Accelerator and Fusion Research Division

1984

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Summary of Activities

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MASTER

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FOREWORD

During fiscal 1984, major programmatic activities in AFRD continued in each of five areas: *accelerator operations*, highlighted by the work of nuclear science users, who produced clear evidence for the formation of compressed nuclear matter during heavy-ion collisions; *high-energy physics*, increasingly dominated by our participation in the design of the Superconducting Super Collider; *heavy-ion fusion accelerator research*, which focused on the design of a four-beam experiment as a first step toward assessing the promise of heavy-ion inertial-confinement fusion; and research at the *Center for X-Ray Optics*, which completed its first year of broadly based activities aimed at the exploitation of x-ray and ultraviolet radiation.

At the same time, exploratory studies were under way, aimed at investigating major new programs for the division. During the past year, for example, we took a preliminary look at how we could use the Bevatron as an injector for a pair of colliding-beam rings that might provide the first glimpse of a hitherto unobserved state of matter called the quark-gluon plasma. Together with Livermore scientists, we also conducted pioneering high-gain free-electron laser (FEL) experiments and proposed a new FEL-based scheme (called the two-beam accelerator) for accelerating electrons to very high energies. And we began work on the design of the Coherent XUV Facility (CXF), an advanced electron storage ring for the production of intense coherent radiation from either undulators or free-electron lasers.

But if looking to the distant future is important (and I think that it is crucial), so also are the developments that ensure our vitality in the near term. During 1984 each of our major continuing programs was characterized by innovation and even by new directions: the high-current MEVVA ion source and state-of-the-art RFQs, improved superconducting materials and cables, a proposal for producing completely polarized beams of hydrogen and deuterium, developments in high-current ion-transport theory, and the fabrication of heat-tolerant x-ray optical components. Programmatic highlights such as these, together with proposals like the two-beam accelerator and the Coherent XUV Facility, attest to an innovative spirit that is our best insurance for the future.

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ACCELERATOR OPERATIONS

THE PROXIMITY OF TWO ACCELERATORS at LBL—the SuperHILAC and the Bevatron—has opened for the scientific community a realm of research opportunities unavailable anywhere else in the world. Though designed and built as independent machines, it is the combination of the two that has pioneered the fields of relativistic heavy-ion physics and heavy-ion biomedicine. This combined accelerator system, called the Bevalac, is operated as a national research facility for studies in nuclear and atomic physics, nuclear chemistry, and astrophysics. In addition, one-third of the Bevalac operating time is devoted to biomedical research, including a unique heavy-ion cancer therapy program and programs in radiobiology, biophysics, and biomedicine.

In 1974 the SuperHILAC, a linear accelerator capable of accelerating all elements to energies of 8.5 MeV/amu, was connected via an evacuated transfer line to the Bevatron, a weak-focusing synchrotron originally built to accelerate protons. Today, the SuperHILAC generates up to 36 pulses per second, two of which are sent to the synchrotron while 34 pulses (usually of a second ion species) are used locally, sometimes for two separate experiments. Every six seconds, one of the pulses sent to the Bevatron is captured and further accelerated to energies up to 2.1 GeV/amu for light nuclei or 960 MeV/amu for uranium.

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Accelerator Operations

The elements currently available to the experimenter are essentially unlimited; in 1984 nineteen different ion species were delivered. For all elements, both partially stripped and fully stripped ions are available. Furthermore, it is now becoming easier to accommodate the needs of different researchers almost simultaneously. When the same ion is required, beamlines and beam energies can be switched in less than one minute. Switching from one ion to another (from neon to gold, for example) takes only slightly longer, though this will not become a routine operation until the local injector is on line.

During fiscal 1984, 6479 hours of beam time were provided to Bevalac and SuperHILAC research programs in nuclear science and biomedicine. Two hundred and thirteen scientists, representing 52 institutions, participated in 69 different experiments. As national facilities, the Bevalac and SuperHILAC are used by qualified researchers from around the world; 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 1. Operating summary for the Bevalac facility, including projections for fiscal 1985 and 1986.

	Fiscal year		
	1984	1985	1986
Bevalac operation (hours)			
Research	3979	3500	3900
Tuning	1269	1110	1250
Machine studies	171	150	200
Unscheduled maintenance	1031	900	1000
Scheduled shutdowns	2334	3100	2410
Total	8784	8760	8760
Beam utilization for research (hours)			
Bevalac nuclear science	2708	2325	2600
Bevalac biology/medicine	1271	1175	1300
SuperHILAC	2500	2200	2500
Total	6479	5700	6400
Number of Bevalac and SuperHILAC experiments receiving beam	69	58	69
Number of participating scientists	213	190	220
Institutions represented			
Universities	28	25	28
National laboratories	5	5	5
Other	19	15	19
Total	52	45	52
Users of beam time (%)			
LBL	50	50	50
Universities	35	35	35
Other national labs	5	5	5
Other institutions	10	10	10

Table 1 summarizes the operations during fiscal 1984 and compares them with our projections for the next two years. About half of the Bevalac beam time is devoted to users not affiliated with LBL. The focus of support for this 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 LBL management. The executive committees of the two users' associations for fiscal 1984 are listed in Table 2.

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 (see Table 2) recommend research time allocations to the Laboratory Director. In addition, the LBL scientific director of each program may allocate about 10% of the available research time on a discretionary basis. Because of the special needs of the patient therapy program at the Bevalac, day shifts during the week have

Table 2. Membership lists for the Users' Association Executive Committees and the three Program Advisory Committees (PACs) for fiscal 1984.

Bevalac Physical Sciences Users' Association Executive Committee

P. N. Kirk, Louisiana State University (chairman)
 H. J. Crawford, University of California Space Sciences Laboratory
 G. J. Igo, University of California, Los Angeles
 P. Lindstrom, LBL
 H.-G. Ritter, GSI
 G. Westfall, Michigan State University

SuperHILAC Users' Association Executive Committee

D. Cline, University of Rochester (chairman)
 M. Blann, Lawrence Livermore National Laboratory
 R. M. Diamond, LBL
 A. Mignerey, University of Maryland
 J. M. Nitschke, LBL

Bevalac Nuclear Science PAC

P. Siemens, Texas A&M University (chairman)
 R. Klapisch, CERN
 T. Ludlam, Brookhaven National Laboratory
 D. K. Scott, Michigan State University
 H. Stöcker, Michigan State University
 E. Vogt, TRIUMF and University of British Columbia

Bevalac Biomedical PAC

M. Bagshaw, Stanford Medical Center
 R. Durand, Johns Hopkins Oncology Center
 R. Fry, Oak Ridge National Laboratory
 J. T. Lyman, LBL
 R. Todd, Pennsylvania State University
 E. Ainsworth, LBL (executive secretary)

SuperHILAC PAC

D. Fossan, State University of New York at Stony Brook (chairman)
 G. Bertsch, Michigan State University
 S. Datz, Oak Ridge National Laboratory
 J. Hardy, Chalk River National Laboratory
 W. F. Henning, Argonne National Laboratory

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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 programs and the other biomedical programs. In the coming years, fast beam switching will make it possible to run nuclear science experiments simultaneously with the therapy program.

Broadly, nuclear physics research at the Bevalac centers around the use of relativistic heavy-ion beams to study nuclear collisions that greatly increase the density and pressure of the nuclear matter. In one example of such research, the first clear evidence for the formation of compressed nuclear matter during heavy-ion collisions emerged from a collaboration between LBL and the Gesellschaft für Schwerionenforschung (GSI). In the reaction $^{93}\text{Nb} + ^{93}\text{Nb}$, the particles coming from the breakup of the niobium nuclei did not scatter in random directions, but instead exhibited a collective flow that can only be explained by nuclear compression. Dense matter of this kind has been hypothesized to exist inside neutron stars, and it plays an important role in theories of the evolution of the universe. Other work focused on the high temperatures (about 100 MeV) reached in these relativistic heavy-ion collisions. In another collaboration, this one between the Institute for Nuclear Study (INS) in Tokyo and LBL, light isotope beams were produced, separated, magnetically focused, and transported to the Heavy Ion Superconducting Spectrometer. At the SuperHILAC, about half of the beam time was devoted to studies of nuclear reactions, the rest of the time going to research on nuclear structure, atomic physics, and exotic nuclei. A highlight of 1984 was the study of reverse kinematics, observed when a heavy beam impinges on a light target. Simultaneously with these programs, the biology and medicine program continued its use of heavy-ion beams in basic studies of biophysics and radiobiology and in a series of cancer-therapy trials.

Compression and Flow in Nuclear Matter. The past year has been one of the most productive in Bevalac history: We saw major progress in understanding the mechanism of relativistic nucleus-nucleus collisions, and several lines of research were being explored for the first time.

The most striking results were obtained in studies of compression and flow in the collisions of very heavy nuclei (see Fig. 1). Evidence for compression effects had previously been presented in streamer chamber studies of negative pion production in collisions of argon with a KCl target. However, studies of the effects of compression on the motion of the neutrons and protons that constitute the bulk of the nuclear matter had been fragmentary and inconclusive. In 1984 the first complete data from the GSI/LBL Plastic Ball were presented, and in addition, the streamer chamber came of age with the presentation of results on more than a thousand completely reconstructed events in the Ar + Pb system.

These results were analyzed using the method of momentum (or energy) tensor analysis, which fits the distribution of all the particle momenta (or energies) in each event with an ellipsoid. For collisions between niobium nuclei, the Plastic Ball data showed that the flow angle was directed clearly away from the beam direction and that the flow angle increased with the multiplicity of secondary particles. This is interpreted as a hydrodynamic effect in which the interacting nuclei are first compressed, then pushed apart as the compressional energy is released. The magnitude of the effect, represented by the flow angle as the collisions change from glancing to head-on, is measured by the multiplicity of produced particles. A similar result was presented by the streamer chamber group. These results have been hailed as proof of the value of detectors that cover the full solid angle and as clear evidence of the value of heavy projectiles. The inadequacy of lighter nuclei is demonstrated by the fact that the Plastic Ball group was unable to identify a clear effect in Ca + Ca collisions, whereas the effect was unmistakable in Nb + Nb.

Research by Accelerator Users: Highlights

Nuclear Physics

Fig. 1. A computer-generated reconstruction of a single $^{93}\text{Nb} + ^{93}\text{Nb}$ collision, shown in the center-of-mass frame of reference. The lengths of the arrows emanating from the point of impact are proportional to the momenta of the emitted particles (which include protons, deuterons, tritons, ^3He nuclei, and alpha particles). The nonrandom distribution of the particle trajectories can be explained most readily as a hydrodynamic effect in which the particles are pushed apart by the release of compressional energy.

High-Temperature Studies. Further progress was made in studying the high temperatures (about 100 MeV) reached in relativistic heavy-ion collisions. The streamer chamber group tackled a long-standing puzzle—the fact that temperatures measured by studying the spectra of emitted protons and pions appear to be different—and explained it by invoking the transformation of a substantial fraction of the nuclear matter into delta resonances. The delta resonances decay by production of a proton and a pion, and the decay kinematics influence the proton and pion spectra. It is only after reconstructing the original delta mass and velocity from the decay proton and pion that the true temperature can be assessed. In further studies of nuclear temperatures, the Plastic Ball group found that measured proton spectra become broader as the multiplicity of produced particles increases. They suggested that this effect is one of reverse kinematics, that is, that in the higher-multiplicity events protons often combine with neutrons to produce deuterons. The loss of degrees of freedom in the combination process raises the apparent temperature.

New Areas of Research. New areas of Bevalac physics were also opened up in 1984. In a remarkable series of experiments, a collaboration between INS and LBL produced secondary beams of many radioactive light nuclei and then studied the interaction cross sections between these nuclei and a variety of targets. As an example, nuclei of ^3He , ^4He , ^6He , and ^8He were produced from the fragmentation of 800-MeV/amu ^{11}B ions interacting with a beryllium target. The deduced interaction radii then showed that ^8He is substantially larger than ^4He . (It was also found that ^6He and ^9Li have the same interaction radii.) Studies are now under way to produce beams of much heavier radioactive isotopes.

Another new field was opened up by a collaboration using the TASS facility to study the direct production of electrons. These are believed to originate from quark-antiquark or $\pi^+\pi^-$ interactions, but previous measurements on $\pi\text{-p}$ and p-p systems have always shown unexplainably large yields. In its first measurements, the TASS group has shown that in proton-nucleus collisions at 2.1 GeV the yield of positrons is less by four orders of magnitude than that of the pions. More sensitive measurements of electron pair (e^+e^-) production will be possible in the dilepton spectrometer, now under construction.

In an LBL-Texas-Japan collaboration, the pion interferometry method was used to measure pion source parameters in $^{56}\text{Fe} + ^{56}\text{Fe}$ reactions. Since pions are not initially present in either the projectile or target, they tag the "hot" space-time region of the interaction where nucleon-nucleon collisions occur above the pion threshold. Knowledge of the pion source may yield information about the space-time geometry and the dynamics of the reaction. Lastly, a series of experiments began in 1984 whose ultimate aim is an understanding of the range-energy relations for low-charge-state ions in various targets. Some preliminary results are presented on pages 49–50, in the account of heavy-ion fusion research.

Research at the SuperHILAC. Research at the SuperHILAC falls into four general categories: nuclear reactions, nuclear structure, atomic physics, and exotic nuclei. The first of these areas of study—typically involving the observation of light fragments emitted following a heavy-ion collision—is the largest, accounting for about 50% of the available beam time. Of particular note during 1984 were measurements of the charge distributions of the decay fragments produced when a heavy beam impinges on a light target. This type of experiment (reverse kinematics) takes full advantage of the capability of the SuperHILAC to deliver intense beams of heavy ions.

Nuclear structure studies were highlighted by the first experiments using Compton-suppressed germanium detectors (from the High Resolution Ball). In one case, the rare ^{80}Kr isotope, from a natural-abundance source, was used as a projectile. In addition, the on-line isotope separator (OASIS) was used to deliver rare isotopes to an array of particle and photon detectors in a low-background counting area to study decay schemes. Atomic physics at the SuperHILAC centers around the spectroscopy of highly ionized atoms, and on resonant electron transfer and excitation (RTE). In an RTE experiment, x-rays emitted simultaneously with electron capture are measured for heavy-ion–helium reactions. SuperHILAC work on the system $\text{V}^{q+} + \text{He}$ showed significant structure in the cross section for this process (see Fig. 2). The exotic nuclei program now centers around OASIS and involves searches for new isotopes in the neutron-deficient rare-earth region. During the last year, six such new isotopes were discovered.

Today, the Bevalac remains the only accelerator in the world capable of producing heavy-ion beams at energies and intensities sufficient to deliver therapeutically useful doses to deep-seated malignant tumors. Accordingly, the largest part of the Bevalac biomedical program continues to focus on radiotherapy using heavy charged particles. This effort, however, reflects only one part of the broad objective of the biomedical program, namely, to better understand the biological effects of heavy ions and to exploit this understanding in developing rational medical therapies. Consequently, the most fundamental part of the biology and medicine program is a basic research effort in radiation biophysics and radiobiology. Yet a third facet of the program is a radiosurgery program, which uses not only the Bevalac heavy-ion beams, but also the 230-MeV/amu helium-ion beam of the 184-Inch Cyclotron.

