully produced cable that meets SSC specifications.

Apart from development work directly or indirectly related to the SSC, we developed and manufactured a 36-strand cable using 0.020-inch-diameter wire, for use at Fermilab. After successful evaluation by Fermilab, this cable was adopted in the design of special low- β quadrupoles for the Tevatron. At the end of 1987, exploratory work was also just beginning on the new warm superconductors.

Broadly defined, the purpose of our beam cooling and beam-control electronics group is to develop electrodes and monitors to understand and improve the operation of the Fermilab Tevatron. Much of our effort during the past few years has been directed toward development of stochastic beam-cooling systems, which provide a means of increasing the intensity of the antiproton beam. Along these lines, we successfully tested models of a new 4- to 8-GHz pickup during 1987. And building on the success of the beam-cooling efforts, we turned increasing attention in the past year to narrow-band Schottky monitors that could sense small random motions of individual particles in a circulating bunch during colliding-beam operation at the Tevatron.

Significant effort has been devoted over the past several years to developing and testing a stochastic beam-cooling system for the antiproton source at the Fermilab Tevatron. In such a system, sensitive electrodes pick up from each passing antiproton the tiny signal indicating its deviation from the mean transverse position and velocity of the beam. That signal is then amplified and transmitted to a kicker electrode, which applies a corrective impulse to the errant particle. A successful system, operating at frequencies up to 4 GHz, is now in operation.

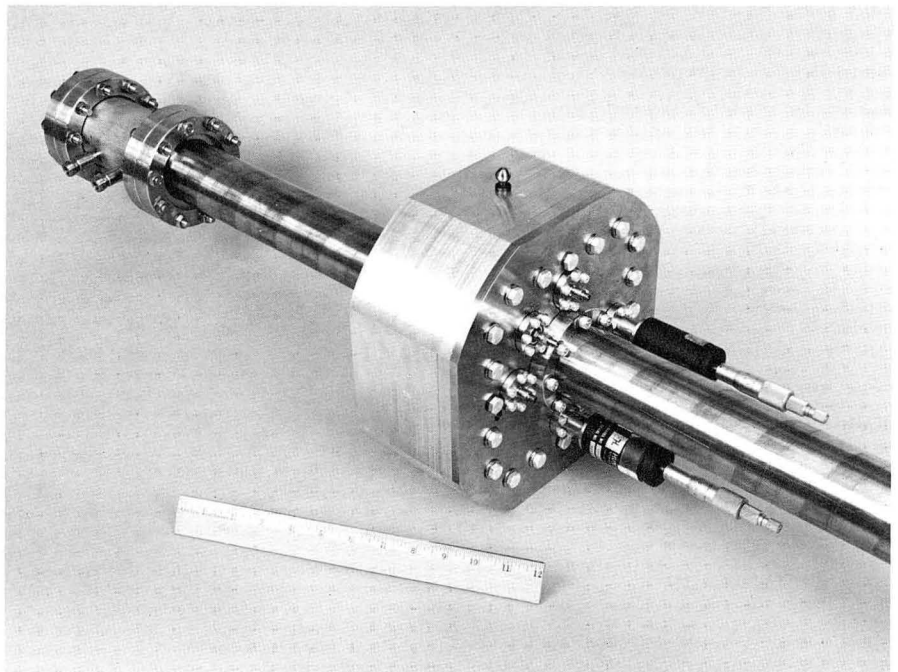
To further increase the flux of antiprotons from the source, however, pickup and kicker electrodes are needed that operate at even higher frequencies. A complication at higher frequencies arises from the complex responses of any single electrode to the electromagnetic waves that propagate through the beam aperture and mix with the desired signal from the beam. We therefore assembled a model having four sets of electrodes and determined that by adding the signals in proper phase the unwanted responses average out; the desired and expected amplitude was therefore produced. Anticipating that about 1000 such sets of electrodes would be needed for any antiproton source upgrade, we are now developing a mechanical design for these electrodes that would be suitable for mass production.

Other Activities

Beam Cooling and Beam-Control Electronics

Another operational challenge at Fermilab is to keep beam densities high in the collider over the many hours of an experimental run. One way of monitoring beam quality is to observe disturbances in the small random motions of the circulating particles, by means of a Schottky monitor. So far, however, detectors at the Tevatron have been unable to see the Schottky signal, owing to the much stronger signals from the coherent motions of the beam as a whole. We have therefore designed and fabricated a narrow-band Schottky detector (Fig. 22) that operates at 2 GHz, at which frequency it should be insensitive to the lower-frequency coherent motions of an undisturbed beam. This single-cavity pickup, within its narrow frequency band, is as sensitive as a few thousand loop-type pickups. This detector has now been installed at the Tevatron; however, our only opportunity during 1987 to observe the new detector's output was during the early stages of operation with fixed targets. Under these conditions, even at the higher frequency, we observed strong coherent signals—interesting and puzzling in themselves, but not yet the desired goal of the detector. Our next observations will be made during operation with colliding beams.

Figure 22. A cavity-type Schottky detector, designed to sense movements as small as 10^{-7} cm in the circulating beam at the Fermilab Tevatron.



CBB 873-1723

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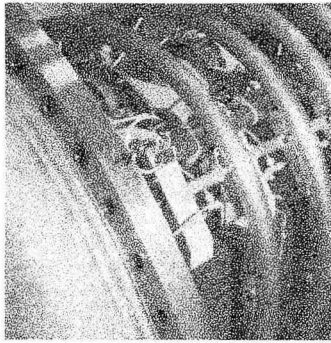
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Publications and Presentations



5.

HEAVY-ION FUSION ACCELERATOR RESEARCH

*... as the culmination
of this research
program, ILSE would
address the main driver
issues for a full-size
heavy-ion fusion
reactor ...*

TWO SCHEMES ARE HELD to have the greatest promise for harnessing the near-limitless potential of fusion energy. The more widely known is magnetic-confinement fusion (see pages 71-83), in which strong magnetic fields are used to contain a continuously burning tritium-deuterium plasma. By contrast, inertial-confinement fusion (ICF) depends on the inertia of a small fuel pellet to keep the deuterium and tritium together for the fraction of a nanosecond it takes them to burn. By repeating this process a few times per second, enough heat can be produced to drive the generators of an electric power plant. ICF therefore relies on a pulsed process, analogous to the repeated mini-explosions in an automobile engine. To provide the intense focused energy necessary to compress and ignite the fuel pellet, two types of ICF "driver" are under active consideration. Laser drivers would use powerful beams of short-wavelength light to heat and "ablate" the pellet surface, leading in turn to compression and ignition of the fuel. The alternative, ion-beam drivers, would rely on high-energy beams of ions, which would deposit their kinetic energy in the pellet and thereby compress it. The thrust of our effort at LBL is to explore the practical possibilities of heavy-ion accelerators, which offer several advantages over lasers as fusion drivers.

The means for this exploration is a series of increasingly sophisticated experiments. The first, which began in 1982, was the single-beam transport experiment. In it we studied in detail the physics of a single high-current heavy-ion beam. Second is the multiple-beam experiment MBE-4, in which four independent high-current beams are transported and accelerated through a multigap accelerating structure. A unique feature of this second experiment is that the ion current is continually amplified during the acceleration process. The past year was highlighted by completion of the apparatus for this proof-of-principle experiment. Finally, as the culmination of this research program, we have proposed a much larger Induc-

Experiment

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tion Linac System Experiment, which would address the main physics and technology issues of a driver for a full-size heavy-ion fusion reactor.

Underlying the promise of this research, and the promise of heavy-ion fusion generally, are the results of a comprehensive feasibility study known as the Heavy Ion Fusion Systems Assessment. This multilaboratory study, sponsored by the DOE and the Electric Power Research Institute and coordinated by the Los Alamos National Laboratory, was completed in 1986. Among its results, it found that the estimated cost of electricity generated by a heavy-ion fusion power plant (see Fig. 23) compares favorably with the estimates obtained in analogous magnetic fusion studies.

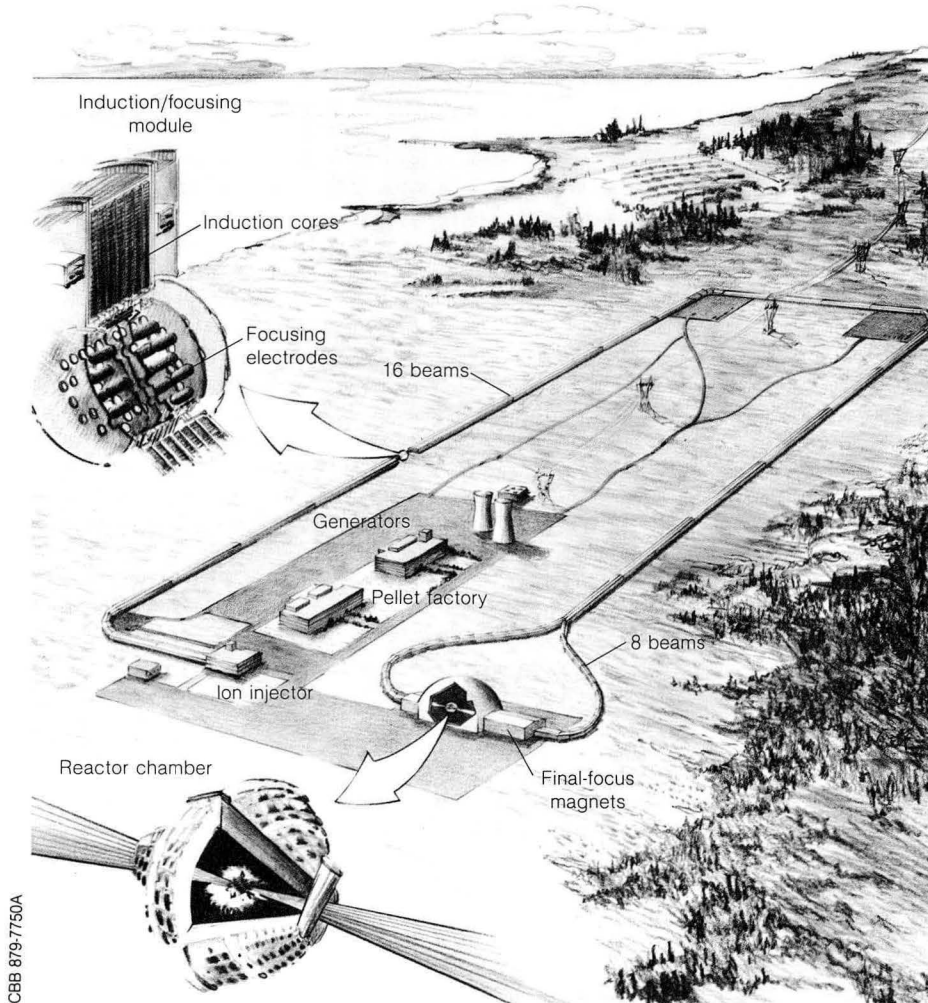


Figure 23. An artist's drawing of an inertial fusion power plant based on a 16-beam heavy-ion induction linear accelerator. The system shown here uses the Cascade reactor chamber design developed at the Lawrence Livermore National Laboratory—one of several concepts that have been studied. In this design, the inner wall of the chamber, which must absorb the punishing effects of x-ray and debris bombardment, is a thick layer of ceramic granules, kept in place by rotating the chamber. The granules are cycled through a heat exchanger, which uses helium as a secondary medium. Except for the pellet factory, the remainder of the plant—primarily steam turbines and generators—relies on conventional technology.

Multiple-Beam Experiment

The highlight of fiscal 1987 was the completion of the apparatus for MBE-4. One of the features of this experiment is its modular design, which has allowed us to conduct a series of studies over the past two years. Long before the apparatus was complete, therefore, we had successfully demonstrated significant amplification in beam current, achieved by suitably shaping the accelerating voltage pulses so as to actually shorten the duration of the ion pulse during acceleration. With all of the hardware in place, we can now pursue in earnest our aim of modeling several of the phenomena we expect to encounter in any eventual heavy-ion driver—especially the consequences of approaching stability limits imposed by space charge (the mutually repulsive charges in a high-current ion beam) and the effects on the optical quality of the beams caused by voltage- and current-amplification manipulations.

MBE-4 Design Concept

Since 1983 heavy-ion fusion driver research in the U.S. has concentrated on the multiple-beam induction linac, which can be visualized as a structure comprising many closely packed channels of beam-focusing lenses in which parallel “beamlets” of heavy ions are transported. Surrounding this structure is a series of ferromagnetic cores, along with the pulser circuitry needed to apply a succession of long-duration, high-voltage accelerating pulses to the beamlets. In MBE-4 four beams of positive cesium ions are accelerated through six accelerator sections (designated A through F), each containing four induction units. Along the entire length of the accelerator, the beams are focused by electrostatic quadrupole lenses, identical in concept to those that might be used in a full-scale driver. In a driver, these would be followed by superconducting magnetic quadrupole lenses, which are effective only at higher ion energies.

One major attraction of the induction linac method, and an important underlying justification for MBE-4, is the relative ease with which the physics and technology of a large driver can be scaled down to a laboratory setting. This benefit arises from the fundamental properties of particle beams dominated by internal space-charge forces. The disruptive effects of space charge are, in fact, somewhat worse in a 10-mA beam at 0.2 MeV than in a 1000-amp beam in a 10-GeV driver. This scaling property allows accurate predictions to be made for the beam physics in a driver, once the behavior of a small accelerator is well-understood. The carefully scaled design of MBE-4, therefore, will allow us to assess the consequences of errors in accelerating voltages, to investigate beam-beam coupling phenomena, and to gain relevant practical experience in accelerating and controlling parallel, space-charge-dominated beams.

Components and Fabrication

During the past year, a major milestone was reached when the final components were installed on MBE-4. Figure 24 shows the completed apparatus. By the end of the year, the 35 focusing elements were aligned to within ± 5 mils (rms) over the entire 17-meter-long accelerator, in preparation for resuming the experimental program.

The final phase of fabrication entailed installation of the four section D accelerator cores, installation of the section E cores and transport sections, and the fabrication and installation of all section F components. During this final period of fabrication and assembly, a small electrostatic energy analyzer was built, similar to the large energy analyzer at the end of the apparatus. This smaller version can be inserted in any of the diagnostics boxes of MBE-4, though it cannot be used at beam energies much above 300 keV, owing to voltage breakdown limitations. It will therefore be most useful for determining the beam energy at the entrance to the accelerator, downstream of section A, and perhaps downstream of section B. The analyzer consists of two coaxial cylindrical electrodes with a radial spacing of 1 cm and a mean radius of 10 cm. In preliminary measurements, we determined

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Figure 24. The completed apparatus for the multiple-beam experiment MBE-4. The injector is at the far end; the rectangular enclosures house the 24 accelerating cores.

the energy dispersion of the beam at two points between the ion source and the first accelerator section. Good agreement was found between the results and those obtained with the larger analyzer during an early phase of MBE-4 fabrication.

The modular design of MBE-4 allowed us to perform experiments at several early stages in the fabrication. During early fiscal 1987, for example, experiments were conducted with four transport sections and three accelerator sections in place.

