As the 1982 fiscal year began, the Accelerator and Fusion Research Division (AFRD) could look back on FY81 with pride in its many accomplishments:

- During the Laboratory's 50th anniversary celebrations, AFRD and the Nuclear Science Division formally dedicated the new (third) SuperHILAC injector that adds ions as heavy as uranium to the ion repertoire at LBL's national accelerator facilities.

- The Bevalac's new multiparticle detectors (the Heavy Ion Spectrometer System and the GSI-LBL Plastic Ball/Plastic Wall) were completed in time to take data before the mid-year shutdown to install the new vacuum liner, which passed a milestone in-place test with flying colors in September.

- The Bevalac biomedical program continued patient treatment with neon beams aimed at establishing a complete data base for a dedicated biomedical accelerator, the design of which NCI funded during the year.

- Our program to develop alternative Isabelle superconducting dipole magnets, which DOE initiated in FY80, proved the worth of a new magnet construction technique and set a world record—7.6 Tesla at 1.8 K—with a model magnet in our upgraded test facility. The Division sent key people to Brookhaven to help develop alternatives for the partially completed Isabelle accelerator.

- Final test results at LBL were obtained by the Magnetic Fusion Energy Group on the powerful neutral beam injectors developed for Princeton's TFTR. The devices exceeded the original design requirements, thereby completing the six-year, multi-million-dollar NBSTF effort. The group also demonstrated the feasibility of efficient negative-ion-based neutral beam plasma heating for the future by generating 1 A of negative ions at 34 kV for 7 seconds using a newly developed source.

- Collaborations with other research centers continued, including: (1) the design of LBL/Exxon–dedicated beam lines for the Stanford Synchrotron Radiation Laboratory; (2) beam cooling tests at Fermilab and the design of a beam cooling system for a proton-antiproton facility there; and (3) the development of a high-current betatron for possible application to a free electron laser.

This impressive list bears testimony to the Division's highly qualified scientific staff and the excellence of the support it receives. It is this unique pool of talent that will make accelerator-related research as important a part of the Laboratory's next 50 years as it has been during its just completed first half century.

Hermann A. Grunder

Note in editing: As this report was going to press, the Bevatron was returned to operation. On February 4, 1982, a beam of C^{+4} was accelerated to various final energies. The C^{+4} run is a truly significant milestone because measured charge-exchange cross sections for C^{+4} electron pickup and loss are significantly higher than for any of the partially stripped heavy ions that we plan to run (e.g., the cross section for C^{+4} is comparable to that for U^{+55} and is two orders of magnitude higher than that for U^{+65}, which we plan to run). This indicates that even at a non-optimum pressure (10 times the design goal) residual gas will play no important role in beam survival for the new ions that we plan to run in FY82 and FY83.
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Joseph B. Rechen
Richard C. Sah
Alfred S. Schlachter
John W. Staples
Emery Zajec
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- L. Hill
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- K. Williams

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  - H. Lancaster (EE project manager)
  - R. Yourd (ME project manager)
  - J. Staples (physics leader)
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- G. Carmignani
- A. Dancosse
- W. Elwood
- D. Embree
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- M. Nolan
- O. Plate
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- F. Bieser
- M. Bronson
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- D. Greiner
- J. Henderson
- K. Lou
- C. McParland
- G. Newell
- J. Porter
- J. Tanabe
- D. Wolgast
- R. Yamamoto

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- Vacuum Improvement
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  - R. Avery (project manager)
  - R. Alta
  - J. Barale
  - P. Batson
  - J. Bercovitz
  - J. Carrieri
  - R. Caylor
  - J. Chin
  - R. Crebbin
  - R. Owinell
  - R. Edwards
  - R. Force
  - A. Glicksman
  - T. Henderson
  - D. Hunt
  - K. Kennedy
  - J. Krupnick
  - A. Lake
  - J. Lax