Biology and Medicine

Biophysics and Radiobiology. Elements of the broad biophysics program range from the chemical characterization of breaks in DNA to life-span studies and studies of radiation carcinogenesis in mice. Despite this breadth, however, many of the studies address the same central issue, namely, the dependence of biological response on linear energy transfer (LET). In a program jointly supported by the National Cancer Institute and the DOE, we have explored the responses of several biological systems to heavy ions, including uranium, lanthanum, xenon, and iron. The heaviest ions produce multiple chromosome alterations with a spectrum completely different from that of aberrations produced by low-LET radiation. It is of particular interest that the heaviest ions can increase cell transformations produced by viral DNA and can produce de novo cell transformations. These findings con-

Fig. 2. Projectile cross sections for 180- to 460-MeV $V^{q+} + He$, for $q = 19, 20$, and 21 . $\sigma_{K\alpha\beta}$ is the cross section for the total vanadium K x-ray production. $\sigma_{K\alpha\beta}^{q-1}$ is the cross section for coincident K x-ray production and single-electron capture.

tradict previous beliefs that such ions have such dense trajectories that they produce only lethal effects.

We also looked at heavy-ion effects on RNA synthesis and at the production of micronuclear fragments after heavy-ion exposure. Tumor radiobiology studies focused on the joint effects of heavy ions and radiosensitizers. Finally, among radiological physics studies, we greatly extended the dynamic range of instrumentation used for measuring fragmentation spectra. In addition, a new method of measuring fragmentation parameters—the time-of-flight method—was tested.

Radiotherapy Trials. A deficiency of dissolved oxygen in the typical cancer cell makes it less sensitive to irradiation than a normal, oxygenated cell. In fact, the lethal dose of x-rays is often three times as high for a cancer cell as for a normal cell. Beams of heavy ions or neutrons, however, are known to be especially effective in killing these hypoxic cells. Consequently, we are currently devoting a major effort to clinical studies on humans—studies whose ultimate aim is to determine whether or not heavy ions are superior to conventional radiotherapy for local tumor control.

An additional advantage of heavy ions (not shared by neutrons) is the ease with which the dose can be localized at the tumor, thus sparing critical normal tissue. Accelerated ions of helium and heavier elements can penetrate deeply into the body, then deposit their energy abruptly at the end of their path. Furthermore, this Bragg peak of delivered dose can be manipulated in three dimensions, so that

a well-defined volume of tissue is irradiated. This localization can then be verified by the use of radioactive heavy-ion beams and positron-emission tomography, two new techniques to which LBL has made major contributions.

Patients for these clinical studies are referred by members of the Northern California Oncology Group and the Radiation Therapy Oncology Group, who together provide the support services for protocol design, patient accrual, statistical services, and data collection and analysis. Patients are treated either at the Bevalac with carbon, neon, or silicon, or at the 184-Inch Cyclotron with helium. Tumors of particular interest include malignant glioma of the brain; selected skin cancers; selected advanced head and neck cancers; locally advanced soft tissue sarcomas; and locally advanced cancers of the pancreas, stomach, biliary tract, lung, and prostate. Helium beams have been used primarily for juxtaspinal tumors, tumors near other critical central nervous system structures, and choroidal melanomas.

Patients are treated with particles alone or in combination with other cancer treatment modalities, such as chemotherapy, surgery, or standard radiotherapy. By studying the different particle beams at different tumor sites, we hope to learn the optimal particle for the treatment of various cancers.

Radiosurgery Program. In a third biomedical program, patients with inoperable intracranial arteriovenous malformations (AVMs) are treated with stereotactic Bragg peak radiosurgery, using focal beams of accelerated heavy ions. As in the radiotherapy program, the effectiveness of heavy ions is tied to the ease with which the dose can be localized at deep-seated target volumes. Using the 184-Inch Cyclotron's helium-ion beam, delivered dose typically falls off to 10% of the peak dose within 4–6 mm of the target. The effectiveness of stereotactic heavy-ion Bragg peak radiosurgery is illustrated in Fig. 3. Related exploratory research is directed at the application of charged-particle beams as neuroscience probes, at the study of brain tissue tolerances and the nature of neurological disease states, and at the development of an effective radiosurgical technique using the Bevalac's carbon beam.

Fig. 3. Stereotactic cerebral angiograms demonstrating the effectiveness of heavy-ion radiosurgery in treating intracranial arteriovenous malformations (AVMs). (a) Lateral view of a right cerebellar hemispheric AVM before surgery. (b) View of same area 10 months after surgery, showing the normal size, shape, and position of the right superior cerebellar artery and its associated branches; blood flow is normal and the AVM has been completely obliterated.

Accelerator Development Activities

Accelerator developments are aimed at more efficient use of operating time, higher beam intensities, and a greater variety of available ions. Completion of the local injector upgrade will be a major step toward the first of these goals. The objective is to allow effectively simultaneous use of beam time by the nuclear science and biomedical programs at the Bevalac. (As an added benefit, much that was learned during the local injector project is now being applied in the development of a radio-frequency quadrupole preinjector for CERN.) A second major upgrade, centered around a unique ion source design, will increase by tenfold the available intensity of uranium beams at the Bevalac. At the SuperHILAC, detector and rf system improvements proceeded on schedule.

Local Injector Upgrade

The Bevatron has accelerated heavy-ion beams since 1971, when deuteron, alpha, and nitrogen beams were made available at energies from 0.28 to 2.1 GeV/amu. These beams were provided by the 20-MeV proton injector—the “local injector.” Since 1974, however, the SuperHILAC has been the usual source of both heavy and light ions accelerated at the Bevalac. While it is possible to switch ion species fairly rapidly by exploiting the three preinjectors at the SuperHILAC, such gymnastics are not routine. Typically, the biomedical program has exclusive use of beam time during weekday working hours, even though the beam is actively used only a few minutes each hour. Now, with the aim of making the radiotherapy program essentially “transparent” to nuclear scientists using heavier ions from the SuperHILAC, a new injector system for the Bevatron, an upgrade of the local injector, is nearing completion. It will make available to the Bevatron a source of ions up to mass 40, independent of the SuperHILAC.

The new local injector, shown in Fig. 4, consists of a sputter PIG ion source and a duoplasmatron, a radio-frequency quadrupole (RFQ), and two Alvarez linacs (a prestripper and a poststripper). The RFQ parameters are shown in Table 3, where it is compared with a second RFQ now under development for CERN (see below). The design ion is silicon, which drives the parameter selection, but the injector will provide useful intensities of ions as heavy as argon. Operation of the new local injector is scheduled to commence in early 1985.

Transfer Line Improvements

Constructed in the mid-1970s, the Bevalac transfer line transports beams from the SuperHILAC to the Bevatron injection area, some 300 meters away (and 45 meters downhill). Over the past ten years, the demand for heavier beams has greatly increased, and the needs of the diverse research program has demanded a sophisticated operations schedule in which ions and energies are frequently switched. As a consequence, we are in the process of upgrading the fast-switching

Fig. 4. Schematic layout of the upgraded Bevatron local injector, showing the two ion sources, the RFQ, and the two Alvarez linacs. The second Alvarez consists of the last 51 cells of the original injector linac.

	Local injector RFQ	CERN RFQ
Design requirements		
Design ion	$^{28}\text{Si}^{4+}$	$^{16}\text{O}^{6+}$
Frequency, MHz	199.0	202.6
Theoretical transmission, %	86	95
Normalized acceptance, mm-mrad	0.5π	0.9π
Beam parameters		
Source voltage, kV	60	15
Injection energy, keV/amu	8.4	5.6
Output energy, keV/amu	200.0	139.5
Geometrical parameters		
Length, m	2.24	0.86
Average bore radius, mm	2.54	1.94
Cavity radius, mm	156	143
Electrical properties		
Peak power, kW	150	20
Duty factor	0.002	0.001
Peak surface field, MV/m	29	26
Stored energy, J	0.6	0.08

Table 3. A comparison of parameters for the Bevatron local injector RFQ and the CERN RFQ.

capabilities of the Bevalac complex. As part of our plan, improvements to the transfer line are under way, the purpose of which is to reduce the tuning time required when switching between ion species.

A review of the beam optics associated with the final foil stripper at the SuperHILAC has resulted in its relocation, allowing for a cleaner separation of final charge states. Charge-state identification and selection has been greatly improved, and transfer line tuning is now performed with a much cleaner beam. Further improvements are planned, notably to the instrumentation associated with beam diagnostics. Existing equipment will be supplemented with beam profile monitors at the major tuning stations along the line.

By means of appropriate modifications to the SuperHILAC, notably the addition of a newly developed heavy-ion source, it should be possible to increase the uranium output at the Bevatron from the 10^7 ions/pulse currently available to 10^8 ions/pulse. This upgrade would allow accurate Lamb shift measurements to be made in U^{90+} and U^{91+} , with important applications to the development of an x-ray laser, among other programs. As now envisioned, the project would comprise four major components: a new high-current ion source and new terminal components, a new high-current accelerating column, a new debuncher and rebuncher between the Wideroe and Alvarez linacs, and new instrumentation. The centerpiece of this anticipated upgrade—the new high-current source—was brought to a high level of development in 1984.

This completely new kind of source uses a metal-vapor vacuum arc (MEVVA) to produce a plasma from which ions are extracted. With this MEVVA source, we have produced a uranium-ion beam current of more than 500 electrical mA. In this source, shown in Fig. 5, a dc arc is established between two metallic electrodes in vacuum. At the negative electrode, metal is vaporized and ionized at "cathode spots"—small regions of extremely intense current concentrations (greater than 10^6 A/cm²). A quasi-neutral plasma of cathode material is created, which plumes away from the cathode. It is this plasma plume that constitutes the prolific source

Intensity Upgrade

Fig. 5. The MEVVA ion source and a schematic depiction of its main elements. An intense ion beam is extracted from a plasma plume produced at the cathode. The source shown in the photograph measures about 20 cm on each side.

of ions from which an intense beam may be extracted.

During 1984 three developmental sources were designed, constructed, and tested. Our main interest is in producing intense uranium-ion beams, but we have produced a wide variety of other ions as well, including boron, silicon, lanthanum, and gold. Beam currents of over 0.5 A have been produced, with over 400 mA delivered into an emittance of 0.05π cm-mrad (normalized). The charge-state distribution varies with the metal and with arc parameters; the uranium spectrum is typically peaked at U^{3+} , with well over 100 mA in this state. MEVVA development work is now aimed at increasing the pulse length and repetition rate, and at increasing the source lifetime.

Other Bevalac Activities

A new beamline, Beamline 44, has been designed at the Bevalac. Construction began late in fiscal 1984, and we expect the beamline to become operational in the spring of 1985. The new beamline will serve both as an improved low-energy beamline and as a spectrometer for subthreshold kaons and antiprotons. The latter will have to be produced in very unusual processes of interest both for astrophysical reasons and as a diagnostic for unusual happenings in nuclear collisions, such as the formation of a quark-gluon plasma. As a kaon line it will deliver kaon intensities a hundred times greater than previous kaon facilities at the Bevalac. As a low-energy beamline, it will allow for a greater variety of heavy ions and energies than is available at the Bevalac's present low-energy beamline. (Plans were also laid in 1984 for improvements to the beam transport system in the External Particle Beam area of the Bevatron. Improvements will be aimed at enhancing the quality of delivered heavy-ion beams, facilitating the production and delivery of secondary isotope beams, and improving the overall beam tune reproducibility.)

During 1984 LBL also continued its collaboration with GSI and CERN to develop a heavy-ion preinjector for experiments at CERN. Fixed-target experiments are planned at the PS accelerator complex at energies between 50 and 225 GeV/amu, using oxygen beams with intensities of about 10^8 particles per second. Designed initially for proton acceleration, the PS complex will undergo several modifications during the next year to permit the acceleration of heavy ions. These modifications include the development of a heavy-ion preaccelerator to be installed on Linac I and the upgrading of equipment in the synchrotron rings to improve beam-monitoring sensitivity.

The preaccelerator, developed jointly by LBL and GSI, consists of an electron cyclotron resonance (ECR) ion source and a heavy-ion RFQ linac. This project represents the first coupling of these technologies into a single package. The RFQ,

built at LBL, accelerates the beam from 5.6 to 140 keV/amu, the energy needed for injection into Linac I. A rebuncher system will be used to optimize the matching of the beam exiting the RFQ. The three Alvarez tanks of Linac I will accelerate the beam to 12.5 keV/amu before it is injected into the CERN synchrotron. A schematic representation of the accelerator complex and the heavy-ion preinjector is shown in Fig. 6.

All of the design features incorporated into the RFQ were pioneered during the development and construction of the Bevatron local injector RFQ. Both machines use the same mechanical alignment techniques for accurate positioning of the vane tips, and both incorporate vane-coupling rings to simplify tuning and to eliminate unwanted dipole modes. An exit-matching section has again been machined into the pole tip geometry to reduce the high divergence of the output beam. In almost every respect, the design problems associated with the CERN model are less severe than those encountered (and successfully dealt with) in the local injector RFQ. A comparison of the two machines is given in Table 3.

During 1984 the experimental facilities at the SuperHILAC were improved by the construction of a facility dedicated to efficient particle-particle-photon coincidence detection. This facility involves a "stopping ion chamber" to measure the charge and energy of one reaction fragment and a set of parallel-plate avalanche detectors to measure the position and velocity of the other. Gamma-ray detectors, including the Compton-suppressed germanium detectors for the High Resolution Ball, can be clustered around the 15-cm-diameter scattering chamber. The High Resolution Ball itself, begun in 1983, is nearly complete. A third detector development project produced the Gas-Silicon-Plastic (GASP) detector, which utilizes a gas-filled ion chamber and a 6.8-cm-diameter position-sensitive silicon detector to measure the charge, energy, and position of heavy-ion fragments.

Improvements to the rf system are on schedule, and nine new power amplifier carts are installed and working. When this project is completed during 1985, we will have a much more energy-efficient rf system, as well as a more reliable one, in anticipation of the future intensity upgrade.

Another development project under way at the end of 1984 was the replacement of the conventional prestripper drift tube magnets with hybrid rare-earth quadrupole magnets. These magnets will increase the focusing strength of the prestripper by 20%, which will result in a 50% increase in beam transmission for the heaviest elements. The magnet design, invented at LBL, is a combination of iron pole pieces and permanent-magnet material. Rotation of the outer layer of

Other SuperHILAC Upgrades

Fig. 6. Schematic illustration of a portion of the CERN accelerator complex, together with the planned heavy-ion preinjector.

magnetic material enables the field strength to be adjusted by greater than a three-to-one ratio. Tests have been completed on model magnets, indicating that the field quality is fully adequate. Design of prototype prestripper drift tube magnets has begun, and a timetable for the replacement of the conventional magnets has been formulated.

Work on a continuously generated liquid-film ion stripper was also successfully concluded in 1984. Large, stable sheets as thin as 260 angstroms ($5 \mu\text{g}/\text{cm}^2$) can now be routinely created. Although particle fluxes above about 10 particle $\mu\text{A}/\text{cm}^2$ damage the integrity of the sheet, this kind of stripper is clearly superior to the more common vapor stripper at low fluxes and for high charge states. For example, the amount of Ho^{17+} produced from a beam of Ho^{7+} is nearly an order of magnitude greater than that produced by a vapor stripper.