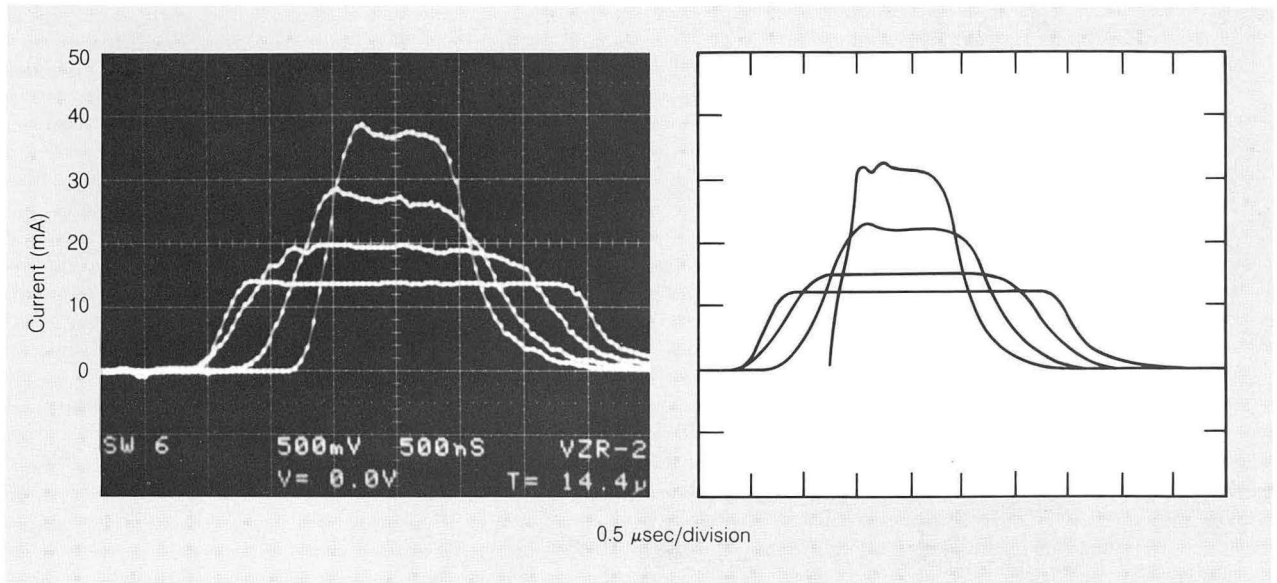
Any eventual heavy-ion fusion driver must deliver beams of extraordinarily high power to the target. This translates more or less directly into a requirement for high-current beams. As a consequence, one of the fundamental aims of MBE-4 is to demonstrate current amplification in an induction linac. In the absence of special measures, the physical length of an accelerated ion bunch grows in direct proportion to its velocity, whereby the current remains constant. Therefore, if we are to amplify the current, the electrical pulses applied to the cores must be specially shaped so as to accelerate the tails of the beam pulses more than the front ends. The duration of the beam pulses, as measured at different points along the accelerator, thus decreases as the ions are accelerated.

During the past year, we conducted experiments with the first 12 accelerating cores (that is, sections A, B, and C) in place. The necessary voltage waveforms were derived iteratively by numerically following the longitudinal motion of the beam particles through the accelerator, taking account of the effects of space charge and the finite gap width. They were generated by a computer code (SLID), such that the resulting current waveform retains a self-similar rectangular shape as the beam is accelerated. Since it is not possible to synthesize exactly the ideal voltage waveforms, we also used SLID to solve for slightly modified downstream waveforms that corrected for upstream errors. In addition, the accelerating voltages at the fourth, eighth, and ninth gaps contained components to control the longitudinal space-charge spreading of the beams, as well as to accelerate them.

A typical experimental result is shown in Fig. 25, which depicts oscillograms for one of the four accelerated beams at the entrance of the accelerator and at the ends of the first three accelerator sections. By electronically integrating traces

Experimental Results

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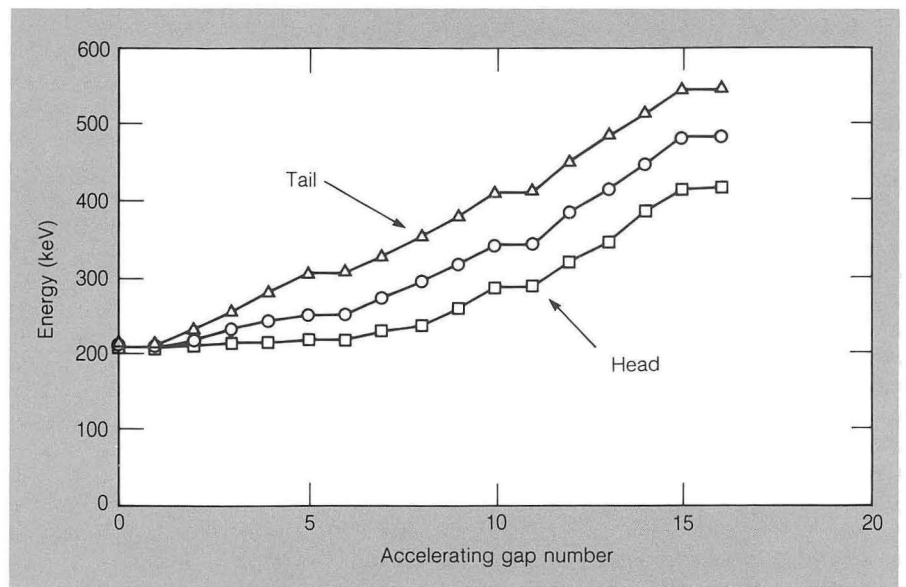
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Figure 25. Measured and computed waveforms for one of the four beams in MBE-4 at diagnostic stations 0, 5, 10, and 15. The data were taken when only 12 of the 24 cores were in operation. The computed waveforms were obtained by the SLID code, given as input the initial beam energy and current, and the accelerating voltage waveforms.

such as these for all four beams, we determined that the charge contained in each beam at any given station varies by no more than 5%. Further, for a given beam, the charge varies by less than 3% along the length of the accelerator. Also shown in Fig. 25 are the current waveforms computed by SLID, given as input the accelerating voltage waveforms and the beam current and energy at the entrance to the accelerator. A graphic illustration of the longitudinal dynamics of the beam is shown in Fig. 26, a plot of the head, tail, and midpoint energies along the first three accelerator sections. The result is a "velocity shear" that allows the beam tail to keep pace with the head.

The transverse dynamics of the beams in MBE-4 is also of critical importance. Indeed, two of the reasons for doing the experiments are to assess the effects of space charge and to examine possible interactions among the beams as they are transported in parallel channels. A crucial diagnostic parameter is therefore the emittance, a measure of the transverse beam size and its divergence. In our

Figure 26. A plot of head, tail, and midpoint energies of an ion beam in the first three sections of MBE-4. The energy, hence velocity, difference between the head and tail (referred to as velocity shear) is a prerequisite for current amplification.



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experiments, emittance measurements are made using a "two-slit method," the apparatus for which is shown schematically in Fig. 27. By scanning the Faraday cup detectors, measurements are obtained of the rms beam size, its mean angle of travel with respect to the ideal axis, its mean position in the focusing channel, and the random transverse velocity of the beam particles. A typical emittance measurement is also shown in Fig. 27. Values for the normalized emittance, calculated from plots such as this, show essentially no emittance growth in the first three accelerator sections of MBE-4.

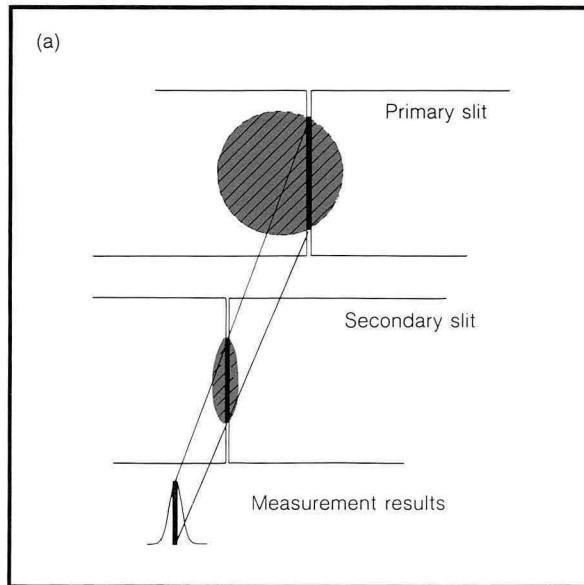
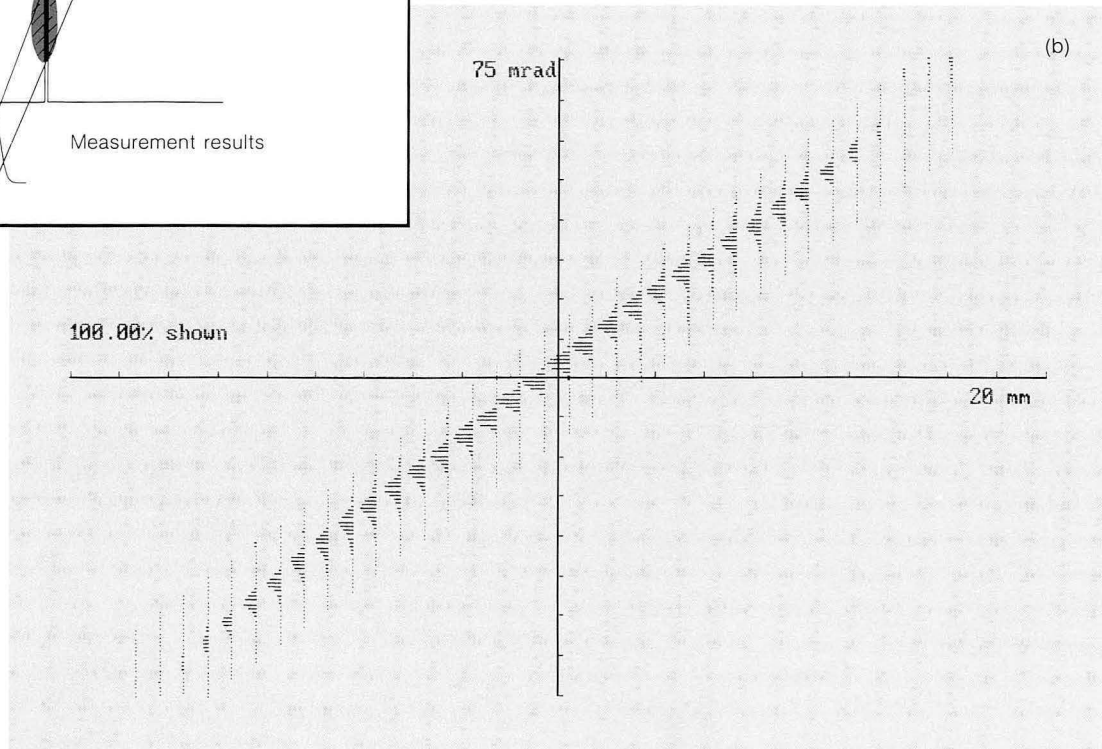


Figure 27. (a) A schematic illustration of the two-slit emittance-measuring concept. For a given position of the primary slit, the secondary slit passes into the detector only those particles with a well-defined transverse velocity. The two-slit apparatus yields measurements of rms beam size, its mean direction of travel, its mean position in the beam channel, and the random transverse velocity of the beam particles. (b) Data from typical emittance measurement. The horizontal axis reflects different positions of the primary slit; the vertical axis, different positions of the secondary slit.



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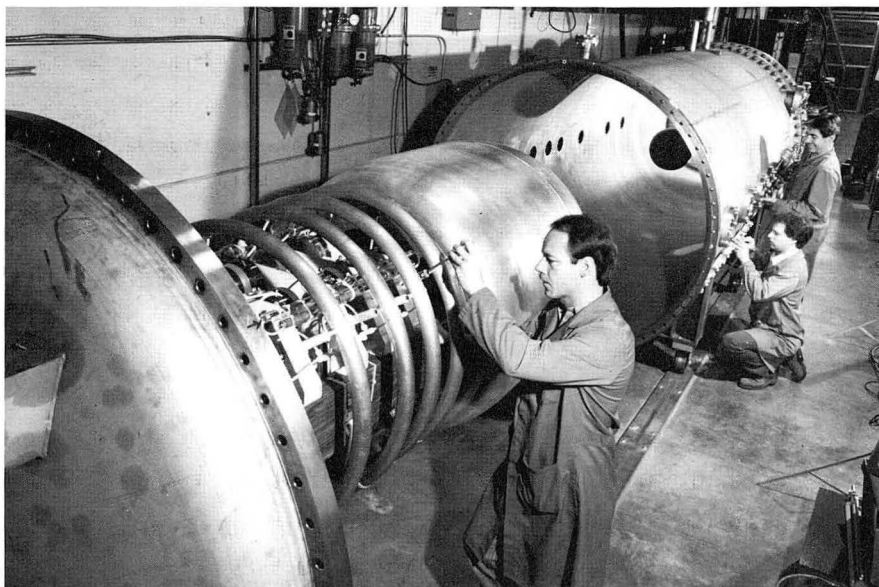
Injector Development

In looking beyond MBE-4, certain challenges become especially evident. One such challenge is the development of a high-current multiple-beam injector for an experiment that lies a step closer to a full-scale driver. Accordingly, a 16-beam, 2-MV injector (Fig. 28) has been under development for the past few years at the Los Alamos National Laboratory. During the last half of fiscal 1987, this project was in the process of being moved to LBL. Several components arrived, and others were shipped. In preparation, the Marx generator system was redesigned, and space was prepared for assembly of the injector. In addition, the 200-kV injector for the single-beam transport experiment was used as a test bed for the carbon arc source intended for use in the 2-MV injector.

Over the past year, there were three main areas of progress on the 2-MV injector that would form the basis for the next step in the HIFAR program (see ILSE, below). Much of the work was done at Los Alamos, where this project began, but several steps were taken at LBL in preparation for further development here. At Los Alamos, the ceramic insulators in which the accelerator column will reside were subjected to a series of acid treatments to remove fillets remaining from the brazing process. Also, a prototype clamp ring for the electrodes was designed and successfully tested. A trial assembly of the insulator column and its external hardware was successful. At LBL meanwhile, the 750-kV pulsed power system was redesigned to reduce trigger jitter and to make possible the conversion of the originally specified conventional Marx generator to an inductively graded Marx.

The ion source for the 2-MV injector is to be a carbon arc source, which has been developed by S. Humphries at the University of New Mexico. During the past year, a duplicate of the New Mexico source was fabricated and installed on the single-beam transport experiment. The source operates by generating a plasma at a carbon arc, then confining it by means of a pair of biased grids. An ion pulse is then extracted by applying a voltage between the second of the grids and the grounded extractor plate. Experiments on this source were aimed at optimizing a number of operational parameters and evaluating the properties of the extracted beam. Perhaps most significant was an observed maximum current density equivalent to 24.5 mA/cm^2 , essentially meeting the requirements for a 16-beam, 8-amp injector. Continuing work aims at improving the trigger lifetime and stability.

Figure 28. Components of the 16-beam, 2-MV injector partially fabricated at LANL and now being completed at LBL. High voltage is generated at the large terminal in the center of the photograph by the Marx generator in the foreground. Ions produced at the terminal voltage will then be accelerated through a column, yet to be fabricated, attached to the far side of the terminal. The entire injector will operate within the pressure vessel seen in the background. During the past year, responsibility for the development of this injector has been transferred to LBL.



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To complete the validation of induction linacs for inertial-confinement fusion, LBL has proposed the Induction Linac System Experiment (ILSE), which would demonstrate, in a scaled model accelerator, the physics and technology of a large driver. The system would include the 16-beam, 2-MV injector now being constructed here, an electrostatic focusing section that accelerates all 16 beams to an intermediate energy, a beam-combining system to merge the 16 beams into 4, a magnetic focusing section that accelerates the resulting beams to a final energy, and a section in which a single beam is bent, then longitudinally compressed and focused onto a small target. At the end of 1987, a basic physics design for ILSE was near completion. Particular effort was devoted to understanding the physics of the combining section and to designing the necessary electrostatic and magnetic focusing and bending elements for such a section.