184-Inch Synchrocyclotron
- L. Kanstein (in charge)
- G. Hampton
- J. MacMullen
- F. Yeater
ACCELERATOR OPERATIONS

INTRODUCTION

The Accelerator and Fusion Research Division operates the SuperHILAC and the Bevatron/Bevalac as national research facilities for studies in high-energy heavy-ion physics, nuclear physics, nuclear chemistry, biomedicine, biophysics and astrophysics. The SuperHILAC has been the U.S. vanguard of discovery of new heavy elements in strong competition with a Soviet effort at JINR, Dubna, and, more recently, a West German effort at GSI, Darmstadt. The facility also plays a pre-eminent role in elucidating many of the global features of the fusion, deeply inelastic (damped), and fission reactions that typify nuclear phenomena. The Bevalac is unique in the opportunity it provides for the study of collisions between nuclei at energies high enough to convert nuclear matter into hadronic matter in which protons, neutrons, their excited states such as delta resonances, and free pions all coexist. A third of its operating time is devoted to biomedical research, including a trial program of heavy-ion cancer therapy.

The SuperHILAC, an Alvarez-type linear accelerator, provides heavy ion beams of lithium through uranium at energies from below 1 to 8.5 MeV per nucleon. Its three injectors can supply two different ion species to five different beam lines on a timesharing basis; that is, the beam is pulsed 36 times each second, and these pulses may be apportioned in any desired ratio between two different ion beams and any number of different energies. Normal operation involves the use of 32 pulses/second of a heavy ion beam by the principal research group at the SuperHILAC, the sending of 2 pulses/second of a second ion beam to the Bevatron for further acceleration to relativistic velocities (this combined operation is called the Bevalac facility), and the use of 2 pulses/second of either beam—at a different energy if desired—for a parasitic experiment at the SuperHILAC. The SuperHILAC has 11 experimental areas.

The Bevatron is a weak-focusing positive-ion synchrotron that can accelerate heavy ions from either the SuperHILAC or a local injector to any energy between 50 MeV and 2 GeV per nucleon. The delivery rate is 10 to 15 pulses per minute, dependent on the operating mode. Beam sharing at the Bevatron is accomplished by the dividing of a specific ion beam at a given energy between two major branches of the beam delivery system on a particular Bevatron pulse, or by diverting the beam on a pulse-to-pulse basis from one target area to another.

Continual effort is given to improving the two accelerators, both in machine operation and experimental facilities, so that they remain at the forefront of scientific investigation.

OUTSIDE USER SUPPORT

Operation of the SuperHILAC and the Bevatron/Bevalac for outside users occupies approximately half of the available research time at each facility. These outside groups are composed of researchers from other national laboratories and universities.

Various committees and support groups have been set up to assist these user communities. The Accelerator Research Coordination Office (ARC Office), augmented by a group of physicists, engineers and support staff, is one such group. Located in the Bevatron building, the ARC Office supports researchers in designing and submitting proposals, mounting experiments, arranging for the loan, construction or repair of detection and data-collection equipment, and in providing the necessary administrative support. Members of its staff are also experimenters who serve as scientific coordinators for the programs at each accelerator. Gary Westfall was the Bevalac nuclear science liaison in FY81, and currently,
Jerry Howard serves as liaison for Bevalac biomedical users, and Michael Zisman is the SuperHILAC experimental coordinator. Fred Lothrop has general coordinating responsibility.

Long-range scheduling is performed by an ARC Office staff committee, which periodically sends notices to all users. The immediate operating program is arranged in weekly scheduling meetings among staff and users, and every effort is made to accommodate users' preferred running schedules.

The SuperHILAC and Bevatron/Bevalac Users' Associations communicate user concerns to the accelerator operations staff. These groups also hold annual meetings to share research results and discuss future directions. The governing body of each group is given in Table I of the Appendix.

