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On the cover: The vacuum chamber for a portion of one sector of the 1-2 GeV Synchrotron Radiation Source described on pages 1-13. The cutouts in the aluminum structure are for the bending, focusing, and correction magnets of the storage ring. The beam of light shown in dark color is from an undulator or wiggler; the other four are from bending magnets.

Accelerator and Fusion Research Division

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Summary of Activities

Lawrence Berkeley Laboratory
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April 1987

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Foreword

As in years past, the pages of AFRD's "annual report" once again portray a research division of rich diversity. In our high-energy physics technology program alone, for example, we continued our multifaceted development of superconducting magnets, contributed significantly to the SSC *Conceptual Design Report*, extended our work on beam-cooling systems for the Tevatron, and made further strides in the investigation of a futuristic concept for linear colliders, the Two-Beam Accelerator. Equally diversified, the Center for X-Ray Optics extended our theoretical understanding of undulators and free-electron lasers, fabricated state-of-the-art optical components for x-ray imaging, and produced dramatic x-ray images of subjects ranging from the sun to secretory vesicles from a rat pancreas. And from the magnetic fusion energy group emerged several new ion sources, successful tests of the RCA-built Common Long-Pulse Source designed here, and continuing developments in theoretical plasma physics.

Beyond these, and many other, important results from 1986, however, were several developments on a larger and more visible scale. The first among these, of course, is the 1-2 GeV Synchrotron Radiation Source, whose construction should begin soon on the site of the old 184-Inch Synchrocyclotron. Much effort during the past year went toward finalizing the design of this facility and toward crystalizing the needs of the user community. The success of this enterprise is reflected in the positive findings of DOE teams who reviewed the design during the summer and in the \$18 million of construction funds included in the President's budget request for fiscal 1988. The past year also saw the start of a second important design effort. In March 1986, the Nuclear Science Division and AFRD, with help from the Biology and Medicine Division, published *The Bevalac Upgrade: A Preliminary Proposal*, a document that laid out a strong scientific case for continuing exploration of nuclear matter at energies around 1 GeV/amu. Prompted by this preliminary proposal, and the favorable community response to it, a concentrated design effort ensued, culminating only a few weeks ago in a conceptual design report for the Bevalac Upgrade.

Another field whose prospects are bright, and whose future is tied to an undertaking of significant scale, is heavy-ion fusion. The results of comparative systems studies suggest that inertial-confinement fusion power plants based on heavy-ion induction linacs can indeed be economically competitive in the 21st century. Accordingly, as a next step in assessing the promise of induction linacs as heavy-ion fusion drivers, a major experiment, the Induction Linac System Experiment, is under serious consideration.

AFRD thus continues to be a division of impressive diversity, and each of its programs was represented in 1986 by a number of notable successes. It is especially heartening to see the prospects so bright for the 1-2 GeV Light Source, and to see the active consideration being given the Bevalac Upgrade and ILSE. These major projects support a vital infrastructure and provide an important institutional focus. In this healthy environment, we can expect in the coming years to match the achievements described in the following pages.

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1-2 GeV SYNCHROTRON RADIATION SOURCE

*... the design clearly
reflects both the most
recent thinking within
the accelerator
community and the
consensus of users ...*

DURING THE PAST YEAR, activity within AFRD has been shaped, to a large extent, by the increasing likelihood that construction will begin soon on a major new research facility—an electron storage ring optimized to produce synchrotron radiation in the ultraviolet and soft x-ray regions of the spectrum. In November 1985, a group of 200 potential users of this facility affirmed the basic parameters of a machine first proposed for construction in 1982 (the Advanced Light Source, or ALS), thus establishing the basis for a six-month period of intensive design effort. This effort culminated in June 1986 with a conceptual design report (CDR) for a 1-2 GeV Synchrotron Radiation Source, colloquially the Light Source.

As a source of radiation with extremely high spectral brightness and considerable coherent power, the Light Source is of great interest to a diverse community 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 industrial lithography, interface studies, atomic physics studies, and studies of living biological systems within the so-called "water window" between 24 and 44 angstroms.

The facility design retains the basic characteristics of the ALS (among principal parameters, only the nominal beam energy changed, increasing from 1.3 to 1.5 GeV), but at a deeper level, it is completely new. In January 1986, for example, following a detailed analysis of several candidate designs, a decision was made to adopt a new machine lattice, the arrangement of bending and focusing magnets that define the dynamics of the electron beam. In addition, an unprecedented effort was devoted to the

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designs of undulators and beamlines—albeit they are still preliminary.

Laying out the details of this conceptual design for public scrutiny is the purpose of publishing the CDR—a preliminary step to approval for construction of any major federally funded project. As a basis for review and planning, a CDR includes a self-consistent and credible facility design, a detailed cost estimate, and a proposed construction schedule. The conceptual design thus describes a thoroughly thought out and workable facility, but it also represents only the first step in arriving at a final design. Subsequent design refinements and a complete set of specifications will ultimately produce the detailed plans that actually serve as the basis for construction. Contributing to this evolution from conceptual design to preliminary design to final design will be results from concurrent research and development programs, as well as ongoing designer-user collaborations.

The synchrotron radiation emitted by a storage ring operating at 1.5 GeV covers the spectrum of photon energies from a few eV to several keV, thus embracing spectral regions of interest in atomic and molecular physics; biology and medicine; the study of chemical dynamics; materials, interface, and surface sciences; and industrial research and technology. New techniques are also visualized, such as pump-probe dynamical response studies involving synchronized picosecond or femtosecond lasers and x-ray or ultraviolet synchrotron radiation.

Science at the Light Source

The brightness of the Light Source will permit spectroscopists to measure effects in very dilute gas samples; relativistic, quantum-electrodynamic, and correlation effects will be readily measurable. Also, the properties of open-shell atoms, atoms in excited states, and highly stripped ions can be studied. These are systems that occur in astrophysical and plasma environments and that may someday serve in x-ray laser schemes. Some of these experiments will involve combinations of the synchrotron source with tunable lasers or with sources of heavy ions. The vibrational structure of molecules will become resolvable, even for core levels, and it will become possible to study the dynamics of energetic processes in atomic inner shells, including resonances that occur on a uniquely fast time scale. The high intensity of the light from the Light Source will allow experimenters to measure the spin polarization of photoelectrons—the third crucial quantity in the photoelectric effect (the others being energy and angle). Thus, the degeneracy in the continuum between the two spin components will be resolved, permitting the complete determination of all transition amplitudes and leading to direct measurements of relativistic interactions in atoms. The brightness of the radiation will also permit measurements on tiny samples of rare materials, such as the radioactive actinides, whose properties have largely eluded determination in the past.

Atomic and Molecular Physics

One of the most attractive potential capabilities of the Light Source lies in the area of imaging small biological specimens—perhaps even macromolecules. The high brightness and considerable coherence of the available radiation offer promise for the success of new techniques—including x-ray microscopy and holography, contact microscopy, and soft x-ray diffraction—for imaging wet, unstained biological samples with sufficiently short exposure times to permit dynamical studies. Utilizing another novel property of the source, biophysicists anticipate switching rapidly between right- and left-circularly polarized light to measure, by a technique known as circular intensity differential scattering, the higher-order structure of polymers in biological systems.

Biology and Medicine

Chemical Dynamics

Interesting applications are also anticipated in the area of chemical dynamics, which encompasses all phenomena in which molecules undergo energetic or chemical transformations. As a photo-analysis tool, the Light Source can produce macroscopic yields of vacuum ultraviolet photoproducts. If operated in conjunction with an infrared free-electron laser, the source would also serve as a powerful tool for studying chemical processes induced by infrared multiphoton absorption. Further, the time structure of the synchrotron light will permit the study of ultrafast processes. For example, the cleavage of the chemical bonds of photoexcited molecules can occur in picoseconds; such processes could be followed by means of special techniques, utilizing the fast pulses and high repetition rate of the new source. Bond-selective photochemistry will also be possible, using a new technique through which specific bonds in large molecules can be cut selectively with tunable ultraviolet radiation, "as with a scalpel." Cluster chemistry is yet another exciting new field, in which aggregates of atoms or molecules are studied to shed light on the properties of substances in the middle ground between isolated atoms and the solid state. Here, the Light Source will be ideally suited to measure such phenomena as the variation of ionization energies with cluster size, which yield data on the onset of bulk properties as the size of the aggregates increases. Finally, photoionization mass spectroscopy and photoelectron spectroscopy can provide valuable thermochemical data that serve to characterize the structure and energetics of reactive intermediates in chemical reactions. The high ultraviolet output of the Light Source will make it possible to conduct such studies with unprecedented sensitivity and resolution.

Materials, Interface, and Surface Sciences

An outstanding challenge in experimental studies of solid surfaces is making real-time measurements on dynamically changing systems. The high brightness of the radiation from the proposed storage ring and its sharp time structure will make it possible to study chemical reactions, phase transitions, and the time evolution of excited states, yielding new insight into intermediate states and reaction dynamics. For example, time-resolved near-edge x-ray absorption fine structure (NEXAFS) can be used to observe phase transitions, chemical reactions of molecules on a surface triggered by a pulse of gaseous reactant, or temperature-induced changes of adsorbed species.

Enhanced spatial resolution is another beneficial consequence of the high brightness of the new source; this will make possible a new class of surface analytic measurements, namely, the combination of microscopic imaging and photoelectron spectroscopy. A photoelectron spectromicroscope will provide images in which the contrast is due to differences in molecular species and chemical environment, as reflected in the binding-energy spectrum. This approach encompasses virtually all of materials science: the analysis of individual grains of polycrystalline samples; the correlation of surface chemistry and contrast due to magnetic domains; studies of chemically active small particles on substrates, as in supported metal catalysts; the morphology and surface chemistry of thin-film growth; and finally, studies of surface chemisorption, which could be applied to surface modification processes in device fabrication.

Another technical capability that should give rise to new opportunities in materials and surface science is electron-spin resolution. Spin polarization of photoemitted electrons is due to the exchange interaction in magnetic materials and the spin-orbit interaction in nonmagnetic materials. For magnetic materials, the opportunities range from very basic questions concerning theories of finite-temperature itinerant magnetism and surface critical phenomena to applications-oriented areas associated with film growth and the properties of magnetic memory and recording devices.

The Light Source will also allow significant advances in core-level spectroscopy, which can be used to understand many complex materials and interfaces that have technological applications. Highlights include the use of core-level shift and intensity measurements in characterizing metal-semiconductor interfaces and the

Fig. 1. Plan view of the 1-2 GeV Synchrotron Radiation Source, together with a detailed view of one sector of the machine lattice, a cross section of a dipole magnet, and a cutaway of the vacuum chamber, showing a photon stop and titanium sublimation pump. Photon stops are arranged to intercept virtually all synchrotron radiation (except that which exits the ring via a beamline), thus ensuring that photon-desorbed gas molecules are produced only in the vicinity of a vacuum pump.

application of extended x-ray absorption fine structure (EXAFS) and photoelectron diffraction to determine the bonding geometries of a variety of surface and interface systems. A consequence of such studies will be predictive capabilities with regard to interface formation and materials engineering, both of which are crucial for many areas of high technology, including developments in microelectronics.

The Light Source furthermore has significant potential for defect spectroscopy of semiconductor interfaces and surfaces, for which no suitable probe now exists. Soft x-ray photoabsorption studies may be extended to determine the local structure around atoms present at great dilution in a host system, and this will be an extremely important achievement in surface studies of precursor states, oxidation, poisoning, and chemical reactions on transition-metal catalysts.

Finally, materials science will benefit from the soft x-ray and vacuum ultraviolet scattering capabilities of the new facility. Scattering at these wavelengths is uniquely suited to studying structures with feature sizes larger than atomic dimensions, but this possibility has not yet been exploited. One possible application is scattering from ultrathin polymer films on solid substrates; such structures are of both scientific and technological interest.

Industrial Research and Technology

Foremost among opportunities in industrial R&D is research in x-ray lithography, addressing issues related to fabrication of devices with 0.25- μm (and smaller) feature sizes. Central to this field will be the development of advanced imaging techniques, rather than proximity printing. Other industrial applications include micromachining, surface scanning, contact transmission microscopy, holography, and polymer characterization and optimization.

Conceptual Design

As described in the CDR, and as shown in Fig. 1, the Light Source consists of an injection system (comprising a linac and a booster synchrotron); a low-emittance storage ring that includes 12 straight sections and is optimized at 1.5 GeV; five insertion devices (four undulators and a 2-T wiggler); five insertion device beamlines; and front-end components and controls for two bending magnet beamlines. (Ultimately, we anticipate construction of 11 insertion devices, and 48 ports will be available for bending magnet beamlines.) Although a descendant of LBL's original 1982 ALS design, the current design clearly reflects the results of more recent thinking within the accelerator physics community, as well as the consensus enunciated at the November 1985 users' workshop as regards critical operating parameters. The designers' responsiveness to the goals established by the November gathering can be judged from Table 1, which compares performance goals with the corresponding design parameters for the Light Source. Unchanged in the new design are the essential features of the ALS: the very low electron beam emittance (a measure of the beam's transverse dimensions and its divergence), the long beam lifetime, the short bunch length, and the wavelength tunability and narrow bandwidth of the emitted radiation. During June and July 1986, the Light Source project passed two critical milestones: a Validation Review conducted by the Assessment and Validation Branch of the DOE's Office of Project and Facilities Management, and a Conceptual Design Review by the Division of Construction, Environment, and Safety in the Office of Energy Research.

Storage Ring

Lattice Design. A small beam emittance is required in any machine intended to produce light of high brightness. (Brightness is a measure of light intensity per unit area per unit solid angle, emitted within a narrow bandwidth.) To achieve a small emittance, a small horizontal beam size is required at the bending magnets, requiring in turn that the beam be strongly focused by quadrupoles. The challenge is to accomplish this with a lattice design having good chromatic properties and a large

	Performance goals	Design values
Beam energy, nominal (GeV)	1.5	1.5
Energy range (GeV)	0.75-1.9	0.75-1.9
Average current (mA)	400	400
Horizontal emittance, rms (m-rad)	$<10^{-8}$	4.08×10^{-9}
Number of straight sections	12	12
Straight section length for insertion devices (m)	6	5
Bunch length, 2σ (ps)	20-50	28-47 ^a
Beam lifetime (hr)	>6	5-8 ^b

^aExtreme values are for 250-bunch and single-bunch modes, respectively, at maximum current.

^bExtreme values are for single-bunch and 250-bunch modes, respectively, at maximum current.

Table 1. Performance goals established by potential Light Source users, compared with machine design values.

dynamic aperture. These goals led to a reevaluation of the lattice used for the 1982 design, a so-called Chasman-Green lattice.

In January 1986, a panel of outside experts met at LBL to discuss lattice candidates. The reviewers were Samuel Krinsky and Gaetano Vignola of the Brookhaven National Laboratory, Helmut Wiedemann of Stanford University, and Sergio Tazzari of the Laboratori Nazionali di Frascati in Italy. Three of the lattice candidates were found to be "potentially equally interesting," which led to intensified study of these designs. Of these three, a "triple-bend achromat" (TBA) lattice was chosen, in part because of its capability for flexible operation (allowing the beam to be tuned independently in each straight section) and its relative insensitivity to magnet misalignments and other perturbations.

The TBA structure, incorporating three gradient bending magnets per achromat (thus its name), was first proposed by Vignola for a 6-GeV synchrotron radiation source. A schematic of a single unit cell, or superperiod, is shown in Fig. 1. Each superperiod has reflection symmetry around a central dipole and consists of a "dispersive region," where the bending occurs, matched to a straight section, 6.75 meters long, reserved for undulators, wigglers, injection hardware, and rf cavities.

Bunch Length and Beam Lifetime. Apart from a low emittance, a long beam lifetime and short electron bunches were perhaps the most important design goals for the storage ring. In practice, the attainable bunch length is determined by the rf parameters and the constraints of the so-called longitudinal microwave instability. The influence of the longitudinal microwave instability is determined in turn by the effective impedance of the ring. On the basis of experimental evidence from the SPEAR electron-positron storage ring at the Stanford Linear Accelerator Center, it is expected that the effective longitudinal impedance will decrease for bunch lengths shorter than the pipe radius. As a consequence, the predicted bunch length for the 250-bunch operating mode is about 20 ps for currents up to about 300 mA, rising to about 28 ps at 400 mA.

Beam lifetime is limited by a combination of two effects, Touschek scattering (large-angle intrabeam scattering) and gas scattering. The former is of particular interest, since it is most severe for short, high-current bunches with low emittance—precisely the properties we are striving for in the Light Source. Overall lifetimes for two operating scenarios are shown in Fig. 2. Multibunch operation meets the lifetime goal of 6 hours.

Fig. 2. Predicted overall beam lifetimes for single-bunch and multibunch scenarios, assuming a magnet gap of 1.4 cm.

Ion Trapping. Among other accelerator physics questions, one attracted particular attention, largely because it cannot be conclusively answered by experience at any operating facility. This was the question of ion trapping.

Ion trapping can result when the electron beam circulating in the storage ring ionizes molecules of residual gas. If the potential of the negatively charged electrons is sufficient to entrap the positively charged ions, the effective local gas pressure rises, leading to a decrease in beam lifetime. Though this phenomenon has been encountered elsewhere, it is potentially more serious at the Light Source, since its efficient operation is especially sensitive to beam size "blowup." According to our computer studies, if the Light Source were filled with the maximum number (328) of electron bunches, all ions up to mass 50 would be trapped within the beam volume, making optimum operation of the storage ring practically impossible. However, by leaving a gap in the train of bunches, resonances are created in the periodic motion of the trapped ions, leading to their loss. Ion trapping thus poses no significant threat to operation of the Light Source, provided that appropriate gaps are introduced into the bunch train during multibunch operation. Three ring-filling scenarios are illustrated in Fig. 3.

Magnets. The magnets of the storage ring are of six types: (i) gradient bending magnets, which have the combined function of bending and focusing the beam, (ii) quadrupole focusing magnets, (iii) sextupole magnets for chromaticity correction,

Fig. 3. Illustration of ion trapping for three filling scenarios. When the storage ring is completely filled with 328 electron bunches, positive ions are trapped (colored bars) by the potential of the negatively charged electrons; however, when a gap is left in the train of bunches, no ions of concern are trapped.