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HIGH-ENERGY PHYSICS

DURING 1984 THE HIGH-ENERGY PHYSICS community in the U.S. took the first decisive strides toward a goal that has captured its imagination and focused its efforts as rarely before—a multi-TeV, high-luminosity proton collider called the Superconducting Super Collider (SSC). The justification for such a scientific tool—its scale can be judged from Fig. 7—rests with the unanswered questions of modern physics. During the past two decades, we have profoundly increased our understanding of the fundamental structure of matter—an understanding that has been synthesized into a theoretical framework called the “Standard Picture.” In this picture, we see matter as comprising families of quarks and leptons, interacting by the exchange of gluons, photons, and W and Z particles. A keystone of this picture is the essential unity of the electromagnetic and weak forces, a unity confirmed in 1983 when the W and Z particles were first observed at CERN. Its successes notwithstanding, the Standard Picture is known to be incomplete. At the very least, there are new phenomena to be observed, and the consensus is that a hadron-hadron collider like the SSC is the tool needed to observe them.

Not surprisingly, then, in 1984 the AFRD high-energy physics program was dominated by work tied, either directly or indirectly, to this national effort. LBL was host to a comprehensive technical and economic feasibility study—the SSC Reference Designs Study—and the Laboratory provided key scientific and administrative staff support to this first step toward an SSC design. In addition, the superconducting magnet program turned increasing attention to magnet designs and cable developments that could be applied directly to the SSC. And our accelerator physics group began to tackle in earnest many of the central questions that must be answered before a final SSC design can be proposed.

One effort did, however, remain focused on today’s accelerators. In support of the Tevatron I project at Fermilab, we continued our work on selected components for stochastic antiproton cooling. In particular, 432 printed-circuit combiners and splitters were fabricated, as were low-noise preamplifiers for two frequency ranges.

Superconducting Magnets

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Fig. 7. The Superconducting Super Collider and the Fermilab main ring, superimposed to scale on a map of the San Francisco Bay Area.

Reference Designs Study

In line with its charter, the Reference Designs Study, which preceded an actual decision to proceed with design R&D, (a) explored the technical feasibility of a 20 TeV $\times$ 20 TeV proton-proton collider, based on three different proposed magnet designs, (b) performed detailed cost estimates for each design, and (c) identified the R&D required to verify design calculations and technical assumptions. The magnet designs that were examined had maximum field strengths of 3, 5, and 6.5 T, and the design circumferences of the collider varied accordingly from 164 to 90 km. The estimated costs for facilities (excluding research equipment) based on these three designs fell within the narrow range between \$2.70 and \$3.05 billion. The most important conclusion of the study, however, was that "the basic principles of design used successfully for existing accelerators can be conservatively extended to a proton collider having the SSC primary specifications of energy and luminosity."

In December 1983, the directors of the U.S. high-energy physics laboratories chartered the National SSC Reference Designs Study to review in detail the feasibility of a range of technical options for the SSC, a 20 TeV $\times$ 20 TeV proton-proton collider having a luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$. LBL served as headquarters for the study, which involved some 150 scientists and engineers from several national laboratories and universities, under the leadership of Maury Tigner of Cornell University. The purpose of the study was to help the DOE and the high-energy physics community (indeed, the scientific community as a whole) decide how best to proceed with this unprecedented accelerator project.

Three dipole magnet designs were chosen to embody a variety of design concepts and to span a range of field strengths. The high-field design (proposed by LBL; see below) has a 6.5-T central field and encloses both beam tubes in a common iron yoke and single cryostat. The medium-field design is a 5-T "iron-free" magnet, with each beam tube and coil in its own cryostat. In this second design, quite similar to the proven Tevatron magnets, all of the field is produced by currents in the superconducting coils. The low-field, iron-dominated 3-T magnet—a so-called superferric design—consists of separate beam tubes and yokes in a common cryostat. The three designs are summarized briefly in Table 4.

In all of the designs, the magnets use superconducting cable of Nb-Ti alloy, cooled to 4.5 K by liquid helium from a large and complex cryogenic system of interconnected refrigerators. A 360-MHz rf accelerating system, similar to those

	A	B	C
Central dipole field, T	6.5	5.0	3.0
Magnet length, m	17.5	14	140
Inside coil diameter, cm	4.0	5.0	2.5×2.4^a
Main ring circumference, km	90	113	164
Magnet design features			
2-in-1 cryostat	x		x
Cold iron yoke	x		x
Conductor dominated	x	x	
Field shaped by iron			x
Magnetically coupled apertures	x		
Saturated iron	x		x

^aPole-face dimensions

Table 4. Main features of the three magnet designs considered in the SSC Reference Designs Study.

currently in operation at electron-positron storage rings, is also common to all designs. Injection energy into the collider was chosen to be 1 TeV. The injector complex consists of a linear accelerator to accelerate the beam to 1 GeV, followed by a 70-GeV conventional-magnet synchrotron and a 1-TeV superconducting synchrotron. To allow credible costs to be estimated for tunneling, a mythical "median site" was chosen for the main ring such that several geological conditions were represented.

The central conclusion of the Reference Designs Study was that well-proven principles of accelerator design can be readily extended to a proton collider meeting the energy and luminosity specifications of the SSC. Furthermore, each of the three reference magnet styles was found adequate as the basis for an SSC facility. The reference designs report also concluded that a vigorous R&D program of about three years' duration would be needed to refine the cost estimates for the magnets, to determine their actual performance, to determine their manufacturability and reliability, and to develop cost-effective methods for their assembly and quality assurance. An important goal of this program will be to produce a significant number of magnets of the design finally chosen for manufacture. These magnets would then be thoroughly tested under conditions simulating actual accelerator operations.

In estimating a price tag for the SSC, the Reference Designs Study focused on the cost of the collider itself. The costs of research equipment, preconstruction R&D, and site acquisition were not considered. Following this prescription, the estimated costs for an SSC facility, based on the three magnet technologies studied, ranged from \$2.70 to \$3.05 billion (in fiscal 1984 dollars). A further breakdown of the costs is shown in Table 5.

Development of 1-meter-long model magnets continued in 1984. Prototypes with 50-mm bores reached new record fields for accelerator-type magnets: 9.1 T for Nb-Ti-wound models and 8.1 T for Nb₃Sn (at 1.8 and 4.4 K, respectively). Increasing attention, however, turned to SSC-related activities. We continued to develop our proposed 6.5-T design by successfully testing four 1-meter models to the design field strength. In a related effort, a team led by LBL demonstrated significant improvements in attainable critical current densities for Nb-Ti; at 5 T the SSC specification of 2400 A/mm² was readily exceeded. Along similar lines, superconducting cable development was highlighted by construction of a cabling machine that provides great flexibility in cable parameter selection and by investigations of unconventional cable configurations.

Superconducting Magnets

Table 5. Estimated costs, in millions of fiscal 1984 dollars, for SSC reference designs A, B, and C. Facilities and systems common to all designs are designated with asterisks.

	Design A	Design B	Design C
Conventional facilities			
Central lab facilities*	86.0	86.0	86.0
Injector facilities*	39.6	39.6	39.6
Experimental facilities*	87.4	87.4	87.4
Collider facilities	398.7	496.1	733.5
Technical facilities			
Injector*	147.2	147.2	147.2
Collider magnets	783.0	955.3	357.5
Collider cryogenics	123.9	115.9	158.2
Other collider systems*	96.8	96.8	96.8
Engineering, design, inspection	255.5	287.0	271.7
Project management, equipment*	154.5	154.5	154.5
Contingency	552.3	589.0	567.2
Total	2724.9	3054.8	2699.6

Advanced Prototype Development

The superconducting magnet R&D program at LBL was organized to develop the technology needed for next-generation high-energy accelerators. In pursuit of this goal, we have developed designs and materials for small-bore, high-field magnets so that we might evaluate critical features of advanced designs, and we have constructed several 50-mm-bore, 1-meter-long models that have generated central fields in excess of 8 T. This program has also produced the first commercial lengths of the internal-tin Nb_3Sn wire that has become the basis for recent Nb_3Sn magnet development at Brookhaven National Laboratory (BNL).

During early fiscal 1984, we concluded the 50-mm, high-field model magnet program by running final tests on four models of two design types. The first design was a four-layer, Nb-Ti "cos θ " magnet; one model reached 9.1 T at 1.8 K. The second design was a "block" type with four "double-pancake" windings. The Nb-Ti version of this design reached 8.8 T at 1.8 K, and the Nb_3Sn version reached 8.1 T at 4.4 K. All magnets, which reached record fields for accelerator type dipole magnets, were tested without iron yokes.

Despite these successes, we recognize that, until materials with much higher current densities are available or until a much cheaper superconductor is developed, fields of 8–10 T will be difficult to achieve at reasonable cost. Accordingly, our SSC effort in 1984 focused on a design slated to achieve a central field of only 6.5 T.

Magnet Development for the SSC

Magnet design A of the SSC Reference Designs Study was the product of a collaboration between LBL and BNL. It is a 17.5-meter-long, two-layer, Nb-Ti design with a 40-mm-diameter coil aperture. This design reflects concerns about both economy and reliability. Among the parameters we sought to optimize were the magnet configuration, magnetic field strength, physical aperture, operating temperature, and assumed current-carrying capacity of the superconductor. A field higher than 6.5 T, for example, would economize on circumference-related costs but would use significantly more of the costly superconductor. A cross-sectional view of the two-in-one dipole design is shown in Fig. 8.

During the past year, we constructed four 1-meter-long, two-layer cold-iron magnets with 40-mm bores. Two models, designated D12-A1 and D12-A2, used rectangular cable, and two, D12-B1 and D12-B2, used keystone cable. Both designs achieved 6.5 T. Figure 9 shows an inner winding of the D12-B2 coil

Fig. 8. Cross section of the SSC reference design A magnet, proposed by LBL and BNL, showing the coils, the iron, and the support shell. The cryostat and support structure are not shown.

assembly. The flared coil ends are necessary because of the relatively stiff, wide cable and the very small bore diameter. Figure 10 shows the magnet with its split-iron yoke assembly. (Production SSC magnets would use a yoke composed of laminated iron sheets.) The winding parameters for the two D12-B models are summarized in Table 6.

Since 1983 one of our high priorities has been achieving high current densities in commercially produced superconductor. A collaboration between LBL, the University of Wisconsin, and Intermagnetics General Corporation (IGC) has now produced commercial-scale successes in using high-homogeneity Nb-Ti (see Fig. 11) and improved heat treatments. These successes can be measured by the significant improvements we have recently seen in the critical current density J_c of Nb-Ti. Niobium-titanium rods with improved compositional homogeneity were provided by Teledyne Wah Chang, then were extruded and drawn into wire by IGC. When standard industrial processing techniques were used, this improved material yielded longer strands between breaks and higher critical current densities. At 5 T, J_c was measured at 2300 A/mm², compared to values of 1800–2000 A/mm² characteristic of good Tevatron material. Furthermore, material from the

Superconductor and Cable R&D

Fig. 9. One end of an inner winding for the D12-B2 model magnet for the SSC. The flared coil ends are necessary because the wide cable and narrow bore tube do not allow a tighter geometry.

Fig. 10. The D12-B2 model magnet, shown in its split-iron yoke assembly. This 1-meter model has achieved the 6.5-T field of the SSC magnet design.

same extrusion billet produced $J_c = 2600 \text{ A/mm}^2$ when processed according to a three-step heat treatment developed by D. C. Larbalestier of the University of Wisconsin as part of our collaborative program.

As a result of this work, we are confident that a specification of 2400 A/mm^2 at 5 T is realistic for the SSC. Manufacturers apparently share this confidence, as demonstrated by their responses to our request for quotations on material meeting this requirement.

Crucial to the production of reliable and consistent magnet performance are stringent controls on cable dimensions and steps to minimize degradations in J_c due to cabling. In recognition of these needs, we recently constructed a cabling machine, shown in Fig. 12, that provides great flexibility in the choice of such parameters as strand tension, number of strands, mandrel shape and position, and planetary spool operation. With this machine, we can establish the parameters necessary for the production of high-quality cable and transfer that information to industry.

We are also investigating unconventional cable configurations, such as an "internal flat" design and cables with internal wedges. The goal of this work is to develop a cable with a higher effective modulus so that the relaxation or distortion caused by clamping and magnet operation will be reduced.

	Inner layer	Outer layer
Number of turns	17	17
Inside diameter, mm	40.0	59.7
Outside diameter, mm	59.3	78.9
End outside diameter, mm	93	97
Precompression, MPa	80	74
Coil length, mm	940	1006
Number of strands	23	30
Strand diameter, mm	0.808	0.635
Copper-to-superconductor ratio	1.3	2.0
Nominal cable dimensions, mm	1.402	1.15
	$\times 1.673$	$\times 1.406$
	$\times 9.30$	$\times 9.53$

Table 6. Parameters for the windings of the two D12-B model magnets.

Fig. 11. Phase diagram for Nb-Ti alloy and γ -ray radiographs showing (a) an inhomogeneous alloy produced in the conventional way and (b) a high-homogeneity alloy produced by a three-step heat treatment developed by D. C. Larbalestier of the University of Wisconsin. The solidification process involves only the upper curves of the diagram; for a solution containing 46.5% titanium, this process can be visualized by following the line shown in color. The first solid appears at about 2250°C and has a composition indicated by point A. As cooling continues, the liquid becomes enriched in titanium, and solid of increasing titanium content appears. At a given temperature, a horizontal line can be drawn between the two curves; the point of intersection with the upper curve indicates the liquid composition, and the point of intersection with the lower curve indicates the composition of solid forming at that temperature. In practice, the volume and composition of the solution are manipulated to ensure that the composition of solid remains within a narrow range. The solid-phase transitions that occur at lower temperatures are important in later heat treatments aimed at optimizing superconductor performance.

Fig. 12. Cabling machine designed and built at LBL for the fabrication of advanced superconducting cable. The machine allows complete control of all cabling parameters, including strand tension, number of strands, and mandrel shape and position.

SSC Accelerator Physics

Accelerator physicists at LBL began intensive work on the SSC in 1983, in support of the proposed 6.5-T magnet design, which, in turn, became reference design A during the Reference Designs Study. In that same study, LBL physicists formed the core of the accelerator physics group led by Fermilab's Don Edwards. In a period of only a few months, that group established preliminary parameters for a near-optimal design, produced conceptual designs based on three magnet types, addressed all significant beam lifetime and stability issues, and identified areas requiring further R&D. Since the conclusion of the Reference Designs Study, work has focused on the key SSC design issue, namely, single-particle stability in an imperfect magnetic field. At the end of fiscal 1984, much of the LBL accelerator physics group took its place in the SSC Central Design Group, whose headquarters at LBL will be the focus of nationwide SSC R&D efforts over the next several years.

From the very beginning of the nationwide SSC effort, LBL accelerator physicists have played a leading role in solving individual problems and in broadly advancing our understanding of the physics issues involved. They have been active in workshops since the 1982 Snowmass meeting and have been at work on lattice designs and exploratory parameter studies since about the same time. At the beginning of fiscal 1984, effort focused on the 6.5-T, two-in-one dipole magnet design proposed by LBL and Brookhaven. This proposal was a product not only of the work of magnet designers, but also of the effort of accelerator physicists who established design parameters and worked on key physics issues.

During the Reference Designs Study, conducted during the first half of 1984, LBL accelerator physicists formed the core of the group charged with optimizing performance parameters, tackling major issues of beam stability and lifetime, and identifying areas in need of further study.

One of the group's principal tasks was selecting beam parameters, given established design parameters such as the luminosity. A summary of the most important of these parameters, chosen as part of the Reference Designs Study, appears as Table 7. Substantial effort also went into designing a fully matched lattice for reference design A, since a lattice design is a prerequisite for all other beam dynamics studies. A simple schematic of the lattice is shown in Fig. 13. All six interaction regions were assumed to be identical, and three identical utility insertions (one each for injection, beam abort, and the rf system) were assumed necessary.