Because there are usually many more shifts requested than are available, proposals for research time are reviewed twice a year by program advisory committees (PAC's). Members are generally chosen from among experts in heavy ion research who may be involved in LBL experiments but are not major facility users. There is one PAC for the SuperHILAC (Table II, Appendix) and one each for the nuclear science and the biology and medicine programs at the Bevatron/Bevalac (Table III, Appendix). These expert panels recommend the allocation of research hours to the LBL director, and, as a rule, their recommendations are implemented.

LBL's Nuclear Science Division appoints a scientific director for each accelerator to provide leadership for the nuclear science research on the floor and to coordinate long-term improvements. Howel Pugh now holds this post at the Bevalac, Richard Diamond at the SuperHILAC. In addition, the Biology and Medicine Division appoints a program manager (presently E. John Ainsworth) for its accelerator-based research. The scientific directors may allocate 10 percent of the research hours on a discretionary basis.

FY 81 OPERATIONS

Research efforts at the SuperHILAC and Bevatron/Bevalac proceeded briskly during FY81 despite major improvement projects and urgent efforts to conserve energy which limited operation severely. Both the nuclear science and biomedical programs, including cancer therapy trials at the Bevatron/Bevalac, were run as fully as the budget and improvement programs would allow. Tables 1 and 2 show the operating experience for the accelerators this year. As in the past, unscheduled maintenance has been kept to a low percentage of scheduled operation, in spite of new equipment being put in service, especially at the SuperHILAC.

At the Bevatron the first and last quarters of the fiscal year were devoted to execution of the planned modifications necessary to produce beams of heavy ions (argon through uranium) at relativistic energies. The SuperHILAC's ABEL injector project was matched by the Bevatron's vacuum improvement project: fabrication and installation of a cryogenic liner (Fig. I) to fit inside the main accelerating ring and provide enough vacuum pumping capability to maintain a pressure of about $10^{-10}$ Torr.

Progress toward this goal went on schedule during the year (see note in the Foreword).

A significant new capability---rapid energy switching---became a routine part of Bevalac operations during the year as a result of single motor-generator operation and continued control system development to improve the accelerator's reliability and efficiency. Software was implemented that enables the system to rapidly establish a new configuration of accelerator parameters and to return to a previously tuned configuration and accurately reproduce beam position. This ability has greatly helped ease the scheduling conflict between the radiotherapy and the nuclear science programs, so that nuclear science experiments can continue accepting beam up to the time a patient is ready for treatment. Switching occurs in less than one minute, treatment takes another two minutes, and switching back another minute, so the nuclear science
Table 1. Summary of SuperHILAC and Bevatron/Bevalac operations during FY81.

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<td>Tuning</td>
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<td>519</td>
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<td>Total Scheduled Operation</td>
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Table 2. Ion species and intensities delivered to experimenters during the year.

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<th>Ion</th>
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<th>Average Intensity$^b$ (ions/pulse)</th>
<th>Percent of total pulses</th>
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<td>Carbon 12</td>
<td>8.0</td>
<td>Protons $1.0 \times 10^{11}$</td>
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<td>Oxygen 16</td>
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<td>Deuterons $1.0 \times 10^{8}$</td>
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<td>Neon 20</td>
<td>7.0</td>
<td>Alphas $1.0 \times 10^{10}$</td>
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<td>Silicon 28</td>
<td>1.7</td>
<td>Carbon 12 $1.2 \times 10^{10}$</td>
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<td>Argon 40</td>
<td>2.0</td>
<td>Oxygen 16 $2.0 \times 10^{9}$</td>
<td>7.6</td>
</tr>
<tr>
<td>Calcium 48</td>
<td>0.2</td>
<td>Neon 20 $1.0 \times 10^{10}$</td>
<td>51.0</td>
</tr>
<tr>
<td>Iron 56</td>
<td>0.2</td>
<td>Silicon 28 $1.0 \times 10^{9}$</td>
<td>3.9</td>
</tr>
<tr>
<td>Krypton 86</td>
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<td>Argon 40 $1.0 \times 10^{7}$</td>
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</tr>
<tr>
<td>Xenon 136</td>
<td>30.0 pmA</td>
<td>Calcium 40 $5.0 \times 10^{6}$</td>
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</tr>
<tr>
<td>Holmium 165</td>
<td>0.5 $^c$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead 208</td>
<td>0.2 $^c$</td>
<td></td>
<td></td>
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</table>

$^a$ at poststripper exit.