(iv) skew quadrupoles to control vertical beam size, (v) small dipole magnets for vertical and horizontal steering, and (vi) special septum and bump magnets for injecting beam from the booster into the storage ring. Of these, the first are particularly interesting, since they reflect one of the essential design features of the TBA lattice (see Fig. 4). The pole tips of these magnets have a hyperbolic contour so that they provide a combined dipole and quadrupole magnetic field. This feature has the primary virtue of keeping the vertical beam size under control in the bending regions, where the vertical size constraint is greatest. In addition, it leads to a reduced emittance and an enhanced ability to manipulate the beam dynamics.

Fig. 4. Cross section of the pole tip of a Light Source bending magnet. The nonparallel pole faces conform to segments of a hyperbolic section and impose a combined dipole and quadrupole field on the electron beam.

Vacuum System. The role of gas scattering in limiting beam lifetime depends on the gas pressure inside the beam tube. A major obstacle to the achievement of the Light Source design goal of 1×10^{-9} Torr is the desorption of molecules from the chamber walls, caused by photoelectrons that are created by photons hitting the walls.

LBL has developed a new approach to this problem, as shown in Fig. 1. The electron beam tube is connected by a long, continuous slot to an antechamber, which contains discrete water-cooled synchrotron radiation absorbers. As shown in Fig. 5, all synchrotron radiation either strikes one of these "photon stops" or passes out of the ring via a beamline port. The desorbed gas is generated at the photon stops, and it can be very efficiently pumped by concentrating most of the pumping capacity nearby. Measurements and computations show that the presence of the antechamber has a negligible effect on the beam coupling impedance; the slot effectively isolates the beam tube from the antechamber at frequencies below about 10 GHz.

Injection System

In the injection system (see Fig. 1), a 50-MeV linac injects the electron bunches into a booster synchrotron, which increases the energy of the beam to 1.5 GeV and injects it into the storage ring. Injection at the nominal operating energy of the storage ring simplifies operation and enhances the reproducibility of experimental conditions. (For experiments requiring operation above 1.5 GeV, the beam can be further accelerated by the storage ring rf system to a maximum energy of 1.9 GeV.)

We visualize two different operating modes, each requiring a different injection scheme. The multibunch mode requires that the storage ring be filled to a current of 400 mA in approximately 250 consecutive bunches (out of a total of 328; as discussed on page 7, the gap is needed to avoid ion trapping). In this mode, the storage ring buckets are filled by 126 repetitive transfers from the booster synchrotron, each transfer involving 17 electron bunches. For the few-bunch operating mode, we assume a current of 7.6 mA per bunch. Here, the bunches are filled one at a time. Filling times are 2.1 minutes in the multibunch mode and 16 seconds per bunch in the few-bunch mode. The few-bunch mode allows the machine to be filled with any pattern of regularly or irregularly spaced electron bunches.

Fig. 5. Plan view of a storage ring sector, showing how the beam stops effectively intercept all synchrotron radiation, except that extracted through a beamline port.

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Insertion Devices and Beamlines

Eleven of the 12 straight sections in the storage ring are available for insertion devices; one straight section is occupied by injection hardware. In each of these 6.75-meter-long straight sections (except one that is partly occupied by rf cavities), 5 meters is available for insertion devices. The conceptual design includes four undulators and one wiggler, the characteristics of which are given in Table 2 and Fig. 6.

The choice of parameters for the undulators reflects several of the basic considerations implicit in insertion device design. For example, it is generally desirable to design undulators with large values of K (which is directly proportional to the magnetic field and the length of the undulator period). A higher K leads to both a wider tuning range and a higher useful flux. On the other hand, the total power generated by the undulator (most of it in unwanted spectral regions) may become unacceptably large at high K 's. The total power from each of our undulators is limited to a few kilowatts. Similarly, short undulator periods are desirable for reaching high photon energies; however, there is a lower limit on the practical period length, since the magnetic field decreases rapidly as the ratio of the period length to the magnet gap becomes small. The minimum magnet gap, in turn, is set by considerations of the electron-beam lifetime and is 1.4 cm for the Light Source.

All of the insertion devices are of a hybrid permanent-magnet and steel design. As the magnetic material, we chose neodymium-iron, which has a stronger remanent field and better mechanical properties than samarium-cobalt.

The extraordinary performance of the 1-2 GeV Synchrotron Radiation Source, especially with regard to brightness, provides opportunities for many new types of scientific investigations. Accordingly, the optical systems in the CDR were designed to demonstrate that extremely high spectral resolution can be obtained with systems that accept the entire photon beam. The surface tolerances for these optical systems are around one microradian, which will require careful fabrication strategies. Nonetheless, we believe that these tolerances are well within existing manufacturing capability for the spherical and flat surfaces upon which all the beamline designs are based.

As alluded to above, an important feature of the optical systems is their phase-space acceptance. We have shown that the phase-space properties of today's state-of-the-art monochromators are such that the entire beam can be accepted, as shown in Fig. 7. As an example, we calculate that we will be able to deliver photons at the oxygen K edge with a relative bandwidth of 10^{-4} , without loss due to

Name	Period (cm)	No. of Periods	Photon energy range (eV) ^a	Critical energy (keV)
Undulators				
U20.0	20.0	23	0.5-95 [1.5-285]	—
U9.0	9.0	53	5-211 [15-633]	—
U5.0	5.0	98	50-380 [150-1140]	—
U3.65	3.65	134	183-550 [550-1650]	—
Wiggler				
W13.6	13.6	16	—	3.1

^aThe photon energy range of the fundamental and the third harmonic (shown in brackets) as K decreases from its maximum value to 0.5.

Table 2. Parameters for the complement of insertion devices chosen for the Light Source conceptual design.

Fig. 6. Spectral brightness as a function of energy for radiation emitted by the four undulators and one wiggler described in Table 2, together with the bending magnets of the Light Source. For the undulators, the tuning range is shown for both the fundamental (solid lines) and the third harmonic (dashed lines). The dotted lines show corresponding curves for spectral brightness at commissioning, when the minimum magnet gap will be 2.5 cm.

phase-space mismatch. The spectral ranges and typical resolutions of the insertion device beamlines included within the scope of the conceptual design are given in Table 3. In addition, the conceptual design includes front ends and controls for two bending magnet beamlines.

Conventional Construction, Cost, and Schedule

The CDR also includes details regarding conventional construction, which entails, most importantly, modifications and additions to the building that now houses the 184-Inch Synchrocyclotron. Outside the scope of the CDR are current plans for 10,000 square feet of office and lab space in existing buildings to accommodate users of the first complement of experimental facilities. However, plans do include provision for 14,000 square feet of future office and lab space in the Light Source building itself. The planned facility also allows for 40-meter-long beamlines.

Commissioning of the Light Source is scheduled to be complete by the end of fiscal 1992. This schedule provides for "beneficial occupancy" of the building before the end of fiscal 1989, at which time testing and installation of the injector system will commence. Installation of the storage ring will follow in 1991, and insertion devices and beamlines will be installed and tested in 1992. Even allowing for a normal shakedown period, we are optimistic that we will see light of unprecedented experimental value before the end of 1992.

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CENTER FOR X-RAY OPTICS

*... wide-ranging
activities were united
by the common goal of
putting to better use
light from the x-ray
and vacuum ultraviolet
regions ...*

AS IN YEARS PAST, the activities of the Center for X-Ray Optics during 1986 were wide-ranging and diverse, but united nonetheless by the common goal of putting to better use light from the x-ray and vacuum ultraviolet regions of the electromagnetic spectrum. Our involvement with x-ray sources ranged from the design of new wigglers and undulators for synchrotron radiation facilities to theoretical investigations of how coherent radiation emerges from noise in high-gain free-electron lasers. New insertion device designs, for example, combine permanent-magnet materials and electromagnets, both to control saturation effects—thus making higher fields possible—and to compensate for field errors.

We also continued our active programs in optical component development. In collaboration with IBM, we fabricated and tested much-improved x-ray zone plates—a kind of circular diffractive structure—with resolving powers of 1000 angstroms for soft x-rays. And at shorter wavelengths, we continued our development of multilayer-coated glancing-incidence mirrors, work that culminated in 1986 in the achievement of submicrometer resolution at 8 keV. To illustrate the practical utility of these and other developments in x-ray optics, we undertook a number of scientific programs, including several aimed at demonstrating the promise of x-ray microscopy for biology and materials science. We also took part in a program that produced the first x-ray images of solar active regions using a normal-incidence x-ray telescope.

In the broad area of x-ray spectroscopy, we were active in both the experimental realm and in instrument design. For example, we developed a new design for high-resolution monochromators and spectrometers for

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the soft x-ray region. This general design will have a major impact on spectroscopic applications of synchrotron radiation, line width measurements of x-ray lasers (and thereby our understanding of the time-dependent physics of lasing processes), and the practical application of x-ray microscopy and holography. We also produced new, high-efficiency x-ray photocathodes based on solid xenon and argon condensed films, and we used picosecond x-ray spectrometry to measure mass ablation rates from laser-irradiated fusion capsules.

Our synchrotron radiation projects group was also active in many areas. We were largely responsible, for example, for the beamline designs described on pages 10–12 for the 1–2 GeV Synchrotron Radiation Source. More broadly, the group made substantial progress on the design and testing of beamlines and beamline components that must function under conditions of high x-ray thermal flux. Studies of such components, including finite-element computational modeling and measurements under extreme thermal conditions, were conducted both at the Stanford Synchrotron Radiation Laboratory (SSRL) and at Cornell (CHESS).

Especially important to the Center have been activities aimed at unifying and broadening the community of XUV radiation users. Accordingly, we have strengthened our interactions with scientists outside Berkeley, in large part through our affiliates program, and we have participated in a number of projects at other institutions. In addition, our student program has been augmented by a new course, "Introduction to X-Ray Physics," in the UC Berkeley Department of Physics, and we were selected for a major University Research Initiative grant to establish ourselves as a Center of Excellence for student research and training.

Our broad interest in sources of x-rays is reflected in recent comparative studies of x-ray lasers, plasmas, and undulators and in studies of compact synchrotron radiation sources and laser-produced plasmas—both possible sources of x-rays for integrated-circuit lithography. The main thrust of our effort, however, remains the design and theoretical understanding of periodic magnetic structures—wigglers and undulators or, collectively, insertion devices—as sources of radiation. During the past year, our theoretical effort was directed particularly toward unraveling the mechanism by which coherence emerges from "noise" in single-pass free-electron lasers. At the same time, we continued to refine our designs of insertion devices, putting forward candidate designs for the 1–2 GeV Light Source, beginning fabrication of a neodymium-iron wiggler for SSRL, and developing innovative approaches to incorporating permanent-magnet material into electromagnetic undulators and wigglers.

Electrons passing through a simple undulator are initially uncorrelated, and they remain uncorrelated as they continue along the device. As the number of the undulator periods, N , increases, however, the interaction between the undulator radiation and the electron beam can lead to density modulations—"bunching"—in the electron beam and to an exponential amplification of the radiation. The undulator thus becomes a so-called high-gain free-electron laser (FEL), and the radiation emitted is called self-amplified spontaneous emission (SASE), by analogy to laser terminology. The transition from simple undulator to high-gain FEL is illustrated schematically in Fig. 8.

Since high-gain FELs operating in the SASE regime do not require the use of high-reflectivity mirrors to form optical cavities, they are promising alternatives to

X-Ray Sources: Theoretical Studies and New Designs

High-Gain Free-Electron Lasers

Fig. 8. Schematic illustration of the evolution of a high-gain free-electron laser from an undulator. The appearance of electron "microbunching" is accompanied by an exponential gain in the intensity of emitted radiation. Saturation follows, when electron motion ceases to remain in phase with the wavelength of the emitted light.

FEL oscillators as generators of intense, coherent radiation at wavelengths shorter than 1000 angstroms. At microwave wavelengths, the principle of SASE has been experimentally confirmed at the Lawrence Livermore National Laboratory (see page 57).

Recently, we have made substantial progress in understanding how SASE emerges and propagates in long undulators. Our analysis, based on the Maxwell-Klimontovich equation, differs from earlier work in two respects. First, we use a microscopic description of electrons in terms of the Klimontovich particle distribution function. Second, the analysis is three-dimensional so that important issues such as guiding and transverse coherence can be clarified. Finding an explicit expression for the amplitude of the coherent amplification in terms of the input amplitude was a hitherto unsolved problem in three dimensions.

An important parameter characterizing high-gain FELs is the dimensionless parameter ρ , which is typically of order 10^{-3} . Figure 8 summarizes the evolution of simple undulator radiation to SASE. For $\rho N \ll 1$, the radiation is an incoherent superposition of radiation from individual electrons, and it is only partially coherent transversely, owing to finite electron beam emittances. The bandwidth is about $1/N$. For larger N but with $0.1 < \rho N \lesssim 1$, the FEL interaction produces bunching of the electrons, resulting in enhanced radiation intensity and coherence. Typically, the radiation is dominated by a single mode, which grows exponentially and is fully coherent transversely. The relative bandwidth is smaller than that of the undulator radiation by a factor of $(\rho N)^{1/2}$. Finally, the exponential growth stops when $\rho N \approx 1$ because of the increased momentum spread induced by the FEL interaction.

Undulator and Wiggler Design

Significant effort in 1986 went into the conceptual design of the five candidate insertion devices described on pages 10–12 for the 1–2 GeV Synchrotron Radiation Source. The foundation of this effort, however, was an ongoing program that has produced a number of insertion devices for operating facilities and a succession of technological design innovations, some now part of operational wigglers and undu-

lators, some still conceptual. The latest of our designs to reach the fabrication stage is a neodymium-iron wiggler intended as the source for Beamline X at SSRL. This insertion device has 15 periods, each 12.85 cm long, and will achieve 1.40 T at the 2.1-cm operating magnet gap.

The magnetic structure, support and drive system, and vacuum system for the Beamline X wiggler is shown in Fig. 9. Neodymium-iron was selected as the permanent-magnet material because it has a 16% higher coercive force than rare earth-cobalt, it chips less, it is easier to bond to common materials, and it is less expensive. The basic building block of the magnetic structure is a half-period pole assembly, each of which includes an electromagnetic coil that is used to correct the wiggler vertical field integral.

Fig. 9. Cutaway elevation of the SSRL Beamline X wiggler currently under construction at LBL, together with a photograph of the nearly complete wiggler in March 1987.

Looking beyond such designs, we continued to design still better undulators and wigglers for use in synchrotron light sources and free-electron lasers. A most promising approach is to incorporate permanent-magnet material into electromagnetic undulators or wigglers in such a way that the magnetic field that can be produced is as large as (or larger than) the field produced with short-period permanent-magnet insertion devices. In addition, the most recent embodiment of this concept is general enough to be applicable to, for example, quadrupole magnets, as well as wigglers and undulators. The basic idea is the following: if one goes from the useful field volume of an electromagnet deeper and deeper into the coil slot, one finds that more and more magnetic flux enters the iron, leading to debilitating saturation of the iron when the structures are small. However, by breaking the coil up into a number of sections, and by placing appropriately magnetized permanent-magnet blocks between the coil sections, one can take magnetic flux out of the iron, thus preventing saturation. This basic design concept is illustrated in Fig. 10.

Studies of Other Sources

We have also undertaken some calculations aimed at clarifying the relative promise of compact synchrotron radiation sources and laser-produced plasmas for x-ray lithography. Laser-produced plasmas are efficient (20–80%) sources of quasi-continuous sub-kilovolt radiation of high peak power, but repetition rates are very low. To compete with synchrotron radiation facilities as compact x-ray lithography sources, significant advances are required in laser technology. For solid-state lasers, new host materials must be developed, which retain the capability of high peak power demonstrated in today's neodymium-glass lasers, yet have higher pumping efficiencies and better heat-dissipation properties. Excimer-gas lasers must advance

Fig. 10. Cutaway view of a dipole magnet based on a "laced electromagnet" design. The permanent-magnet material (color) is placed so as to remove flux from the iron pole piece, thus preventing saturation of the iron. The electromagnetic coils are shown in gray.

by two orders of magnitude in peak power and another 10- to 100-fold in repetition rate. Figure 11 compares the average flux delivered to a lithographic mask and resist by a compact synchrotron radiation source with that delivered by a laser-plasma source, assuming that the necessary advances are made in laser technology. We assume the same high-throughput x-ray monochromator and collection optics for both systems.

Fig. 11. Plot of delivered average photon flux as a function of photon energy for a compact synchrotron radiation source and a moderate-sized laser-plasma facility, assuming significant advances in laser technology. The computation assumes a peak power of 10^{10} W and a 1-kHz repetition rate for the laser.

X-rays pose unique problems for optics designers because they cannot be focused by conventional means: Images cannot be formed by refraction, and specular reflectivity at near-normal angles is negligible. Fortunately, several unconventional techniques are available. Fresnel zone plates, for example, are circular structures whose alternating opaque and transparent zones serve to focus soft x-rays by diffraction. Also, mirrors can be used effectively to focus higher-energy x-rays by glancing-angle reflection. In addition, by using multilayers of atomic thicknesses, the usefulness of reflective optics can be substantially extended—even to the production of normal-incidence mirrors for use with radiation in the vacuum ultraviolet. During the past year, we made significant strides in developing each of these techniques, and we are successfully extending their practical application in experimental science. Other experiments in x-ray imaging have included holography studies and preliminary work with a new contact microscopy station.

X-Ray Imaging

Zone Plates and Soft X-Ray Microscopy

Circular diffractive structures known as Fresnel zone plate lenses are one means of circumventing the difficulty of focusing soft x-rays with wavelengths in the 10- to 100-angstrom region. When used with a suitable source of x-rays, a zone plate can focus radiation to a resolution roughly equal to the outer zone width. In collaboration with colleagues at IBM's Watson Research Center, we have been fabricating gold zone plates of ever-improving quality and resolution. Figure 12 shows a 57- μm -diameter zone plate with an outer zone width of 700 angstroms. The lens has 156 working zones and a 1.3-mm focal length at 31 angstroms. The 1300-angstrom-thick zones rest on a 1000-angstrom-thick silicon nitride substrate. A similar lens, with a 1000-angstrom outer zone width had a measured diffraction efficiency of 5.2%. The zone plate of Fig. 12 is expected to perform as well, with even better resolution. A 500-angstrom zone plate is nearing completion, and preliminary work has begun on 300-angstrom lenses.