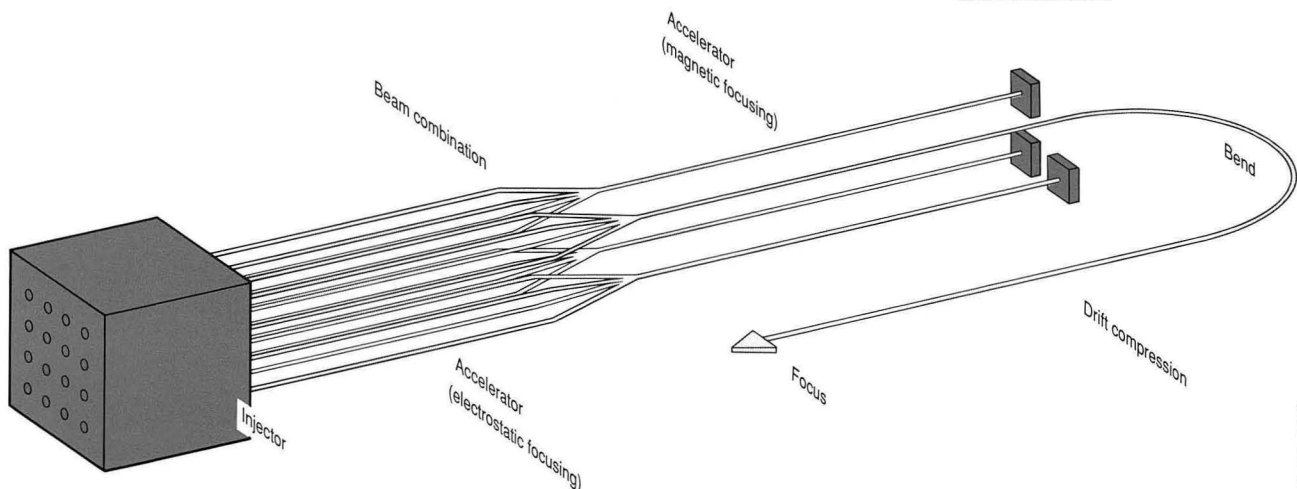
ILSE was conceived to address several of the yet-untested concepts that must be embodied in any practical heavy-ion fusion driver: the transverse combination of space-charge-dominated ion beams, the transition from an electrostatic to a magnetic beam-transport system, the magnetic bending of ion beams that are both space-charge dominated and increasing in energy, current amplification by "drift compression," and the focusing of intense ion beams to a 2-mm-diameter spot. A schematic for a system in which these various beam manipulations could be attempted is shown in Fig. 29.

Current amplification in ILSE would be achieved by means of the same type of pulse shaping already demonstrated with MBE-4. However, the injected beam currents would be considerably higher, owing to the design of the new injector. Likewise, the peak power in the beam on target would be more than a 1000 times that of MBE-4. The parametric design of ILSE was based on a careful cost-benefit analysis of the physics and technology issues still to be addressed by the HIFAR program. We estimate that the fabrication of ILSE would cost an additional \$28 million (fiscal 1987 dollars), spread over four years.

Induction Linac System Experiment

Conceptual Basis

Figure 29. A schematic diagram of the proposed Induction Linac System Experiment, conceived to address remaining issues crucial to the concept of heavy-ion inertial fusion. As the experiment is now visualized, an initial total current of 8 amps would be amplified to about 18 amps at the end of the magnetic-focusing accelerator section; one of the four beams (with 4.5 amps) would then be further compressed longitudinally to achieve an additional threefold current increase.



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Beam Combination

Physics Designs. In a full-scale inertial fusion driver, the required power on target would demand intractably long bunches at the low-energy end of the accelerator, unless beams are combined, perhaps several times, somewhere along the length of the machine. During the past year, we examined the physics designs of several candidate beam combiners, each of which has its distinct set of advantages and disadvantages. Until recently, the alternatives being considered consisted of a short series of electrostatic quadrupoles and electric or magnetic bends. Each of four beams would be deflected through a bend, followed by a reverse bend, after which all four beams would emerge into a common channel, separated by only a few centimeters. Such systems can be relatively short and inexpensive, but they are not intrinsically achromatic. That is, because of the head-to-tail “velocity tilt” of the ion beam, different parts of the beam would follow different trajectories. A challenging, but possible, solution is to ramp the fields of the bending elements (and possibly the focusing elements as well) during the passage of the beam. The difficulty of this approach, however, has prompted us to examine inherently achromatic combiner designs.

A variety of preliminary achromatic designs has now been examined. The shortest such systems are the most complex in that they involve both electrostatic and magnetic bends with relatively high fields. Longer combiners can be made entirely with electrostatic bends and quadrupoles. One such all-electrostatic system contains six full focal periods and requires only two very weak bends, in addition to the quadrupoles. It may even be possible that the bending and focusing functions could be combined in the same elements. We shall continue to study these preliminary physics designs in the coming year.

Beam Dynamics. Emittance growth during beam combination occurs for two reasons. First, the betatron motion of the particles causes them to fill the “holes” present between beams when they first emerge into the common focusing channel. This phenomenon, called geometric emittance dilution, has been extensively studied in the context of “stacking” in storage rings. Second, space-charge forces cause beams to expand into the available spaces; the changes in electrostatic field energy become manifest as transverse kinetic energy. During the past two years, we have looked carefully at the extent to which these two effects cause emittance growth during four-to-one beam combination at an energy of 100–500 MeV. (In assessing our findings, it is important to note that a transverse emittance increase of about a hundredfold is permissible along the entire length of a fusion driver.) In both analytical and particle simulation studies, we assumed that four identical beams of uniform density emerge from a combiner into a common channel defined by a round conducting pipe.

For beam parameters such as those we expect in ILSE, two analytical results are of particular interest. First, not surprisingly, transverse emittance growth due to space charge dominates that caused by geometric dilution. Second, the total effect is approximately an eightfold increase in emittance, judged to be an acceptably small value. (During a four-to-one combination, a twofold increase is the minimum possible.) Particle simulation results are consistent with this finding. Figure 30 shows the emittance of a combined beam over 50 periods downstream of the combiner, assuming an asymmetric geometry for the initial beam configuration (see inset).

Bending and Focusing Elements. The emittance studies reported above assumed a beam-beam separation of only 3 mm in the common channel just downstream of the beam combiner. Innovative hardware designs will be needed if this is to prove a realistic assumption. On the other hand, beam merging will take place after only 40 focusing elements, suggesting a negligible 0.5-mm transverse misalignment in the beams, assuming typical tolerances. It thus seems plausible to get the beams very close together by using thin bending and focusing elements, then to scrape off any beam halo. Along these lines, we have investigated two new

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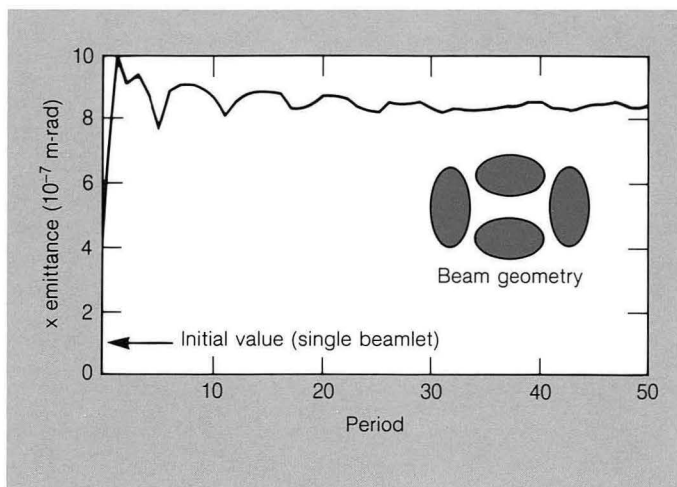


Figure 30. Plot of horizontal normalized rms emittance over 50 lattice periods downstream of a beam combiner, as computed by the particle simulation code SHIFTXY. The inset illustrates the assumed asymmetric geometry of the beams as they enter the common channel. In agreement with analytic studies, these results indicate that the fourfold increase in current resulting from the combining is accompanied by an eightfold increase in transverse emittance, an acceptably small change. Significant also is the fact that the emittance increase occurs within a few periods of the beam combiner.

types of final combining elements: multielectrode "squirrel cages" for electric dipoles and quadrupoles, and multiwire current distributions with iron boundaries for magnetic dipoles and quadrupoles.

The electric elements are more suitable for beam-merging scenarios in which it is necessary to change the fields significantly during the 1- μ sec beam pulse, but they also entail the risk of electrical breakdown. The magnetic elements are better matched to achromatic systems (see previous page), though they could be pulsed on a millisecond time scale, allowing the use of small, uncooled conductors carrying several hundred amperes of current. A magnetic quadrupole array is shown schematically in Fig. 31.

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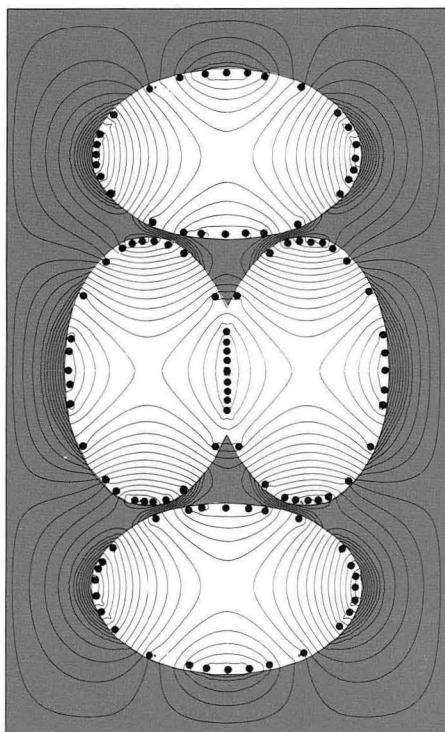


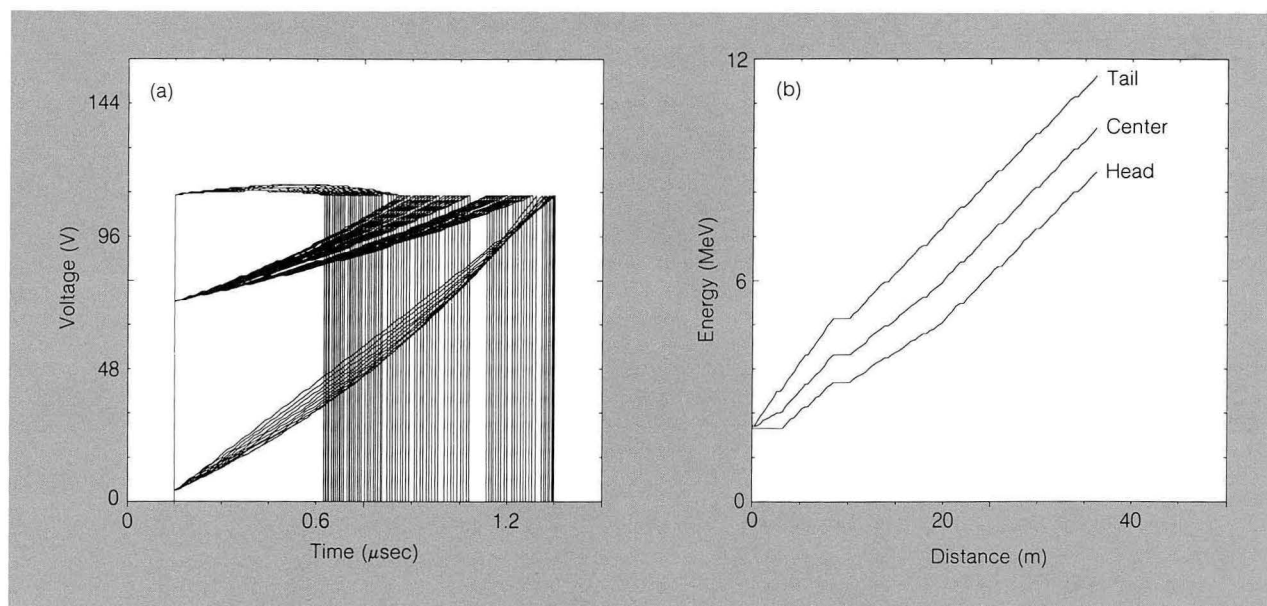
Figure 31. Computed field lines in a four-beam quadrupole array designed to be used as the last element in the merging section of ILSE. The conductors shown, each about 1 mm in diameter, represent the minimum number needed to give acceptable fields over the beams, which would nearly fill the apertures. A very thin iron septum between beams is sufficient to redirect the external field from one aperture to the next.

Other Design Considerations

Figure 32. (a) Voltage waveforms for a reference ILSE accelerating schedule and (b) a plot of the resulting head, tail, and midpoint energies, as functions of distance along the accelerator. Note that the bunch head is not accelerated until $z = 3$ meters and that no acceleration occurs at the combiner (between $z = 8$ and $z = 10$) or at the short diagnostics sections.

Quadrupoles Magnets. Several quadrupole magnet designs for ILSE have been considered over the past years, including both dc-powered and pulsed systems. Standard dc designs were considered first, but the cross-sectional area of the required conductor led to an undesirably large interbeam spacing, which translated in turn into a larger and more expensive induction accelerator. An iron-dominated pulsed design was also considered, but the present preferred option is a current-dominated design that uses a large number of small conductors, cooled by conduction to the outside. Among other things, this option is preferable for correctly treating the quadrupole end effects.

Waveforms and Longitudinal Beam Parameters. ILSE poses several difficult design problems with regard to a proposed "accelerating schedule." The first stems from the length of the bunch entering the accelerator from the 2-MV injector. This length, 6.8 meters, is about one-fifth the length of the entire accelerator, making it difficult to achieve significant bunch shortening without appealing to very high values of the velocity shear. (For comparison, MBE-4 is 18 times the length of the initial bunch.) This, in turn, leads to a second problem, namely, the constraints on the velocity shear that must be observed at the beam combiners and at the 180° bend at the exit of the accelerator. A reference design that solves all of these problems is illustrated in Fig. 32, which shows both the accelerating voltage waveforms and the energy of the ion bunch (head, middle, and tail) as a function of distance along the accelerator.



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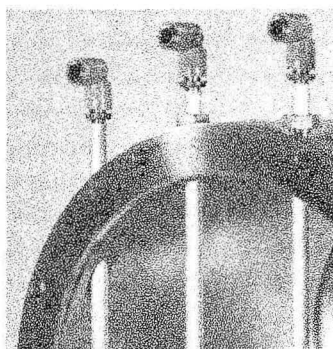
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6.

MAGNETIC FUSION ENERGY

... research on ion production, acceleration, transport, and diagnostics, complemented by an active program in theoretical plasma physics . . .

PERHAPS THE BEST-DEVELOPED SCENARIO for assuring an adequate energy supply for the coming century is to “burn” a deuterium-tritium fuel that has been confined by a powerful magnetic field. As with any fusion energy source, the appeal of this scheme has many facets: The supply of fuel is virtually inexhaustible, the reaction products contain no long-lived radioactive isotopes, and since there is no solid fuel core, melt-downs cannot occur. However, largely because of the enormously high temperatures involved, the technological challenges are profound. Nonetheless, the past decade has seen a steady increase in the temperatures, plasma densities, and confinement times achieved in experiments in the U.S. and abroad. Furthermore, the next generation of experiments is expected to reach the crucial goal of scientific breakeven, at which point a fusion experiment will actually produce more energy than is used to heat the fuel.