Beam lifetime and stability were also major issues examined in the Reference Designs Study. Intrabeam scattering and other scattering phenomena appear to be well-understood, and the criteria for stability in the face of collective effects have now been derived. Feedback systems will be required to damp longitudinal and transverse coupled-bunch modes. The lower limit to the bunch spacing may, in

Bunch spacing, m	10
Luminosity, $\text{cm}^{-2}\text{sec}^{-1}$	10^{33}
Normalized transverse emittance (ϵ_N), μm	1.0
Betatron amplitude function at interaction point (β^*), m	1.0
Crossing angle, μrad	75
Number of particles per bunch	1.4×10^{10}
Number of bunches	9000
Number of particles per ring	1.3×10^{14}
Mean number of interactions per bunch collision	3.3

Table 7. SSC beam parameters selected during the Reference Designs Study, assuming a 90-km ring circumference.

Fig. 13. (a) General layout of the SSC lattice, assuming a 90-km circumference. Each superperiod contains 122 "regular cells," two experimental straight sections, and a utility straight section. Dashed lines indicate the locations of 100-meter half cells. (b) Schematic of a regular cell, comprising ten bending dipoles (B), two quadrupoles (focusing, QF, and defocusing, QD), and two spool pieces (S) containing correction elements.

fact, be determined by the bandwidth required for these feedback systems. The choice of a 10-meter bunch spacing is consistent with realizable systems.

Perhaps the most significant and challenging problem faced by the accelerator physics group during the Reference Designs Study was the relationship between aperture and the field quality of the superconducting magnets. Indeed, this remains the central physics issue facing the SSC Central Design Group. The problem can be summarized as one of accounting for the effects of systematic and random field errors on the beam orbit and on the "dynamic aperture" of the machine. Understanding these effects will allow the physical aperture, and thus the cost, of the SSC to be minimized. For a given design, evaluation of the dynamic aperture, within which a stable orbit can be maintained, depends on a careful assessment of achievable field quality and inevitable alignment errors. Solving the other half of the problem—establishing the dynamics of the beam—depends on both numerical solutions to the equations of motion ("tracking studies") and approximate analytical solutions. Both approaches are subjects of intense ongoing effort.

Beam Cooling

In support of the Tevatron proton-antiproton collider project at Fermilab, we are designing, producing, and testing selected components for stochastic antiproton cooling. In particular, our efforts have concentrated on printed-circuit signal combiners and splitters, and on low-noise preamplifiers designed for operation at both 1–2 and 2–4 GHz.

Stochastic beam cooling is a technique for reducing the variations in transverse position and momentum that are inherent in any particle beam. Signals indicating deviations from the mean are produced in sensitive pickup loops, combined by means of sophisticated low-noise circuitry (see Fig. 14), amplified, and transmitted to downstream kicker electrodes. There the amplified signals are applied to the beam as corrective impulses.

During 1984 the final design and production of selected components for a Fermilab antiproton-cooling system based on this principle were carried out at LBL. Printed-circuit boards for signal combiners and splitters were fabricated from special low-loss materials; there were eight circuit designs in the 432 boards produced. We also completed the development of low-noise preamplifiers for the 2- to 4-GHz range. Nine of these units and 12 preamplifiers for the 1- to 2-GHz range were fabricated. The pickups, combiners, and preamplifiers operate at liquid nitrogen temperature, thus providing a fourfold improvement in the signal-to-noise ratio compared to room-temperature operation.

In addition to providing many of the individual components, we supplied designs and technical assistance for the fabrication and assembly of the complete cooling systems at Fermilab. Pickup loop geometry was revised to fit the production arrays, input circuit layouts were made, and commercial components were specified, with prescriptions for their modification where needed. We also developed antennas for test-exciting the production arrays.

We also directed research effort at several potential problems. As an example, the beam tube through the pickup structures can act as a waveguide, thus transmitting traveling waves that would introduce false signals into the cooling systems. Absorbers of ferrite appeared to be a promising means for suppressing such waves, but we were unable to estimate the losses in ferrite at high frequencies. Consequently, we devised a stripline-cavity fixture to measure ferrite samples and conducted computer analyses of network analyzer outputs from the cavity. At year's end, the complex permeability and permittivity of candidate ferrites had been obtained at frequencies up to 5.5 GHz.

Fig. 14. Pickup loops and combiners for the Tevatron stochastic beam cooling system; one combiner cover plate has been removed to show the circuits inside. High-frequency signals are produced sequentially in the pickups by beam particles passing through the rectangular beam tube. These signals pass into the striplines of the combiners, where printed-circuit patterns are designed to impose appropriate delays on the signals and to match their impedances. Eight signals are thus combined into a single 50-ohm output.

We also modified and calibrated our modulated electron-beam facility for testing pickup responses, so that we could extend our measurements up to 4 GHz. From test results and measured characteristics of all input-circuit components, it is now possible to predict the signals that will appear at the preamplifier outputs in operating cooling rings.

SSC Magnets

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MAGNETIC FUSION ENERGY

IN MAGNETIC FUSION REACTORS of the future, part of the energy generated by the continuous fusion reaction will serve to maintain the temperature of the plasma. Only when the reactor is ignited, either for the first time or following a shutdown, will an independent means be needed to heat the plasma to about 10^8 °C. Today's magnetic fusion experiments, on the other hand, do not produce enough energy to maintain a continuous reaction; thus, these experimental devices must operate in short pulses. Since the plasma must be heated to the ignition temperature before each pulse, the need for plasma heating is critical. LBL's most prominent role in the national magnetic fusion program is the development of one such means for plasma heating, namely, the injection of energetic beams of neutral atoms.

These neutral beams comprise hydrogen or deuterium atoms, produced by neutralizing multi-megawatt beams of either positive or negative ions. Our work on both positive- and negative-ion-based beams is coupled with the research efforts at the Tokamak Fusion Test Reactor (TFTR) at Princeton, the Magnetic Fusion Test Facility (MFTF-B) at Livermore, and Doublet III at GA Technologies, Inc., in San Diego. In 1984 the DOE, together with representatives from these three major experimental facilities, selected an LBL positive-ion prototype as the common source module for all national program needs starting in the mid-1980s.

Increasingly, however, attention is turning to negative-ion-based systems, since, at high energies, positive ions are only inefficiently converted to neutral species. Because of the high energies foreseen for negative-ion systems, the resulting neutral beams may provide a means for generating and maintaining potential barriers in tandem mirror fusion systems, in addition to offering an alternative to rf heating for heating the plasmas in next-generation tokamak reactors. As currently conceived, the necessary neutral-beam injector will include a source of D^- ions, an accelerator and beam transport system, and a neutralization region.

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We are working actively on two different ion-source designs and have concentrated on transverse field focusing as the underlying concept for the accelerator and transport sections.

Among the offspring of neutral-beam development, a scheme for producing intense nuclear-spin-polarized beams has emerged from our atomic physics program. This technique, which we call collisional pumping, is of potential interest not only to the magnetic fusion community, but also to nuclear physicists.

Increasing attention is turning to negative ions as the source for intense neutral beams, principally because they can be efficiently neutralized even at high energies (above 150 keV/particle for deuterium). Nonetheless, one of the highlights of 1984 was the choice of an LBL positive-ion source as the common long-pulse source for experiments at TFTR, MFTF-B, and Doublet III in the coming years. In a series of 80-kV, 30-second tests at the Neutral Beam Engineering Test Facility, the LBL source produced an average current of over 40 A. Negative-ion source development continued to focus on two different designs. The surface-conversion source—the better understood of the two—can now be considered a practical tool, largely because of advances that allow us to effectively control cesium contamination. Development of the volume-production source also moved forward, notably in the areas of increasing the extracted current and reducing the electron content of the beam.

Neutral-Beam Development

In April 1984, the DOE and representatives of TFTR (Princeton), MFTF-B (Livermore) and Doublet III (GA Technologies) selected LBL as the developer of a Common Long-Pulse Source (CLPS) to provide neutral-beam heating for the three major confinement experiments in the U.S. Accordingly, most of the year's activity was directly related to the long-pulse program.

LBL's selection was based on two factors: first, the performance of our prototype source in 80-kV, 30-second tests, and second, the fact that we proposed a common design for all three users. The tests of the two competing designs were carried out at LBL's Neutral Beam Engineering Test Facility (NBETF). Compared to its competitor, the LBL accelerator produced 30% more current, in a beam of smaller divergence, from a significantly smaller source. During the 500-shot test, the average current produced with deuterium was 40.3 A. In addition, the same source has produced 57 A of hydrogen at 80 kV, for 5 seconds.

LBL's 12 cm × 48 cm design (see Fig. 15) was developed to meet the requirements of all three users and to fit existing space envelopes. For all three sources, the plasma generator and accelerator structure will be identical. The only difference will be in the accelerator gaps and the plasma mask on the source grid. Both MFTF-B and Doublet III will use the full accelerator aperture, whereas TFTR will mask the accelerator to 12 cm × 43 cm. The accelerator is a water-cooled tetrode comprising four sets of molybdenum grid tubes brazed to a stainless-steel structure. Each electrode, in turn, is composed of four modules. Beam focusing, if desired, is accomplished by tilting the modules slightly with respect to one another. The design parameters of the CLPS are summarized in Table 8.

Lawrence Livermore National Laboratory is coordinating the industrialization effort for the CLPS with RCA, who won the contract to commercialize the LBL design. LBL is providing engineering review and technical consulting services to ensure compliance with LBL design and operating specifications. We will also test and evaluate the first manufactured sources on NBETF.

Positive-Ion-Based Systems

The goal of the negative-ion-based neutral-beam program is to develop systems capable of injecting megawatts of deuterium atoms into magnetically confined plasmas for very long times (hours to months). For applications to mirror reac-

Negative-Ion-Based Systems

Fig. 15. Full-scale model of the LBL long-pulse source design, chosen in 1984 as the Common Long-Pulse Source for the major magnetic confinement experiments in the U.S.

tors, the requirements are 1 to 10 MW at 200 to 500 keV. These beams are used to tailor the ion-velocity distribution in the end cells for control of the plasma potential and thermal conductivity. In the case of tokamak reactors, 25 to 100 MW of beam power are required at 400 to 1000 keV. Here the neutral beams are used to heat the plasma to ignition or for current drive. In none of these cases can a beam of neutral atoms be produced efficiently from positive ions at the required beam energy. It is therefore necessary to begin with beams of negative ions, which can be converted to neutral (atomic) beams with at least 60% efficiency at the needed energy.

	TFTR	MFTF-B	Doublet III
Voltage, kV	120	80	80
Current, A	70	≤ 50	80
Beam species	Deuterium	Hydrogen	Hydrogen
Pulse length, seconds	2'	30	5
Focus	Unfocused	10 m or unfocused	10 m

Table 8. Parameters for the TFTR, MFTF-B, and Doublet III versions of the Common Long-Pulse Source.

Surface-Conversion Source. Our "workhorse" negative-ion source is of the surface-conversion type, in which the negative hydrogen ions are created at a molybdenum electrode—the converter—embedded in a hydrogen plasma containing a trace of cesium. This source routinely produces 1 A of H^- ions, and the output is stable for hours at a time. Ion currents up to 1.4 A have been demonstrated for a 25-cm-wide "ribbon" beam.

We have now built and operated a single-aperture accelerator in conjunction with this surface-conversion source. In 1984 beam output reached 1.25 A of H^- at 80 keV, with a pulse length of 30 seconds and an electron content of about 10%. The pulse length was limited by the heating of the resistive divider that supplied the high voltage to the intermediate accelerator electrode. Emittance measurements indicated that 90% of the ions were within 1.1×10^{-3} rad-m. The shape of the emittance profile agreed well with the one calculated by our ion optics code WOLF. This source and accelerator, mounted on the Test Stand IIIA beamline, are shown in Fig. 16.

A major accomplishment of the past year was learning how to operate the source and accelerator in the presence of cesium. More or less continuous injection of cesium is required during source operation to maximize the yield of H^- and to maintain a constant output. By lining the ion source with thin sheets of molybdenum or stainless steel, which are heated to 300–900°C by the plasma, we were able to reduce the consumption of cesium to about 1 gram per week and to virtually eliminate contamination of the source by cesium compounds. Contamination had previously required tedious cleaning of the source every time it was opened to air. Converters with integral cesium dispensers were also tested, one with a shower-head disk and the other with a porous disk. Both of these electrodes reliably produced H^- currents equal to or greater than that produced by a comparable solid electrode with front-surface cesium deposition. In addition, we have learned that by running bursts of several short beam pulses during source operation, we can keep the accelerator clean and maintain voltage-holding capability even during cesium injection. These two advances have made the surface-conversion source a practical tool.

Fig. 16. Surface-conversion ion source and single-aperture accelerator, mounted on Test Stand IIIA.

In a separate development, applicable not only to surface-conversion sources, but to other designs as well, we have recently demonstrated that directly heated LaB_6 filaments are capable of functioning well in dense plasmas. Their lifetimes are typically much longer than that of a conventional tungsten filament. Further, the lifetime can be substantially increased by appropriately shaping the LaB_6 filament, as shown in Fig. 17.

Fig. 17. Shaped LaB_6 filament operating at 70 V with an arc current of 60 A. The temperature is constant (1820 ± 20 K) along the 10-cm length of the filament.

Transverse Field Focusing. The next step in the accelerator development program is to demonstrate that we can transport our 1-A beam of H^- around corners. This capability will be used to advantage in two ways in a neutral-beam system. First, we can transport the ion beam through a two-stage differential cryopump to remove gas from the source as quickly as possible, thus minimizing H^- loss by collisional stripping. And second, we will ultimately be able to transport a high-energy beam of negative ions through a maze in the neutron shielding of a reactor.

These goals can be achieved by an electrostatic beam transport system using transverse field focusing (TFF) optics. Pairs of curved sheet electrodes can both deflect and focus the beam. A TFF transporter designed to accept a 1-A, 80-keV beam is shown in cross section in Fig. 18; Fig. 19 shows the completed assembly. This transporter will form the basis for a two-stage differential pumping section. The cryopanel for this pump have been designed but not yet constructed. The transporter also serves to match the beam emittance to a TFF accelerator using the same beam optics principles. The design of the accelerator is now under way.

Volume-Production Source. In parallel with our work on surface-conversion sources, we are continuing our efforts to develop a more advanced negative-ion source—the so-called volume-production source. In this source, negative ions are produced in the plasma itself, and no converter electrode or cesium is required. An additional advantage to the volume source is that the ion “temperature” is less

Fig. 18. Cross-sectional view of a TFF transporter, located between a negative-ion source and 80-keV preaccelerator, at the left, and a TFF accelerator. Negative-ion beams are deflected, focused, and accelerated by the curved sheet electrodes.

Fig. 19. The completed TFF transporter, with its housing removed. The beam channel is between the vertical bars at the center of the photo and the curved sheet electrode behind them. An ion source will be mounted at the left; cryopanel is at the right.

than 0.5 eV, compared to 5–6 eV in the surface-conversion source. This lower temperature produces beams of much lower emittance. This new source is not without difficulties, however. The H^- output is (at present) substantially lower—milliamperes rather than amperes—than that of the surface-conversion source. In addition, it is more difficult with the volume source to keep electrons out of the beam. Our experimental program is aimed at solving these two problems.