The promise of these devices is to allow us, for the first time, to obtain images of intact, perhaps living, biological cells, as well as to probe inorganic materials with elemental specificity. Soft x-ray microscopes based on zone plates might be used, for example, to form subcellular images, resolved to better than 1000 angstroms and highlighting the concentrations of specific elements. The same

Fig. 12. Close-up views of a gold Fresnel zone plate (above). The opaque outer zones are spaced less than 700 angstroms apart. Zone plates such as this one can be used in soft x-ray microscopes to give a resolution approximately equal to the zone spacing. A soft x-ray image of a wet, protein-containing zymogen granule is shown at right, resolved to about 1000 angstroms.

microscope could also be used to study surfaces, thin-film formation, and material properties, with like capabilities. As an example of a biological application, consider one potential use. Models of enzyme secretion and vesicular transport in cells are widely accepted but only weakly and indirectly supported by experimental evidence. This is largely because it is not possible to follow such processes with the electron microscope in real time, and the objects in question (the vesicles) cannot, for the most part, be resolved by light microscopy. Our initial attempts to develop the means to carry out x-ray microscopy experiments involve the use of the advanced scanning x-ray microscope at the National Synchrotron Light Source (NSLS), equipped with a zone plate of the kind just described, to image secretory cells from the pancreas of a rat. About 90% of the nitrogen in cells is contained within various proteins; as a result, measurements at the nitrogen K edge may provide us with the first direct estimation of the relative distribution of proteins within various subcellular compartments of intact cells. Our first experiments along these lines, in collaboration with UC San Francisco, SUNY Stony Brook, IBM, and NSLS, produced preliminary results in early 1987 (Fig. 12).

At higher photon energies, zone plates are not useful; instead, we must rely on grazing-incidence mirror systems to focus the radiation. We have, for example, developed a multilayer x-ray mirror system to focus 8-keV x-rays from a synchrotron x-ray source. The system uses a Kirkpatrick-Baez geometry with two multilayer-coated mirrors (see below) to focus the x-rays separately in the horizontal and vertical planes. In this application, the multilayer coating provides several advantages over uncoated optics: It provides wavelength selectivity, it increases the size of the solid collection angle (by increasing the angle of grazing incidence), and it greatly reduces classical aberrations, thus allowing greater resolution and even relaxing requirements on the surface quality of the mirrors. In tests during the past year at SSRL, we were able to obtain a focused x-ray spot 40 μm wide by 10 μm high. Furthermore, calculations indicate that this size is source size limited; therefore, even smaller spots are possible.

Fabrication and Characterization. Developments in multilayer technology have centered primarily on the use of our advanced sputtering system, which was fully operational for the first time in 1986. With it we were able to characterize many candidate materials and materials combinations for x-ray multilayers. The lateral uniformity of our multilayers was also investigated and improved. Furthermore, in the course of the year, several subsystems of the sputtering apparatus were interfaced with a computer to better control and monitor the deposition process.

Characterization of our multilayers consists most often of diffractometer measurements at hard x-ray wavelengths (typically 1.54 angstroms) at small grazing angles. Reflectivity measurements at these short wavelengths allow us to sample many orders of multilayer reflectivity, which can then be analyzed to learn more about the composition profiles across the layers. Good fits to our experimental data for tungsten-carbon multilayers have been gotten by using theoretical models that assume diffuse interfaces between layers—interfaces that may have different widths for tungsten on carbon and for carbon on tungsten.

We have also begun to measure reflectivities at longer wavelengths at near-normal incidence, where multilayers will find the bulk of their applications. We have concentrated especially at wavelengths between 150 and 375 angstroms, a region especially relevant to the development of free-electron and x-ray laser cavity mirrors. We have also initiated a collaboration with LBL's National Center for Electron Microscopy to use electron microscopy to characterize our multilayer structures.

A multilayer system that has been especially closely studied is the tungsten-carbon system mentioned above. The atomic arrangements that make up the layers of these structures, which can be as little as 20 angstroms thick, have an important bearing on optical performance and stability. Accordingly, we have begun to

Hard X-Ray Microprobe

Multilayer Technology

study these arrangements, especially how they depend on layer thickness and annealing. Our goal is to correlate this understanding with the multilayer's optical performance so as to better understand the limits of performance.

Applications. The goal of our characterization efforts, of course, is to enhance the utility of multilayers as optical elements. One application that we have in mind is the use of multilayers as pre-monochromators in synchrotron radiation beamlines. Bragg reflection from such pre-monochromators, rather than the usual total reflection at grazing incidence, can substantially reduce the total power transmitted to the monochromator by the first optical element, at the same time maintaining comparable efficiency at the photon energy of interest. Plans to test this concept at the National Bureau of Standards Beamline X-24A at NSLS are now under way. In preparation for this experiment, we have investigated new materials combinations that would minimize the pre-monochromator's critical energy, while yielding a strong, narrow multilayer Bragg peak not far above the critical energy. The combination of vanadium and silicon carbide is currently the favored choice for a photon energy around 1.5 or 2.0 keV.

Another of our multilayer optical instruments was recently used with a source of a very different sort. During the past year, we successfully collaborated with the Lockheed Palo Alto Research Laboratories to obtain the first x-ray photograph of a solar active region, using a normal-incidence x-ray telescope. The instrument was flown as part of a comprehensive rocket payload to study the sun's soft x-ray and extreme ultraviolet emissions. The telescope's passband covered two emission lines of Si^{11+} at 44.02 and 44.16 angstroms. Since ionization of silicon to Si^{11+} requires temperatures of the order of 2.0×10^6 K, the photographs we obtained (see Fig. 13) show only the hottest part of the solar corona. Images such as these promise to yield a wealth of information on the structure and dynamics of the upper solar atmosphere, and we expect to continue this program using sounding rockets and, eventually, the space shuttle.

Fig. 13. An x-ray photograph (a) of a solar active region, juxtaposed with a magnetogram (b) of the same region, at the same scale. The x-ray photograph was taken with a rocket-borne normal-incidence telescope developed in collaboration with the Lockheed Palo Alto Research Laboratories. In the magnetogram, the light and dark areas are regions of opposite magnetic polarity, which are often linked by streams of x-ray-emitting plasma.

In earlier years, we have been successful in demonstrating that the classical holographic method, as used in the visible region, could be applied in the soft x-ray region. We showed that a hologram of a sparse, two-dimensional test object could be recorded on photographic film using 31-angstrom x-rays and reconstructed using a helium-cadmium visible-light laser to give a final image resolution of about 1 μm . During 1986 we sought to take the important and difficult step into the regime of spatial resolutions below 1000 angstroms. Our approach was to coherently illuminate the sample and a stack of resist detectors, as shown in Fig. 14. The first detector records a contact micrograph of the sample, and the three subsequent ones record a superposition of the partially attenuated incident beam and the diffracted beam from the sample; in other words, we get three holograms. Our eventual intention is to digitize and computer process these redundant recordings to give values for the amplitude and phase of the diffracted field over the whole area of the recording. These data, plus similar ones from different illumination directions, should allow a numerical reconstruction of the three-dimensional object.

During fiscal 1986, our recordings were made using bending magnet radiation from the 750-MeV storage ring at NSLS. Because of the need to coherently illuminate the entire recording field, exposures took about a day. However, in early fiscal 1987, we made about 25 multiple holograms of pancreatic cells, using the 10-pole undulator beamline on the 2.5-GeV ring at NSLS. Exposures with the undulator radiation typically required about one hour and showed considerable improvement in quality.

Fig. 14. Experimental arrangement for recording a contact micrograph and three holograms at distances of 200, 400, and 600 μm from the sample. This setup was designed to allow three-dimensional reconstruction with better than 1000-angstrom transverse resolution.

Soft x-ray contact microscopy is a high-resolution imaging technique that may be used to look at biological materials in a living or "wet" state. It may also be used to "write" integrated-circuit patterns. For biological samples, image contrast is due to absorption by carbon and nitrogen near their K edges. Figure 15 illustrates the technique. A biological sample is placed on a resist, usually polymethylmethacrylate (PMMA) on a silicon or Si_3N_4 substrate, then exposed to x-rays. The resist is then developed in methyl isobutyl ketone (MIBK) or a solution of MIBK and isopropyl alcohol. The result is a relief map that can be viewed by electron microscopy. The resolution of this technique may be diffraction limited, but it depends on a number of factors, including sample thickness and source size. Typical resolution is about 300 angstroms. The apparatus for exploiting this technique is now operational in our laboratories, and we have just begun exposing biological samples, mainly sickled and normal red blood cells.

X-Ray Contact Microscopy

Fig. 15. The procedure for performing soft x-ray contact microscopy of biological samples. Image contrast depends on the difference in x-ray absorption above and below the *K* edges of biologically important elements.

Another major thrust of the Center's efforts is the development of tools and techniques for x-ray spectroscopy, based on the full range of high-intensity x-ray sources, including storage rings, laser-produced plasmas, and x-ray lasers. We have, as examples, proposed monochromator designs for the 1–2 GeV Light Source (see pages 10–12), designed a high-throughput x-ray monochromator, made high-resolution measurements of molecular x-ray spectra at NSLS, and, in a collaborative effort with the Lawrence Livermore National Laboratory (LLNL), made plans to measure x-ray laser line widths. We have also completed a comprehensive three-part study of the absolute response of x-ray photographic films. Along somewhat different lines—but ultimately tied to the goal of making absolute spectrometry possible—we have continued our development of efficient x-ray photocathodes based on films of solid rare gases. Finally, we applied some of our methods to measurements at Omega, the large laser-produced plasma source at the University of Rochester.

X-Ray Spectroscopy

Soft X-Ray Monochromator. Efficient collection and utilization of the soft x-ray and extreme ultraviolet radiation (30–300 eV) from laser-produced plasma sources require a monochromator with high throughput (solid angle acceptance $\times$ efficiency) but only moderate resolution. We have now designed and constructed a novel instrument meeting these requirements. Simple in principle, it uses a spherical grating that rotates about an axis to perform the wavelength scan, while focusing in the sagittal direction is achieved with a premirror set orthogonally to the grating, as shown in Fig. 16. This premirror can be a simple strip of glass, bent to the correct radius. For synchrotron radiation applications, the high throughput feature of this monochromator can be traded for high resolution, leading to performance better than that of conventional instruments such as toroidal grating monochromators.

Tools and Measurements

X-Ray Laser Line Width Measurements. In a joint project with LLNL, we have undertaken a project to measure the time-dependent line width of the Livermore selenium laser (209 and 210 angstroms). The spectral resolution ($\lambda/\Delta\lambda$) required for this experiment is very high—in excess of 10,000. At the x-ray laser wavelength, such resolution is difficult or impossible to obtain using conventional

Fig. 16. Schematic diagram of a high-throughput monochromator, based on a cylindrical glass "premirror" and spherical, conventionally ruled gratings.

spectroscopic techniques; consequently, we are constructing a special spectrometer that uses a grating with varied line spacing, together with crossed mirrors to eliminate astigmatism and to form an image of the emitting region for each spectral line. A streak camera at the focal plane will be used to examine the time structure of the laser pulse. The resolution of the instrument will be limited by the streak camera to about 10,000. With a higher-resolution detector such as film, the resolution would approach 30,000.

This type of instrument has great potential for achieving high resolution on both bending magnet and undulator beamlines at synchrotron radiation facilities, using fixed slits. Indeed, some of its practical advantages (erect field, simple scanning mechanism, simple optical surfaces) make it appear an attractive alternative to existing monochromator designs. We are undertaking a design study to determine the suitability of these advanced optical designs for application at both Aladdin and the 1-2 GeV Light Source.

Molecular X-Ray Spectroscopy. X-ray emission and absorption spectroscopy permits detailed study of the electronic structure of molecules. In particular, synchrotron radiation promises the capability of studying the electronic states of individual elements within compounds and alloys, and of impurities, clusters, and minor constituents embedded in solid systems. X-ray emission spectroscopy has already been used to study dilute metal alloys, rare gas solids, and fragile compounds that are damaged by electron excitation. Molecular x-ray spectra are rich in overlapping strong and weak structural details arising from the complex atomic environment of the molecule.

Recently, Cl-K β emission and Cl-K absorption spectra from Freon 11, 12, and 13 were measured at NSLS. These molecules are of particular interest because of their suggested role in the chemistry of the upper atmosphere. For the first time, an x-ray emission spectrum of a molecule was obtained solely with excitation below the ionization threshold.

Absolute X-Ray Spectrometry

As part of an effort to develop the means for performing absolute x-ray spectrometry, a characterization effort has been directed toward photographic film, the most common position-sensitive "detector" in x-ray optics. As a result of this effort, relatively simple analytical, two-parameter models have been developed for the first time for the absolute characterization of x-ray films. For example, an analytical model for a new Kodak two-emulsion film shows excellent agreement with experimental data for film density as a function of exposure.

Both temporal and spatial resolution can be achieved with arrays of x-ray diodes, x-ray streak cameras, or microchannel plate arrays. For all of these, however, highly efficient photocathode materials are required in the 100- to 10,000-eV region. Over the past few years, we have developed accurate models and experimental procedures for characterizing x-ray photocathodes, and we have demonstrated that the alkali halides, particularly cesium iodide, can be 10 to 100 times more efficient than the usual metal photocathode (for example, gold). This past year, in collaboration with AT&T Bell Laboratories, we have extended this work to experimental photocathodes of solid xenon and argon. Our preliminary results suggest that the rare-gas solids have secondary electron yields an order of magnitude greater than the high-efficiency alkali halides. These "super" photocathodes may be of critical importance for measurements of x-rays of very low intensities.

An example of how the tools and techniques of absolute spectrometry can be applied to experiment is shown in Fig. 17. The contours shown there are time-dependent spectra obtained from irradiated gold-on-plastic-on-glass microballoons of the sort being developed for inertial-confinement fusion (ICF). Spectra such as these allow thermal transport and mass ablation rates to be calculated from the time-dependent behavior of spectral line intensities. These results are of considerable importance in understanding energy absorption and transport in ICF experiments.

Fig. 17. Perspective plot of x-ray intensity from a laser-produced plasma (over a range of wavelengths) as a function of time, recorded with a high-resolution streak camera. Corrections for the spectrometer response function would increase the intensity on the long-wavelength side by 40%. These data were obtained during experiments at the University of Rochester.

Resting firmly on a foundation comprising the many programs already described are our synchrotron radiation projects—projects involving the design of beamlines and beamline components for facilities now operating or soon to be built. During the past year, we continued to put significant emphasis on the design and testing of components that can tolerate high x-ray fluxes—fluxes high enough to melt or badly distort the usual mirrors and crystals. A water-cooled copper mirror that can absorb several kilowatts of power has been delivered to NSLS and is now in use with its new X-17 soft x-ray undulator. A second system will be installed soon on the new VUV branch of Beamline VI at SSRL. At a more fundamental level, studies of thermally loaded mirrors and crystals, including finite-element computational modeling and measurements of actual temperature contours, were conducted at both SSRL and Cornell. Also for SSRL, as well as high-brightness, high-flux beamlines at future facilities like the 1–2 GeV Light Source, we designed a new high-resolution spherical grating monochromator.

The thermal load associated with the intense photon beams available from new insertion device beamlines imposes very demanding requirements on focusing elements and monochromators. The total thermal power and the localized heat density from these new synchrotron sources can easily distort mirror surfaces and significantly reduce monochromator output flux. During the last year, we measured the temperature contours on the first monochromator on the LBL-Exxon wiggler beamline at SSRL, one of the world's most intense synchrotron radiation sources, and we carried out similar measurements at Cornell's CHESS facility. We also developed computer programs to calculate photon power distributions produced by wiggler and undulator sources, power losses in various beamline components (for example, graphite filters and beryllium windows), temperature distributions on mirrors and monochromator crystals, and stresses and surface distortions of optical elements.

These computer programs were also used in the design of a water-cooled mirror for both the X-1 beamline at NSLS and the VUV branch of the LBL-Exxon beamline at SSRL (see Fig. 18). At SSRL the peak absorbed power density on the optical surface of this mirror is expected to be 5.2 W/mm², but a detailed analysis of the chosen geometry determined that the maximum surface slope error due to thermal distortion will be less than 300 μ rad. Each mirror was fabricated using a dispersion-strengthened copper alloy for high strength and high thermal conductivity. The polished surface, plated with electroless nickel, has irregularities of less than 10 angstroms (rms), which minimizes x-ray scattering.

The high flux from insertion device beamlines also demands new monochromator designs. Accordingly, LBL is developing a high-resolution spherical grating

Synchrotron Radiation Projects

Fig. 18. A water-cooled mirror, installed for testing on the X-17 undulator beamline at NSLS. This mirror will be permanently installed on the X-1 beamline, and a second will be used on the 54-pole wiggler beamline at SSRL.

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monochromator (SGM) that will first be used on the VUV branch of Beamline VI at SSRL. Special attention is being given to the factors that influence the resolving power of the monochromator: optical aberrations, fabrication tolerances for the spherical gratings, distortions due to thermal stresses in the grating, and the stability and alignment of the whole slit-grating-slit setup. As an example, we are establishing new standards for specifying and qualifying figure and microroughness tolerances. At LBL we carry out tests on the quality of witness samples and delivered end products, making microroughness and flatness measurements and performing thermal cycling tests. Thermal distortions are a particular concern. For this reason, we have used direct water-cooled metal grating substrates to minimize thermal deformation. This is the first time this technique has been applied to a VUV monochromator.

LBL's participation in the development of beamlines for SSRL also continued throughout 1986. Our effort on the VUV branch of the 54-pole wiggler beamline (Beamline VI), for example, is now well under way, paced by the developments in optical component and monochromator design already mentioned.

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ACCELERATOR OPERATIONS

... if the U.S. is to maintain its preeminence, a new medium-energy heavy-ion facility is needed; the upgraded Bevalac is such a machine ...

THE BEVALAC CONTINUES to play a unique role, both in the national nuclear science program and as a research facility for biological and medical research. Owing largely to the Bevalac's pioneering successes, especially in the field of relativistic heavy-ion physics, other heavy-ion synchrotrons and storage rings will soon be operational, including some whose aim is to push to much higher energies. Until at least the early 1990s, however, the Bevalac will remain a one-of-a-kind source of the heaviest ions at energies up to nearly 1 GeV/amu.