LBL’s involvement with the magnetic fusion program began in the 1950s, then, in the mid-1970s, took a natural change in course because of a need for ion sources and accelerator systems. To ignite the fusion reaction for each “shot,” an influx of energy is necessary. A favored way of providing this energy is to accelerate ions—usually deuterium—then to make them electrically neutral so that they can penetrate the plasma-confining magnetic field as energetic atoms.

Whether the neutral beams begin as positive or negative ions is, in principle, unimportant, but the practical differences are considerable. On the one hand, high current densities are easier to generate with positive ions. In addition, extracting negative ions into an accelerator is complicated by the presence of like-charged electrons, and the ease with which negative ions can be stripped of their excess electrons makes vacuum requirements exceedingly stringent. Early work thus concentrated on positive

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ions, and today the major experiments in the U.S. rely on positive-ion-based neutral-beam systems developed here. On the other hand, at higher energies—such as those that would be needed for larger fusion experiments and for many accelerator applications—only negative ions can be efficiently neutralized. Accordingly, our current efforts focus on negative-ion systems, not only for fusion energy applications, but also for industrial uses and for defense. Work encompasses both theoretical and experimental research on ion production, acceleration, transport, and diagnostics, and it is complemented by an active program in theoretical plasma physics.

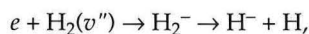
The first negative-ion source able to deliver more than an ampere of steady-state H^- was a so-called surface-conversion source, in which hydrogen ions are produced on the surface of a molybdenum electrode embedded in a hydrogen plasma. The ion yield is optimized by adding a layer of cesium to the electrode—a measure that can have the unpleasant side effect of contaminating the accelerator downstream. Largely because of this problem, which is especially serious when one contemplates steady-state operation, our current efforts focus on a second type of H^- -source, in which the ions are produced in the plasma itself, without converter electrodes or cesium. During the past year, we continued to study the incompletely understood mechanism of negative-ion production in a well-characterized volume source, and at the same time, continued an experimental program whose main goal is to increase the current available from volume-production sources.

Ion Source Development

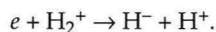
The so-called multicusp plasma generator, developed at LBL in 1983, was the first source to successfully produce H^- ions by the volume-production mechanism. This type of source has now amply demonstrated its ability to produce uniform and quiescent plasmas with high efficiency. In one incarnation of this concept, shown in Fig. 33, a 20-cm-diameter source chamber is surrounded externally by 10 columns of samarium-cobalt permanent-magnet material, whose cusplike field lines serve to confine the plasma, as well as the electrons emitted by two tungsten filaments. A water-cooled magnetic filter (the bars near the open end of the source) prevents energetic electrons from entering the extraction region, where both positive and negative ions are present, along with “cold” electrons.

Ion Production in Multicusp Sources

Earlier experiments had shown that the dominant ion-production process in this source is likely to be either dissociative attachment of electrons to vibrationally excited H_2 ,



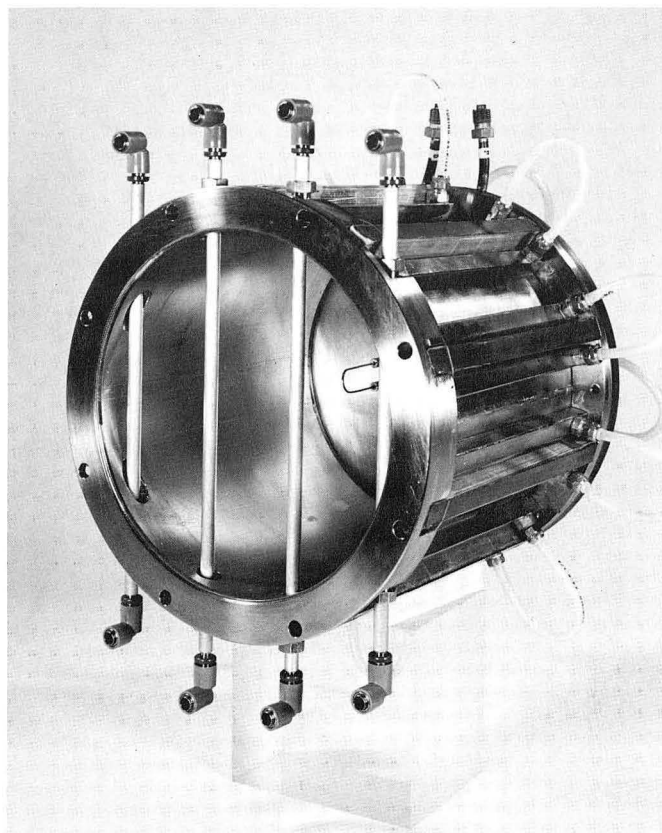
or recombinational attachment of electrons to H_2^+



During the past year, we demonstrated convincingly that the latter process is unimportant, at least at modest discharge powers. We did this by operating the source shown in Fig. 33 with a mixture of xenon and hydrogen, at a voltage that ionized only the xenon. Therefore, essentially no positive hydrogen ions (H^+ or H_2^+) were present. Since H^- continued to be produced as before, positive hydrogen ions can play no important role in its formation.

With a conceptually similar, but much smaller, multicusp ion source, we have

Figure 33. A view into the source chamber of a 20-cm-diameter volume-production H^- source. Barlike permanent magnets on the outside of the chamber wall establish a magnetic field inside the chamber that confines the plasma and the primary electrons, which are generated by tungsten filaments. A permanent-magnet filter, comprising the four rods at the open end of the source, prevents energetic primary electrons from crossing into the extraction chamber. During operation the source is typically mounted on a four-electrode acceleration system.



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produced significantly higher source plasma densities and have accordingly observed extracted ion densities as high as 250 mA/cm^2 , more than ten times that observed with the larger source. Another virtue of this smaller source is that it is capable of steady-state operation, owing to water cooling of the source wall and the surrounding magnets.

During the past year, we also successfully used the small multicusp source to generate Li^- , thus taking an important step toward a possible plasma diagnostics system based on high-energy neutral lithium beams. A schematic diagram of the small ion source, together with a mass separator and Faraday cup, appears as Fig. 34. The source of lithium ions is a sample of lithium metal placed inside the source chamber, though tests have also begun with a small lithium oven mounted on the source body. The production mechanism appears likely to be dissociative attachment of cold electrons to Li_2 , strictly analogous to the production reaction for H^- . Maximum extracted current densities have been 1.9 mA/cm^2 , but we have not yet devoted any effort to optimizing the magnetic filter geometry, extraction bias potential, or the lithium vapor pressure. We also expect improvements in these areas to reduce the extracted electron-to-ion ratio, which was measured as about 250:1.

Sheet-Plasma Source

During 1987 we designed, built, and began testing an ion source (Fig. 35) in which the H^- ions are produced from a plasma sheet typically less than 1 cm thick. The motivation was a report by J. Uramoto, of the Institute of Plasma Physics in Nagoya, that high current densities could be obtained over large areas with such a plasma geometry. Verification of these results, together with an understanding of them, would be of extreme importance to our program. To make possible a wide range of parametric studies, our source was designed to allow independent

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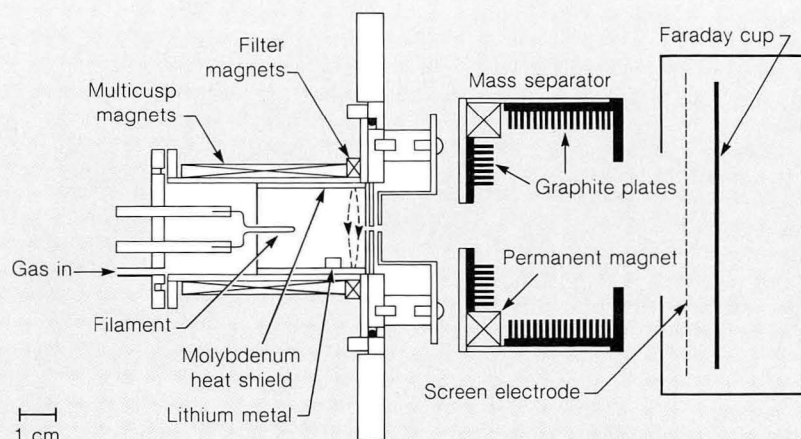


Figure 34. A schematic cross section of a small multicusp source, in a configuration that has been used to produce Li^+ ions. The mass separator efficiently removes electrons from the extracted beam, before the beam current is measured with the Faraday cup. A mass spectrometer can be substituted for the mass separator and Faraday cup to establish the isotopic ratio of the extracted beam.

variation of the arc current and voltage, the flow rate and pressure of the source gas, the length and thickness of the plasma sheet, and the voltage and location of the extractor. In our preliminary experiments, however, we observed a maximum extracted ion density of only 7 mA/cm^2 , leading us to conclude that the sheet geometry alone does not enhance the ion yield. Furthermore, our findings are difficult to reconcile with any straightforward theory. For example, the consequences of varying the arc power, gas pressure, or sheet thickness were unexpected and hard to explain. Work is under way to determine the processes involved in the sheet plasma ion source and to optimize the ion output.

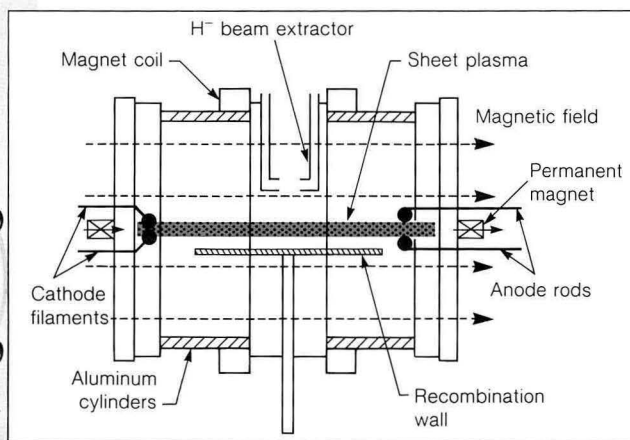
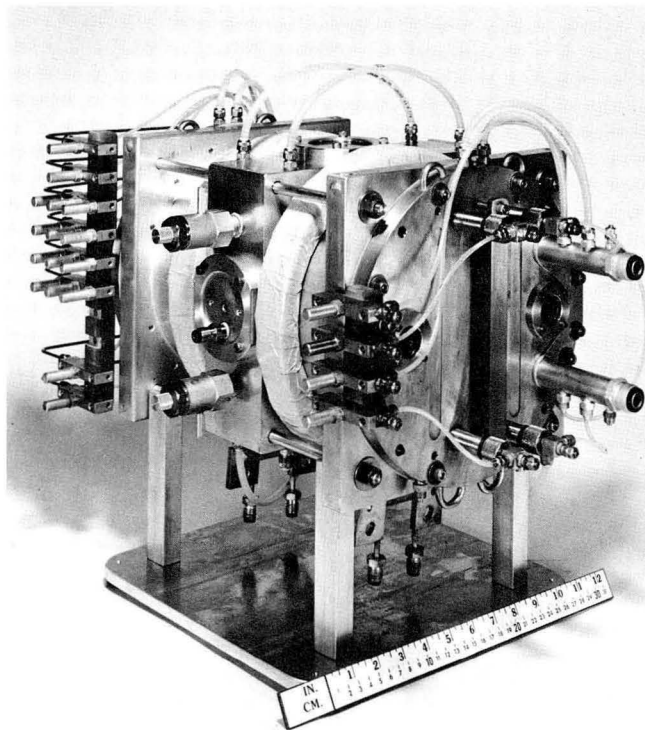


Figure 35. A photograph and a horizontal cross section of an ion source designed to produce ions from a sheet-like plasma distribution. Results elsewhere have suggested that such a configuration might yield high negative-ion densities over large areas, but results with this source (despite a design that allows variation of critical parameters) have not confirmed these earlier findings.

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Large-Aperture Source and Accelerator

As part of our program to develop high-current, high-brightness beams of H^- , we continued our testing of a volume-production source with a 6.7-cm^2 extraction area, coupled to a 100-keV accelerator. At the design current density of 30 mA/cm^2 , the accelerator will produce 200 mA of H^- . In an effort to optimize this source and accelerator, we have now studied the current dependence on filter magnet orientation, filter-to-extractor distance, extractor bias voltage, gas flow, and discharge power. The effect of different filter magnet orientations is shown in Fig. 36. We also made careful measurements of beam emittance, as well as the effect of the total acceleration voltage on emittance. In line with theoretical expectations (but contrary to some results from 1986), we observed little dependence of the normalized emittance on acceleration voltage. It is possible that a higher electron-to-ion ratio had some bearing on our earlier findings.

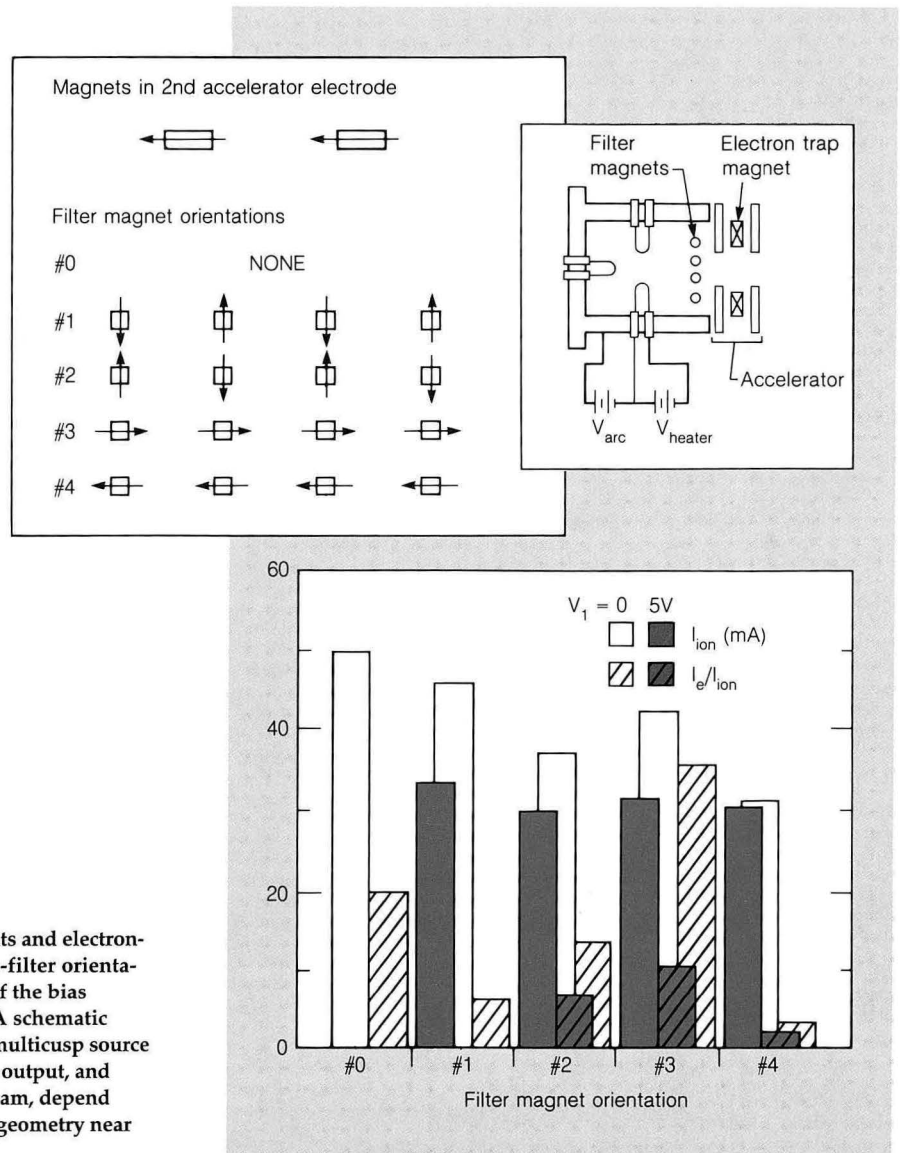


Figure 36. A plot of extracted H^- currents and electron-to-ion ratios for the different magnetic-filter orientations shown at the top, for two values of the bias voltage (V_1) on the plasma electrode. A schematic cross section of a magnetically filtered multicusp source is shown in the inset. The negative-ion output, and especially the electron content in the beam, depend strongly on the details of the magnetic geometry near the entrance to the accelerator.