Our efforts to control the electron content in the volume-produced beam are carried out on Test Stand I. We have rebuilt a small positive-ion source as a volume-production source to study this problem. The rods that define the six slots of this multiple-aperture source contain permanent magnets to deflect the electrons from the beam before they gain too much energy. A careful parametric study has now been carried out: Unoptimized H^- beam outputs of up to 25 mA have been measured calorimetrically, and higher currents have been measured electrically under conditions that exceed our steady-state capabilities. Prospects are good for improving the negative-ion output of this source by an order of magnitude.

A second volume-production source being developed is the magnetically filtered multicusp source shown in Fig. 20. This source has been shown to provide high-quality H^- beams with sufficient current density to be useful for both neutral-beam and accelerator applications. We have explored different schemes to improve the efficiency of this H^- source, the most successful being a geometry in which the extractor is placed very close to the magnetic filter. We also found that the extracted electron current is much reduced with this optimum geometry.

NBETF

The Neutral Beam Engineering Test Facility (NBETF) is a major national facility for testing and diagnosing ion sources developed in conjunction with the neutral-beam program. In over six hundred 30-second shots, it has proven itself capable of 80-kV, 40-A operation. In addition, we have carried out some source testing with hydrogen at 57 A and 80 kV, using 5-second shots. Furthermore, improvements to the cooling system have been made in anticipation of 120-kV operation with up to 65 A.

In support of CLPS development, the NBETF was used in early 1984 to test both LBL and Oak Ridge National Laboratory sources at 80 kV. Following selection of the LBL source for commercialization, tests have continued on the LBL

Fig. 20. Schematic diagram of a magnetically filtered multicusp volume-production ion source.

source, which will eventually operate at 120 kV on TFTR (see Table 8). Other activities during 1984 included tests of a magnetic beam-species purification technique for MFTF-B.

Following minor changes to the water flow bellows, the beam dump calorimeter now provides reliable beam-quality and power-dissipation measurements for long-pulse source testing (see Fig. 21). The dump has been tested with up to 4.6 MW of beam power, and it is estimated to be capable of handling as much as 8 MW.

Fig. 21. Calculated power-density contours for a 30-second, 80-kV shot on NBETF. The maximum calculated power density was 766 W/cm²; measurements were made at the NBETF's actively cooled beam dump.

Concurrent with the design and testing of neutral-beam systems, work continued in 1984 on developing appropriate beam diagnostic techniques. As an outgrowth of these efforts, a technique was proposed for producing intense beams of electron- and nuclear-spin-polarized atoms. This technique, which we call collisional pumping, could be used not only to heat and fuel a fusion plasma, but also to make possible new kinds of nuclear physics experiments. Theoretical work also continued, the aim being a better understanding of the processes and interactions that occur in plasmas.

Atomic Physics and Theoretical Studies

The broad purpose of LBL's ongoing neutral-beam atomic physics program is to provide quantitative data required for developing and using neutral-beam systems. Our two principal goals are to develop noninterfering, on-line diagnostic techniques and to study atomic and molecular processes relevant to negative-ion sources.

Atomic Physics

In pursuit of the first goal, we continued our development work on a laser-fluorescence diagnostic method to measure the composition of neutral beams (including impurities) during injection into a plasma-confinement experiment. We have now detected oxygen (in a metastable state) and several heavy-metal impuri-

ties in neutral beams. We are now extending the technique to lighter elements, for which vacuum ultraviolet radiation is required. We are also extending this technique to measure the energy distribution and the emittance in beams of fast hydrogen and deuterium atoms. This, too, will require the generation of vacuum ultraviolet (Lyman) radiation to excite ground-state hydrogen and deuterium atoms or visible (Balmer) radiation to detect metastable excited hydrogen and deuterium atoms. For this work, we have available at LBL an intense tunable laser light source, covering the wavelength range from vacuum ultraviolet to infrared.

Our ion-source research covers both the surface-conversion and volume-production mechanisms for H^- and D^- production. Interest in the latter mechanism is especially strong, since it is less well understood. However, our calculations for dissociative attachment of electrons to vibrationally excited hydrogen molecules indicate that this mechanism is at least partially responsible for the H^- production in volume sources. Future measurements will correlate the distribution of H_2 vibrational states with extracted H^- . We are also studying the production of Li^- , which can be efficiently neutralized at high energies to form a beam of fast lithium atoms. These, in turn, can be used for diagnostic measurements of fusion-produced alpha-particle distributions. Production mechanisms for Li^- include surface, volume, and charge-transfer processes. We have measured a maximum efficiency of 5% for the production of Li^- by charge transfer to Li^+ ions in metal-vapor targets.

As an outgrowth of our support of neutral-beam development, we have proposed a new technique for producing polarized particle beams. This technique (which we call collisional pumping, by analogy to optical pumping) uses multiple charge-changing collisions in a polarized target gas to produce an intense nuclear-spin-polarized beam of hydrogen, deuterium, or tritium ions or atoms. Figure 22 shows the calculated polarization and neutral fraction for 2.5-keV H^+ or D^+

Fig. 22. Plot of the calculated polarization (P , polarization of hydrogen atoms; P_z , vector polarization of deuterium atoms; and P_{zz} , tensor polarization of deuterium atoms) and neutral fraction (f_0) for beams of 2.5-keV/amu H^+ and D^+ after passing through a sodium target, as functions of target thickness.

incident on an electron-spin-polarized sodium-vapor target. The remarkable result is that for a sufficiently thick target the emerging beam will be entirely neutral and entirely electron- and nuclear-spin polarized. A proton or deuteron beam can thus be entirely polarized, whereas in present polarized-ion sources, only a small fraction of the beam can be converted to polarized ions. Spin-dependent atomic processes can then be used to efficiently convert the polarized atom beam to nuclear-spin-polarized H^- or D^- for subsequent acceleration. We calculate that a polarized neutral beam of very high intensity could be made and perhaps used to heat and fuel a fusion plasma with polarized reactants. A source of polarized ions could also be used with an accelerator for studies not currently feasible of spin-dependent nuclear processes.

Finally, using the SuperHILAC, we have extended our studies of resonant electron transfer and excitation (RTE) in measurements with fast, highly charged vanadium and calcium ions colliding with helium atoms. This process is analogous to dielectronic recombination, an important energy-loss mechanism in high-temperature plasmas. During 1984 we observed, for the first time, structure in the energy dependence of the RTE cross section (see Fig. 2 on page 7), indicating formation of intermediate excited states of the ion.

During the past year, our theoretical studies continued in the areas of nonlinear dynamics and plasma heating. Our studies of nonlinear dynamics emphasize continuous media, including waves, fluids, and plasmas, and are unified by the use of modern differential geometric methods. The plasma heating program embraces both basic and applied plasma theory. Among our achievements during 1984, we formulated a covariant action principle for the interaction of a Vlasov plasma with an electromagnetic field. For the field represented as an eikonal wave, a covariant Lie transform converts the action principle to describe the self-consistent evolution of the oscillation-center distribution and the linear wave propagation. Applications are planned to free-electron lasers and to the turbulent transport of magnetoplasmas.

We also continued our exploration of WKB methods in phase space. WKB theory is usually formulated in x -space, where it is subject to singularities at caustics and where it is unable, in general, to provide uniform approximations to wave fields. There is no salvation in k -space, for the same problems arise there as well. A deeper analysis of this problem leads to a formulation of WKB theory in phase space, which avoids the difficulties surrounding caustics. Our new formulation is expressed in terms of two kinds of wave operators, Heisenberg and metaplectic, and the results provide considerable insight into the foundations of WKB theory.

Other work culminated in a geometric interpretation of Hamiltonian perturbation theory, which advanced, in turn, our understanding of the Hamiltonian structure of plasma physics. A Hamiltonian structure on a certain jet bundle was shown to give the correct perturbed dynamics; we showed that this structure is intrinsic in five ways and that it is related to a physically natural path space and iterated tangent bundle. We have also elucidated the structure of this theory for systems with symmetry and for situations where Lie transforms or the methods of averaging are appropriate. This new structure leads to a deeper insight into both mechanical systems (like gyrotron) and nonlinear wave systems.

Finally, much effort has gone into deriving a self-consistent theory of ponderomotive stabilization. For a magnetically confined plasma irradiated by a high-frequency current source, an action principle was formulated to derive the self-consistent low-frequency evolution of plasma, field, and rf amplitude. The plasma is acted on by ponderomotive forces and magnetization, and the density and magnetic-field perturbations in turn affect the rf amplitude pattern. The evolution equations are converted to an energy principle for determining stability in the presence of the rf field. In addition, our studies of the Hamiltonian structure of the system allows Arnold's stability method to be applied.

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HEAVY-ION FUSION ACCELERATOR RESEARCH

DURING THE PAST YEAR, LBL continued to play a leading role in studying high-current heavy-ion accelerators that could eventually be the basis for generating power by means of inertial-confinement fusion. Such schemes foresee the use of lasers or beams of particles, focused on small pellets of deuterium and tritium, as ways of compressing and heating the fuel to the point that a thermonuclear reaction occurs. Approaches taken elsewhere concentrate on lasers or light-ion accelerators as the drivers of the reaction, but heavy-ion accelerators are especially attractive in light of their efficiency and high repetition rates.

In particular, the LBL program centers around the study of the induction linac (see Fig. 23) as the means of accelerating intense heavy-ion beams. The choice of this technology was based principally on three points: (a) the induction linac is conceptually simpler, and probably cheaper, than alternative acceleration methods; (b) considerable experience has already been accrued in its use; and (c) the most serious technical issues confronting development of the linac can be resolved with a small or medium-size accelerator. In line with this third point, the program for exploring the physics and technology of linac development involves three major steps. The first, already well under way, is the single-beam transport experiment (SBTE), in which a high-current cesium beam is transported through 41 focusing-defocusing quadrupole pairs. Second is the multiple-beam experiment (MBE), in which multiple independent beams will be transported through a single accelerating structure. Finally, the program culminates in the High-Temperature Experiment (HTE), which will focus and overlap multiple high-current beams on a 2-mm-diameter spot. This final step will be designed to provide a firm basis for evaluating heavy-ion accelerators as inertial-confinement drivers.

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Fig. 23. Schematic cutaway of an induction linac. Each "ferromagnetic" core acts like the core of a transformer, the pulsed voltage being applied to the primary circuit and the beam acting as the secondary. Proper timing of the pulses establishes a gradient for accelerating bunches of charged particles.

The principal goal of the SBTE is to study the stability of a high-current beam of heavy ions (Cs^+) as it is transported through an array of quadrupole magnets. Initially, the destabilizing effect of mutual electrostatic repulsion was the main uncertainty, but results continue to support estimates of maximum transportable current—without deterioration of brightness—that are much higher than those suggested by simple theory. Also as part of the SBTE, we have measured the attenuation of the Cs^+ beam as a function of gas pressure, which has allowed us to measure both the electron-capture and electron-loss cross sections for the ion in nitrogen at 160 keV.

Single-Beam Transport Experiment

The apparatus for the SBTE consists of an ion source, an injector, a matching section comprising 5 quadrupoles, a transport section of 82 quadrupoles, and a diagnostics chamber. It was designed to explore the limits of stability for a space-charge-dominated heavy-ion beam in an alternating-gradient lattice. Identifying stability thresholds is of particular importance as we seek to optimize the design for the proposed HTE.

The motion of a single particle in a lattice such as that of the SBTE is sinusoidal and can be characterized by a phase advance σ_0 , which expresses, in units of degrees, the fraction of a full (360°) oscillation executed per lattice period. In a high-current beam, however, the mutual electrostatic repulsion of the particles provides a defocusing force that acts to increase the period of the oscillations and thus to decrease the numerical value of the phase advance, now designated as the depressed phase advance σ . The larger the beam current transported, the smaller the value of σ .

Since our ultimate aim is to carry as much current as possible in an induction linac, it is crucial to establish a lower limit for σ . Contrary to speculation that for $\sigma_0 = 60^\circ$ the limit might be in the neighborhood of 24° , or even 40° , our experiments indicate that it must be below $\sigma = 8^\circ$. Work continues in an effort to establish whether any lower limit exists. For $\sigma_0 > 90^\circ$, on the other hand, instabilities have been identified at values of σ as high as 90° .

Stability Limits

Other Studies

Recent additions to the SBTE have allowed us to deliberately misalign the beam to check the importance of such misalignments in a real lattice. Simulations recently run for misaligned intense beams predicted significant emittance growth. Our experiments, however, showed no effect larger than the usual measurement variations, though misalignments to date have been limited to those causing only a small beam loss (3- to 4-mm maximum offset). The measurement of misalignment effects continues.

The vacuum system for the SBTE has also been recently upgraded, allowing us to lower the pressure to about 1.0×10^{-7} Torr. This low pressure assures us that less than 0.5% of the beam will undergo charge-changing collisions with the background gas. The measurements of electron-capture and electron-loss cross sections that underlie this assurance were made during systematic studies of beam attenuation in the SBTE at different pressures.

In addition to the transverse focusing experiments for which they were designed, the SBTE and its high-current cesium injector provide an opportunity for performing longitudinal physics studies such as bunch compression and bunch end control experiments, and studies of the propagation of charge and velocity disturbances. The latter can range from the single-particle regime at low beam intensities to the space-charge wave regime at high beam intensities. A few such exploratory experiments were performed on the well-instrumented SBTE beam during 1984. For example, the effect of a discrete energy jump part way along a beam bunch was studied theoretically with a one-dimensional code and experimentally on the SBTE. At low currents, bunching occurs, whereas at high currents, plasma waves produce a smoothing effect.

Multiple-Beam Experiment

A self-consistent engineering design for a 16-beam MBE was completed in May 1984, our plan being to demonstrate as much of the accelerator physics and to develop as much of the technology for the HTE as possible on a relatively small scale. In light of budget constraints, however, emphasis was then shifted to a scaled-down four-beam design, called MBE-4. Its objective is to serve as a "proof of principle" for the HTE, whereas the technology development must await a larger-scale experiment. MBE-4 will be approximately 12 meters long, but when measured in units of initial pulse length, it is twice as long as the electrostatic portion of the HTE and two-thirds the length of the entire accelerator. It will be injected with 0.2-MeV cesium to study the beam dynamics of 2-MeV sodium in the HTE.

The 16-Beam Design

Much of our effort during fiscal 1984 was directed toward the design of a 16-beam MBE, which was to be constructed and installed at LBL. This experiment was intended to demonstrate much of the accelerator physics that would be involved in the HTE and to develop technology on the scale necessary for that future experiment. Budget actions in July, however, made it clear that this experiment would not be carried out in the near future. As a consequence, our emphasis shifted to a smaller experiment, MBE-4, discussed below.

Before this shift in programmatic development occurred, however, a preliminary conceptual design for the 16-beam experiment was developed. The 16 beamlets (up to 6 μ sec in duration) are obtained from a source/injector being developed at the Los Alamos National Laboratory (LANL). Each beamlet is generated on a concave hot surface and electrostatically accelerated to 2 MeV through a series of electrodes inside an evacuated alumina insulating column. The column is powered by a Marx generator with a triggered diverter switch that ends the current pulse. At the output of the injector, each beamlet passes through a matching section consisting of ten quadrupole arrays. Between the quad arrays are steering and diagnostic sections that allow the beams to be steered into the accelerator. With the adjustment of the quad voltages, the LANL beams can be precisely matched into the accelerator.

Through the entire accelerator and transport sections, the 16 beamlets are contained and focused by an electrostatic quadrupole array consisting of 32 electrodes arranged in a rectangular grid so as to form apertures for 21 beamlets. To facilitate beam handling, only the outer 16 apertures would be occupied, as shown in Fig. 24. The quad arrays are arranged in a FODO lattice with a period of 63 cm.