The idea of the Bevalac was born in the early 1970s, inspired by the proximity of two accelerators at LBL—the SuperHILAC, a linac capable of accelerating all elements to energies of 8.5 MeV/amu, and the Bevatron, a weak-focusing proton synchrotron with a rich history of discoveries in high-energy physics over nearly two decades. In 1974 these two machines were linked by an evacuated transfer line, thereby giving birth to the Bevalac. 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 seconds one

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184-Inch Synchrocyclotron

G. Hampton
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S.L. Baba
L. Kanstein
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C.R. Siero

Administrative Support

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K.E. Williams
E. Wise

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 1986, eighteen 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 stripped and fully stripped ions can be delivered.

Also during the past year, much of the work was completed on a project to increase fivefold the uranium output at the Bevatron by upgrading one of the SuperHILAC injectors, and work continued on a new drift tube magnet design for the SuperHILAC. Of more significance for the long term, however, was a preliminary design effort aimed at outlining a future upgrade of the Bevalac, involving mainly the replacement of the 30-year-old weak-focusing synchrotron with a modern strong-focusing machine. This effort was marked by a document entitled *The Bevalac Upgrade: A Preliminary Proposal*, published in March 1986. During the rest of the year, we continued work on clarifying the requirements of both nuclear science users and biomedical researchers and on refining the design.

During fiscal 1986, we delivered 3012 hours of beam time for nuclear science and biomedical experiments at the Bevalac, and another 1754 hours of beam to SuperHILAC users. Nearly 200 scientists, representing 46 institutions both here and abroad, participated in 52 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 4 summarizes Bevalac operations during fiscal 1986 and compares them with operations during 1985 and with projections for fiscal 1987. The 10% decline in research hours reflects the budget constraints of the past year. That we did as well as the table indicates is a tribute to continuing improvements in efficiency; the ratio of unscheduled shutdowns to research time at the Bevalac continues to decline. Operational efficiency during scheduled radiotherapy runs was also given a boost as the light-ion local injector became fully operational. Because of the special needs of the patient therapy program at the Bevalac, day shifts during the week have traditionally been reserved for this purpose. Parasitic beam time between patients, off-hour shifts during the week, and weekends have been shared between the nuclear science program and other biomedical experiments. With the "local" in place, neon can be delivered to the therapy program, while the SuperHILAC remains ready to supply heavier ions to nuclear science experimenters. A rapid switch of injectors, and changes to other accelerator parameters, now allow productive use of the time between patient treatments for the first time.

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, researchers at the Bevalac and SuperHILAC have formed users' associations that meet periodically to exchange scientific information and to convey their views to

Table 4. Operating summary for the Bevalac facility for fiscal 1985, 1986, and 1987 (projected).

	Fiscal year		
	1985	1986	1987
Bevalac operations (hours)			
Research	3353	3011	3100
Tuning	1079	968	800
Machine studies	204	215	215
Unscheduled maintenance	769	642	650
Scheduled shutdowns	3355	3923	3995
Total	8760	8760	8760
Beam utilization for research (hours)			
Bevalac nuclear science	2236	2044	2067
Bevalac biology/medicine	1117	968	1033
SuperHILAC	1950	1754	1800
Total	5303	4766	4900
Number of Bevalac and SuperHILAC experiments receiving beam	58	52	52
Number of participating scientists	199	195	195
Institutions represented			
Universities	25	26	26
National laboratories	5	5	5
Other	15	15	15
Total	45	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

LBL management. The members of the executive committees of the two users' associations for fiscal 1986 are listed in Table 5. Proposals for research time are submitted twice a 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 5, 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

J. Wefel, Louisiana State University (chair)
 D. Beavis, Brookhaven National Laboratory
 S. Fung, University of California, Riverside
 P. Lindstrom, LBL
 A. Mignerey, University of Maryland
 H.-G. Ritter, GSI

SuperHILAC Users' Association Executive Committee

W.-U. Schröder, University of Rochester (chair)
 J. Alexander, State University of New York at Stony Brook
 D. Dietrich, Lawrence Livermore National Laboratory
 G. Wozniak, LBL

Bevalac Nuclear Science PAC

P. Siemens, Texas A&M University (chair)
 P. Braun-Munzinger, State University of New York at Stony Brook
 H. Gutbrod, GSI
 T. Ludlam, Brookhaven National Laboratory
 H. Stöcker, Frankfurt University

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)
 G. Bertsch, Michigan State University
 H. Britt, Lawrence Livermore National Laboratory
 W. Meyerhof, Stanford University

Table 5. Membership lists for the Users' Association Executive Committees and the three Program Advisory Committees (PACs) for fiscal 1986.

During 1986 the focus of nuclear physics research at the Bevalac continued to be the study of nuclear matter under extraordinary conditions. High temperatures and pressures, for example, can be created in head-on collisions of nuclei, whereas grazing collisions frequently produce fragments containing extreme numbers of protons or neutrons. One of the ultimate goals of studying such systems is an equation of state for nuclear matter. To further the quest for such an equation, a major new detector, the Dilepton Spectrometer, has recently been constructed, and, as a result of a parallel effort, a conceptual design for a time projection chamber is nearing completion. Along somewhat different lines, projectile fragmentation studies continue to reveal detailed information about unstable nuclei and to elucidate the details of the fragmentation process itself. In addition, pion studies continue to play a major role in the Bevalac experimental program. At the SuperHILAC, reaction mechanism studies remain the largest area of interest, followed by atomic physics studies, the production of exotic nuclei, and nuclear structure studies. 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 detailed understanding of radiation biophysics and radiobiology. The broad scope of this latter effort includes radiological physics, radiation chemistry, cellular and molecular biology, experimental tumor radiobiology, studies of the responses of animal tissues to radiation, and radiation carcinogenesis.

Research by Accelerator Users: Highlights

Nuclear Physics

The central theme of the heavy-ion research program carried out at the Bevalac continues to be the production and study of "extreme conditions" in nuclear matter. These studies can take a variety of forms. For example, in head-on collisions between nuclei at the Bevalac, unique, but short-lived ($\tau \sim 10^{-23}$ seconds), nuclear systems can be created at high temperatures (in the range of 50–100 MeV) and high densities (twice to four times normal densities). Studies of this nature allow us to probe the nuclear equation of state in regions not accessible in the ground or excited states of nuclei. Apart from the intrinsic interest of high-density nuclear matter and the interplay between the fundamental forces in the nuclear environment, the behavior of such matter determines the dynamical evolution of stars and necessarily played a role in the formation of the elements from the time of the original Big Bang. Thus, these experiments open a rare window, allowing us to glimpse both the large and the small of our universe.

Complementing this area of research are studies of grazing collisions between nuclei. Such studies at the Bevalac provide a unique means for creating nuclear fragments containing extreme numbers of protons and neutrons, enabling us to study ground-state nuclear matter out to the very limits of stability. In addition, other areas of the physical sciences benefit from the unique capabilities of the Bevalac, as evidenced by recent pioneering atomic physics studies of one- and two-electron uranium and the calibration program for detectors to be flown on balloons or in the space shuttle.

Nuclear Equation of State. Early results from the streamer chamber and the Plastic Ball gave us the first glimpse of the possible effects of nuclear compression on experimental observables such as pion production and the finite flow angle associated with matter streaming from the hot, compressed interaction region of two colliding nuclei. These measurements sparked a mini-renaissance in the theoretical community, and substantial improvements followed in the models used to extract the nuclear incompressibility constant from experiments. It is now felt that momentum-dependent nuclear potentials and a proper treatment of the absorption of hadrons in the nuclear medium must be critically evaluated before we take the next step toward obtaining a nuclear equation of state.

Improvements in theory often compel refinements in experimental measurements, if we are to distinguish between competing theories. For example, a recent transverse momentum analysis, applied to a sample of about five hundred 1.8-GeV/amu Ar + KCl streamer chamber events, found that the data could not be used to pin down the value of the nuclear incompressibility constant to better than $K \simeq 300 \pm 100$ MeV. Not only must the statistical sample of such events be dramatically improved, but the dynamical range of measurements in terms of particle energy and type must also be increased, before we can make further progress toward an equation of state. As a consequence, researchers at the Bevalac are now looking to a next-generation 4π electronic detector to replace the Plastic Ball and streamer chamber; studies center around a time projection chamber (TPC). Initial estimates call for such a detector to identify and measure most of the 200 or so mid-rapidity charged particles (p, d, t, ^3He , ^4He , $\pi^\pm$, $K^\pm$) produced at the Bevalac during each central Au + Au collision at 1 GeV/amu, as well as measuring K^0 's and Λ^0 's. The conceptual design for a TPC is nearing completion.

New Probes of the Equation of State. Two experimental approaches can be taken to study the nuclear equation of state. The first of these involves measuring as many of the particles as possible in a central collision. This program has been partially carried out with the streamer chamber and Plastic Ball detectors, and it will be pursued further with a future TPC at the Bevalac. The second approach is to limit one's attention to those few particles that are thought to be particularly sensitive to one or more phases of the collision process. Dileptons and kaons are in this class of experimental observables.

It is generally accepted that dileptons (at the Bevalac, e^+e^- production) probe

the hot, compressed phase of the collision process. Since leptons interact only weakly with matter, they exit the production volume without distortion and provide us with a new probe of the early history of the collision in which they were created. This is in sharp contrast to the strong scatterings and absorptions felt by pions, nucleons, and other light fragments liberated in the collision. To pursue this experimental approach, a major new detector called the Dilepton Spectrometer (DLS) has been constructed by a collaboration consisting of researchers from LBL, Johns Hopkins University, Louisiana State University, Northwestern University, UCLA, and Clermont-Ferrand II (France). An artist's conception of the DLS, located on Beamline 30 at the Bevalac, is shown in Fig. 19. The DLS consists of twin magnetic arms, each containing drift chambers for tracking and scintillation hodoscopes and highly segmented Cherenkov detectors for identifying electrons and positrons.

The DLS is designed to measure the e^+e^- mass spectrum from about 100 to 800 MeV. At Bevalac energies, there should be two sources of such pairs: (i) the cascading baryons in the hot, compressed phase (virtual bremsstrahlung $\rightarrow e^+e^-$) and (ii) pionic annihilation ($\pi^-\pi^+ \rightarrow \text{virtual photon} \rightarrow e^+e^-$). These two contributions provide quite different mass spectra. The DLS program will start with proton-nucleus studies in early fiscal 1987 and then move on to heavier projectile-target combinations. These studies will give us a new perspective on the process of central collision by selecting the early phase of the collision (cascading baryons) and, at the same time, allow us to look at the later stages (via pionic annihilation), and perhaps even provide new insights into the pion dispersion relation in hot, dense matter.

Kaons are strongly interacting hadrons and as such can suffer severe distortions through scattering and absorption processes in nuclear matter; nevertheless, their study does yield valuable new information regarding collision dynamics. In particular, experimenters using Beamline 44 as a secondary-particle channel are studying the production of K^- mesons by heavy ions, as a function of projectile mass and energy. Negative kaons are substantially below threshold at all Bevalac energies; therefore, production of K^- 's must proceed via some relatively cooperative nuclear effect, such as high Fermi-momentum tails or correlated nuclear clusters. By pursuing measurements to as low a bombarding energy as possible, one should enhance

Fig. 19. Artist's conception of the Dilepton Spectrometer, now in operation on Beamline 30. Electron-positron pairs produced in a segmented target are detected in the two arms, which comprise (i) a three-cell Cherenkov gas counter, (ii) a 16-element scintillation hodoscope, (iii) drift chambers and a magnetic dipole, (iv) a 20-cell Cherenkov gas counter, and (v) a large 16-element scintillation hodoscope.

these cooperative effects. In addition, recent theoretical estimates suggest that K^+ production at 800 MeV/amu would be a sensitive probe of the nuclear equation of state. However, owing to the extremely low expected cross sections for such processes, greatly enhanced beam intensities are required. This promising new territory of research thus awaits the Bevalac Upgrade (see page 43).

Projectile Fragmentation: Radioactive Beams and Nuclear Correlations. Continuing progress has been made in using the process of projectile fragmentation to produce and study beams of radioactive nuclei. This pioneering program has been developed and brought to fruition at the Bevalac by several Japanese groups. Both the HISS facility (Beamline 42) and the new Beamline 44 area are being employed. Interaction cross sections of unstable beams have already been measured, and nuclear radii were extracted for the first time in 1985 for ${}^6\text{He}$, ${}^8\text{He}$, and ${}^{11}\text{Li}$. Extensions of this technique will be the first to study the radii of unstable nuclei up to the *sd* shell, as well as measuring the energy dependence of the interaction cross section of unstable nuclei—particularly β -unstable nuclei.

The HISS facility has also been used to study the multifragment breakup of light projectiles such as ${}^{12}\text{C}$. These studies aim at understanding the fragmentation process by answering such questions as, Are these direct or indirect (intermediate-channel) processes? One way to gain some insight into the process is to measure the correlations among outgoing fragments. For example, Fig. 20 shows the effective mass correlation between a proton (*p*) and an alpha particle (α) from the fragmentation of ${}^{12}\text{C}$. The sharp peak is due to the continuum decay of ${}^5\text{Li}$. The observed width is only about 2 MeV—dramatic evidence of the power of the HISS detection system. These types of studies offer new ways of probing nuclear structure effects in the fragmentation process at both low and high energies.

Also in the area of projectile fragmentation, the necessary elements of a program to measure the magnetic moments of polarized unstable nuclei have recently been demonstrated on Beamline 44. Initial polarizations (using the tilted-foil technique) of about 1–2% have been observed for ${}^{39}\text{Ca}$ fragments from a primary ${}^{40}\text{Ca}$ beam. Experimental refinements will be necessary before a systematic effort can begin, but all the components for such an effort are in place.

Fig. 20. A plot showing the effective mass correlation of protons and alphas emitted in the fragmentation of ${}^{12}\text{C}$. The sharp peak at a mass corresponding to that of ${}^5\text{Li}$ indicates that such a species existed as a transient intermediate in the fragmentation process.

Pion Production. Pion studies continue to play a major role in the Bevalac experimental program. Pion abundances can provide insight into compressional effects, while the π^-/π^+ ratio in different regions of phase space can be used to test the role of the Coulomb force in nuclear collisions and $\pi^+\pi^+$ or $\pi^-\pi^-$ correlations (Hanbury-Brown/Twiss effect) can be used to measure the space-time structure of the pion-emitting source.

Early investigations involved relatively light systems (for example, Ca + Ca), which are now being replaced by pion experiments with much heavier projectiles. For example, significant Coulomb effects have been isolated in subthreshold pion studies in La + La collisions, a finding that equips us with an exciting new tool for understanding reaction dynamics in both peripheral and central collision processes. At higher energies, a two-component structure has been revealed in recent streamer chamber data for the La + La system. The first component is characterized by a temperature that can be associated with the production of Δ -isobars in these central collisions (that is, reflecting the kinematics of Δ -decay). However, there is a surprising similarity between the temperatures extracted from model calculations of the high-density phase of the collision and the slopes of the second component of the pion spectra. It is tempting to ascribe this second component to pions from the fireball-like stage of the collision. Continued theoretical and experimental efforts are needed to quantify these speculations. It is becoming evident, however, that with the unique heavy projectiles available at the Bevalac new insights into the collision process will be uncovered by studying pions.

Research at the SuperHILAC. Beams of heavy and 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 facility in the U.S. delivering microampere beams of xenon, rare earths, gold, lead, and uranium above the Coulomb barrier. Reaction mechanism studies, principally by outside users, take the largest share of machine time (about 45%).

The very fundamental process of kinetic energy dissipation among the various degrees of freedom available in a deep-inelastic reaction is still not understood and is therefore under study by several groups using different techniques. A new development at the SuperHILAC is the ability to determine the energy division in such reactions by measuring the multiplicity distribution of neutrons emitted from the primary fragments in flight. This is done by using a large detector tank of doped liquid scintillator, obtained from Oak Ridge by a University of Rochester group. Results from a first experiment indicate that at the times of neutron emission the energy is not divided according to the masses of the fragments; that is, the system is not in thermal equilibrium.

Another group, a collaboration between Carnegie-Mellon and the State University of New York at Stony Brook, has studied the correlations among light charged particles emitted in fusion reactions, using to good advantage inverse kinematics, that is, the bombardment of a light target with a heavy projectile. From their studies, they found the shape of the composite system to be prolate—and the more so, the larger the relative size of the smaller reactant. A different use of inverse kinematics involved the bombardment of ^{12}C by 8.4-MeV/amu ^{232}Th to study the fission of $^{244}\text{Cm}^*$. A radiochemical study years ago had found an anomalously high (though still very low) yield of light fragments in the fission decay of ^{241}Pu , leading to a suggestion that rare ternary fission events were involved. The present experiment showed these to be binary fission fragments, and such an increase in the binary yields is now expected on the basis of liquid-drop calculations and from effects of the $Z = 8$ and $Z = 82$ shell closures. These results again show the close connection between asymmetric (binary) fission and light-particle evaporation.

Atomic physics studies have now increased to the point that they share time equally with exotic nuclei production and nuclear structure studies, the other main programs at the SuperHILAC. Heavy-ion beams are used directly in beam-foil spectroscopy and for the study of excitation, ionization, and electron capture

processes with gaseous targets, while 4- to 5-MeV/amu uranium and gold beams are used to produce low-velocity (cold), highly charged ions in a gas target. Resonant transfer and excitation (RTE)—the capture of a bound target electron and simultaneous excitation of the projectile (an inverse Auger transition)—is a good example of the type of two-electron processes possible in energetic ion-atom collisions. Scientists from LBL, Western Michigan University, and a number of other universities and institutes in the U.S. and Europe are carrying on a very productive collaborative study of these and other excitation and electron capture and loss processes.

Work on nuclei far from stability has progressed greatly during the past year, in particular because of improvements to the spectroscopy facilities available to study the products obtained from the on-line isotope separator, OASIS. An interesting case was a collaborative effort by an Oak Ridge-LBL-University of South Carolina group on the β -delayed proton emitter ^{151}Yb . Their results pointed the way to an explanation for the discrete proton peaks seen in the β -delayed proton spectrum for this and other nuclei.

A collaboration between scientists from the University of Rochester, LBL, and the University of Uppsala continued its Coulomb excitation studies, using ^{136}Xe , ^{208}Pb , and rare-earth ion beams at the SuperHILAC, as well as beams available at Brookhaven, Rochester, and Uppsala. These studies make use of the new Rochester least-squares-fit Coulex code to yield essentially model-independent values for the (up to 200) matrix elements linking excited levels. Work on ^{248}Cm just published gives, for the first time, static quadrupole moments, not just to spin 2+ and 4+, but to 20+. These data provide a unique determination of the prolate, axially symmetric shape of this nucleus over the spin range measured and set severe limits on nuclear structure models.