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The central requirement for any neutral-beam-based plasma-heating or current-drive system of the future is a relatively high energy. In the Toroidal Ignition and Burn Experimental Reactor (TIBER), for example, at least 500 keV will be needed. In fact, there may be advantages in going to even higher energies as a way of reducing the current required and hence the size and cost of the injector. Indeed, present plans for the International Thermonuclear Experimental Reactor (ITER) call for a 1.5-MeV neutral-beam energy. Furthermore, it will probably be desirable to vary the energy at constant current. Initially, one wants a low beam energy to prevent "shine-through," after which the energy would be ramped to a higher steady-state value as the plasma density increases. Likewise, for some plasma diagnostics schemes—usually aimed at alpha particles produced by deuterium-tritium fusion—the beam energy must be swept over a wide range, corresponding to the velocity range of the alphas. For both of these applications, it is important that ion current not be sacrificed at lower energies. To answer these needs, we have developed conceptual designs for rf acceleration of negative ions, for a variable-energy accelerator based on an electrostatic ring system, and for variable-energy, constant-current accelerators based on electrostatic quadrupoles.

A conceptually simple approach to accelerating ions is an axially symmetric channel of washerlike electrostatic rings, with voltages dictated by the desired final energy. Such a system implicitly allows the final beam energy to be varied. Accordingly, we have studied an electrostatic ring system that would allow acceleration of an H^- beam of less than an ampere to an energy between 100 and 500 keV. Our studies concentrated on a single-channel design, but the system is such that it could be easily scaled to multiple channels for plasma-heating applications. Indeed, conceptual designs have already been devised for multiple-hole neutral-beam systems for TIBER.

Our computer model for acceleration to 500 keV included a preaccelerator in which electrons would be swept away by a magnetic field and from which beam would exit at 100 keV, followed by eight 10-cm-long cells, each providing a 50-keV energy boost (see Fig. 37). When configured as a constant-energy transport system, the first and third rings of each cell are loaded with 100 kV, while the voltage on the second is chosen such that the exit phase space matches the entering phase space. This gives a periodic solution for the particle motion, the result of which is no appreciable emittance growth beyond the first cell. The system of Fig. 37 likewise produces little emittance growth, and the final energy may be varied simply by varying the voltages at the rings.

An even more promising approach to variable-energy, constant-current acceleration is to use electrostatic quadrupoles (ESQs) for focusing. A schematic for an ESQ-focused dc accelerator, designed to deliver 200 mA of H^- at any energy between 100 and 800 keV is shown in Fig. 38. This system requires smaller voltage differences between adjacent electrodes than does the design above, and it has the added advantage that transverse fields sweep out all low-energy charged particles, such as those that might be created by ionizing collisions with residual gas or by secondary emission from surfaces.

Accelerators for Negative Ions

Variable-Energy Accelerators

Figure 37. A computer-generated schematic of a single-channel, variable-energy accelerator. Voltages on the washerlike electrodes are chosen to match input and output phase space at each cell and to achieve a given final beam energy. The voltages indicated here, producing a 500-MeV beam of H^- , are near the maximum for this configuration.

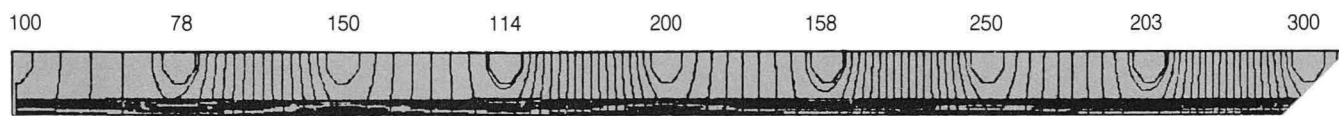
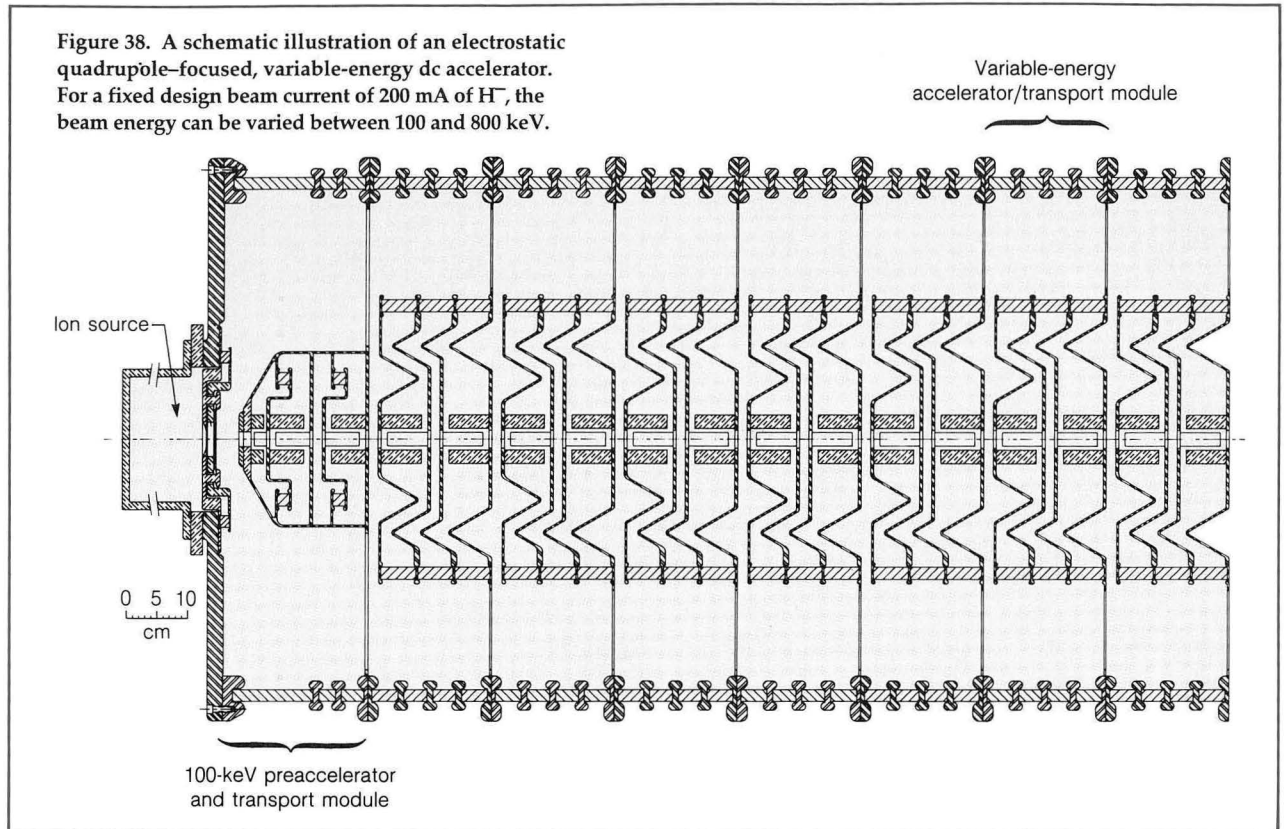


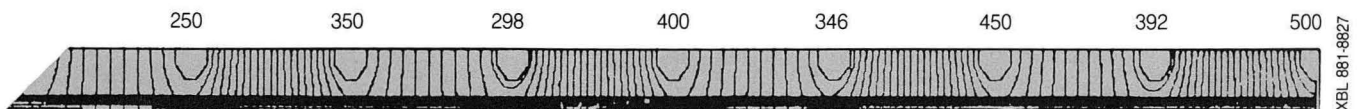
Figure 38. A schematic illustration of an electrostatic quadrupole-focused, variable-energy dc accelerator. For a fixed design beam current of 200 mA of H^- , the beam energy can be varied between 100 and 800 keV.



Radio-Frequency Acceleration

One candidate for accelerating high-current negative-ion beams to energies of 1 MeV or higher is a multiple-aperture Wideröe linac, driven by switched dc power. A major advantage of this approach is that it might allow next-generation neutral-beam injectors to use high-voltage power supplies already in place for today's plasma-heating systems.

In our one-dimensional model of a 1-MeV accelerator, we assumed that radial space-charge effects—the effects due to the mutual repulsion of the like-charged ions—would be taken care of by electrostatic or magnetic quadrupole lenses, and we did not include the effects of longitudinal space charge. We also ignored the variation in voltage seen by a single ion in each accelerating gap (the “transit-time effect”). If we assume an initial ion energy of 400 keV and a 26% energy gain per gap, the final energy can be reached with only five gaps. With these assumptions, we found that a practical sinusoidally driven rf linac could accelerate beam to a mean energy that is 89% of that for an ideal square-wave-driven accelerator. The energy spread was found to be $\pm 20\%$. Of particular importance, we also found that the accelerating gaps could be driven with a simple LC circuit excited by switched dc power. Further study of this concept is under way, including investigation of longitudinal space-charge effects, transit-time effects, beam emittance, and buncher optimization.



Along with our major design activities and testing programs on ion sources and accelerator systems, the magnetic fusion group has also made notable progress in several more specialized areas—all, however, ultimately born of our interest in producing high-energy neutral-beam systems. One area of interest has been the development of lanthanum hexaboride (LaB_6) cathodes as copious sources of electrons. We were originally stimulated by the possibility of using such cathodes in place of tungsten wire in ion sources, but they might also plausibly be used as electron emitters in high-power free-electron lasers. We have also continued our study of diagnostics systems for burning-plasma experiments. And finally, as a complement to our developmental efforts, we also maintained our active program of study in theoretical plasma physics.

Whereas the pulsed neutral-beam ion sources used today for plasma heating typically operate with more than 20 tungsten filaments, future fusion reactors will require more durable cathodes, suitable for long-pulse or dc operation. One possible answer to this need is a directly heated LaB_6 cathode, with a coaxial configuration that minimizes the magnetic field produced by the heater current and thereby minimizes the perturbations on the trajectories of the emitted electrons. During the past year, we further developed this concept, improving both the mounting structure for the unit and the design of the cathode itself.

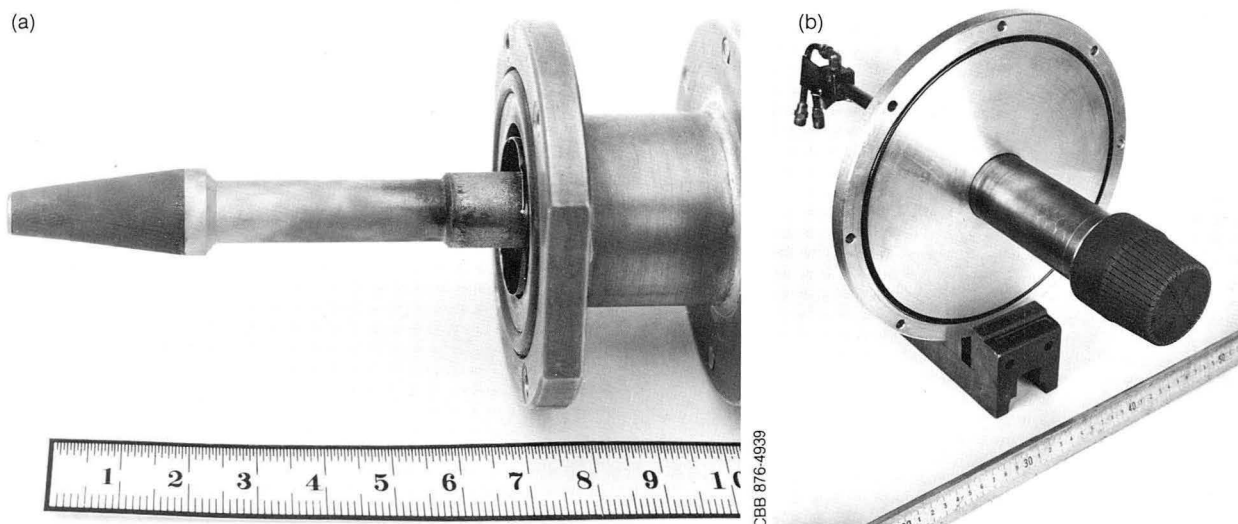
One version of this cathode comprises a thin, hollow cylinder of LaB_6 (actually an assembly of five shorter cylinders), with two LaB_6 end caps. An electrically isolated tantalum conductor runs through the center of the structure and carries the heater current. The center conductor is connected to the cathode material at the tip of the structure by means of a molybdenum nut and rhenium foil. The multisegment cathode was designed to prevent damage due to thermal stresses. This cathode has now been tested successfully in a plasma generator. In one test configuration, only one of two such cathodes was heated to establish a discharge, after which the second was heated solely by ion bombardment from the surrounding plasma. Eventually, both cathodes were able to sustain stable discharges in the absence of any heater current.

Ohmic heating of the cylindrical LaB_6 geometry effectively limits the attainable discharge current. To increase this achievable current, we designed the tapered cathode shown in Fig. 39. With this geometry, we have obtained a dc discharge current of 200 amps, a value limited by the power supply.

Other Activities

LaB_6 Cathodes

Figure 39. Two new lanthanum hexaboride cathode designs: (a) a tapered configuration that produces a uniform temperature distribution during steady-state operation with high discharge currents and (b) a large-area cathode designed to explore the possibility of using LaB_6 cathodes as intense electron emitters for free-electron laser applications. In the large-area cathode, the radial cuts were necessary to reduce thermal stresses during operation.



Large-area, directly heated LaB_6 cathodes have also been proposed for use as electron emitters for high-power free-electron lasers, where intense electron beams are required. The virtues of such cathodes are the same that make them appealing for fusion applications: low evaporation rates, inertness, high emission densities (up to 100 A/cm^2), and uniformity of emission over large areas. A significant disadvantage is the tendency of LaB_6 to crack due to thermal stresses. In trying to achieve high currents, therefore, we have fabricated coaxial LaB_6 cathodes in which radial cuts were made in the 5-cm-diameter disklike faces to relieve stress (Fig. 39). Segmented cathodes have now been cycled from room temperature to test temperatures up to 15 times without signs of cracking. The cathodes have operated at temperatures as high as 2150 K, corresponding to an emission current density greater than 75 A/cm^2 .

Diagnostics

Hydrogen atoms are thought to be important in H^- sources, owing to the part they play in H^- destruction reactions and charge-exchange mechanisms. By knowing the atomic hydrogen concentration, along with the H^- output and the plasma parameters of a given source, we can hope to better understand the chemistry of the source. During the past year, we took the first steps toward this goal. We demonstrated an ability to measure the ground-state hydrogen atom density, as well as the temperature, as functions of arc current, arc voltage, and total gas density.