$^b$ on target.

$^c$ $10^{10}$ available but not requested in FY81.
Figure 1. A model of the triple-walled vacuum liner that provides an ultrahigh vacuum in the curved portions (quadrants) of the Bevatron magnet pole gap. The inner liner of the rectangular cross section insert is held at a nominal temperature of 12 K. At this temperature, there is little outgassing from the materials, and most gases are frozen out on the surface. An activated charcoal pump operates at the same temperature to remove the remaining gases, particularly hydrogen. The inner-cu!-bore liner is surrounded by 30 layers of superinsulation and then a middle liner, which is cooled to liquid nitrogen temperature (77 K). The middle liner reduces the amount of heat that reaches the inner bore and also pumps a number of gases and water vapor. This liner is also surrounded by superinsulation and then a room-temperature liner which primarily supports and protects the inner liners and superinsulation. The copper-clad printed circuit board material that is used for the inner and middle liners is etched to interrupt the flow of eddy currents induced by the changing magnetic field while still providing a thermal path to maintain liner temperatures (CBB B17-7630).

The experiment continues with typically only a four-minute interruption.

For complete flexibility, switching must be between different beam lines, energies and ions. As of the end of 1981, the first two goals had been successfully met—during a typical radiotherapy day the beam has been switched as many as thirty times between different caves at different energies. Addressing the third goal, ion switching on a one-minute basis, requires the use of two independent injectors, each tuned with one of the ions to be used. During the year, a plan evolved to have the SuperHILAC inject the high-mass beams for relativistic nuclear physics experimentation while the Bevatron's local injector would produce all beams required for therapy, namely ions up to silicon. To do this, the local injector would have to be upgraded.

The local injector upgrade project grew naturally out of our work to adapt radio-frequency quadrupole (RFQ) linacs to the acceleration of heavy ions (see "Heavy Ion RFQ Linac Development"). The central element in the upgrade project, the RFQ is designed to be compatible with existing facilities and is the most economical solution to obtaining the required beam intensities. The elements in the system include:

- An ion source very similar to the one presently used at the Bevatron and a low-voltage (50 kV) preaccelerator to focus a Si+ beam into the RFQ.
• The RFQ, which is 2.4-m long and operates at 200 MHz, capturing and accelerating 85 percent of the beam to an energy of 200 keV/nucleon.

• A new Alvarez accelerator, operating at 200 MHz in the 2-beta-lambda mode, that will further accelerate the beam to 800 keV/nucleon, at which point it will be stripped to a q/A of at least 0.30.

• The present linac injector, an Alvarez machine also operating in the 2-beta-lambda mode, which will be modified to accept the 800 keV/nucleon beam and will accelerate it to 5 MeV/nucleon, its present energy.

The schedule for this project calls for construction and testing of the full-scale, full-power model in FY82, and completion of the Alvarez modifications and final assembly and commissioning by the end of FY83.

**BEVATRON/BEVALAC HIGHLIGHTS**

The major focus of Bevatron/Bevalac activities this year was modification for uranium beams capability prior to and following a five month period of operation for nuclear science, radiotherapy, and biology. Modifications to the west tangent tank were completed at the end of the first quarter of the fiscal year. Accelerator operation was suspended in July 1981 so that installation of the vacuum liner could proceed (Fig. 2). By early September, the cryogenic pumping system had been installed in the four quadrants of the machine and passed its heat load and pumping tests. Test results showed excellent agreement with expectations that a pressure of $5 \times 10^{-10}$ Torr could be reached, and so by the end of the fiscal year installation of equipment in the tangent tanks was proceeding on schedule (see the note in the Foreword).