The linac itself consists of 25 combined focusing and induction units, each a full lattice period (63 cm) long and each containing two electrostatic quad arrays for focusing the 16 parallel beams. Fourteen induction cores are contained in each unit. Each core can generate up to 175 kV for 3 μ sec across a single accelerating gap. The cores are powered by individual pulsers, whose firing times are varied to generate the proper voltage waveforms (see Fig. 25). The resulting "acceleration schedule" shows that, typically, the accelerator will accelerate 2-MeV sodium-ion beams 5.4 meters long to 4 MeV at the beam head and 6 MeV at the beam tail, with a current amplification of approximately 1.6-fold (from 2.4 to 3.5 A). Many other acceleration schedules are possible.

Fig. 24. Transverse and longitudinal cross sections of an electrostatic lens array for the 16-beam MBE. Each such array is encircled with 14 induction cores, which establish the accelerating gradient.

We now have a substantial body of data on the electric-field characteristics of several configurations of quadrupole focusing elements, and we have looked at a number of alternative physical layouts for the MBE linac. An important part of this effort was a study of the effects of misalignments (see above) and similar departures from ideality. For example, computer simulations suggest that displacements of about 0.1 mm may be caused by the electric field produced by the ion beams between focusing regions, assuming initial beamlet currents of 100–200 mA. Other simulations were aimed at optimizing the ratio of focusing electrode radius to beam clearance radius. The results suggest that the ratio should be chosen to minimize nonlinearities in the focusing field, that is, that the disadvantages of emittance growth outweigh any cost savings realized by reducing the electrode radius. More detailed summaries of our theoretical studies of beam dynamics can be found on page 51.

Theoretical Considerations

The four-beam MBE is designed to model much of the accelerator physics that we expect to encounter in the HTE, but on a much smaller scale. A comparison of MBE-4 parameters with those of both the HTE and the 16-beam experiment is shown in Table 9. A graphic size comparison of the 4- and 16-beam designs is shown in Fig. 26.

MBE-4

Fig. 25. A possible set of voltage waveforms, at 5, 10, and 15 meters from the point of injection, for the 16-beam MBE. This sequence would produce an "acceleration schedule" designed to achieve maximum kinetic energy gain; Na⁺ ions would be accelerated from 2 MeV at injection to 6 MeV.

Several design features of MBE-4 are worth special note. First, the diameters of the focusing electrodes (50 mm) and the beam apertures (44 mm) are the same as those in the conceptual design for the 16-beam experiment. These choices minimize the dodecapole harmonic component of the electrostatic focusing field. Furthermore, we will be able to explore the same longitudinal space-charge effects

	MBE-4	MBE-16	HTE
Number of beams	4	16	16
Injection energy, MeV	0.2	2	2
Ion	Cs (or K)	Na (or Cs)	Na
Injection current/beam, mA	5 (10 max)	150 (300 max)	300
Final current/beam, mA	20 (40)	300 (600)	6000
Lattice half-period, m	0.24	0.32	≥ 0.3 (varies)
Peak gap voltage, kV	30	250	250
No. of accelerating gaps	25	25	~500
Cores/gap	3	14	?
Total length, m	12	25	450
Length/injected pulse length	12 (5)	3.5 (8)	18
Final energy (variable), MeV	1	8	125
Minimum value of $\omega_p^2/2\omega_0^2 = [1 - (\sigma/\sigma_0)^2]$	0.94	0.94	0.98

Table 9. A comparison of the principal parameters for MBE-4, the conceptual design for the 16-beam experiment (MBE-16), and the High-Temperature Experiment (HTE).

Fig. 26. Comparison of the relative sizes of the 16-beam MBE design and MBE-4.

we foresee for HTE. The last entry in Table 9, $\omega_p^2/2\omega_0^2$, is a measure of the space-charge defocusing spring constant divided by the mean restoring spring constant; it indicates that MBE-4 addresses the space-charge-dominated regime.

MBE-4 will also demonstrate significant energy amplification ($\times 4$), current amplification ($\times 4$), and hence power amplification ($\times 16$)—an important step toward the HTE, where energy and current amplifications are to be 60- and 20-fold, respectively. Finally, the accelerating voltage impulses in MBE-4 are relatively large because of the lower injection energy. Effects might, therefore, be seen in MBE-4 that will not be significant in the HTE. Nonetheless, their study can contribute significantly to our understanding of longitudinal space-charge behavior.

To minimize costs, MBE-4 will incorporate existing apparatus and components to a large degree. An existing 1-A cesium source, which operates reliably at 200 to 400 kV, will be converted to four small Pierce sources with aluminosilicate emitter buttons. The matching section will utilize existing probe drives where feasible. Acceleration will utilize existing Astron cores (0.7 V-sec), silicon-steel cores (0.9 V-sec), and Metglas cores (0.1 V-sec), as well as existing silicon-steel tape (0.8 V-sec) and Metglas tape (0.1 V-sec), which can be wound into cores as funds permit. The induction insulators will be of relatively inexpensive glass-ceramic.

An integral part of our experimental program is the investigation of fundamental phenomena that we expect to encounter as we move toward the HTE, as well as the development of materials and components that will be needed in advanced linacs. In the past year, this developmental work has focused on diagnostics, source designs, insulators, and core materials. Experimental activities have been highlighted by continued work on collective-focusing effects and by the first phase of an experiment at the Bevalac that will ultimately yield range-energy data on low-charge-state heavy ions.

As part of our experimental program, considerable effort went into the design of improved diagnostics and into the development and characterization of linac components. Our acquisition of phase-space information, for example, has been made easier by two diagnostics developments, one a computer-controlled two-slit arrangement, and the other a two-dimensional imaging setup using an optical multichannel analyzer.

Source developments have been highlighted by a room-temperature fabrication technique by which aluminosilicate emitters can now be easily made. Emitters of singly charged sodium, potassium, and cesium have been made by this technique, and their emission limits have been measured as essentially equal to those of sources made by melting material onto the heater face. Preliminary meas-

Other Experimental and Developmental Activities

Diagnostics and Component Development

urements, however, indicate somewhat higher emittances. Four such sources will be needed in the candidate gun design for MBE-4, each with an area of 10 cm^2 . A prototype Cs^+ emitter has been made and tested on the SBTE, and work continues on ways to reduce the emittance. If emittances are not sufficiently low with the alumino-silicate sources, cesium-coated tungsten or iridium hotplates offer an alternative.

We have also looked at an important aspect of insulator use, namely, how they behave as a function of conditioning. We tested insulators in the form of rods, $3/4$ inch in diameter and 12 inches long. These rods were installed in a mockup of the MBE electrostatic quadrupole (see Fig. 27), which was mounted, in turn, in the vacuum space of a 200-kV test stand. The results for sintered alumina and fused quartz showed that the behavior of the insulators was quite similar. For dc as well as pulsed voltage, the conditioning occurred over a period of several hours, and the breakdown voltages increased as much as twofold from beginning to end.

In collaboration with Allied Chemical Corporation, we have also been engaged in a program to engineer an induction linac core package using their Metglas amorphous magnetic glass ribbons. For three different materials, we have looked at dc hysteresis loops and pulsed magnetic behavior, including losses per pulse, for pulse widths from tens of microseconds down to less than $1 \mu\text{sec}$. In addition to cores manufactured by the standard method of annealing the finished cores in an applied field, we also examined cores made from as-cast material, as well as material rewound into finished cores after annealing. The as-cast material appears not to be useful for this application, whereas the rewound material looks like a viable option.

Range-Energy Measurements

Of critical importance to the problem of how ion beams will interact with fusion targets is the range-energy relation of heavy ions in cold matter. A unique feature of beams in heavy-ion fusion accelerators will be their very low charge states. Such beams, upon penetrating the target, will have ionic charge states far from the equilibrium values characteristic of their velocity and the target material. As a consequence, both the rate of energy loss, dE/dx , and the effective charge Z^* of the incident heavy ions will initially be low; Z^* will then increase to its equilibrium

Fig. 27. A mockup of an MBE electrostatic quadrupole array, used for high-voltage testing. The electropolished stainless-steel rods are 50 mm in diameter; the aperture diameter is 44 mm.

value as electron stripping takes place. The low initial values of dE/dx and Z^* will tend to increase the range of the ions in the target.

To obtain data pertinent to heavy-ion fusion, an experiment is being conducted at the Bevalac to measure the range-energy relation for Au^{12+} , Au^{32+} , and Au^{61+} , incident on hydrocarbon and gold targets. A crucial aspect of this experiment is the availability of rigid, low-charge-state beams of heavy nuclei at the Bevalac.

The first phase of the experiment was performed in July 1984, using Au^{61+} beams at $E = 150$ and 50 MeV/amu to establish the charge-equilibrated energy-loss rates and ranges of these ions in high- and low- Z targets. The preliminary results are shown in Fig. 28. These results show remarkable agreement with theoretical predictions based on proton range-energy data and heavy-ion range data.

The goal of the neutralized-beam focusing experiment is to demonstrate focusing of a charge- and current-neutralized Cs^+ beam by a solenoid magnet. The theoretical idea is that a beam of positive ions and electrons, strongly coupled through space-charge forces, should come to a common focus, rather than the two components being focused independently (in accord with their different charge-to-mass ratios).

Experiments in 1983 produced unclear results, apparently because the temperature of the secondary electrons produced by the neutralizing grid—about 40 eV—obscured the collective-field focusing effect. In recent experiments, therefore, neutralization has been achieved either by passing the ion beam through a plasma, which serves as a source of cold electrons, or by relying on electrons emitted thermionically from tungsten filaments. It is now clear that the collective lens focuses

Neutralized-Beam Focusing Experiment

Fig. 28. (a) Range-energy relations and (b) measured energy-loss rates for gold ions in hydrocarbon (CH) and gold targets. The theoretical curves are based on scaling of the proton range-energy relation and available heavy-ion range data. The data illustrated are preliminary.

the beam; however, quantitative details are still not in accord with the simple theory. A program of computer simulations is under way to resolve the discrepancies.

Theory

Much of our theoretical program is directed toward simulations of space-charge-dominated beams, in particular, the transverse dynamics of such beams. These simulations may ultimately be tested on MBE-4. In addition, we continued our efforts to optimize the design of the HTE accelerator. In particular, we sought to limit the plausible choices of ion species and final energy, based on computer models of the target, final focus, and accelerator system.

Transverse Beam Dynamics

Some remarkable new theoretical results regarding the transverse beam dynamics of space-charge-dominated beams have emerged from our studies. Among them, three are worth special note. First, we found that imperfect electrostatic quadrupole designs can result in a dodecapole component of the field. Emittance growth is not seen for on-axis beams but can be significant for off-axis beams. Similarly, in our simulation studies, image forces have little effect on the emittance of on-axis beams, provided the beam radius does not exceed 80–85% of the aperture. If missteered, however, a beam exhibits a strong oscillation in rms emittance, modulated by a low-frequency beating. Analytic work accounts for the oscillatory-beat behavior in terms of a resonance between the coherent betatron oscillation and a third-order mode, but cannot yet shed light on the accompanying monotonic growth in emittance seen in the simulation. Finally, again according to simulation results, a surprising amelioration of the effects due to images on off-axis beams can be effected if external field nonlinearities are introduced.

HTE System Model

To guide the choice of major parameters for the HTE, a simple model of the target, final focus, and accelerator system has been devised. Our aim is the design of a minimum-cost system that will achieve the underlying goals of the HTE, namely, to heat a solid-density target to temperatures of 50–100 eV and to provide a basis for evaluating the induction linac as a potential fusion driver. These goals are reflected in the choice of ion mass A , energy E , pulse length Δt , current I , and the number N of simultaneously accelerated beamlets. The target model takes into account the principal processes involved in energy deposition and loss expected to be present in a fusion pellet. The accelerator system model incorporates the main driver features of a high-brightness source, electrostatic and magnetic focusing, and acceleration limits due to maximum gradient, core mass, and velocity tilt. Current limits are imposed in the final compression and focus zone, and they connect the target and accelerator models.

To reach a desired final temperature T , beam irradiance must be selected to balance the black body emission rate and to supply the specific energy to the target required to raise the temperature. To do this, we set the pulse length proportional to $RT^{3/2}/N$, where R , the particle range, is proportional to $E^{3/2}/A^2$. Two constraints are applied at this point. First, the range must exceed 0.004 g/cm², because stripping of electrons would otherwise be very incomplete, and deposition would not be similar to that in a fusion driver. Second, the pulse length must not be so great that the target disassembles during heating. For a given temperature, these constraints effectively limit the available E - A parameter space to an oblique band, as shown in Fig. 29.

A third constraint on E and A is the allowable perveance per beamlet in the final focus. This is a limit on the line charge or current that can be precisely controlled and focused. At present the best estimate of the upper limit for this dimensionless parameter, in the context of HTE, is 2×10^{-4} . The resulting boundary in the E - A plane is also shown in Fig. 29. For given T , N , and spot size r , the parti-

Fig. 29. Energy and mass number boundaries for a beam used to heat an aluminum target to a temperature of 80 eV. Values for A and E are constrained to an oblique band by the requirements that the ion range R in aluminum exceed 0.004 g/cm^2 and that the target remain intact during heating. (This second requirement sets an upper bound on the pulse length Δt , which in turn establishes a maximum allowable energy for a given mass number.) A third requirement, namely, that the beam be precisely controllable, further reduces the allowable parameter space to the cross-hatched area.

cle energy must lie above a critical value that is only weakly dependent on A ($E_{\text{crit}} \propto A^{0.2}$). The parameters for a minimum-cost accelerator are established by this critical line.

For high values of A , the required pulse length is very short, and the accelerator length is largely determined by the maximum allowable gradient (about 0.5 MV/m). For low values of A , the pulse length is long, and acceleration must be at a much reduced rate to avoid an unacceptable concentration of core material. The high-mass option appears to be the cheaper one at present, with $140\text{-MeV } K^+$ ions providing a good match to an 80-eV final temperature in aluminum.

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CENTER FOR X-RAY OPTICS

FISCAL 1984 MARKED THE FIRST FULL YEAR of operation for LBL's Center for X-Ray Optics. During this period, members and affiliates of the Center continued their efforts to develop a broadly based program for advancing experimental capabilities in the soft x-ray and ultraviolet (collectively, the XUV) spectral regions. Extending from photon energies of several eV to several keV, this is a region of many important atomic resonances and molecular transitions, and as such, it offers great research opportunities for a large class of pure and applied sciences. However, largely because efficient optical components (such as lenses, mirrors, and coatings) are unavailable and because sources of bright, coherent radiation do not yet exist, this valuable spectral region has not been exploited as rapidly as have longer-wavelength regions. In recognition of this situation, the Center for X-ray Optics was organized in late 1983 to help develop the needed optical components and radiation sources, and to demonstrate new capabilities for high-resolution and phase-sensitive experiments.

During 1984 we set up laboratories for x-ray experimentation and development; we played an important role in understanding the coherence properties of undulators, as well as their relationship to the development of free-electron lasers and atomic XUV lasers; we continued to play a pioneering role in the development and fabrication of improved permanent-magnet structures; and we continued to design and build state-of-the-art beamlines to complement high-power wigglers and high-brilliance undulators at synchrotron radiation facilities.

We also took the first steps toward forming a network of formal collaborators—Affiliate Members—who share our interests, complement our abilities, and generally participate in our efforts to make these new techniques and technologies more widely available to the community. Along the same lines, a joint research agreement has been signed with IBM's Watson Research Center in New York; an LBL employee now works full-time in IBM's Electron Beam Lithography Group on the fabrication of diffractive x-ray structures.