In measurements of the atomic density so far, we have measured the attenuation of Lyman β radiation, produced by resonant four-wave mixing in mercury vapor. However, Lyman γ and δ radiation (as well as radiation from higher-order transitions) can be generated in the same way, as might be necessary for sources with higher atomic line densities. With a multicusp ion source, the signal level observed was far above the noise due to background plasma radiation; hence, we are assured that this method can be used with sources having higher background. We also verified the linearity of our detectors and the associated electronics, and we confirmed that the bandwidth of the diagnostic radiation is sufficiently small, relative to the Doppler width of the transition.

Theoretical Plasma Physics

Our program in theoretical plasma physics is divided roughly equally between basic theory and applied theory, with strong coupling between the two. That is, we select applied problems that are particularly amenable to the methods we have developed in our basic program. Two examples of this synergism illustrate the achievements of the program during the past year.

For several years, we have been developing a Lagrangian-Hamiltonian approach to nonlinear plasma dynamics. The motivation was to systematize the self-consistency aspects of the interaction among waves, resonant particles, the background plasma, and the background field. When the problem of rf stabilization was brought to our attention as a result of N. Hershkowitz's experiments on Phaedrus at the University of Wisconsin, we were in an excellent position to tackle it. We developed a sound theory, based on these Lagrangian-Hamiltonian methods, that demonstrated that the rf power needed for stabilization was tenfold higher than what had been proposed on the basis of non-self-consistent ponderomotive-force arguments.

As a result of a new approach to linear mode conversion and earlier work on phase-space eikonal methods, we are now able to deal with mode conversion in a fully three- or even four-dimensional setting, whereas previous work had been strictly one-dimensional. During the past year, an application arose when an expert review pinpointed the two-dimensional aspects of second-harmonic mode conversion as the first of the problems related to ion cyclotron resonance heating still to be solved. Owing to the foundation of basic theory that had already been laid, we are now on the verge of a complete solution.

Ion and Plasma Sources

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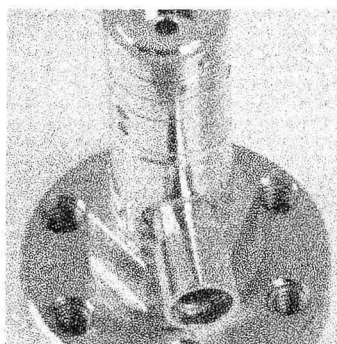
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7.

EXPLORATORY STUDIES

... laying the groundwork for vital future programs: beyond the ALS are low-emittance damping rings for TeV-scale colliders; beyond the SSC, perhaps the TBA ...

DURING 1987 EXPLORATORY STUDIES continued to be an essential element in any vision of AFRD's future. Fundamental accelerator physics research, focusing not only on the next generation of machines, but also on concepts still on the distant horizon, lays the groundwork for a wide range of vital future programs in the division. Work on the Advanced Light Source (see also pages 1-8) was of both immediate relevance and long-range import. Among the questions addressed were critical issues of beam stability under realistic operating conditions—in the presence of undulators, for example. At the same time, our ALS work served as a springboard for further-reaching studies into high-brightness, low-emittance storage rings such as the damping rings envisioned for future TeV-scale linear colliders. All such rings fall into very much the same category as third-generation synchrotron radiation sources like the ALS. Our involvement with the ALS also prompted deeper investigations of the beam dynamics and optics of undulators and wigglers. Theoretical studies of free-electron lasers (FELs) were carried out in this context.

Much of our work was also of particular relevance to the high-energy physics community. Looking to the near term, members of our Exploratory Studies Group made crucial contributions to the design efforts for the proposed Superconducting Super Collider (see also pages 49-54). At the same time, looking much further to the future, a second group continued its highly successful studies of a futuristic linear accelerator scheme known as the Two-Beam Accelerator. Much effort in this area turned during the past year from FELs to relativistic klystrons as the source of power for highly efficient and relatively compact future colliders.

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Accelerator Physics for the ALS

In concert with preliminary design efforts, considerable attention was focused over the past year on accelerator physics issues pertinent to the ALS. Broadly speaking, most of these issues revolved around questions of beam dynamics, especially in the storage ring. We examined, for example, the effects on beam stability of unavoidable random and systematic errors in magnetic field, and we evaluated schemes to correct the distortion of the ideal closed orbit caused by field errors. Of even greater interest and importance is the question of how the fields of the magnetic insertion devices will affect the dynamic stability of the electron beam. The preliminary answer is that they have a decided effect, which may require that the undulator gaps be opened during the crucial period of beam injection.

Dynamic Aperture

It is well-known that introducing nonlinear magnetic elements into a storage ring imposes a limit on the excursions a stable particle may execute. Should an electron find itself outside the so-called dynamic aperture defined by this limit (as a result, say, of striking a gas molecule), it will eventually be lost by colliding with the vacuum chamber wall. A large dynamic aperture is therefore necessary during injection, when the newly injected electrons execute betatron oscillations with an amplitude of about 10 mm. It is also required for long beam lifetimes, since elastic and inelastic scattering processes or the emission of a high-energy photon can result in large-amplitude betatron motion. These oscillations must remain stable long enough for the restoring properties of "radiation damping" to bring the errant electrons back into the core of the beam.

In electron storage rings such as the ALS, designed to produce high-brightness synchrotron radiation, the dominant nonlinear effects come from the strong sextupole fields that are required for chromatic correction. Figure 40 shows the dynamic aperture of the "bare" ALS lattice, without errors and without undulators, as well as the dynamic aperture in the presence of systematic and random errors in the magnetic multipole fields. The width of the crosshatched region reflects different distributions of random multipole components in the simulations.

In all storage rings, the closed orbit about which the electrons oscillate varies from the ideal trajectory, largely because of quadrupole magnet misalignments and dipole field errors. This variation, the closed-orbit distortion, causes the beam to pass off-center through the strong lattice sextupoles, producing a random quadrupole component. This in turn can have a significant effect on the dynamic aperture and the stability of the beam. To minimize the closed-orbit displacements (CODs), the ALS is therefore provided with 96 beam-position monitors and 120 corrector magnets. The effectiveness of these correctors can be

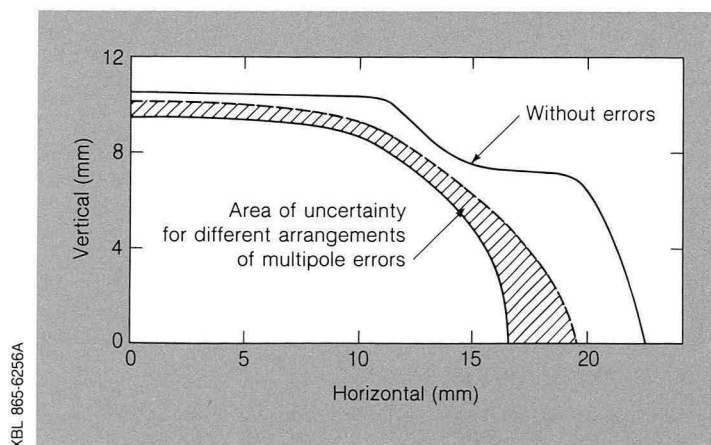
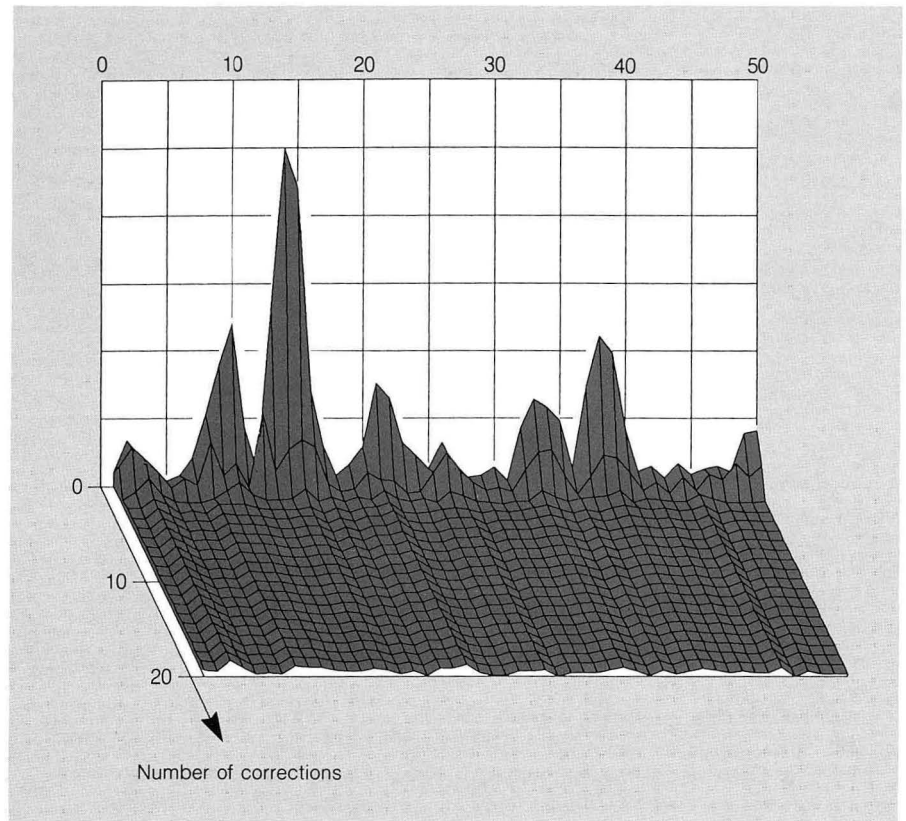


Figure 40. The calculated dynamic aperture for the ALS, with and without systematic and random errors in the magnetic multipole fields. The dynamic aperture defines the cross-sectional area within which the beam is stable.

Figure 41. A three-dimensional plot of the harmonic distribution of horizontal closed-orbit beam displacements at 96 locations around the ALS lattice. The magnitude of the Fourier amplitude is plotted as a function of orbital harmonic number during a sequence of 20 iterative orbit corrections. Closed-orbit distortion is caused primarily by quadrupole magnet misalignments and dipole field variations; the horizontal component is corrected by 72 horizontal corrector magnets.



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seen in Fig. 41, where the harmonic distribution of horizontal CODs, for a given set of random errors, are shown over the course of 20 corrective iterations. During this time, the displacements are reduced to a level that does not seriously diminish the dynamic aperture.

Effect of Insertion Devices

The ALS will be the first storage ring of its kind to have a large fraction of its circumference (about one-third) occupied by insertion devices. The effect of these magnetic devices is one of the most serious outstanding issues confronting the next generation of synchrotron radiation sources, one that must be addressed by all laboratories hoping to operate such facilities. During the past year, we approached this question by considering the effect of one and four 1.15-T undulators on the dynamic aperture of the ALS. The major effect of each of these "symmetry-breaking" elements is that of a strong lens. This extra focusing can be matched into the lattice using the quadrupole pairs adjacent to the device, and the resulting tune shift is then accommodated by adjusting the quadrupoles in the remaining insertion regions. The result is a "matched" insertion. Nonetheless, the effect of four matched insertion devices on the dynamic aperture is significant. Fortunately, undulators can be "turned off" (or at least their effects reduced) by increasing the gap or switching off the current. Thus, a possible scenario would be to turn the insertion devices off during the critical injection period, when the aperture requirements are most stringent. (The dynamic aperture reduction is not sufficient to affect the properties of the stored beam.) We are also exploring the concept of adjusting the linear lattice, by means of suitable quadrupoles, such that favorable phase relationships between sextupoles are achieved.

Lattice Studies and Other Activities

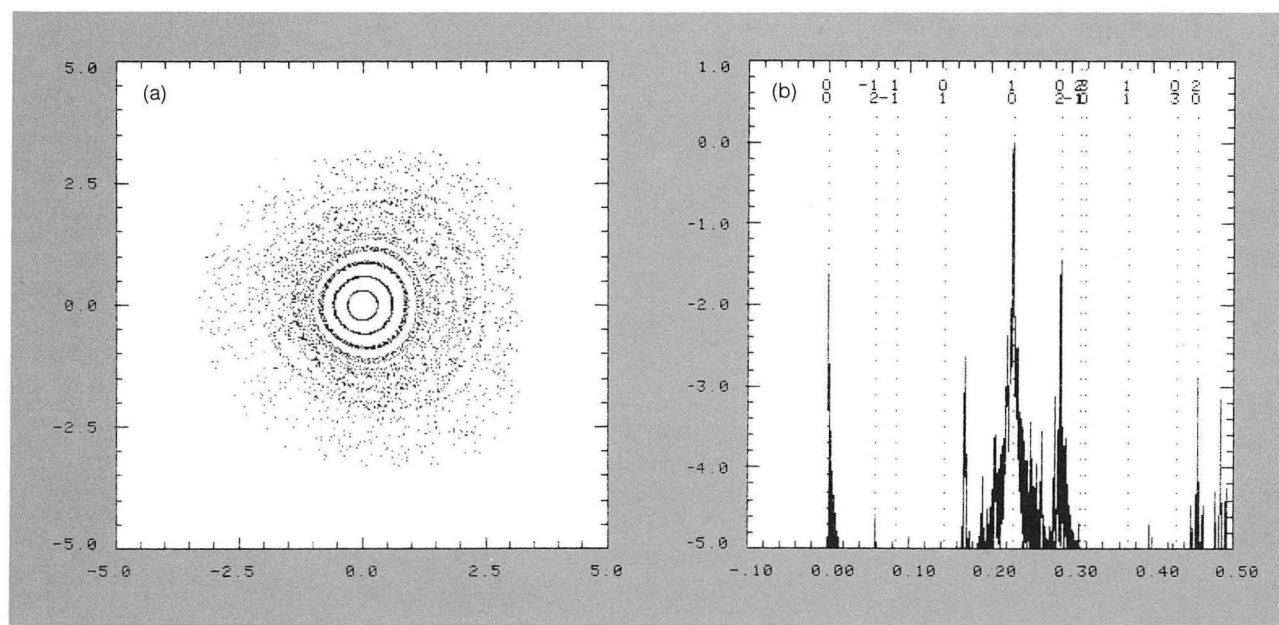
The ALS is a model of a highly nonlinear lattice of modest size. It includes very few, but very strong, nonlinear elements such as sextupoles. Excellent chromatic and dynamic behavior is achieved by clever but sensitive cancellation of large lattice parameters. In particular, the betatron phase shift between sextupoles is a crucial quantity, requiring careful control. The perturbing effect of undulators is largely due to their effect on these phase shifts. It is therefore of the highest importance to understand in detail the nonlinear effects and the detailed resonance structure of the bare lattice. We have thus launched a dedicated research program on this topic. A preliminary look at single-particle trajectories in the horizontal betatron phase space lying within 30% of the stability boundary (see Fig. 42) shows an intricate pattern of movement, apparently driven by numerous isolated and overlapping resonances. A Fourier analysis of such a trajectory shows a nested dense population of narrow and broad resonances of such high order that we need powerful harmonic analysis algorithms to extract the detailed Fourier spectra.

Another important area of activity has been the study of the beam-storage ring coupling impedance beyond the cutoff of the beam tube, that is, above the frequency at which electromagnetic disturbances start to propagate along the beam tube as waveguide modes. This is especially relevant for machines such as the ALS that are designed to store very short bunches (rms lengths of 10–20 psec). A few of the issues under study have been the basic nature of high-frequency behavior and the appropriate power law roll-off of the impedance as a function of frequency, the effects of single localized structures as compared to periodic structures, the impedance of a curved vacuum chamber as a whole, and impedance measurement techniques at these high frequencies.