Despite this major upgrade, significant physics was accomplished, and the radiotherapy...
and related biology programs moved well toward their goals of establishing preferred treatment modalities for certain forms of cancer.

Nuclear Science Facilities

Three new nuclear science experimental facilities were brought on line this year and used for data gathering.

The first, a collaboration between LBL and GSI, Darmstadt, West Germany, is called the Plastic Ball and is a hollow-cored sphere composed of over 800 detector-photomultiplier units uniformly arranged over the surface of the sphere and occupying most of its volume (Fig. 3). The major use for this detector system is to study the fragmentation of target nuclei at the center of the sphere when a large number of secondary particles is emitted. More than six million high-multiplicity events were recorded on magnetic tape prior to the July shutdown, and the data are being analyzed.

The second new facility at the Bevatron is HISS, LBL's Heavy Ion Spectrometer System (Fig. 4). Central to HISS is a large-volume superconducting dipole magnet capable of producing a 3.5-Tesla field in a 1-meter gap. Detectors are arrayed downstream of the target and magnet for study of projectile fragmentation with large numbers of secondary particles. HISS and the Plastic Ball are thus complementary in their roles as major detection systems for the very heavy ion beams that will be delivered in 1982.

Figure 3. A joint GSI-LBL effort, the newly completed Plastic Ball/Wall detector system recorded high multiplicity target fragmentation events during a series of experiments before the July shutdown (C88 818-8087).
The HISS magnet was successfully cooled in March and was maintained in the superconducting state through the running period. Several experiments were conducted which allowed nuclear scientists to test and debug new large-scale detectors and software systems.

For low-energy studies a 60-inch scattering chamber was acquired from the University of Maryland and installed in place of the 36-inch unit previously used.

International interest in relativistic heavy ions, available only at the Bevatron/Bevalac, continued strong in FY81. Support for some of the research programs as well as research instruments have resulted from collaborations between LBL and Japanese researchers, who have operated and maintained a pion spectrometer in Beam 30 and are also building detectors for the new HISS facility. Close collaboration between GSI and LBL resulted in the Plastic Ball detection system described above and in efforts to improve the streamer chamber facility. In every case, a commitment has been made to a facility at the Bevalac and not just to instrumentation of a particular experiment.

Biomedical Facilities

Strong confidence in the Bevalac biomedical program was demonstrated during the year when the National Institutes of Health approved a proposal for the design of a new accelerator dedicated to the biomedical uses of heavy ions. The design project will lead to a construction...
proposal in 1983 (see "Dedicated Heavy-Ion Medical Accelerator").

Meanwhile, patient treatments continued during FY81 in the Bevalac's trial program of cancer radiotherapy. By the end of the year, approximately 80 patients had been treated since the program began, with a total of over 900 individual treatments delivered. Neon beams were used for all FY81 treatments; however, radiobiology work performed at the end of the year points towards potential benefits to be gained using a heavier beam such as silicon. Many of the treatments in FY82 are expected to be conducted with silicon beams.

Continued development of the control system has upgraded the reliability and efficiency of the irradiation procedures. Simplified operator-entry procedures and improved data handling have facilitated the control of the highly complex, interwoven treatment and radiobiology schedules to the point where a single operator can now handle the entire biomedical program. These control system improvements, along with the Bevalac's rapid switching program, have allowed for treatments of up to 21 therapy ports per day—almost a factor of two improvement over the best previous performance.

The EMI 7070 CT scanner, located in the Research Medicine Building, was commissioned in the spring of 1981 and has been scanning patients routinely since then, with ever-improving reliability. As a result, heavy-ion treatment planning improvements are being continuously implemented.

**SUPERHILAC HIGHLIGHTS**

The long-awaited third injector needed to bring high intensity beams of the heaviest ions, such as gold, lead, and uranium, to both the SuperHILAC and the Bevalac became a reality in 1981. Called ABEL, the S3 M injector was formally dedicated on October 2, 1981, capping the Laboratory's week-long 50th anniversary celebration.