Biology and Medicine

The biomedical research program at the Bevalac is at the forefront of radiation and structural biophysics, providing new information on the relationships between charged-particle energy absorption and biological effects. The program can be conveniently divided into two components. The most visible of these is the cancer radiotherapy program, which takes advantage of the Bevalac's unique ability to produce heavy-ion beams at energies and intensities sufficient to deliver therapeutically useful doses to deep-seated malignant tumors. The second component of the medical program is a broad research effort aimed at a more basic 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 is used in the radiosurgical treatment of inoperable intracranial arteriovenous malformations.

Medical Programs. The Bevalac radiotherapy program has demonstrated unequivocally that superior local cancer control can be achieved with heavy ions for small tumors in the eye and near the spinal cord or the base of the brain. The underlying reason is the sharply peaked energy-range relationship for charged particles, which permits the dose to be precisely localized. Since the Bevalac program began in 1975, about 550 patients have received partial or full-course radiotherapy treatments with various ions, primarily helium and neon, but also carbon and silicon.

The most definitive medical results have been achieved with helium, but there is reason to believe that carbon offers several clear advantages, including a reduced penumbra, less "range straggling," and the ability to verify the position of the Bragg peak by detecting the decay products of radioactive ion beams. It is further expected that for certain tumors at certain depths even heavier ions, such as neon, silicon, or perhaps argon, will produce superior local control. This expectation is based on both the excellent dose-localization properties of these ions and their enhanced biological effects, including their ability to kill hypoxic cells and their effectiveness on cells at all stages of the mitotic cycle.

Current goals of the radiotherapy program are to continue randomized trials with neon ions and to pursue further pilot studies with heavier ions, primarily silicon. The human diseases included in the present protocols are inoperable large-cell cancer of the lung and cancer of the prostate.

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

The first of these, radiological physics, contributes to our understanding of primary particle fragmentation in tissues, by means of both experimental measurements and the development of transport models. In a related vein, studies of the physics and chemistry of energy absorption in biological systems have increased our understanding of the mechanisms of radiation action. A significant current research program is concerned with the radiation-induced production of such chemical species as hydroxyl radicals, which may attack DNA molecules and cause genetic damage, leading to cell death, mutation, or cancer.

In the cellular and molecular radiobiology program, important studies have been conducted on the inactivation of cells irradiated and propagated *in vitro*, and inactivation cross sections have been determined in terms of nuclear size and the stage of the mitotic cycle. Of fundamental interest is the observation that the maximum level of relative biological effectiveness (RBE) occurs at a lower value of linear energy transfer (LET) for proliferative cells in normal tissues, such as intestine or bone marrow, than for cells irradiated and propagated *in vitro*. The goal of this and related programs is to learn more about the relationships between charged-particle track structure and biological effects by emphasizing studies at the molecular level. The essential experimental requirement is to vary the charged-particle track structure in a predictable manner by accelerating ions of different charges to the same energy. The effects being studied include DNA damage, cell killing, mutation, neoplastic transformation, and other nonlethal forms of cellular damage.

Our tumor radiobiology program is studying the effects of heavy-ion beams on a transplantable rat rhabdomyosarcoma (a cancer of striated muscle tissue). The objective is to determine the relative effect of various cellular processes on the response to both sparsely and highly ionizing radiation. The studies are designed to provide information on the time course and dose dependence of repopulation, repair of cellular damage, and rates of tumor regrowth. Another series of studies on tissues from experimental animals have been largely completed for neon ions, but more work is needed for silicon. Studies involving the plateau portion of the Bragg curve have yielded new information on the inactivation and repair of radiation injury in relation to LET. Major accomplishments included the demonstration that LET alone is an inadequate predictor of biological response and that particle mass, independent of LET, also has an effect, probably related to track structure.

Finally, our carcinogenesis program involves studies on neoplastic transformation of cell cultures and carcinogenesis in mice. The risk of radiation-induced cancer, mutation, and other deleterious late effects is a vital issue for occupationally exposed workers, both on earth and in space.

Bevalac Upgrade and Other Activities

The history of relativistic heavy-ion physics is essentially the history of recent nuclear physics research at the Bevalac. If the U.S. is to maintain its preeminence in this field, however, a new facility is required that will deliver ions at energies in the range of 1 to 2 GeV/amu, at much higher intensities than those now available at the Bevalac. Such a machine would complement a heavy-ion collider designed for much higher energies, now high on the agenda of the national nuclear science community. A preliminary proposal for an upgraded Bevalac answers this need for what should now be called a medium-energy heavy-ion facility. The upgrade would involve replacement of the current Bevalac with a modern, strong-focusing synchrotron (Fig. 21), but would make cost-effective use of the existing complex of injectors, shielding, experimental areas, and detectors. Concurrent with this long-range planning for continued productivity at the Bevalac, ongoing improvement projects progressed on schedule: Much of the work on upgrading the Abel injector at the SuperHILAC was completed, and new prototype drift tube magnets were completed and readied for testing.

Bevalac Upgrade

Within the past few years at the Bevalac, hot, dense nuclear matter was created in the laboratory for the first time. To continue the fruitful exploration of nuclear matter under extraordinary conditions, however, new machines are needed. One such machine would be a collider providing heavy-ion beams at extreme relativistic energies. Such a collider has already been proposed for construction by the Brookhaven National Laboratory. A complementary machine would be a fixed-

Fig. 1. Plan view of the upgraded Bevalac.

target synchrotron, operating in the energy range of today's Bevalac but providing beams of much higher intensities. Such a machine is the upgraded Bevalac.

In addition to enhancing beam intensities by two to three orders of magnitude, the upgraded Bevalac would offer several secondary advantages over the current machine:

- High-intensity beams of secondary radioactive nuclei would become available for the first time.
- Beam quality and microscopic time structure would be significantly improved relative to present performance.
- Macroscopic duty factors could be increased to almost 100%, up from 20% now.
- Operational flexibility, reliability, and economy would be greatly improved.
- Pulse-to-pulse switching would make the nuclear physics and biomedical programs essentially transparent to each other.

Figure 22 illustrates the anticipated improvements in intensity and utilization efficiency.

The upgraded Bevalac, as currently conceived, is shown in Fig. 21 (we have continued to refine the preliminary design first presented in March 1986). An abbreviated list of parameters appears as Table 6. In Fig. 21, a modern synchrotron is shown within the existing Bevatron shielding, representing a low-cost option compared with larger-circumference designs. With this design, 100-fold intensity increases are foreseen, owing to increased injection efficiency, rf capture, extraction efficiency, and cycling rate.

The 24 bending magnets (12 with a 3.73-meter effective length, 12 with a 1.43-meter effective length) provide a 22 cm $\times$ 7 cm good-field region for the injected beam, with sufficient clearance for a cryogenic vacuum chamber. The maximum dipole magnetic field is 1.7 T, and 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 been modeled after the successful Bevatron design to assure a maximum pressure of 10^{-10} Torr. A final crucial element in the envisioned 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 operation of the SuperHILAC serves as a model for the future operation of the upgraded Bevalac.

Circumference (m)	136.0
Maximum rigidity (T-m)	17
Maximum intensity for light ions (s^{-1})	10^{11}
Mass range	protons to uranium
q/A range	0.168 to 1
Maximum dipole field (T)	1.72
Vacuum (Torr)	1×10^{-10}
Minimum cycle time to full field (s)	1.15

Table 6. Major parameters for the proposed Bevalac Upgrade. This list reflects values that were published in the *Conceptual Design Report* in February 1987.

During 1986 much of the work was completed on the project to increase the uranium output at the Bevatron by a factor of five, to 5×10^7 ions per pulse. The parts of the project completed by the end of fiscal 1986 included improvements to the vacuum system in the injector upstream of the Wideröe linac, installation of two new 70-MHz bunchers and one new 23-MHz buncher to increase the amount of beam accepted by the Alvarez and Wideröe linacs, and addition of a "bouncer" to the Cockcroft-Walton power supply to enable the acceleration of the increased

Accelerator Improvement Projects

Fig. 22. Schematic illustrations of both the intensity increase and enhanced flexibility expected in the upgraded Bevalac. In the upper plot, maximum beam intensity is plotted as a function of mass number for beams delivered during fiscal 1986 and for beam that would be available following the SuperHILAC intensity upgrade (now in progress) and the Bevalac Upgrade. The lower plot illustrates the projected improvement in pulse-switching capability.

XBL 874-896B

CURRENT OPERATION

UPGRADED BEVALAC

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current expected from the new metal-vapor vacuum arc (MEVVA) ion source. Magnets to transport the MEVVA beam into the injector have been completed, and final installation of the MEVVA source is expected during 1987.

Regarding the MEVVA itself, development continued in several directions. The maximum extraction voltage was increased to 100 kV, the voltage that will be used at the SuperHILAC. A new version of the source (MEVVA IV, shown in Fig. 23) was also fabricated, in which 16 cathodes—of the same or different materials—are mounted. This allows cathode materials to be changed or cathodes to be refreshed with minimum downtime. We also increased the maximum repetition rate for the source to 30 pulses per second. In addition to its anticipated use as an ion source for the Abel injector, small MEVVA sources are in use at Livermore and at Cornell, and we have done some preliminary work to demonstrate its utility in the area of metallurgical ion implantation.

As part of a project to upgrade the drift tube focusing magnets of the SuperHILAC, we have constructed a new prototype permanent-magnet quadrupole, having adjustable field strength. As shown in Fig. 24, the unique feature of the magnet design is the rotatable outer ring of iron and samarium-cobalt, which serves to vary the quadrupole magnetic field. In contrast to previous designs, this prototype uses ball bearings in place of slide bearings to eliminate mechanical failures. These magnets are intended to increase the focusing strength in the SuperHILAC prestrip-
per section, thus increasing the transmitted intensity of high-mass beams.

Fig. 23. MEVVA IV, the latest of the innovative high-current metal-vapor vacuum arc ion sources. This version has 16 cathodes in a "Gatling gun" arrangement, which allows rapid replacement of old cathodes or changes in cathode material.

Fig. 24. A prototype of an adjustable permanent-magnet quadrupole, developed for use as a drift tube magnet at the SuperHILAC. The field in the beam aperture is shaped by the four iron pole pieces visible in this photograph. Permanent-magnet material placed in the areas between the poles, as well as inside the rotatable outer ring, can be used to change the strength of the field.

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Publications and Presentations

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HIGH-ENERGY PHYSICS TECHNOLOGY

*... between the
Tevatron of today and
the linear colliders of
the 21st century lies
the SSC, the focus of
most of our efforts ...*

OUR SUPPORT of the high-energy physics community has several aspects, ranging from activities at the Tevatron, the highest-energy machine in operation today, to exploratory research on linear colliders of the distant future. Between the present and the 21st century, however, lies the Superconducting Super Collider (SSC), currently the top priority of the nation's high-energy physicists and the focus of most of our efforts in this field. In particular, we continue to play leading roles in the development of high-field superconducting magnets and in accelerator physics studies at the SSC Central Design Group.

Our superconducting-magnet program has a quarter-century-long history of magnet development, the broad aim being to develop practical accelerator-type magnets with the highest possible fields. Activities over the past years have encompassed studies of several superconducting materials and a variety of magnet designs, and our achievements have included record magnetic fields. During 1986, however, all of our work in this area—even that with further-reaching implications—was dominated by the imminence of the SSC. Such activities included continued design and testing of 1-meter-long model dipoles, the design of SSC quadrupole magnets, and the development of much-improved superconducting cable. Even more tightly tied to the SSC effort was the work of AFRD accelerator physicists assigned to the SSC Central Design Group, where their most visible achievement was their significant contribution to the SSC conceptual design report, published in March 1986.

Looking even further to the future is our ongoing development—including successful experimental tests—of the concept of the Two-Beam Accelerator (TBA), a high-gradient linac that would be powered by microwaves from a free-electron laser (FEL). The impetus for this program is the axiom that, beyond the SSC and Europe's LEP, higher energies

Superconducting Magnets

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demand a new technology—in particular, a way of generating high accelerating gradients in a linear collider. During 1986 the TBA effort was marked by the fabrication of prototype hardware and by continued successes in coaxing high power from a microwave FEL.

Also part of our program of support for high-energy physics during the last several years has been our work on a stochastic antiproton-cooling system for Fermilab's Tevatron. Having successfully installed a system that operates at 4 GHz, we worked during 1986 on pushing the frequency to 8 GHz, as part of an effort to produce a fourfold increase in antiproton flux.

The past year was highlighted by the continuing success of the magnet-testing program, as well as a revised design for the main SSC dipole magnets and a new design for the quadrupoles. A significant innovation in the program of testing 1-meter-long model magnets was the addition of a preconditioning step at 1.8 K—a preliminary step that effectively eliminated the "training" behavior usually seen when the magnets are tested at 4.4 K. Models incorporating fine-filament superconductor were also tested successfully, and the expected reduction in undesirable magnetization effects was observed experimentally for the first time. Concurrently with the magnet design and testing efforts, we continued our program to develop better superconducting cable for the SSC. By fiscal year's end, current densities of 3800 A/mm² had been recorded in Nb-Ti wire (almost 40% above the value specified for the SSC conceptual design), and one manufacturer had produced fine-filament wire with a current density above 3400 A/mm².

Dipole Design. As the single largest contributor to the cost of the SSC, the dipole magnets have been a focus of R&D effort for several years. Even apart from their cost, the dipoles warrant close design attention: The strength of the dipole field ultimately determines the size of the collider rings, and the uniformity of the dipole field strongly influences the lifetime of the stored beams. Nearly 8000 dipoles must be manufactured to close tolerance, and over its 20-year life, each magnet must be expected to survive 10^4 acceleration cycles, about 20 warm-up and cool-down cycles, and a significant radiation dose. During the past year, with these requirements in mind, we redesigned the SSC dipole, giving particular attention to the demand for field uniformity. This new design, shown in Fig. 25a, is a four-wedge design (so-called because of the number of spacer wedges in each quadrant of the cross section), in contrast to the previous three-wedge design.

Like previous designs, the magnet is 17 meters long and consists of two layers of superconducting Nb-Ti cable, clamped with stainless-steel collars (though we have now developed an aluminum alloy collar that gives better support at lower cost). The collared subassembly is then held in an iron yoke. The coils of the magnet will be wound on automated winding machinery and then formed to a precise size in a molding operation in which the epoxy in the epoxy-impregnated cable wrap is cured to form a rigid structure.

Magnet Testing. The choice of the four-wedge dipole design followed the development of improved analytical tools for appraising different magnet designs. Ten 1-meter-long test dipoles were then built and tested. Figure 26 shows the results of these tests, together with the last two tests of the older three-wedge dipole design (C7 and C8). These results confirmed theoretical predictions and affirmed the reliability and accuracy of the analytical techniques we had developed.

Figure 26 also illustrates another development of the past year, namely, the addition of a preliminary low-temperature conditioning step to the "training" pro-

Superconducting Magnets

Magnet Development for the SSC

Fig. 25. Cross-sectional views of the SSC dipole magnet design (a) and the quadrupole design (b). The photographs of the collared coils were obtained from model magnets, which had been sectioned as part of our magnet "autopsy" program.

gram of the model magnets. Without this step, a magnet at its operating temperature of 4.4 K will typically reach higher and higher fields during successive trials, each trial terminated by a "quench," in which the coils cease to be superconducting. The accepted hypothesis is that these training quenches are caused when small field-induced mechanical movements within the conductor cause enough frictional heating to initiate a sudden local transition from the superconducting state to a normal state. After a series of such quenches, a fully trained magnet emerges. If,

Fig. 26. Training curves for the 12 model dipoles tested at LBL during fiscal 1986. The solid circles and triangles indicate the magnetic field at which a quench occurred at 4.4 K. Eight of the magnets were conditioned at 1.8 K, a step that effectively eliminated the training behavior seen in the other magnets.

on the other hand, the magnet is first energized to a high field at 1.8 K, the mechanical settling-in associated with training occurs without causing a quench; the lower temperature provides the margin of safety necessary to preserve the superconducting state. Eight of the magnet tests shown in Fig. 26 included a low-temperature conditioning step.

A final feature of Fig. 26 is the increase in the maximum field achieved with the last four magnet models, as compared with the earlier ones. This improvement can be attributed largely to advances in superconductor development (see also below). The coils of these four models were fabricated from experimental fine filaments of Nb-Ti having diameters of 5–8 μm . In addition to reaching maximum central fields of 6.9–7.0 T at 4.4 K (and 9 T at 1.8 K), these magnets confirmed our theoretical expectation that magnetization effects would be reduced with the finer filaments. (These undesirable effects result from currents induced in the wire by the dipole magnetic field; since the wire is superconducting, the induced currents persist and thus produce significant field distortions at low fields.)

In concert with our magnet-testing program, we developed a powerful method for determining the unavoidable distortions to the magnet cross sections introduced by the manufacturing process. In this "autopsy" procedure, a mechanical model, or a complete magnet (after testing), is cut into transverse sections, and the positions of individual cable turns, and even individual strands, are measured with a digital encoder. The digitized data are then used to calculate the deviations of these positions from the idealized positions, and to estimate the effects of these deviations on the uniformity of the magnetic field. This information, in turn, has directed our efforts to develop manufacturing processes that minimize coil distortions.

Quadrupole Design. During 1986 we also finalized the design of the quadrupole magnets adopted for the SSC conceptual design. The two-layer magnet design is shown in Fig. 25b. It is based on the same 30-strand cable developed for the outer layer of the dipole magnet, and when powered in series with the dipoles, the quadrupole field gradient is 230 T/m. Before building a working model, we constructed several mechanical models of this magnet to verify the correct conductor placement. The first model magnet tests are scheduled for fiscal 1987.

Superconductor and Cable R&D

During fiscal 1986, efforts continued in our program to demonstrate that a fine-filament Nb-Ti superconductor could be fabricated, without significant sacrifice in critical current density. To this end, LBL directed the efforts of several industrial vendors, using different manufacturing approaches. Before year's end, one of these approaches produced several billets of wire with $J_c > 2750 \text{ A/mm}^2$, including one with $J_c = 3450 \text{ A/mm}^2$ (see Fig. 27). This successful approach involved an extension, simple in principle, of the standard process of producing multifilamentary wire. Rods of copper-sheathed Nb-Ti are packed into a copper extrusion can, or billet, then extruded at an elevated temperature to produce a rod several centimeters in diameter. This rod is then drawn in a series of steps to its final diameter. A single billet can thus produce a hundred thousand meters of wire in which each Nb-Ti rod has become a single tiny filament.