To pursue some of these topics, we hosted a workshop entitled "Impedance beyond Cutoff," August 18–21, 1987, which was attended by accelerator physicists from around the world. A consistent and cogent picture of the frequency spectrum of beam-storage ring coupling impedance seems to have emerged. The proceedings of the workshop and its main conclusions will appear as a series of papers in a special issue of *Particle Accelerators*.

We also carried out beam dynamics studies on the injection system of the ALS, using the code PARMELA. The design goal is to obtain high-intensity beams of consistently high quality (low emittance and small energy spread) at the end of

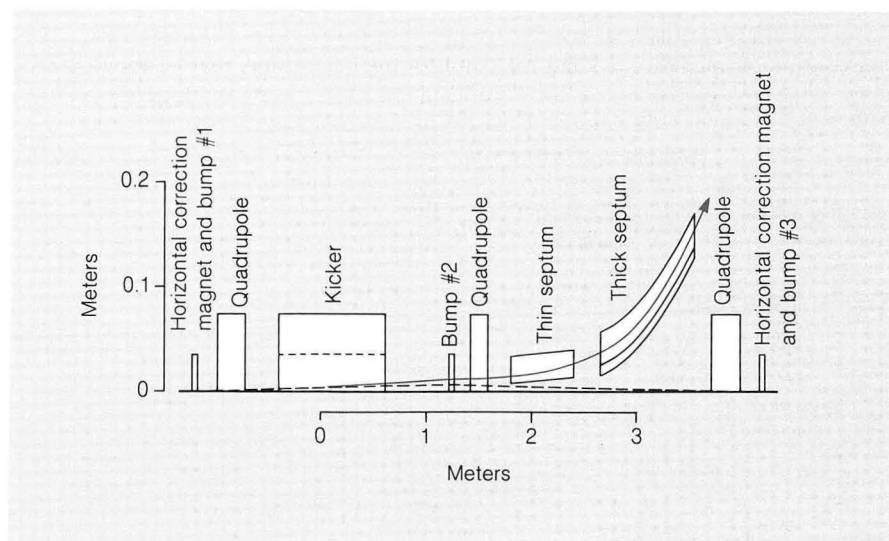
Figure 42. (a) A horizontal phase space plot for several individual particles, each with a different oscillation amplitude, observed at the same location over many orbits, and (b) a Fourier spectrum showing the intricate harmonic content of the motion of a particle launched at the outer region of (a). The horizontal and vertical axes of (a) are suitably normalized; in (b) the horizontal axis shows frequencies in units of the fractional horizontal tune, and the vertical axis shows the relative strength of the Fourier harmonic amplitude.



the 50-MeV linac. Our results indicate that the design specifications can be confidently met. Additional work on the injection system of the ALS has gone into the optimization of the booster extraction system. Figure 43 is an anamorphic diagram of the revised system, which increases the clearance of the extracted beam and which should consequently enhance the reliability of the entire injector.

The Exploratory Studies Group is also responsible for the ALS parameter list, which serves as the primary reference document for workers on the project. The list gives the performance parameters and characteristics of the various parts of the machine; special sections are devoted to magnet properties, power supplies, and experimental beamline apparatus. An important use of the parameter list is to establish in a readily accessible document the nomenclature for machine components that will be used in drawings, documents, and the computer control system. The parameter list currently contains some 1900 entries.

Figure 43. An anamorphic diagram of the booster extraction system. The beam is displaced (dashed line) in the extraction region by means of three "bump" magnets, then extracted by powering a fast kicker magnet, which deflects the beam (color) through two magnetic septa.



XBL 881-8630

Studies on an Infrared FEL

During 1987 we undertook a feasibility study of an infrared FEL that would use the ALS injector linac. Such a source would complement the ALS itself, offering coherent radiation of high peak power in a spectral region of great interest for physics, chemistry, and biology. In particular, it would allow studies of the dynamics of chemical (molecular), atomic, and electronic transitions in gas, liquid, and solid phases. Such studies are now difficult to perform, since no comparable atomic or molecular lasers exist today. In addition, it is worth noting that the physics and technology of infrared FELs are rather well-known by now, so that their performance can be predicted with reasonable confidence.

As a result of our study, we concluded that such an FEL is entirely feasible; it would be tunable over a spectral region from 3 to 30 μm and would have peak and average powers of 1–12 MW and about 1 kW, respectively. The radiation would have full transverse coherence and partial longitudinal coherence over most of its range. At the shortest wavelengths, transverse coherence would be compromised somewhat because of the finite beam emittance. This could be restored at the cost of some output coherent power. At the longest wavelengths, we would expect some loss of output coherent power, owing to radiation phase slippage over the bunch length. The initial gain of a single-pass laser appears to be more than sufficient (significantly greater than 30%) for the cavity to oscillate, even after subtracting the energy required to establish the fundamental mode in the cavity. The gain remains at this value even at high levels of saturation.

In terms of practical considerations, the required fast gun-pulsing circuit is already available, and, as shown in Fig. 44, sufficient space is available inside the main storage ring to house such a facility, including the laser oscillator and experimental halls. Some extra shielding would be needed. The klystron envisioned to power the ALS linac is capable of delivering the 6- μm rf pulses necessary for FEL operation, provided suitable pulse-forming networks are added to the driver and a special pulsing circuit is attached to the gun. Assurances would be necessary, however, that the fabrication and operation of such an FEL would not have any deleterious effect on the operation of the ALS as a user facility.

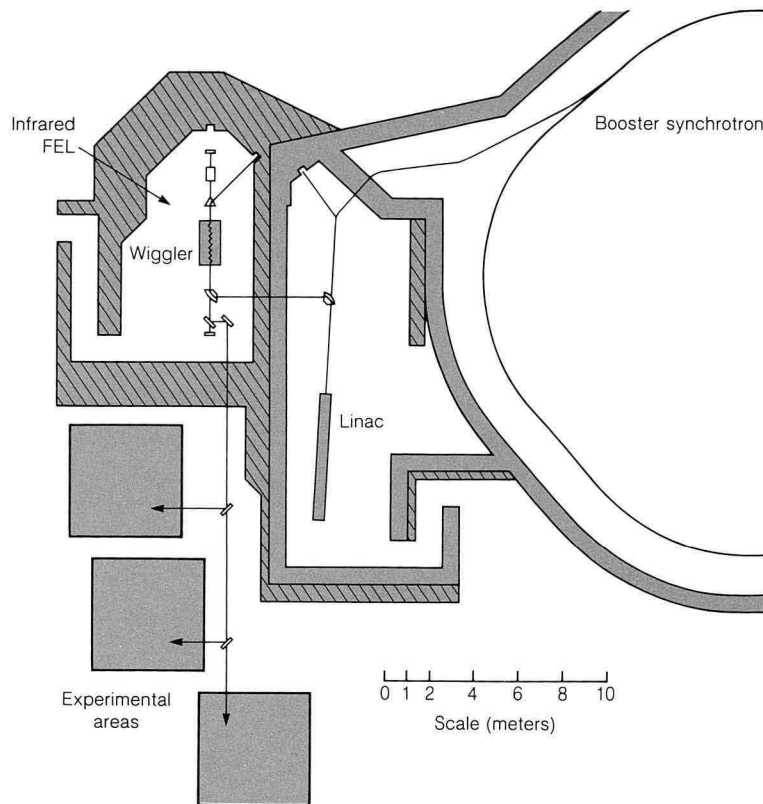


Figure 44. Layout of a possible infrared FEL, which would use the ALS injector linac as a source of electrons. The crosshatched areas indicate additional required shielding. Such an FEL would be possible only if its fabrication and operation did not disrupt operation of the ALS as a user facility.

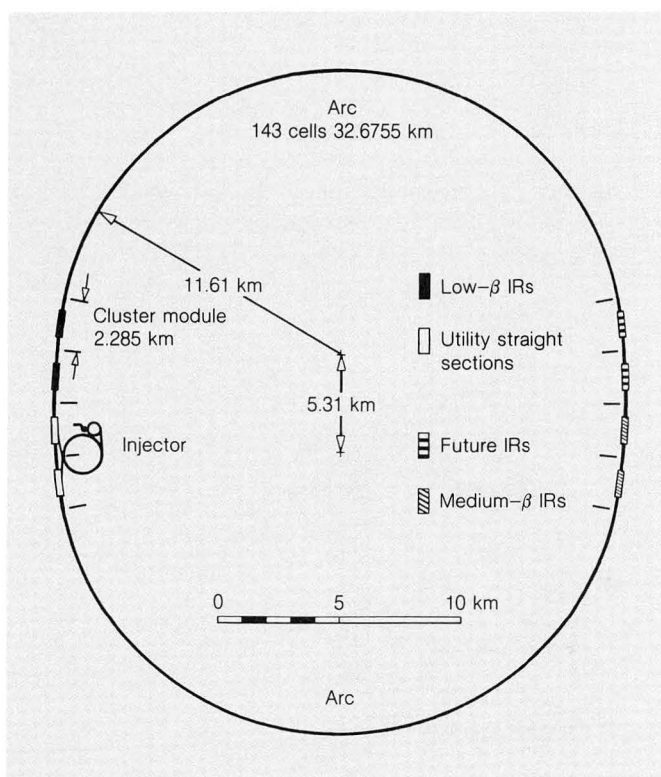
SSC Activities

Accelerator physicists at LBL have been part of the nationwide effort to define the next facility for high-energy physics research since the early 1980s. They played significant roles in the seminal Snowmass meeting of 1982 and contributed to the reference designs report of 1984. At the end of that same year, several AFRD physicists took their places in the SSC Central Design Group, whose headquarters are now at LBL. During the past year, we maintained our active role. We contributed to important lattice improvements, made significant advances in a number of theoretical areas, and participated in a crucial experiment at Fermilab that affirmed an underlying assumption of the SSC conceptual design as regards beam dynamics.

Lattice Improvements

The overall structure of the SSC main ring was set in the conceptual design report (CDR) of March 1986: It is made up of two arcs and two clusters of straight sections, as shown in Fig. 45. The eight straight sections include four experimental

Figure 45. A schematic of the Superconducting Super Collider, showing the clustered interaction regions now planned.



interaction regions (IRs); two utility straights for injection, beam abort, and rf systems; and two straights not yet defined, but likely to be rebuilt in the future as IRs. Among several lattice changes made since publication of the CDR, the most important has been to increase the cell phase advance from 60° to 90° . This increases the focusing strength, lessening the effects of magnetic imperfections. As a result, it became feasible to lengthen the cells from 192 to 228.5 meters, as well as to reduce both the tunnel length and the numbers of quadrupoles and correction elements. Several improvements were also made within the IR straight sections.

In addition to making these refinements to the basic lattice design, we collaborated in studies of possible future modifications and additions. An important example concerns provision for the later construction of by-passes for such purposes as allowing repair of detectors without shutting down the machine, permitting construction of new IRs without operational interruptions, and allowing greater concentration of facilities on one side of the ring. To make it possible to add a by-pass to either cluster, it is necessary to include two transition regions in each, to which future by-passes could be attached. We now have designs for by-passes going around one, two, three, or four IRs, with an equal number of IRs in both branches.

SSC Simulation at the Tevatron

During May 1987, LBL accelerator physicists participated in a crucial experiment at Fermilab's Tevatron, as part of a team that included members from both the SSC Central Design Group and Fermilab. The experiment looked at beam behavior under the influence of a strong (sextupole) nonlinearity. The 16 "distortion sextupoles" in the Tevatron were powered at equal currents, either 15 or 30 amps. A transverse kicker was then used to excite betatron oscillations of the whole beam. Turn-by-turn readings of beam position were then recorded at two locations. The strong sextupole nonlinearity led to substantial transverse tune dependence with amplitude—that is, the beam displayed a phenomenon known

as “smear.” This smear or “beam decoherence” was measured as a function of nonlinearity and machine tune.

The experimental results were then compared to multiparticle simulations, which involved the tracking of 1000 particles for 200 turns on Livermore’s Cray-XMP computer, using the code MARYLIE 3.0. The beam-position monitor “readings” from the simulation were then analyzed by strict analogy to the experimental data. A comparison of results for the 15-amp sextupole excitation is shown in Fig. 46. The excellent agreement validates the concept of smear and the related notion of “linear aperture,” relied upon heavily in the SSC CDR as a tool to estimate the well-behaved stability region of a nonlinear dynamical system like the SSC lattice.

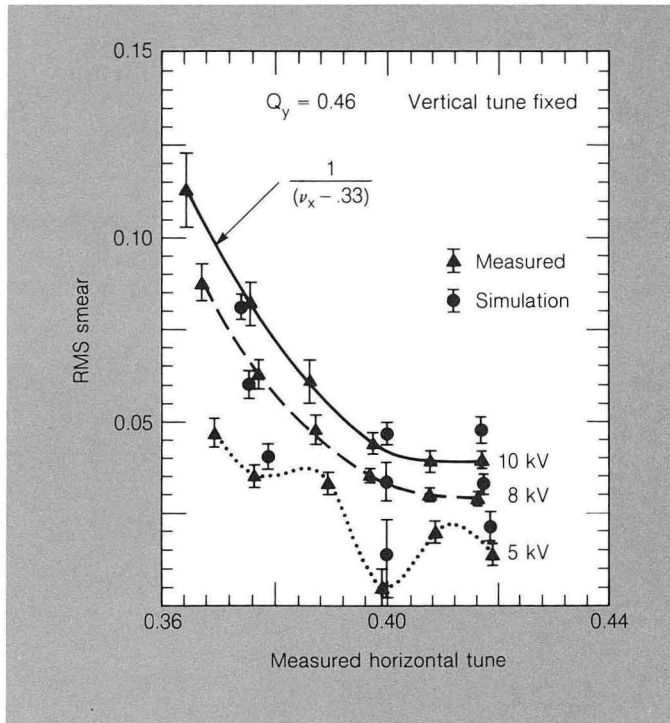


Figure 46. A plot of the “smear” observed during experiments at Fermilab’s Tevatron, as a function of measured horizontal machine tune, for three different kicker voltages. The “decoherence” of the beam when perturbed by strong sextupole nonlinearities was accurately predicted by theory, thus lending credibility to the concept of linear aperture, a mainstay of the SSC conceptual design.

Canonical Integration. In an important theoretical achievement during the past year, canonical integration methods were unified with perturbation theory. Using these tools, one can routinely evaluate one-turn “maps” of storage rings to machine precision and perform perturbation analyses on these maps. This unified approach is based on the concept of “phase advance” and by-passes the Hamiltonian. It approaches any calculation from the point of view of the symplectic integrators used in the tracking codes of the SSC. In addition, this work has produced several new tracking codes.

The power of this method has already manifested itself in other applications. In particular, K. Yokoya has used it at KEK to study spin-orbit coupling in storage rings, a particular coupling of $Sp(4)$ [orbital] and $SU(2)$ [spin] groups.

Connected with the topic of symplectic integration are the correction schemes for systematic errors and their generalization to random errors. We have sharpened our general analytic abilities for correction scheme studies by providing simple analytic tools for the SSC, as efficient substitutes for tracking. The effect of various correction schemes can now be computed exactly to first order in the multipole errors. The algebraic manipulations needed to increase the present power of these techniques will be the subject of a long-term research study.

Other Nonlinear Beam Dynamics Studies

Chromaticity Calculations. During the last year, LBL physicists also studied the effects of the first-order fringe fields of rectilinear magnets. An improved understanding of the nature of bends with small radii of curvature has led to a final reconciliation of the results from SYNCH and MARYLIE for the chromaticity of small rings. Refinements were made in the calculations of linear and higher-order chromaticity in the SYNCH program. It will now be possible to determine whether the IR quadrupoles in the SSC have significant fringe-field effects.