The Center for X-Ray Optics also played an important role in organizing a new division of the Optical Society of America, entitled "X-Ray and Ultraviolet Techniques," which will help foster communications by organizing meetings and supporting a special archival journal.

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By October 1984, two of the Center's laboratories—the x-ray mirror coating lab and the visible optics lab—were well on the way to completion. The others—the soft x-ray spectroscopy lab, the low-energy electron spectroscopy lab, and the molecular multilayer lab—awaited the arrival of equipment from the University of Hawaii. The layout of the Center's labs is shown in Fig. 30 as we expect them to look in the spring of 1985, when the labs will be fully operational.

X-Ray Laboratories

X-Ray Mirror Coating Laboratory

During the past year, an atomic-layer coating facility was designed and partially completed. When finished, this facility will allow deposition of x-ray- and vacuum ultraviolet-reflecting multilayer coatings of high optical quality, using magnetron sputtering techniques. Important parameters affecting the quality of the deposited layers will be accurately controlled during a deposition run. These parameters include the power supplied to the sputtering source, the rotation speed of the substrate, the gas pressure, and the gas purity. The system will be computer controlled to allow the layer characteristics to be changed easily.

In addition to the multilayer fabrication equipment, the laboratory will have apparatus for measuring multilayer performance at x-ray and vacuum ultraviolet wavelengths. For characterizing the structures at ordinary x-ray energies (4–20 keV), a diffractometer will be used, consisting of a conventional x-ray tube (Mo, Cr, Cu) and a two-circle goniometer. For the soft x-ray and vacuum ultraviolet spectral regions, a special vacuum reflectometer is being constructed. Depending on the desired wavelength, the reflectometer will utilize either a conventional x-ray tube or a gas discharge tube of the Penning type. By use of these two techniques, therefore, it will be possible to characterize reflector surfaces in the photon energy range from 50 eV to 4 keV.

A number of important projects will be carried out with the multilayer coating facility, including studies of the effects of substrate quality on the performance of multilayer reflectors and studies of more fundamental materials science issues, including interfacial atomic arrangements, their stability, and their relationship to optical performance. We also plan to investigate the effects of high heat loading on multilayer structures, as well as the possibility of depositing multilayers on strongly curved surfaces.

The multilayer laboratory will be in full operation in the spring of 1985. Meanwhile, we are collaborating with other laboratories to make a start on some of the basic questions that interest us. Using the facilities of the Center for Materials Research at Stanford University, we have built various multilayers, including some designed to reflect 400- to 500-angstrom radiation at normal incidence, a capability that could eventually lead to practical cavity mirrors for a short-wavelength free-electron laser. In addition, an x-ray microscope of the Kirkpatrick-Baez type, using multilayer coatings for energy selection, has been constructed and is now being tested with 1.54-angstrom x-rays. This instrument should allow efficient, high-resolution imaging of laser-produced plasmas and other self-luminous sources.

Visible Optics Laboratory

Research into methods of x-ray microscopy and holography is an integral part of the work of the Center. Accordingly, our visible optics laboratory is equipped with an air-supported optical table for the reconstruction of holograms made with x-rays or extreme ultraviolet radiation at synchrotron radiation facilities. The laboratory is also used to align optical instruments (x-ray microscopes, beamline components, etc.) in visible light prior to their use with x-rays. A nearby general-purpose photographic darkroom, used to process and print both visible and x-ray films and holograms, will also be used in support of research on the properties of new recording materials at x-ray and extreme ultraviolet wavelengths. In addition, a clean room has been constructed for preparation of multilayer substrates and for general handling of x-ray optical systems. This room is equipped with two vertical laminar flow hoods and clean benches for dry operations. Later, a wet processing bench will be added for simple microfabrication operations, such as cleaning wafers and etching.

Soft X-Ray Spectroscopy Laboratory

The x-ray spectroscopy laboratory, which will be in full operation by February 1985, consists of three vacuum spectrographs operating between 0.1 and 10 keV: (a) a flat-crystal scanning spectrograph, used in multilayer characterization, absolute crystal reflectivity measurements, and molecular and solid-state spectroscopy;

(b) a fixed-analyzer spectrograph, used to perform absolute calibrations of elliptical and mirror monochromators in the low-energy x-ray region; and (c) a curved-crystal, high-sensitivity spectrograph (including a position-sensitive detector), used in "fast" spectroscopy for time-resolved measurements and for radiation damage studies.

The electron spectroscopy laboratory consists of an electron spectrograph and an absolutely calibrated fluorescent source for use in the 0.1- to 10-keV spectral region. The high-sensitivity electron spectrograph, consisting of a 20-inch precision hemispherical analyzer, is used in measuring secondary-electron energy distributions from x-ray photocathodes. The absolutely calibrated x-ray facility, with filtered fluorescent x-ray sources and a proportional photon-counting monitor, is used in absolute photocathode quantum yield measurements, photoelectric detector calibrations, and characterizations of photographic films for this same region. Also in this laboratory is an evaporation station used to form low- and high-density x-ray photocathodes, as well as thin films and single-element x-ray mirror coatings.

Low-Energy Electron Spectroscopy Laboratory

To fabricate long- d -spacing artificial crystals especially suited for soft x-ray analyses, a special molecular multilayer laboratory is available. With the equipment in this lab, molecular multilayers of the Langmuir-Blodgett type have been constructed with $2d$ spacings of 70 to 160 angstroms. These artificial crystals, which have achieved theoretically predicted values for peak integrated reflectivities and spectral resolving power, are deposited on surfaces of any curvature and can thus be utilized in a variety of soft x-ray spectroscopic analyzers.

Molecular Multilayer Laboratory

The critical barrier to scientific exploitation of the XUV spectral region is the lack of radiation sources analogous to the intense lasers available in the visible and infrared. Undulators, operating in a storage ring of advanced design, are a first step toward filling this need, but we are looking even beyond these yet-to-be-realized sources. In particular, we are studying transverse optical klystrons and free-electron lasers, as well as the low-emittance ring designs that would be necessary to make them practical tools.

Partially Coherent Radiation

Throughout 1984 the Center played a major role in calling the attention of the scientific community to the new opportunities offered by high-brilliance undulator radiation. In large part because of our efforts, the community now widely recognizes that undulators in a low-emittance storage ring offer substantial coherent-power capabilities: tens of milliwatts of tunable soft x-rays with full spatial coherence and with a longitudinal coherence length of several micrometers. (Figure 31 summarizes some of the properties of undulator-produced radiation and illustrates the concept of longitudinal coherence.) More important, such capabilities have now become a realistic possibility, mainly because of recent advances in undulator magnet technology and in storage-ring design. A comparison of coherent power generated with undulators and several other sources of XUV radiation is shown in Fig. 32.

Even more progress, particularly toward longer coherence length (narrower spectral features) and higher peak power, can be expected by extrapolating from undulators to free-electron lasers (FELs). To facilitate research in this direction, we have been studying an advanced photon facility—which we call the Coherent XUV Facility (CXF)—where research on several radiation sources could be carried out. (A schematic representation of the CXF is shown in Fig. 33, and a more detailed discussion of its design can be found in Section 6.)

Fig. 31. (a) Schematic illustration of an undulator. Partially coherent radiation is produced when a thin, pencillike electron beam of energy E_e traverses a periodic magnetic structure. The emitted radiation is relativistically contracted to wavelength λ_x and condensed to a narrow forward cone. (b) Illustration of the concept of longitudinal coherence. For radiation of mean wavelength λ and bandwidth $\Delta\lambda$, the coherence length L is determined by the distance a "mean wave" and an "extreme wave" (wavelength $\lambda \pm \Delta\lambda/2$) can travel until they are 180° out of phase. At a given wavelength, the coherence length is inversely proportional to the bandwidth, thus longitudinal coherence can be considered a measure of monochromaticity.

In such a ring, undulators, already well-understood, would deliver broadly tunable, spatially coherent soft x-rays and vacuum ultraviolet radiation of bandwidth $\lambda/\Delta\lambda \approx 10^2$. In addition, a pair of crossed undulators would offer complete polarization control in the vacuum ultraviolet. In a third leg of the ring, a transverse optical klystron would generate coherent radiation at laser harmonics, the electron beam playing the role of a nonlinear medium. The eventual goal of the CXF, however, would be to produce intense, fully coherent, tunable radiation from an FEL, at wavelengths shorter than 1000 angstroms. Two approaches are possible here, one based on feedback of radiation by reflection from end mirrors, the other based on the development of a high-gain, single-pass FEL operating in a special by-pass section. The latter route imposes stringent requirements on electron beam quality, and it requires a long ($N \approx 10^3$) narrow-gap undulator.

As part of our CXF studies, we have recently evaluated the potential performance of an FEL, using a two-dimensional simulation code (FRED) at the Lawrence Livermore National Laboratory. Typical results indicate that a peak coherent power of tens of megawatts can be achieved at 400 angstroms, in a narrow ($\lambda/\Delta\lambda \approx 10^6$) spectral peak. However, several important issues need to be clarified. For example, early results indicate that the radiation generated by FEL action tends to remain close to the electron beam rather than being diffracted away, suggesting an effective focusing mechanism. Analytic studies of this effect

Fig. 32. Plot of coherent power as a function of photon energy, for several radiation sources. The cross-hatched area at the left shows the domain of atomic and molecular lasers. Laser harmonic and mixing techniques extend this domain to slightly higher energies, but only at the cost of available coherent power. As shown by the dashed line, broadly tunable coherent power between 10 and 100 eV is achievable by the use of long magnetic undulators (U_A through U_D) in a low-emittance storage ring. In the soft x-ray region, which encompasses the important K -absorption edges of carbon, nitrogen, and oxygen, only undulators provide an assured route to significant coherent power levels in the near future. The λ^3 dependence, extrapolated to the operating region of a 6-GeV ring, reflects the falloff in coherent power with increasing energy, assuming a constant electron-beam emittance. Coherent power is defined here as having full spatial coherence and a longitudinal coherence length of $1 \mu\text{m}$.

Fig. 33. Schematic depiction of a plausible design for a Coherent XUV Facility. The straight sections are used for a soft x-ray undulator, a pair of crossed undulators for producing variably polarized radiation, a vacuum ultraviolet FEL operating in an optical cavity, and a transverse optical klystron. A by-pass, through which the electron beam might pass only ten times per second, contains a high-gain, single-pass FEL.

are now in progress. Another important question is how a coherent signal develops from noise in a high-gain, short-wavelength FEL. A proper understanding of this subject is crucial to predicting the coherence characteristics of radiation from such an FEL.

Synchrotron Radiation Projects

X-ray optical techniques are currently being applied in several important synchrotron beamline projects. These projects involve powerful wigglers (at the Stanford Synchrotron Radiation Laboratory, SSRL), high-coherent-power undulators (at Brookhaven National Laboratory), components under intense thermal loading, and sophisticated x-ray optical systems designed to reduce aberrations and improve spectral resolution. These projects are important to the synchrotron community as a whole, not only because of the new high-flux experimental opportunities they offer, but also because they help to secure a technological base for the next generation of storage-ring photon sources.

The LBL-Exxon project at SSRL's Beamline VI—to which LBL contributed the 54-pole wiggler magnet itself and most of the beamline components—has now culminated in the world's most powerful source of laboratory x-rays. The hard x-ray branch line successfully went into operation in the spring of 1984 at power levels up to 700 W. An x-ray mirror produces a focused x-ray beam with an upper cut-off energy of 23 keV. Graphite foils are used to control the power loading on the monochromator crystals. The low-energy cutoff of about 3 keV is determined by the high-vacuum beryllium window. During 1985 we expect to run the line for the first time at its full 1700-W design power level. This beamline is now in full use by groups from both LBL and Exxon, as well as by others during SSRL's share of the beam time. This ambitious project now calls for two additional branch lines, one for soft x-rays and one for the vacuum ultraviolet.

The soft x-ray branch is intended to cover the photon energy range extending from 0.5 to 4 keV. The beam is condensed by a two-mirror (toroid plus cylinder) system, providing horizontal deflections of 3° and 2°, respectively. The final focal spot at the sample should be about 1 mm × 3 mm. The monochromator crystals will be protected from the intense wiggler radiation by a pre-monochromator employing artificial multilayer structures (see page 58). The monochromators will be separated from the ring and from the experimental chamber by separate differential pumping stages. This pumping arrangement will permit experiments to be conducted either at higher pressures, as required in lithography, or at lower pressures, as might be the case for surface science studies. Almost all of the sub-systems on this beamline involve major extensions of previous technologies to cope with the uniquely high power loading.

Present work on the vacuum ultraviolet branch is directed toward defining the optical system that will provide beams best-suited to user needs. Priority is being given to the 0.1- to 1-keV spectral region, our goal being to push the lower limit to as long a wavelength as possible. Design studies are concentrating on a coma-reduced toroidal grating monochromator (TGM) system with a zoom-type focus. We anticipate that this system—the first water-cooled TGM in the world—can be configured to provide the required wavelength range and resolution.

X-Ray Center scientists are also active participants in the soft x-ray undulator project (X-1) on the 2.5-GeV storage ring at Brookhaven's National Synchrotron Light Source (NSLS). When operational, the X-1 line will have the highest coherent power of any existing soft x-ray storage-ring source. It is thus well-matched to the scientific and technical interests of the Center for X-Ray Optics. It is here (and at the nearby U-15 line) that we will first test and use microfabricated Fresnel lenses and gratings that emerge from the LBL-IBM agreement mentioned above. The X-1 line will also be an excellent source for early experimentation with x-ray microscopy and microholography. Our group will directly participate in

this project by developing and providing the mirror system that receives intense, unattenuated radiation from the undulator.

Apart from designing optical systems for operational storage rings, we are also pursuing a more general approach to x-ray thermal loading problems. We are developing a computational modeling capability and, at the same time, establishing experimental test stations (using both electron and x-ray heating) where models can be confirmed and corrected. Figure 34 shows a computer model of the optical surface of a monochromator crystal, distorted by the thermal load imposed by an x-ray beam. In 1985 we will put significant effort into measuring both the temperature distributions on irradiated surfaces (using an infrared imaging system) and the resulting surface deformations (using visible-light interferometry).

Fig. 34. (a) Finite-element model used to estimate distortions and thermal stresses on an optical surface due to temperature gradients in a monochromator crystal. (b) Computer-generated image showing the (exaggerated) thermal distortion. Calculations such as these will be confirmed by measurements, and ray-trace analyses will predict downstream effects.

Periodic permanent-magnet structures are at the heart of many future radiation sources. These include sources of both coherent and incoherent radiation—w wigglers, undulators, several approaches to free-electron lasing, and transverse optical klystrons. Important issues include controlling field errors, achieving strong fields at moderate cost, and coping with the details of fringe field control. Among our many studies and design projects, several stand out: the Livermore wiggler project for Beamline VIII at SSRL, a collaboration with AT&T Bell Laboratories to study the effects of field errors in long undulators, the design of a microwave FEL undulator to be used at Livermore, and the design of a crossed undulator pair for polarization control at NSLS.