To produce fine-filament wire, in which the filaments have a diameter of only a few micrometers, the billet must be packed with thousands of Nb-Ti rods. In addition, to prevent deleterious reactions between the titanium in the superconductor and the surrounding copper matrix, each rod must be surrounded by a "diffusion barrier" of niobium (or some other nonreactive metal). Figure 28 is a photomicrograph of the filaments in a sample of superconducting wire that was manufactured by this method.

At the same time that work continued on producing high- J_c wire, we put

Fig. 28. Scanning electron photomicrograph of the Nb-Ti filaments in a sample of superconducting wire. Each filament is surrounded by a non-reactive "diffusion barrier," which prevents the formation of intermetallic compounds of titanium and copper. In this photograph, the copper matrix has been etched away.

increasing emphasis during 1986 on the optimization of other, equally important parameters. For example, cable-fabrication techniques were improved to the point that critical current degradation was reduced from the 10–15% range (typical of cable fabricated in fiscal 1985) to about 5%. More broadly, we identified several mechanical characteristics of the superconductor strands that are especially important in the fabrication of cable with satisfactory mechanical properties. Surprisingly, some superconductor that meets the stringent ductility requirements for strand fabrication fails to meet similar requirements for cable fabrication. Because of the complex combination of tension, torsion, and bending that occurs during the cabling process, we have devised an additional screening test to characterize unacceptable material. In addition, we have devised a test that predicts whether or not a strand will produce an acceptably flat cable after fabrication. This test is being used to guide our development of strand geometries and processing conditions.

Finally, our accumulated experience with cabling has been used to prepare specifications for a prototype production cabling machine. These specifications have been discussed with cabling machine manufacturers, and we plan to order such a machine during 1987. This machine will provide cable for SSC model magnets during the continuing R&D phase and then be used as a model for the production machines needed for the manufacture of SSC cable.

SSC Central Design Group Activities

During the past year, AFRD scientists continued to play leading roles in activities at the SSC's Central Design Group, headquartered at LBL. For the first half of the fiscal year, most of these activities were geared toward completion of a detailed conceptual design report (CDR) for the SSC, which was published in March 1986. Division physicists and LBL engineers were, for example, responsible for the method adopted to estimate the total cost of the SSC (\$3 billion in 1986 dollars). They also played (and continue to play) a major part in accelerator physics studies, including lattice design, evaluation of beam instabilities, and estimates of beam lifetime.

Conceptual Design Report

The central purpose of the SSC is to produce reactions among the elementary constituents of matter at the highest possible energies. As summarized in the CDR, its primary design parameters remain unchanged: Proton beams are to be brought into collision at six interaction points, at a center-of-mass energy of 40 TeV, in such a way as to produce a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. Unlike the earlier reference design, however, the conceptual design has the interaction points clustered, two near the injector complex and four on the opposite side of the ring (see Fig. 29). As a consequence, the ring is now somewhat elongated, rather than circular. The circumference is 83 km.

The SSC injector system has also been redesigned. It now consists of a source and linear accelerator, followed by a cascade of three booster synchrotrons, which successively bring the protons up to 7.1, 100, and 1000 GeV. The final booster synchrotron makes use of superconducting magnets; the others use conventional copper and iron magnets to permit rapid cycling. The collider itself comprises two rings of superconducting electromagnets (as described in the previous section), one

Fig. 29. Schematic layout of the SSC. The collider ring, 83 km in circumference, contains two counterrotating beams of protons, which are made to collide at six locations around the ring (only four of which will be developed initially).

above the other, in an underground tunnel. Nearly 8000 dipoles and 2000 quadrupole magnets will be required in these two rings. The CDR that describes this detailed design was reviewed in depth by various DOE offices and their consultants. The reviews confirmed that the comprehensive technical design is sound and achievable within the projected costs and schedules.

While the CDR cost estimate details for the various technical and conventional systems of the SSC were developed by many individuals, the overall methods were the responsibility of LBL team members. In particular, we developed a comprehensive work breakdown structure (WBS), encompassing all aspects of the construction project. The WBS, together with appropriate cost-estimating guidelines and computerized data assembly, provided for the assembly, tracking, and analysis of all cost and schedule details. Ongoing related efforts include the development of a management information system appropriate for the SSC construction project itself. Such a system will be necessary to coordinate all project working groups and to integrate cost, schedule, and performance data from these groups so as to maintain an always-current picture of the project status.

The main emphasis of the SSC accelerator theory group's work during much of the past year was also the CDR. AFRD members of this group were instrumental in many areas, in particular, the design of the SSC lattice, studies of the beam's dynamic and chromatic behavior (which dictate allowable tolerances on systematic and random magnetic multipole errors), and investigations into beam instabilities and beam lifetime.

The lattice design effort was planned so as to serve two purposes: (i) to investigate general issues, such as cell structure and the optics of the interaction regions, and (ii) to provide a general lattice, containing all the essential elements, that could be used to study overall accelerator physics issues relevant to the CDR. The resulting lattice contains eight "insertions": two low- β interaction regions; two medium- β interaction regions; two utility insertions for injection, extraction, and rf cavities; and two insertions for unspecified future requirements.

Theoretical studies of beam dynamics and instabilities included simulation studies of coherent beam-beam effects, investigations of power losses due to mechanisms such as parasitic modes in rf cavities and other components, and studies of the effects of space-charge forces. Another important beam dynamics issue for the SSC is the limitation imposed on the beam current by the onset of coherent instabilities. Such instabilities are driven by the electromagnetic coupling of the beam with various elements in the beam chamber, including rf cavities, beam collimators, and beam-position monitors. (Other contributors to the coupling impedance are the resistive wall of the vacuum chamber, space charge, and coherent synchrotron radiation.)

Based on our evaluation of these interactions, the various single-bunch and coupled multibunch collective instabilities (both longitudinal and transverse) were estimated for the SSC. The accelerator physics code ZAP, developed at LBL, was used extensively in computing the growth rates, coherent frequency shifts, and Landau damping rates for these instabilities. In particular, the task of computing the fastest growth rates and Landau damping rates for the very many possible coherent normal modes of the SSC beam (there are about 16,600 circulating bunches, hence an equal number of coherent modes in any degree of freedom) was handled by ZAP. The results provided the input for designing the transverse and longitudinal dipole feedback systems for the SSC.

Intrabeam scattering (that is, multiple small-angle Coulomb scattering of particles within a bunch) and large-angle Coulomb scattering within a bunch (Touschek scattering) were also studied using ZAP, but neither was found to have an important impact on beam lifetime. On the other hand, investigations into the effect of noise in the rf system on the longitudinal phase space of the beam indicated the need for rf phase feedback systems.

Accelerator Physics

Beam Cooling

The technique of stochastic cooling is applicable to particles such as antiprotons circulating in a ring. Sensitive electrodes pick up from each passing particle the tiny signal indicating its deviation from the mean transverse position and velocity of the beam. That signal is then amplified and transmitted along a chord of the ring (while the beam follows a longer arc) to a kicker electrode, which applies a corresponding corrective impulse to the errant particle. Our principal activity during 1986 was to design and test components for a higher-frequency cooling system, which could significantly increase the cooling rate at Fermilab's Tevatron and quadruple the available beam flux.

The rate of proton-antiproton collisions in the Tevatron increases with the density and number of antiprotons that can be collected and concentrated by the stochastic beam-cooling system. The rate at which this cooling can proceed is limited by the presence of noise in the weak detected signals and by the width of the frequency band passed by the electrodes, which now extends up to 4 GHz. To produce a fourfold increase in cooled antiproton flux, our group is trying to design pickups that operate up to 8 GHz and have twice the signal strength per unit length of beam tube. Aided by computer modeling of lower-frequency responses, we have now generated a promising new electrode geometry. Using hardware models, however, we have also uncovered variations in gain and phase at frequencies above 6 GHz—variations that, while anticipated, are unpredictable in detail. At these high frequencies, electromagnetic fields can propagate in waves through the open beam aperture. The goal of this ongoing program is to devise an acceptable design that deals with these effects.

Building on our experience with the sensitive electronics required for beam cooling, we are now developing a Schottky beam monitor for the Tevatron. If sufficiently sensitive and free of interfering signals, a beam pickup can provide the Schottky spectrum for the circulating particles, which describes deviations from the mean motion of the circulating beam, thus making available information about any degradation in the all-important beam density. For this purpose, a narrow-band 2-GHz cavity resonator, with associated electronics, has been constructed and installed in the Tevatron. It will be studied to learn if this approach provides a useful signal, free of the coherent beam signals that plague lower-frequency monitors.

Two-Beam Accelerator

The concept of the Two-Beam Accelerator (TBA) continues to look like the most promising of many innovative ideas for pushing accelerator technology beyond the SSC. All such new ideas share a common premise, namely, that circular machines larger than the SSC are likely never to be built and that linear machines operating at accelerating gradients now available would likewise be impractically large and expensive. The goal then is to develop a way to produce much higher gradients as the basis for a linear collider of reasonable length. In the TBA, a free-electron laser (FEL) is the source of power, in the form of high-power microwaves. These microwaves would be coupled to an adjacent traveling-wave structure, where they would produce a longitudinal accelerating gradient at least ten times as high as those now practical. Recent success in generating high gradients in test structures and in producing over a gigawatt of microwave power from an FEL confirm the promise of the TBA.

Experimental Progress

In a schematic sense, the TBA consists of (i) an FEL, which, among other things, must be shown to be an efficient source of high-power microwaves; (ii) a high-gradient structure, which must be shown capable of sustaining a high accelerating gradient (as well as being compatible with large-scale manufacturing techniques);

and (iii) a means of efficiently coupling the FEL output power to the linac structure. The past year saw progress on all fronts.

Free-electron laser experiments continued through much of 1986 at the Lawrence Livermore National Laboratory's Electron Laser Facility (ELF), which uses a 3.3-MeV, 1-kA electron beam generated by the Experimental Test Accelerator there. In previous experiments, we amplified a 50-kW input microwave signal (at 35 GHz, or 8.6 mm) to 180 MW and, furthermore, showed that this power level was reached in the first 1.4 meters of a 3-meter-long undulator. An effect called "saturation" (see page 16) prevented the amplification process from continuing throughout the length of the undulator. We have now overcome the problem of saturation by "tapering" the wiggler, that is, by reducing the downstream magnetic field so that the oscillating electron beam remains in resonance with the radiation it produces. As a consequence, we have now amplified 15-ns microwave pulses to 1.8 GW, which represents an efficiency of 40% in converting electron beam kinetic energy into electromagnetic energy.

Complementing these successes with the FEL, we tested seven-cavity prototype high-gradient structures at ELF in 1985 and produced accelerating gradients up to 180 MV/m. New 34-cavity accelerator sections were fabricated in 1986 (see Fig. 30), both by electro-forming techniques and by brazing. These sections will undergo a thorough high-temperature bakeout and will be tested at high vacuum—steps that were not possible with the smaller structure, owing to time constraints. Accordingly, we expect to demonstrate significantly higher gradients with these new structures.

If the TBA is to prove practical, a significant fraction of the FEL microwave power must be extracted periodically and coupled to the adjacent accelerator structure. (The energy of the electron beam in the FEL, meanwhile, will be replenished by conventional induction modules.) During the past year, we fabricated a prototype septum coupler (see Fig. 31) and carried out some preliminary tests on it. The septa of the structure function as "scoops" designed to gracefully remove a fraction of the microwave power. Our first tests have suggested two modifications to the

Fig. 30. A prototype accelerating structure for the TBA; this prototype has 39 cavities, though the design scheduled for high-gradient tests has only 34. A similar seven-cavity structure achieved an average accelerating gradient of 180 MV/m in 1985, despite the lack of preconditioning.

Fig. 31. A prototype septum coupler, similar to the hardware that might be used in a TBA to extract microwaves from the FEL.

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prototype design. First, modifications to our fabrication techniques will be necessary to avoid sparking at high fields, and second, changes in the details of the septum configurations will probably be necessary to ensure that equal amounts of power are extracted into each waveguide. With our first design, the predicted fraction of power was extracted by the first pair of septa, but the fraction diverted by the second pair was considerably reduced.

For the future, a preliminary proposal has been prepared that would culminate in construction and testing of a 30-meter model TBA with the parameters listed in Table 7.

Theoretical Considerations

As the concept of the TBA matures, increasing theoretical attention is being paid to issues that must be confronted in a full-scale collider. For example, Can an FEL be operated in a "steady-state" mode, in which energy would be pumped in and removed essentially continuously? The answer to this question is, apparently, yes. In a careful simulation study of longitudinal dynamics in a steady-state FEL, we found essentially no particle loss. When followed through several periods of such an FEL, a single particle executes a rather complicated trajectory in phase space, with discontinuous jumps occurring as its energy is boosted by the induction modules; nonetheless, an ensemble of particles remains stable over many meters.

Length (m)	30
Accelerating gradient (MeV/m)	250
Waveguide dimensions (cm)	5×2
High-gradient structure filling energy (J/m)	10
Wavelength (cm)	1.0
Relativistic factor, γ	10
Undulator wavelength (cm)	16
Undulator field parameter, a_u	2.3
Relativistic factor change (m^{-1})	0.55
Current (kA)	2.0
Pulse length (ns)	18
Standing power in FEL (GW)	2.0
Induction unit spacing (m)	2
Synchrotron period, Ω_s/c (m)	4.3
RF field parameter, a_r	0.06

Table 7. Parameters for a proposed 30-meter-long test model of the Two-Beam Accelerator.

The issue of sideband growth has also received considerable attention. The potential problem is that, 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. This phenomenon has now been studied in some detail: We understand its origin, and we have worked out the theoretical relationship between sideband growth rate and frequency on the one hand, and such parameters as waveguide cross section on the other. Theory does not, however, satisfactorily answer such crucial questions as how the growth rate decreases as the sideband frequencies move away from the fundamental.

A third challenge facing a full-scale TBA—and perhaps the most daunting—is in the area of phase stability and control. During the past year, we completed a study of the sensitivity of the microwave phase to errors or variations in microwave frequency, undulator magnetic field strength, FEL beam current, and FEL beam energy. The results indicate that even very small deviations in these parameters produce unacceptably large phase errors. The phase is especially sensitive to variations in beam current. To overcome this practical problem, we have explored several feedback schemes, including the use of ferrites or ferroelectrics in the waveguides. The idea is to partially fill the waveguides with a material whose magnetic or electric properties can be readily changed. A signal that is proportional to phase error could then be used to modify the phase velocity of the electromagnetic wave in the waveguide.

Still other studies have focused on wake effects, which appear not to pose a serious problem; improved capture in the initial section of a TBA; and transverse effects in a steady-state FEL. Though no problems are anticipated, this last topic, in particular, warrants further study; no careful attention has been given, for example, to the design of the FEL reacceleration units or to the beam dynamics of the electrons passing through them.

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HEAVY-ION FUSION ACCELERATOR RESEARCH

*... our plans for
exploring the physics
and technology of
induction linacs
involve a series of
increasingly
sophisticated
experiments ...*

THERMONUCLEAR FUSION offers an attractive long-term solution to the problem of future energy supplies: Virtually inexhaustible supplies of fuel are available, fusion products are notably free of the long-lived actinides generated by fission power sources, and meltdowns cannot occur. The technological challenges, however, are profound, both for magnetic-confinement fusion (see pages 77-86) and for inertial-confinement fusion (ICF), in which enormous amounts of energy must be focused on tiny pellets of fuel. Notwithstanding the challenges, the promise of ICF has prompted active research programs aimed at developing high-power lasers and light- and heavy-ion accelerators as the "drivers" that would compress and ignite the deuterium-tritium fuel.

Our effort at LBL is concentrated on drivers based on heavy-ion beams (which can be produced reliably and efficiently at high repetition rates)—in particular, on heavy-ion induction linear accelerators. The attractions of this latter concept, in comparison with the heavy-ion rf linacs being studied in West Germany, Japan, and the USSR, are (i) its simplicity (see Fig. 32), (ii) the considerable experience accrued in its application to high-current electron-beam acceleration, and (iii) the ease with which it can be extrapolated to large facilities on the basis of experiments with smaller test accelerators.

In line with this last point, our current plan for exploring the physics and technology of induction linacs involves a series of increasingly sophisticated experiments. The first, which continues to yield results of fundamental significance for our understanding of high-current heavy-ion beams, is the three-year-old single-beam transport experiment (SBTE). Second is the multiple-beam experiment (MBE-4), the apparatus for which is now nearing completion. In this experiment, we are already exploring the physics of four independent beams as they are accelerated and transported through a multigap accelerating structure. Most significantly, we have already demonstrated the novel feature of current amplification, which will be required in a driver. Finally, we have proposed a much

Experiment

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Fig. 32. Simplified schematics of rf and induction linacs, illustrating the principles by which each might produce the high-current beams of heavy ions required for fusion energy applications. (In each case, the illustration depicts only a single beam on target; about 16 would actually be required in a driver.) The length of the arrows representing the ion beams signifies the physical length of the ion bunch, the height of the arrows indicates the kinetic energy per ion, and the thickness represents total current. Current is amplified in the rf linac scheme by use of multiple transfer, storage, and bunching rings; in the induction linac, it can be done by shaping the accelerating voltage pulses in a series of perhaps several thousand induction modules.

larger Induction Linac System Experiment (ILSE), which would address the main physics and technology issues of a full-size heavy-ion fusion reactor driver, at about a one-tenth scale for many key accelerator parameters.

During the past two years, we also took part in a broad assessment of heavy-ion fusion as a prospective source of electrical power. Several reactor types and target designs were considered, and the results were encouraging: The cost of electricity, based on a 1000-MWe power plant, was estimated to be about 5.5 cents/kW-hr. Though independent of our accelerator research program, this study provides a firm underpinning for our continuing efforts.

Multiple-Beam Experiment

By far most of our activities during 1986 were centered around MBE-4. Though on a much smaller scale, this four-beam experiment is being conducted to model many of the same phenomena we might expect to encounter in any eventual heavy-ion fusion driver—in particular, the consequences of approaching stability limits imposed by the mutually repulsive charges in a high-current ion beam. By fiscal year's end, about half of the MBE-4 apparatus was in place, and owing to its modular design, we were able to conduct experiments concurrently with fabrication. Perhaps the most significant of these experiments successfully demonstrated appreciable amplification in beam current, achieved by suitably shaping the accelerating voltage pulses and thus actually reducing the pulse duration during acceleration.