Space-Charge Effects. Tracking simulations were done for the SSC's low-energy booster, using the program TEAPOT, suitably modified to include the space-charge forces and to take into account coupling in all three dimensions of phase space. The simulations were done at the injection energy, where the space-charge effect is potentially largest. Nonetheless, tune shifts with amplitude were smaller than the values assumed in the CDR, a finding that potentially allows the current in the booster to be increased or the injection energy lowered. We also studied the effect of the nonlinearity by comparing the phase space with and without synchrotron oscillations, and with and without space-charge forces; we concluded that the effect is small. Of broader significance, these investigations led to the development of a very practical approximation for the electric field of an arbitrary charge distribution, such that the approximate expression is accurate both at short and long distances to any desired order. The form of the expression is computationally tractable, is manifestly singularity-free in the round-beam limit, and is well-suited for simulations involving space-charge effects.

The "Flip-Flop" Phenomenon. In electron-positron storage rings, two identical beams can fall into an equilibrium state in which one beam has a different size from the other and in which the transition to the mirror configuration exhibits "hysteresis." We have now considered a simple one-dimensional model based on one proposed by K. Hirata at KEK. This model includes the essential ingredients of (linear) beam-beam kicks and radiation damping, and it assumes Gaussian bunches. We calculated the equilibrium states analytically and found solutions with equal and unequal beam sizes. However, a stability analysis showed that only the equal-size solution is stable.

Two-Beam Accelerator

Among the many ideas proposed in the past few years for the colliders of the next century, the concept of the Two-Beam Accelerator (TBA) remains perhaps the most promising. As any next-generation linear accelerator must, the TBA embodies a means for developing exceedingly high accelerating gradients, so as to keep operating costs and physical length within reasonable bounds. In its original form, the TBA used an FEL as a source of high-power microwaves, which would be coupled to an adjacent traveling-wave structure, where they would produce a longitudinal accelerating gradient at least tenfold greater than those now practical. During the past year, an alternative version in which a relativistic klystron serves as the power source has gained significant attention. Collaborative experimental work on both versions of the TBA were in progress during 1987 at the Lawrence Livermore National Laboratory.

Progress on an FEL-based TBA

Theoretical work on an FEL-based TBA continued through 1987, and a first high-gradient accelerating structure, fully intended to be part of a prototype accelerator, was fabricated and readied for testing. However, during most of the year, no facility was available to pursue experimental FEL work. Livermore's Experimental Test Accelerator (ETA), the site of dramatic successes in 1985, was rebuilt as ETA II, but is not now available for TBA experiments. The only

experiments actually conducted on ETA during the past year were preliminary tests on the septum coupler that would remove power from the FEL and route it to waveguides for transfer to the high-gradient accelerator. Observed breakdown voltages were much lower than expected, but beam time was unavailable for testing the leading hypotheses for why this should be so. It is thought that a simple "beam scraper" may solve the problem by removing the halo of electrons that surrounds the high-current beam. We hope to have a suitable source available in the future for these and other tests.

The high-gradient accelerator structure shown in Fig. 47 was fabricated in early fiscal 1987 and is now ready for testing as soon as a suitable high-power microwave source can be made available. The brazed 34-cavity structure operates at 33.31 GHz and was machined to tolerances of $\pm 1.25 \mu\text{m}$. In 1985 we observed accelerating gradients of 180 MV/m in a seven-cavity prototype structure, manufactured to far looser tolerances and without benefit of high-vacuum conditioning. We anticipate even more impressive results with the new structure.

Theoretical attention continued to focus on issues of sideband growth and phase stability. The potential sideband problem is simply stated: As the electrons in the FEL "slip" in phase with respect to the co-propagating electromagnetic pulse, radiation at unwanted frequencies can be produced and amplified. We have now studied this phenomenon in some theoretical detail and have corroborated our predictions in a collaborative experiment on the Columbia University FEL. The findings showed that the sideband frequency can be controlled by controlling the slippage between the electrons and the group velocity of the microwaves in a waveguide. It thus appears that sidebands are not a problem.

Phase stability is a more challenging problem. Our studies suggest that microwave phase is very sensitive to errors or variations in microwave frequency, undulator field strength, FEL beam energy, and especially FEL beam current. It now appears that it would be necessary simply to discard the microwaves, starting again with fresh and properly phased radiation, when the phase error becomes unacceptably large. The loss in efficiency entailed in this "inelegant" solution appears to be small.

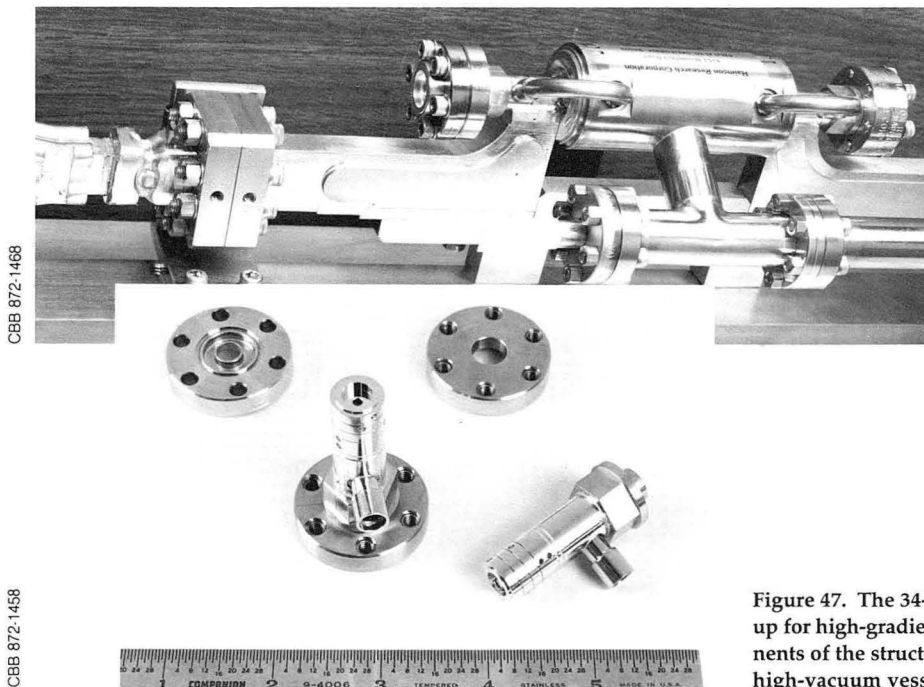
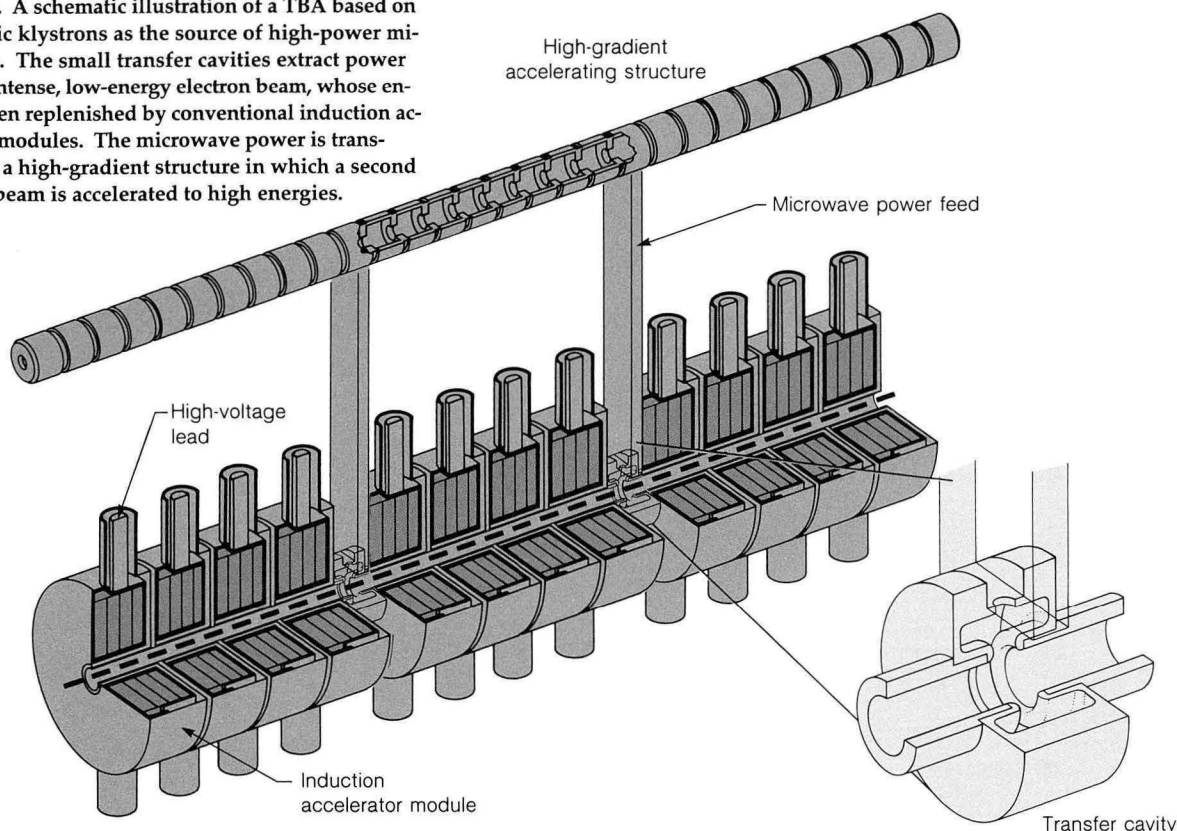


Figure 47. The 34-cavity TBA accelerator structure set up for high-gradient testing. The inset shows components of the structure, which is hidden within its high-vacuum vessel in the larger photograph.

Figure 48. A schematic illustration of a TBA based on relativistic klystrons as the source of high-power microwaves. The small transfer cavities extract power from an intense, low-energy electron beam, whose energy is then replenished by conventional induction accelerator modules. The microwave power is transported to a high-gradient structure in which a second electron beam is accelerated to high energies.



Relativistic Klystron TBA

A TBA based on a relativistic klystron is a new concept, initially proposed by W. K. H. Panofsky of the Stanford Linear Accelerator Center (SLAC). As shown in Fig. 48, a series of transfer cavities replaces the FEL of the original TBA design. Microwave power is extracted from a bunched low-energy electron beam in these cavities and transferred to the high-gradient accelerator, which would be identical to that in the FEL-based TBA. The energy of the high-current beam would be replenished as before by induction accelerator modules.

A number of issues raised by this new concept were dealt with theoretically in 1987. Among them is the question of the optimum rf frequency. Since the achievable accelerating gradient increases with frequency and the energy stored in a collider decreases, a high frequency would appear desirable. On the other hand, physical structures become unreasonably small at high frequencies. As a suitable frequency at which to begin work, we compromised with 11.4 GHz. We also addressed various potential beam instabilities, including the resistive wall instability and the beam breakup instability, caused by the interaction of the beam with the transfer cavities. A few of the parameters for a conceptual 375 GeV $\times$ 375 GeV collider design that addresses these and other issues are listed in Table 5.

The past year also saw the beginnings of an experimental program on the relativistic klystron concept, carried out in collaboration with Livermore and SLAC. At Livermore's Accelerator Research Center (ARC), a conventional 8.57-GHz klystron, designed and built at SLAC, produced peak power of 75 MW at an efficiency greater than 50%, when coupled with the 200-amp ARC beam. In addition, a peak field of 220 MV/m was observed, with no sign of breakdown. Experiments are planned with longer tubes, designed for the chosen 11.4-GHz operating frequency.

Low-energy beam	
Current (kA)	1.6
Energy (MeV)	50
Transfer cavities	
Number	2 per meter
RF voltage (MV)	~1
Frequency, GHz	11.7
Beam pipe radius (mm)	6
Induction cells	
Number	4 per meter
Voltage (kV)	250
High-energy beam	
Final energy (GeV)	375
Repetition rate (Hz)	120
Operating frequency (GHz)	11.4
Luminosity ($\text{cm}^{-2}\text{sec}^{-1}$)	10^{32}
Bunch length, rms (mm)	1.9
Bunch transverse size, rms (μm)	0.5
Number of particles per bunch	6.8×10^{10}
Normalized emittance (mrad)	6.25×10^{-5}
High-gradient structure	
Total length, each accelerator (km)	1.74
Accelerating gradient (MV/m)	215
Breakdown surface field (MV/m)	537
Peak power (GW/m)	1.42
Distance between rf feeds (m)	1

Table 5. Conceptual design parameters for a 375 GeV $\times$ 375 GeV linear collider based on the concept of a relativistic klystron TBA.

Our beam dynamics studies for the ALS are a direct stepping stone to more speculative studies of low-emittance damping rings for short-wavelength (40-angstrom) FELs and for future linear colliders, including so-called wiggler lattices, which are dominated by alternating bends that increase the rate of radiation damping. Physics issues include lattice options, collective effects, ways of increasing beam brightness, and the feasibility of single-pass ultraviolet FELs and infrared oscillators. During 1987 we also collaborated with the designers of third-generation synchrotron radiation sources in Trieste, Italy, and in Taiwan. And in Berkeley, one member of the Exploratory Studies Group shared in the teaching of an advanced graduate course in accelerator physics offered in the UC Berkeley Department of Physics. We see such educational activities as crucial insurance for a vital future in advanced accelerator physics research. Along similar lines, we continued to supervise the development of an accelerator physics code library, accessible to all users of the Laboratory's computer system.

Several AFRD physicists participated actively in the International Committee for Future Accelerators Workshop on Low-Emittance Beams, held at the Brookhaven

Other Activities

National Laboratory in March 1987. The purpose of the workshop was to investigate the techniques now available for producing low-emittance beams, to explore the limitations of these techniques, and to look at new possibilities. This study was motivated by two conceivable uses for low-emittance beams: (i) to serve as part of a high-energy linear collider, which would require very small beam sizes to achieve a suitable luminosity, and (ii) to make possible a short-wavelength FEL, which would require very low longitudinal and transverse emittances.

As part of the working group on storage-ring collective effects, we analyzed the performance of several different lattice types, using the LBL accelerator physics code ZAP. Our results indicate that it should be possible to meet the requirements for a collider damping ring, but that the FEL requirements cannot be achieved without significant—and probably unacceptable—compromises in beam intensity and damping time. In the context of exploring alternative approaches, we also explored lattices having a zero momentum compaction factor—that is, lattices in which the longitudinal motion of the individual particles, relative to one another, is reduced to zero. Such a lattice has appealing virtues, but its requirements are severe. Whether or not it might be feasible must be determined by further study.

During the summer of 1987, two members of the Exploratory Studies Group participated in the early design phase of the Sincrotrone Trieste, a 1- to 2-GeV synchrotron radiation source to be built in Trieste, Italy. Our work covered several areas of common interest to Trieste and LBL. For example, collaborative investigations included the effects of undulator gap restrictions on the storage ring impedance, collective effects (bunch lengthening, emittance growth, beam lifetime, coupled-bunch instabilities, etc.) that affect storage ring performance, the possibilities for both infrared and vacuum UV FELs (the latter driven either by a linac or by a booster synchrotron), and alternative injection system designs.

Our group has also been involved, in an advisory capacity, with the early design of the Taiwan synchrotron radiation facility. For the most part, we have provided guidance on issues related to lattice design, including discussions of the appropriate criteria to apply in designing a lattice and a study, using ZAP, of the relative performance expected from two alternative lattices proposed by the Taiwan staff.

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