Permanent-Magnet Structures

Early in 1984, the Center for X-Ray Optics agreed to design a wiggler for use by a system-wide University of California consortium, headed by a Livermore team, on Beamline VIII at SSRL. During the rest of the year, a conceptual design was completed. The proposed wiggler, though similar to that for Beamline VI, is a more cost-effective design. The new magnetic structure uses Nd-Fe-B rather than SmCo₅, because it is less expensive and magnetically stronger. The design incorporates a rigid vacuum chamber rather than a variable-gap chamber, again reducing costs. In addition, the performance of various transverse configurations of magnetic structures was studied to understand pole-width and end-configuration trade-offs. Construction is expected to begin in early 1985.

In collaboration with B. M. Kincaid of AT&T Bell Laboratories, we have undertaken a study of field errors in long undulators, including the effect of random construction errors, such as excitation and gap errors, in hybrid undulators. Designs are being developed that will passively reduce, and possibly cancel com-

pletely, the angular errors of the beam trajectory that are caused by such construction errors. Our study results will affect all work with long undulators, as well as transverse optical klystron experiments and, eventually, XUV free-electron lasers.

As part of a third effort, a new 25-meter hybrid undulator is being designed for use in the Livermore-LBL microwave FEL project (see page 65), now slated to move to the Advanced Test Accelerator at Livermore.

The crossed undulator pair being designed for use at Brookhaven's NSLS will allow complete control of polarization. When combined with the usual merits of undulator radiation (high spectral brilliance, sharp spectral peaks, diffraction-limited focusing, etc.), the new polarization control will provide a powerful new tool for biological probing. The version designed for use at NSLS consists of two identical electromagnet structures, each consisting of five 15-cm periods.

In addition to these major projects, the Center is involved in an effort to modify one superconducting wiggler, one permanent-magnet undulator, and one permanent-magnet wiggler at NSLS, as well as preparatory work for research on insertion devices for a future 6-GeV synchrotron radiation facility.

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EXPLORATORY ACCELERATOR STUDIES

SOME OF THE MOST FORWARD-LOOKING PROJECTS in AFRD defy strict assignment to one of the established programs. On the other hand, they embody the theme (and spirit) of the division as well as our other ventures. These riskier projects may be undertaken to explore unproven options for future accelerators or storage rings, or they may be projects aimed at putting accelerators to work in new ways. In this second category, for example, falls our design work on a heavy-ion medical accelerator—the Advanced Biophysical Research Accelerator. This National Institutes of Health-sponsored design—a collaborative effort by AFRD and the Biology and Medicine Division—was completed during 1984. The place of heavy ions in medicine and biophysical research is discussed at some length on pages 6–8.

Our more exploratory efforts included experimental free-electron laser (FEL) studies at Livermore's Experimental Test Accelerator, with an eye toward the possibility of a high-gradient linear collider; design work on a low-emittance electron storage ring that could be used in several schemes for generating vacuum ultraviolet radiation and soft x-rays; and preliminary studies of a small relativistic heavy-ion collider that could give us our first look at the quark-gluon plasma.

Free-Electron Laser

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Minicollider

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Free-Electron Laser

When a properly designed electromagnetic field is imposed on a beam of electrons, the electrons will give up kinetic energy in the form of coherent radiation. The result is a free-electron laser. Together with workers at Lawrence Livermore National Laboratory, we have now used an FEL to amplify 34.6-GHz microwave radiation several thousand-fold. This potential source of power has stimulated thinking about a new concept in linear colliders, namely, a two-beam accelerator. In such a device, the microwaves emitted from an FEL would be coupled by means of waveguides to an adjacent traveling-wave structure, where they would produce a high longitudinal electric gradient. In this structure, a second beam of electrons could be accelerated to very high energies.

Experimental Results

The electron laser facility at Lawrence Livermore National Laboratory uses the beam generated by the Experimental Test Accelerator (ETA) and is attached to the end of the ETA's beam propagation section. The laser facility itself comprises a beam-conditioning region, an interaction region (the FEL), and a diagnostics region. At the entrance to the interaction region, a microwave signal of the desired frequency can be introduced. This signal is then amplified in the 3-meter FEL wiggler and propagated into the diagnostics region, where pulse shape, total energy, and frequency spectrum are measured. During 1984 this FEL yielded dramatic results, both in the superradiant mode, that is, with no input microwave signal, and as an amplifier of microwave radiation.

When a 3.3-MeV electron beam with a current of 450 A was passed into the wiggler, we observed an output signal of over 2 kW, indicating a signal gain of 13.4 dB/m from the 0.35-W noise level. With a 30-kW input signal, the FEL produced a peak power of 80 MW. Significantly, this peak power was achieved in the first 2.2 meters of the 3-meter wiggler. To profitably use the entire wiggler, the magnetic fields must be manipulated, or "tapered," to match the diminishing energy of the electron beam. Experiments are now under way using a tapered wiggler.

Two-Beam Accelerator

If a linear accelerator capable of accelerating an electron beam to TeV energies were to operate at the gradient of the Stanford Linear Collider (17 MV/m), it would be many kilometers long, and it would consume prodigious amounts of power. Fortunately, both of these practical difficulties can be circumvented by going to high frequencies and operating at a high accelerating gradient. The concept of a two-beam accelerator (TBA) has evolved along these lines. It is seen as operating at high gradients (about 500 MV/m) and at high frequencies (about 30 GHz), and consequently, as being a relatively efficient means for converting power from the power lines into an accelerating potential.

The TBA concept can be summarized briefly. An intense low-energy beam (of about 20 MeV) is made to traverse a series of wiggler magnets, undergo free-electron lasing, and emit microwaves. The microwaves are coupled to an adjacent traveling-wave structure (as shown schematically in Fig. 35), where they produce a high longitudinal electric gradient. In this structure, a second, relatively low-intensity electron beam is accelerated to very high energies. The energy lost to the microwaves from the first electron beam is made up by induction accelerating units located between wiggler magnets. Parameters for a plausible TBA, envisioned as half of a collider, are given in Table 10.

Preliminary study has already focused on some of the issues that confront the TBA concept. Among these are the question of maximum achievable gradients, which are limited both by surface field breakdown and by surface heating effects; the practicality of transporting an intense low-energy beam of high quality over distances of a kilometer or more; the nature of the linac structure for the high-energy beam; the phase and amplitude stability of the rf output of the FEL; and the means of coupling the FEL and the high-gradient structure.

Fig. 35. Schematic of a two-beam accelerator. An intense, low-energy beam of electrons in the upper structure (a free-electron laser) provides the power for accelerating electrons in the high-gradient structure to very high energies.

Table 10. Parameters for a possible TBA.

Accelerator	
Average gradient, MV/m	500
Frequency, GHz	30
Length, m	5000
Pulse repetition rate, kHz	6.5
Average input rf power, GW/m	2.2
Stored energy, J/m	40
Luminosity, $\text{cm}^{-2}\text{sec}^{-1}$	10^{33}
Low-energy beam	
Initial energy, MeV	20
Peak current, kA	2.1
Bunch length, m	19
Power, GW	45
Energy, kJ	2.9
High-energy beam	
Final energy, TeV	1.0
Bunch length, mm	1
No. of electrons/bunch	7.5×10^9
$\Delta E/E$	0.10
Bunch radius, μm	0.1

The availability of coherent radiation sources in the vacuum ultraviolet and soft x-ray regions of the spectrum depends on advances in insertion device technology and on the design of storage rings to exploit these advances. In particular, if ultraviolet and x-ray FELs are to become practical, a moderate-energy ring must be available that is capable of storing electron beams of high current and very low emittance. Such a ring could, in addition, serve as a test bed for other advanced concepts, such as crossed undulators and transverse optical klystrons (see pages 58–61). Our efforts to design such a ring, which we call the Coherent XUV Facility, had just begun at the end of fiscal 1984, but a preliminary parametric study was completed by the end of the fall and is summarized below.

Coherent XUV Facility

Considerable effort in the second half of 1984 was devoted to a feasibility study of an electron ring that could be used to produce coherent high-power radiation in the vacuum ultraviolet and soft x-ray spectral regions (collectively, the XUV

region). This work, carried out in collaboration with the Center for X-Ray Optics (see Section 5) and with two members of Brookhaven's National Synchrotron Light Source, addressed, in particular, the problems associated with the use of a stored electron beam with a single-pass FEL.

When a bunch of electrons interacts coherently with an FEL undulator, the momentum spread in the bunch increases, and some energy is transferred from the electrons to the photon beam. If this interaction occurs during every turn in a storage ring, the disruption to the particle dynamics would cause the beam to be lost in a few machine revolutions. Therefore, following a suggestion made by J. B. Murphy and C. Pellegrini, our design places the FEL not in the ring but in a by-pass section, as shown in Fig. 36. The beam, initially circulating in the ring, is injected into the by-pass, where it interacts with the undulator and produces coherent radiation. It is then reinjected into the ring, where the synchrotron radiation damps the momentum oscillations to the equilibrium value. The beam is then ready to be injected into the by-pass again. One burst of coherent radiation is thus produced every damping time. Another important advantage of the by-pass is that it allows the use of a narrow-gap undulator without significantly reducing the gas-scattering lifetime of the beam.

In addition to including such a by-pass, however, the design of any storage ring to be used with a single-pass, high-gain FEL will be constrained by far subtler considerations. In fact, the level of electron ring performance demanded by the FEL has never been achieved in an existing storage ring. The requirements are: (a) a moderate beam energy (less than 1 GeV), (b) a high peak current (a few hundred amperes), (c) a small emittance (about 10^{-8} m-rad), and (d) a small relative momentum spread (about 0.1%).

Fig. 36. A lattice design for a Coherent XUV Facility, comprising 18 bending dipoles with superimposed gradient fields and 36 quadrupoles. The by-pass across the interior of the ring would accommodate a 20-meter high-gain FEL.

Designing a machine to meet these stringent demands is complicated by the fact that coherent and incoherent collective effects, which depend strongly on the lattice design, determine the achievable performance. In fact, we soon recognized that optimization of such a machine demanded a new computer code. For this reason, we have started developing a new code, called ZAP, which will allow us to make a preliminary evaluation of the performance and parameters of any storage ring. This code utilizes the parameters of a lattice and other relevant machine data (impedance, residual gas pressure, rf voltage, etc.) and computes the beam dynamics and performance characteristics (equilibrium emittances, growth times of instabilities, lifetimes, FEL quality factors, etc.). The code is still under development, but it is already able to determine whether or not the features of a proposed lattice lead to a machine design consistent with the physics needs. In addition, the program has been written with an eye toward systematic machine design studies that will allow a better understanding of the relationships among parameters.

The performance guidelines for the Coherent XUV Facility suggest several approaches to the lattice design. One way to achieve a high peak current, for instance, is to impose a large momentum compaction to increase the threshold of the microwave instability. The high value of the dispersion associated with such a lattice, however, requires a large aperture, and because of single and multiple intra-beam scattering, it also causes emittance growth and short lifetimes. The opposite approach of reducing the momentum compaction inevitably leads to a reduced peak current, but, in principle, it is possible to compensate for the reduced peak current by designing a lattice with a small emittance, thus preserving the high charge density required for FEL operation.

Several lattice concepts have already been explored, and their relative merits assessed, with the code ZAP. Some of these lattices are variants of the basic design that has been adopted by most storage rings dedicated to synchrotron radiation. Others, however, embody a different design concept, utilizing combined-function magnets, as recently suggested by G. Vignola of Frascati and Brookhaven. An example of this promising approach is shown in Fig. 36. This illustrated ring consists of 18 bending dipoles with superposed gradient fields and 36 quadrupoles. It provides considerable space in the straight sections for conventional undulator devices, and the by-pass can accommodate a 20-meter FEL undulator. Some results of our optimization study are given in Fig. 37, which shows the predicted intrabeam-scattering and Touschek lifetimes for one of the lattices, along with the equilibrium emittance value, the bunched-beam volume density, and the FEL figure of merit ρ . Table 11 summarizes the performance characteristics that appear to be achievable with this design.

Higher peak currents should be achievable with a lattice design having higher dispersion, if sections are filled with damping wigglers. The wigglers would have the purpose of increasing the radiation damping, thus balancing the effect of the increased emittance growth due to intrabeam scattering.

In summary, the results of our parametric studies so far indicate that high-density, low-energy beams suitable for XUV FELs are within the grasp of existing technology.

Beam energy, MeV	750
Peak current (single-bunch operation), A	200
Transverse emittance (rms), rad-m	10^{-8}
Momentum spread (rms)	0.002
Bunch length, psec	40

Table 11. Estimated achievable performance characteristics of a CXF based on the lattice of Fig. 36.

Fig. 37. Preliminary results of a parameter optimization study for a CXF. Touschek and intrabeam-scattering lifetimes (τ_T and τ_{IBS} , respectively), transverse emittance ϵ_x , bunched-beam volume density, and the FEL figure of merit ρ are plotted as functions of beam energy.

Minicollider

One of the most exciting prospects before nuclear physics today is the observation of the postulated quark-gluon plasma. To produce this state of matter, it is necessary to produce a nuclear temperature and baryon density sufficiently high to deconfine the elemental constituents of the nucleus. Current theory suggests that this can be done in at least two distinct ways, either at very high energies, which would produce high temperatures but low baryon densities, or at relatively low energies, which would produce very high baryon densities. During 1984 we tentatively investigated a design concept for a small heavy-ion collider—the Minicollider, to be injected by beams from the Bevalac—that would explore this second regime of nuclear states.

In collaboration with the Nuclear Science Division, we have begun preliminary planning for an experiment that would probe the phase transition to a deconfined state of nuclear matter known as the quark-gluon plasma. It is believed that this state can be observed and studied in the baryon-rich environment that would be created by central uranium-on-uranium collisions at center-of-mass energies of a few GeV/amu. It thus appears that this experiment could be carried out with a collider ring that utilizes the existing Bevalac complex as an injector.

Such a collider ring, which we have called the Minicollider, would have a circumference of about 250 meters and would be located largely in the present Bevalac experimental area. Early designs indicate that luminosities of 10^{24}

$\text{cm}^{-2}\text{sec}^{-1}$ might be achievable, implying a total U-U event rate of about seven per second. A few hours would be necessary to collect data from a meaningful number of central collisions. The achievable luminosity is limited by intrabeam scattering, not by the emittance of the Bevalac beam.

The underlying concept of the Minicollider is to maximize the use of existing facilities, to minimize the impact on existing Bevalac research programs, and to exploit existing technology so as to avoid the costs of extensive R&D. As presently conceived, therefore, the Minicollider would consist of twin superconducting accelerating rings to achieve center-of-mass energies of 1–4 GeV/amu. The superconducting dipoles would have a maximum field of 3–4 T and would employ existing superconducting materials and techniques. Stochastic cooling would be used to help offset the effects of intrabeam scattering and to ensure lifetimes of 24 hours or more. Figure 38 compares the projected performance of the Minicollider with that of existing fixed-target heavy-ion accelerators.

The sequence of events required to store beams in the new rings would be as follows: The SuperHILAC would provide partially stripped uranium ($38+$ to $40+$) for injection into the Bevatron. (By not stripping at the SuperHILAC exit, we make significantly higher intensities available to the Bevatron.) The beam would then be accelerated to about 400 MeV/amu, extracted in a single turn, stripped to $92+$, and transferred to the collider. Accumulation in the collider rings would proceed over many Bevatron pulses, permitting 10^8 to 10^9 ions to be stored in each beam. Final acceleration in the Minicollider would be done slowly, placing minimum demands on the superconducting magnet design. Continuous stochastic cooling would be employed to maintain beam quality.

Fig. 38. A comparison of projected Minicollider performance with that of operating or planned fixed-target heavy-ion accelerators. Energies, in the target frame of reference, are plotted as a function of projectile mass number.

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