Conceptual Basis for MBE-4

An induction linac driver can be envisioned as a transport lattice comprising many closely packed channels in which parallel "beamlets" of heavy ions are accelerated. Surrounding the lattice are massive induction cores of ferromagnetic material, along with the pulser circuitry needed to apply a succession of long-duration, high-voltage pulses to the beamlets. A source of heavy ions would operate at 2–3 MV, producing the required net charge per pulse. At the source end of the driver, a large number of electrostatic quadrupole channels appears to be the least expensive option (this is discussed further on page 74). These will be followed downstream by a smaller number of superconducting magnetic quadrupole channels. Some beam combining will therefore be required.

MBE-4 is designed to model much of the physics of the low-energy, electrostatically focused section of a considerably longer driver. Four parallel Cs^+ beams are extracted from thermionic aluminosilicate sources in 2.5- μs pulses and injected into the linac at 200 keV. When the experimental apparatus is completed in the summer of 1987, acceleration to about 1 MeV will be possible. We also expect to see current amplification from 10 to more than 40 mA, due both to an increase in beam velocity and to a decrease in bunch length. The carefully scaled design of MBE-4 and the use of multiple beams will allow us to assess the consequences of errors in accelerating voltages, to investigate beam-beam coupling phenomena, and, more broadly, to gain practical experience in accelerating and controlling parallel, space-charge-dominated beams.

Components and Fabrication

By September 1986, 12 of the 24 accelerating units and 4 of the 6 transport sections of MBE-4 were in place, as shown in Fig. 33, and a few weeks later, we successfully transported four cesium ion beams through this fully instrumented apparatus. Diagnostics in place included three pairs of "harps" (specially designed beam-profile monitors), three pairs of emittance slits, five sets of Faraday cups, and an energy analyzer. Except for the energy analyzer, which is the final component of the system, each of the diagnostic devices may be placed at any diagnostic port, where it samples each of the four beams.

The induction cores (12 in all) for the three accelerator sections now opera-

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Fig. 33. A composite photograph showing MBE-4 as it appeared at the end of fiscal 1986. The large tank at the left is the four-beam source, followed by a beam-conditioning unit, four of the eventual six accelerating sections (three with induction modules in place), and the energy analyzer.

tional differ slightly in design from one section to another, but all comprise various combinations of single and triple Astron cores, 1.4-inch-wide silicon-steel cores, and 4-inch-wide silicon-steel cores. Cores for the three sections to come have been designed along somewhat different lines, as shown in Fig. 34. Instead of 30 kV of accelerating voltage being applied at each core, we intend to apply 60 kV at each of the central cores of a four-core section, reserving the outer cores for special trim pulses that might be needed for bunch shaping. The voltage pulsers and cores required for the final three sections have already been acquired and tested. In addition, the trigger pulsers that fire the pulse circuits have been modified to give more reliable long-term performance.

Small vacuum leaks at the voltage feedthroughs to the electrostatic quadrupoles were corrected by replacing the Re-X insulators with Pyrex, but the discovery of the leaks prompted a thorough study of insulator materials and configurations. Current speculation regarding the cause of the problem is that the metal embedment in the insulator cracked as a result of deformation caused by repeated evacuation and venting of the system. Improper treatment of the metal during the forming process is suspected as the underlying cause.

A final hardware component of MBE-4—one that leads directly to a discussion of experimental results—is the recently installed automated energy analysis system. This system automatically sets and measures the voltage applied to the curved

Fig. 34. Schematic layout of the induction cores for accelerator sections D, E, and F, together with a diagram of the 120-kV pulser to be used with these sections. This pulser circuit applies the full accelerating voltage to the two central induction modules, leaving the outer modules for pulse trimming and other corrections.

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plates of the energy analyzer, records the integrated oscilloscope trace that corresponds to the detected pulse, averages the results for each energy, then stores the data and changes the analyzer voltage to repeat the process at another energy. The data shown in Fig. 35 were acquired and plotted in about 30 minutes.

Experimental Results

The modular design of MBE-4 has allowed us to perform experiments one section at a time since fabrication began. Experiments were conducted early in fiscal 1986, when only the first accelerating section was in place, then again midway through the year, with two accelerating sections installed.

The longitudinal dynamics in MBE-4 is prescribed by a calculated schedule of applied voltage waveforms, which dictate acceleration and current amplification. This schedule is designed in such a way that, as the beam is accelerated, the current is amplified but the current waveform maintains its initial shape. (The current waveform is the time-dependent current, as measured at a fixed location.) The individual voltage pulses are also designed to control longitudinal space-charge forces at the bunch ends. A significant outcome of early experiments during the past year was a confirmation of our ability to model the behavior of the beam envelope and the phase-space distribution of accelerated beams. The accuracy of such models is directly related to our ability to generate suitable acceleration schedules.

Because longitudinal space-charge forces must be carefully compensated by the accelerating waveforms if MBE-4 is to operate properly, we sought to determine the degree to which these forces are reduced by the conductors that surround the beam. The extent of this reduction is characterized by a "geometrical" factor g , where a smaller number corresponds to a greater reduction in space-charge forces. The determination of g is illustrated in Fig. 36, which shows the experimental

Fig. 35. Data from MBE-4, acquired and compiled by an automated data system. Each trace in the three-dimensional plot represents the average of eight pulses, with the energy analyzer set at the energy shown. The data can then be compiled in a plot of mean energy vs time, as shown at the right.

Fig. 36. Energy and current waveforms used in the empirical determination of the longitudinal space-charge factor g . The dotted curves are the measured waveforms at gap 10; the solid lines are computed waveforms, based on the indicated values of g and the waveform measured at the entrance of the accelerator. This analysis yielded $g = 2.8 \pm 0.6$.

current and kinetic energy waveforms for a drifting beam at the exit of the second accelerating section, together with simulations of these waveforms, assuming different values of g . The simulated results were produced by the beam-propagation code SLID. The value of g was determined to be 2.8 ± 0.6 .

With the modules of two accelerating sections on, beam current is amplified by a factor of about 1.6, as shown in Fig. 37. (Figure 37 also shows our success in predicting current and energy waveforms with the SLID code. The theoretical predictions shown there were based on measurements of the beam current and energy at the entrance to the accelerator and on the voltage waveforms applied at the eight accelerating gaps.) The final current profiles shown in Fig. 37 show some minor modulations due to small systematic errors in the applied voltage waveforms. However, these modulations have been significantly reduced in comparison with those evident in earlier results; they now correspond to less than 1% of the typical gap voltage and less than 0.1% of the beam kinetic energy. We achieved this reduction with a tuning procedure in which we monitored the output waveforms while turning on and optimizing the gap voltages sequentially. (In early fiscal 1987, using the apparatus in the state illustrated in Fig. 33, we amplified current by a factor of more than 2.5.)

Random errors can also be detected in the applied voltage waveforms, due mainly to pulser timing jitter. Current modulation due to such errors is about ten-fold smaller than that due to systematic errors; however, random errors are difficult to correct and may be left to accumulate over the entire linac. We will pay increasing attention to these errors as the remaining modules are added to MBE-4.

Fig. 37. Oscilloscope traces showing current-pulse shapes (beam current vs time at a fixed point) at the entrance and exit of the accelerator. These traces illustrate current amplification by a factor of 1.6. Also shown is a comparison between a measured final pulse shape and the result of a computer simulation, based on the initial pulse shape and the voltage waveforms applied at each of the accelerating gaps.

The accelerating voltages themselves are produced at each gap by two to four pulsers, whose outputs are combined. These outputs are either simple capacitor discharges or waveforms with shapes given by $1 - \cos \omega t$. In the second accelerator module, the rise times of the capacitor discharge pulsers at the first three gaps have been adjusted to control longitudinal spread at the head of the bunch. The fourth gap includes a trim pulser to control longitudinal spread at the tail. Pulser voltages are adjustable to a maximum of 25 kV, and the trigger time has a resolution of 10 ns.

Theoretical and experimental studies of the behavior of space-charge-dominated ions beams—that is, beams in which mutually repulsive like charges dominate the dynamics—are of obvious relevance to MBE-4, but they also look forward to a larger proof-of-principle experiment and even to an eventual heavy-ion fusion driver. During the past year, these studies have focused on the problem of combining multiple beams into one, on optimization of the computer code SLID, and on the effects of beam mismatch (which occurs when the periodicity of beam properties is not in phase with that of the transport lattice).

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 accelerator. In the lower drawing of Fig. 32, for example, an initial pulse four times as long as those shown would be needed to produce the same pulse on target, in the absence of beam combination. We have approached this problem of combining beams as comprising two parts. First, how does one get, say, four beams in independent alternating-gradient structures into close proximity within a single structure? And second, can one "stack" these beams to form one beam with acceptably little emittance growth? (Emittance is a measure of beam quality that reflects both the transverse beam size and the transverse energy of the particles that compose it.)

The first step must therefore induce a double bend in each beam, converting four independent parallel beams into four nearly contiguous parallel beams. Attempting these bends in the absence of any focusing forces leads to problems associated with the high space charge; consequently, we visualize a system such as the one shown in Fig. 38. Here, the bends are separated by regions filled with quadrupoles that prevent significant beam growth. In any scheme, the magnets for both bending and focusing must be of novel designs, since the space between beams is highly restricted. We have therefore begun studies of pulsed current-sheet dipole and quadrupole arrays, which may require a clearance of only a few millimeters between beams. Applying these concepts to a system such as MBE-4, where ion velocities are very low and magnetic bending is thus relatively ineffective, requires further refinement, but efforts in this direction have begun.

The mixing that follows in the common alternating-gradient channel downstream of the double bend has been studied by computer simulation, principally to determine the transverse emittance growth that accompanies the process. Our initial studies were restricted to round beams, but we looked at the effect of the prox-

Studies of Beam Dynamics

Combining Beams

Fig. 38. A schematic design for a beam-combining section of a multiple-beam accelerator such as ILSE. The four solid curves in the upper part of the figure delineate the four transverse extrema of a single beam as it is brought toward the center line of a four-beam system. In the lower part of the figure, the transverse cross sections of all four beams are shown.

Fig. 39. A comparison between an experimentally measured current waveform (a) with two computed waveforms, one that neglects the so-called transit-time effect (b) and one that properly accounts for it (c). The finite time the ion pulse spends in the accelerating gap tends to smooth out the high-frequency fluctuations in the applied voltage.

imity of the four beams, varying both the separation of the beams in the x and y directions and the ratio of the x and y separations. The results show that the total emittance growth in each transverse direction can be held roughly to a factor of two, provided the beams are in close proximity as a result of the double bend.

Code Development

The code SLID is an indispensable tool in operating MBE-4 and in analyzing experimental data. It is used (i) to design accelerating voltage waveforms for a given set of conditions, (ii) to predict the energy and current pulse shapes as functions of time at any location along the linac, and (iii) to explore ways to alter experimental conditions to produce more favorable performance. Several recent improvements have made the code even more useful.

One improvement was the inclusion of an accurate value of the geometry factor g , which was measured as described on page 67. A second was the incorporation of the finite ion-transit-time effect; previously, the code had ignored the finite time an ion spends in the accelerating gap. This simplification had the effect of overestimating the high-frequency fluctuations in current pulse shapes (caused by high-frequency voltage errors in the accelerating modules). As shown in Fig. 39, predicted pulse shapes agree much more closely with experimental observations, now that the transit time is accounted for.

The code now uses a one-dimensional model and assumes zero longitudinal emittance. As more modules are added to MBE-4, voltage errors may lead to longitudinal emittance growth, and three-dimensional end effects are likely to become significant. We have begun to modify the code so that it can be used to predict these phenomena.

Studies of Beam Mismatch

The single-beam transport experiment continued to serve as a crucial test bed for studying fundamental phenomena. One such phenomenon, now studied both theoretically and experimentally, is emittance growth due to beam mismatch. The question we asked was, What kind of emittance increase can we expect from the mismatching that inevitably occurs at transitions in the accelerator system? By adjusting quadrupole voltages in the matching section of SBTE, we were able to answer this question by exciting either symmetric or antisymmetric mismatches. (Symmetric oscillations produce a sausage-like beam envelope, in which $\Delta x = \Delta y$; antisymmetric oscillations are characterized by $\Delta x = -\Delta y$.) The results showed that symmetrically mismatched beams are difficult to distinguish downstream from initially matched beams, but that antisymmetric mismatches can induce significant emittance growth.

During the past year, a draft program plan was developed that addresses the needs of heavy-ion fusion accelerator research over the next five or six years. The cornerstone of this plan is a multiple-beam accelerator experiment of significantly larger scale than MBE-4, in which more energetic ions could be focused and bent with magnetic fields. This experiment, designated the Induction Linac System Experiment (ILSE), would test, at a reduced scale, many of the beam-manipulation systems that would be required in an ICF driver. The aim of such an experiment would therefore be to assemble the remaining data needed for a sensible assessment of the induction linac as a practical driver for commercial fusion power.

ILSE was designed 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 1- to 2-millimeter-diameter spot. A schematic diagram of ILSE, showing the regions in which these various manipulations would occur, appears as Fig. 40, and Table 8 presents a comparison of the beam parameters for MBE-4, ILSE, and an envisioned fusion driver.

The Induction Linac System Experiment

Fig. 40. Schematic diagram of the proposed Induction Linac System Experiment, designed to test the concepts of beam combining, magnetic focusing, the bending of a high-current beam, and drift compression.

Parameter	MBE-4	ILSE ^a	Driver
Ion	Cs ⁺	C ⁺ (or Al ²⁺)	Bi ³⁺
Injection voltage (MV)	0.2	2	3
Final voltage (MV)	1.0	10	3.3×10^3
Final current (A)	0.1	30	6×10^4
Beam energy (J)	0.1	75	3×10^6
Ion velocity/c	0.004	0.04	0.3
Accelerating gradient (MV/m)	0.07	0.22	0.5
Number of beams	4	16→4	64→4
Pulse width (μs)	2→1	1→0.5	24→0.1
Charge (μC)	0.1	9	900
Initial bunch length (m)	1.1	5.6	70
Final perveance (normalized)	3.8×10^{-4}	3.6×10^{-4}	5.6×10^{-5}

Table 8. A comparison of principal parameters for MBE-4, the proposed Induction Linac System Experiment, and a possible driver for a heavy-ion fusion power plant. Parameters for ILSE are based on 16 beams of 0.1 μC/m from the injector.

As ILSE is now conceived, 16 beams of singly or doubly charged ions from an injector being developed at the Los Alamos National Laboratory would be matched to an electrostatic transport system and accelerated from 2 to 4 MV. The beams would then be combined into four, matched to a magnetically focused linac, and further accelerated to 10 MV. Three of the beams would then be discarded, and the fourth bent through a large angle, compressed longitudinally, and focused. The length of the experimental apparatus would be about 50 meters.

Figure 41 shows the results of some calculations that correlate beam current and energy, phase advance per period (σ_0), and either quadrupole voltage (electrostatic focusing) or magnetic field strength (magnetic focusing).

Fig. 41. Parametric plots of maximum transportable current, energy, phase advance per period, and either quadrupole voltage (for electrostatic transport, upper plot) or magnetic field (for magnetic transport, lower plot), for a possible ILSE accelerator. The broad bars represent illustrative acceleration scenarios in which either the current (gray) or the bunch length (color) is held constant.

More or less independent of our theoretical and experimental accelerator research program, we have participated in a broad "systems assessment" of heavy-ion fusion, a paper study consisting largely of parametric studies aimed at understanding the cost and performance tradeoffs implicit in different heavy-ion fusion induction linac driver designs. In brief, the study concluded that in terms of the projected cost of electricity heavy-ion fusion compares favorably with magnetic fusion. The study also led to increased interest in using multiply charged ions. In related efforts more closely tied to our experimental program, we have quantitatively explored the concept of a driver with a large number of beams, perhaps 64, at the injector end, which are then merged to form 16 beams on target (see Table 8). We have also evaluated multiple pulsing of the accelerating gaps to increase the power on target for a given driver.

Systems Study and Driver Design

The Heavy Ion Fusion Systems Assessment (HIFSA) has been conducted over the past three years with the specific goal of evaluating the prospects of induction linac drivers as economical generators of electric power. In addition to LBL, principal contributors to the study have included the Los Alamos National Laboratory, the Lawrence Livermore National Laboratory, McDonnell Douglas Astronautics Co., and the University of Wisconsin. Four different reactor types and five different target designs were included in the study. Final ion kinetic energies for the driver designs ranged from 5 to 20 GeV, and total beam energies varied from 1 to 10 MJ. The results show that the cost of electricity, based on a 1000-MWe plant using ions with atomic weight 200 and charge state +3, would be about 5.5 cents/kW-hr. The familiar economies of scale hold (the cost is higher for a 500-MWe plant and lower for a 1500-MWe plant), but the results appear to be otherwise insensitive to a wide variation in driver parameters.

Systems Assessment

The use of multiply charged ions in a full-scale fusion driver is at least superficially attractive, since any required kinetic energy or electrical current can be achieved over a shorter distance, given a fixed cumulative applied accelerating voltage. Furthermore, the beam radius, required magnetic focusing field, and pulse duration appear not to be sensitive to charge state. On the other hand, beam manipulation during final transport and focus becomes more difficult as the charge state of the ion increases. For example, for beams of equal electrical current, the particle current is inversely proportional to charge state; consequently, to achieve the same power on target, greater longitudinal compression is required for the more highly charged beam. Nonetheless, increased attention is being given to high-charge-state scenarios, especially since promising ion sources are being actively developed (see, for example, page 46).

Despite the possible advantages of using multiply charged ions, we assumed singly charged bismuth ions in our detailed exploration of beam "parameter space" for a fusion driver. We first defined seven cases, each characterized by a reasonable and self-consistent set of parameters for transverse beam dimensions and focusing electrode potentials, given a required total charge of 300 μC . For each case, the bunch length and the maximum permissible accelerating gradient were then computed for scenarios with 16, 32, 64, 128, and 256 beams at the low-energy end of the accelerator. (The maximum average accelerating gradient is limited by the requirement that the bunch length not decrease in the electrostatically focused portion of the driver, since focusing potentials were assumed already to be at a maximum.) These computations were based on a number of assumptions regarding beam dynamics, but the results illuminate an important point: To minimize the length of the low-energy (electrostatic) portion of the driver—that is, to take advantage of the highest achievable accelerating gradients—128 or even 256 beams offer the greatest promise.

Other Driver Design Considerations

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MAGNETIC FUSION ENERGY

... efforts focus on negative-ion systems for the much larger fusion experiments of the distant future, for industrial applications, and for defense ...

SINCE ABOUT 1975, LBL has been an active player in the national magnetic fusion program, primarily in its leading role as developer of neutral-beam systems for major experiments at Princeton, Livermore, and GA Technologies in San Diego. These experiments, unlike the self-sustaining reactors of the future, typically run for only a fraction of a second (at most, a few seconds) and thus require an influx of energy to heat the plasma with every pulse. Energetic neutral beams—usually either hydrogen or deuterium atoms—continue to be the method of choice for supplying this energy in most of today's large experiments. Historically, then, our efforts have been directed toward the development of sources of either positive or negative ions, systems for accelerating and transporting these ions, and means of efficiently neutralizing the ions to produce the required neutral atoms.

During the past year, our work in these same areas has had a much broader base—in part because the near-term needs of the fusion program have been satisfied with the success of the positive-ion-based Common Long Pulse Source. Ongoing efforts thus focus on negative-ion systems for the much larger fusion experiments of the distant future, for industrial applications (perhaps including ion implantation in semiconductors), and for defense. The interest in negative ions is based mainly on the fact that, at high energies (as needed, for example, to penetrate the larger plasma volumes of future fusion experiments or reactors), positive ions cannot be efficiently neutralized.

In parallel with these ongoing studies and in support of our experimental efforts, we also maintained active, though smaller, programs in atomic physics and theoretical plasma physics.

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The development of a large source capable of 30-second pulses of positive ions was at the center of LBL's fusion effort in the early 1980s. Developed for use at the Tokamak Fusion Test Reactor (TFTR) at Princeton, the Magnetic Fusion Test Facility (MFTF-B) at Livermore, and the D-IIIID tokamak at GA Technologies, this source—the Common Long-Pulse Source (CLPS)—is now being produced by RCA. Nonetheless, we have remained active over the past two years in the process of technology transfer, and during 1986 we concluded the qualification tests on the first commercially produced units. The success of the original design has been borne out in these tests, which yielded results that met or surpassed all design requirements. Also during 1986, experimental results from Princeton, operating with older LBL-designed 0.5-second ion sources, have exceeded all expectations—thus earning the name "supershots."

Common Long-Pulse Source

Though most of our work on positive-ion-based neutral-beam systems was completed in 1984, the past two years have been highlighted by successful tests of the first units commercially manufactured by RCA. The first CLPS plasma generator was delivered to LBL for testing in August 1985, and work continued through July 1986. Configured to the needs of TFTR—the national fusion program's top priority—the complete source met or exceeded all design goals. During 120-kV, 2-second operation on our Neutral Beam Engineering Test Facility (see Fig. 42), the optimized source produced 74 amps, with a $0.7^\circ \times 0.4^\circ$ divergence. The atomic fraction was 81% (somewhat higher at 105 kV), and 87% of the beam power was on target 12 meters downstream.

Fig. 42. One of the RCA-fabricated Common Long-Pulse Sources, mounted for testing on the Neutral Beam Engineering Test Facility.

A few improvements were also made to the CLPS design. Modifications included, for example, changes in the shapes and numbers of the cathode filaments, in response to suggestions made by colleagues at JAERI. During the past year, our work on the CLPS was also rewarded in another way: *Research & Development* magazine presented an I-R 100 award to the designers of the plasma density probe used to monitor plasma density and uniformity in the ion source, thus recognizing it as one of the outstanding technological products of the year. This water-cooled probe, six of which are required on each source, will be used under conditions where surface heat fluxes may reach 25 W/cm^2 for 30 seconds.

Finally, it is fitting to point to the promise of the CLPS by noting the recent successful experiments at TFTR—so-called “supershoots”—which pushed plasma temperatures to a record $2 \times 10^8 \text{ K}$, using neutral-beam systems designed at LBL and based on LBL-developed 0.5-second positive-ion sources (the predecessors of the CLPS). The success of these experiments, which exceeded all expectations, was apparently due in large part to the fact that the energetic beams were able to penetrate to the core of the plasma and deposit both energy and fuel there.

Negative-Ion-Based Neutral-Beam Research

Whether 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 pumping requirements exceedingly stringent. As a consequence, only positive-ion systems have been developed for ongoing and near-term magnetic fusion experiments. 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 work now concentrates on negative ions—on generating higher currents from sources, on novel transport schemes, and on efficient neutralization scenarios. During 1986 a particularly active area of research was source development, where we were especially encouraged by continuing progress in coaxing high currents from experimental volume-production sources, and in our growing theoretical understanding of them.

Source Development

Today, the only negative-ion source that can deliver more than an ampere of steady-state H^- is the 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. In addition, this volume-production source produces a beam of inherently higher quality than does the surface source.

The drawback with the volume source is its substantially lower H^- output. One of our ongoing efforts, therefore, is enhancing the output, both by experimental manipulation of such parameters as source dimensions, wall material, and plasma make-up, and by theoretical studies aimed at understanding in detail the mechanism of ion production. An example of these latter studies is our effort to monitor ground-state hydrogen atom densities in volume-production sources. Hydrogen atoms are thought to play an important role in H^- sources, both in the destruction of H^- ions and in the modification of the ion energies through charge exchange. During the past year, we began a new experimental study to determine neutral hydrogen densities by looking at the absorption of Lyman radiation (pro-

duced by frequency tripling the output of a dye laser). In another series of experiments, using an easily modifiable filtered bucket source, a parametric study of ion extraction was undertaken, with particular attention to variables such as aperture size and number.

Most of our studies of volume-production mechanisms and sources have centered on the source shown in Fig. 43a. Recently, however, we have developed two other embodiments of the same basic design (also shown in Fig. 43). The first of these (Fig. 43b) has a source chamber that is only 2.5 cm in diameter and 4 cm long, compared with the 20×24 -cm dimensions of the larger source. The smaller volume allows production of higher plasma densities, thus greater ion current densities. In fact, we have measured current densities greater than 240 mA/cm^2 (from a 1-mm-diameter aperture), compared with a maximum of 40 mA/cm^2 for the large source. In addition, since the entire source chamber wall and the surrounding dipole magnets are water cooled, the source is capable of steady-state operation at high discharge power.

Fig. 43. Three volume-production negative-ion sources, all embodying the generic design shown in the schematic cross sections. (a) A view into the source chamber of a 20-cm-diameter source. The bar-like permanent-magnet filter prevents energetic primary electrons from crossing into the extraction chamber. (b) A small multicusp H^- source, which has produced current densities as high as 240 mA/cm^2 . (c) A 30-mA source designed as the first step toward the production of high-quality 200-mA beams.

A second recently fabricated source represents the first step toward an ultimate goal of producing 0.2 amp of H^- from a volume source and accelerating it to 100 keV. Furthermore, we intend that this future source be capable of even higher currents if multiple apertures are used. The source and accelerator fabricated during 1986 have more modest goals, namely, the acceleration of 30-mA, 0.5-second pulses of H^- to 100 keV; the source is designed to produce 30 to 40 mA/cm². A photograph of the source is shown in Fig. 43c. In preliminary experiments, we extracted current densities of about 17 mA/cm² from the source and accelerated beam to 66 kV.

Impelled by a desire to diversify our ion source work, rather than to produce beams of high current alone, we have also developed a small steady-state microwave ion source, in which the electromagnetic field of the radiation plays the role of hot filaments in more conventional sources. This source is fabricated from a quartz tube enclosed in a cavity operated at 2.45 GHz; up to 500 watts of power can be coupled to the source plasma. Ions are again produced by a volume process, usually from gas within the source, but negative metallic ions can also be produced by installing different metal plates (beryllium, copper, aluminum, etc.) on the extraction electrode (see Fig. 44). We have also successfully extracted high-charge-state positive-ion beams, such as Ne^{3+} , from this source, as well as electrons at a density of greater than 10 A/cm². Finally, this same source geometry has been used to produce low-energy H^+ , as well as atomic oxygen at a fluence greater than 10^{14} atoms/(cm²-s).

LaB₆ Cathodes

Our exploration of lanthanum hexaboride cathodes had modest beginnings—a desire to develop long-lived filaments for steady-state and high-duty-factor ion sources. Our interest has grown, however, as the potential of these cathodes, with different geometries and operating under different conditions, has become clearer for a number of applications. The directly heated cylindrical design shown in Fig. 45 has been highly successful in realizing the original purpose of these filaments, that is, to serve as electron emitters in the plasma generator of an ion source. The magnetic fields generated by the heater and by the discharge current are minimized by the special coaxial construction, thus enabling electron emission at very low discharge voltages. At higher voltages, we have obtained a discharge current greater than 100 amps from a single cathode unit in a steady-state ion source. Similar geometries are now being used in the construction of special cathodes for a variety of other applications.

Among the more novel applications that have been suggested for LaB₆ cathodes is their possible use as large-area, planar electron emitters in free-electron lasers and their use as emitters of cold electrons for the neutralization of positive

Fig. 44. Schematic cross section of a small microwave ion source, capable of producing both positive and negative ions. Ions can be produced from the gas within the quartz tube or from material placed at the extraction electrode. The outside diameter of the microwave cavity is about 2.5 cm.

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Fig. 45. A directly heated, coaxial lanthanum hexaboride cathode, capable of producing a steady-state current of 100 amps. The coaxial design minimizes the magnetic field around the cathode, allowing the production of very cold electrons.

ions during industrial-scale ion implantation of insulators. A use already successfully studied was in a Dudnikov-type Penning ion source. It is generally believed that H^- in most such sources is first formed on the cesiated surfaces of the cathodes. Some of these ions then undergo resonant charge exchange with neutral hydrogen atoms near the emission slit, whereupon low-energy H^- can be extracted. However, we successfully operated a Penning source without cesium (simply a means of lowering the work function of the cathode) by using LaB_6 as the cathode material. In fact, we have obtained total currents of about 100 amps during short-pulse operation, and with appropriate gas filling, we have demonstrated H^- current densities comparable to those obtained from conventional cesiated cathodes. Our results have also pointed to the need for further study of the postulated mechanism of ion production, since it appears unable to account for the high currents we observe.

For the past several years, an important aspect of our neutral-beam program has been the development of the transverse field focusing (TFF) accelerator and transport system. The TFF concept, illustrated in Fig. 46, entails a series of curved sheet electrodes, which transport and accelerate the beam (in our case, H^-) along a sinuous path. This has two important advantages. First, it isolates the ion source and accelerator section from energetic neutrons that would be produced in the reacting plasma downstream. And second, it allows efficient differential pumping, because, as shown in Fig. 46, the solid curved electrodes effectively divide the TFF chamber into two halves. This differential pumping capability is important in reducing beam loss caused by background hydrogen gas in the beamline. Another feature of the TFF design is the imposition of a transverse magnetic field at the second bend of the transport section, the purpose of which is to deflect electrons, inevitably created in any negative-ion source, from the beam path.

During 1966 we successfully transported 640 mA of H^- at the TFF design energy of 80 keV. Insulator breakdown limited the pulse length to 40 ms (430 ms at 48 keV), but we were able nonetheless to confirm that the beam could be properly steered through the beam channel. It is likely that the breakdown problem

Negative-Ion Transport: Theory and Experiment

Fig. 46. Schematic illustration of the concept underlying the transverse field focusing accelerator. The curved electrodes effectively isolate the source from the high-vacuum beamline downstream. Electrons are deflected upward by a local magnetic field; as they lose momentum, they are drawn out of the beam path by the electrostatic field.

could be solved simply by shielding exposed insulator surfaces from the beam. Effective cryopumping reduced beam loss to less than 15%, and we observed little or no emittance growth, as demonstrated in the plots of Fig. 47.

During the past year, we also looked at issues pertinent to the TFF concept from a theoretical perspective. For example, we looked in detail at the internal dynamics and emittance growth mechanisms in space-charge-dominated beams. We then extended our purely theoretical studies by using a numerical simulation code to follow particle dynamics when a beam is improperly matched to the transport channel. Two cases were studied: (i) nonuniform beams injected into a linear channel and (ii) uniform beams injected into a nonlinear channel. When mismatch was included, the emittance was shown to grow slowly, but it reached much larger values than when the beam is properly matched.

Neutralizer Studies

Beyond the accelerator and transport section of any neutral-beam system is the neutralizer, necessary to convert the charged particles to neutral species. For this component of the system, the efficiency with which ions can be neutralized is the critical parameter, but the neutralizer's contribution to beam divergence and its

Fig. 47. Emittance plots obtained at the entrance (color) and exit of the TFF accelerator, showing negligible emittance growth in the accelerator section. The entrance emittance is given as a 90% contour.

effect on brightness must also be considered. In 1986 we continued to study neutralizers along mainly theoretical lines.

At beam energies below about 50 keV (for hydrogen), positive ions are the preferred source of neutrals: They can be neutralized as efficiently as negative ions, they can be produced at much higher current densities, and they are less prone to loss due to charge-changing collisions in the beamline. Above 50 keV, however, the decreasing efficiency with which positive ions can be neutralized tends to negate their other advantages, and at around 80 keV (again, for hydrogen), negative ions become the only practical source of neutral beams. Above this energy, the issue is the choice of neutralizer design rather than the charge of the ions. Below 80 keV, a cell of hydrogen gas serves as an effective passive neutralizer; at higher energies, consideration must be given to alternative designs, including, at the highest energies, solid and liquid films. A spectrum of beam energies, showing the ranges over which several types of neutralizers might be useful, is shown in Fig. 48.

One of the neutralizers applicable to high energies, a high-charge-state plasma neutralizer, has been subjected to more detailed study at LBL. Such a neutralizer offers the potential of 85% neutralization efficiency (compared with 50–60% for a simple gas cell), but the plasma density required to achieve this efficiency depends on the average ionic charge state in the plasma. To check our theoretical studies, we have constructed a small multicusp plasma generator to serve as a plasma neutralizer (see Fig. 49). Preliminary measurements indicate that this generator produces an argon plasma with an average charge state between +2 and +3 for a steady-state discharge.

Fig. 48. Approximate useful energy ranges of several neutralizer designs.

Fig. 49. A small plasma generator, fabricated to test the concept of a high-charge-state plasma neutralizer. This generator produces an argon plasma with an average charge state between +2 and +3.

Fusion Diagnostics and Theoretical Studies

Concurrent with the design and testing of neutral-beam systems, work continued in 1986 on developing a noninterfering, on-line diagnostic technique for burning-plasma experiments. Another effort, grounded in our interest in atomic and molecular physics, is our theoretical study of the physics of negative-ion sources—a study that underlies and parallels the source-development efforts described above. Basic theoretical plasma physics research also continued, the aim being a better and broader understanding of processes and interactions that occur in plasmas.

Diagnostics Development

Alpha particles produced in a deuterium-tritium fusion reaction are born at an energy of 3.5 MeV. Most are trapped in the magnetic field confining the plasma, subsequently slowing down as a result of interactions with plasma ions and electrons, thereby heating the plasma. In a "burning" plasma, the fusion-produced alpha particles provide sufficient heat to sustain the reaction. A new generation of tokamaks is being planned in which a primary goal will be ignition of the plasma by this process. An essential diagnostic for these experiments will be the measurement of the spatial, temporal, and velocity distributions of the fast alpha particles as they slow down.

Two neutral-beam-based methods are especially promising as alpha diagnostic techniques: (i) single-electron capture by the alpha (He^{2+}) and subsequent detection of the emitted photon, and (ii) two-electron capture by the alpha and subsequent detection of the escaped neutral helium atom. We have studied both of these approaches conceptually—in particular, with regard to ion source and accelerator technology (see Fig. 50). Though many promising avenues are available for further exploration, it is clear that even a proof of principle lies far ahead of us. A substantial development program will be required to demonstrate that these concepts can be developed into a working diagnostic system. We are currently reexamining the design requirements for such diagnostic tools, and a part of our neutral-beam development effort is motivated by this future application to fusion experiments.

Theoretical Plasma Physics

During the past year, our theoretical studies in nonlinear dynamics and plasma physics embraced a range of diverse but related topics:

- Our analysis of ponderomotive stabilization of flute modes in mirror-confined plasmas has been extended to obtain specific numerical stability criteria, to pro-

Fig. 50. Conceptual schematic of an accelerator based on electrostatic quadrupoles, designed to produce a high current of hydrogen neutrals for fusion diagnostics and other applications.

- pose superior antenna designs, and to study the advantage of feedback control.
- A covariant principle for the propagation of electromagnetic waves in non-uniform anisotropic media has led to a compact coordinate-free expression for the transport of the polarization phase.
- A study of self-consistency in electromagnetic plasma-wave absorption has led to a determination of background-field evolution, driven by cross-field diffusion of resonant guiding centers.
- A manifestly gauge-invariant and Lorentz-invariant expression has been derived for the ponderomotive Hamiltonian of a particle in a nonuniform Maxwell field, taking account of all drifts. This will be of use in free-electron laser studies and in astrophysics.
- The study of momentum conservation in a guiding-center plasma has led to the discovery of an electric dipole moment associated with a drifting guiding center.
- Differential-geometric techniques have led to a direct determination of particle dynamical invariants for motion in a Maxwell field of general symmetry.
- The Lagrangian Lie transform has been developed as a powerful tool for analyzing a broad range of nonlinear plasma processes in a gauge-invariant way.

We also investigated several aspects of the phase-space approach to wave asymptotics, which we had previously developed. It turns out that the new approach is superior to traditional WKB theory for several theoretical purposes. For example, with our new approach, one can evaluate certain integrals over the wave field, such as energy and normalization integrals, which are difficult to do in WKB theory, owing to caustic divergences. Another example concerns the Maslov index, which enters into normal-mode or quantization conditions in multidimensional problems. We have found algebraic rules for manipulating the Maslov index and deriving relations obeyed by it, which could only have come out of the phase-space approach. We have also begun an investigation of the relationship between wave asymptotics and phase spaces that are not flat, such as occur in separable or partially separable problems. Altogether, we are pursuing the phase-space dynamics of wave asymptotics in several new directions.

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