ABEL consists principally of an ion source, a 750-kV Cockcroft-Walton preaccelerator (Fig. 5), and a Wideröe linac. During the first part of FY81, the ion source was installed and tested in the Cockcroft-Walton terminal house, drift tubes were fabricated and installed in the Wideröe linac, and the conventional beam transport lines were completed. In April 1981, the first test beams were transmitted through the Wideröe linac and into the first (prestripper) tank of the SuperHILAC. Two months of shakedown testing interspersed with delivery of argon and iron beams to experimenters followed before the summer shutdown. As a result of these efforts, a major design goal—1 particle milliampere from the ion source for the heaviest ions—was easily achieved. Much of the remainder of the year was spent in adjusting the new system to improve transmission efficiency and reliability. Among other things, this work involved:

- Improving the vacuum from $10^{-6}$ to $10^{-7}$ Torr in the section of the beam line between the column exit and the Wideröe linac entrance.
- Improving replaceable ion source parts as they wore out to increase source reliability.
- Installing a 23-MHz buncher at the entrance to the Wideröe linac.
- Upgrading a quadrupole magnet in the line between the Wideröe linac and the first Alvarez tank.
- Replacing a shorted quadrupole in the Wideröe linac.
- Replacing the vapor stripper with an improved model to efficiently strip the beam from the Wideröe linac to the required charge state for injection into the SuperHILAC. Work continues on limiting oil migration outside of the stripper box, which adversely affects the vacuum.
ABEL's microprocessor-based control system operated reliably from the start. Many of its features, which had been designed to speed the tune up process and allow greater operator access, proved their worth. Among these features are the multiknob control panel (each knob can be dynamically assigned and labeled), two touch-sensitive CRT screens for monitor and control, digitized scope presentation for analog and graphic display of system parameters, and operator access to the data base via BASIC language.

The control system enabled the operators to efficiently use ABEL's nondestructive beam monitoring instrumentation to fully characterize and control the beam. A set of five beam profile monitors, which consist of wire grids that are insertable into the beam, proved far superior to television paddles. Intercepting only about five percent of the beam, these new profile monitors may prove useful for auto-tuning and emittance measurements throughout the SuperHILAC. In addition, a series of beam transformers provided information on peak beam intensities greater than 100 eua without interfering with the beam.

Although the primary focus at the SuperHILAC in FY81 was on the completion of the new third injector, progress was made in other areas, especially those described below.

- **Rf Stability.** The rf system is being upgraded toward the goal of 33 percent duty cycle for all masses. During the summer shutdown, the two new amplifier carts that will replace the three rf carts that now power rf Tank 2 were more than half finished. When the carts are completed and installed in
FY82, they will provide greater rf stability, especially for the high duty cycle, high-gradient running typical of ABEL beams.

- Improved Strippers. The high-intensity heavy-ion beams from the new injector drastically reduce the lifetime of the carbon foils presently used to strip the ions at 1.2 MeV. Cracked ethylene foils have been tested as a possible replacement. The idea of a constantly regenerated liquid film was also pursued through construction of a beam box to test the film generation apparatus with actual beam.

- Post-Accelerator Buncher. A low-power, full-scale model of a promising triple-gap buncher was tested for rf behavior, and measurement of the field strengths between the gaps matched theoretical predictions.

184-Inch Synchrocyclotron

The 184-Inch Synchrocyclotron continued to operate as a dedicated medical accelerator, providing helium ions for both radiotherapy treatment and biological experiments. During FY81, 111 patients received 1500 treatments for cancer and other diseases. Most of the patients were in the ongoing program to compare helium and heavier ions with conventional radiotherapy in the treatment of cancer.

Beam development concentrated on improved sharpness of the edges of the treatment field so that tumors very near sensitive structures, such as the spine, may be treated. For example, an area up to 6 cm diameter at a depth of 20 cm exhibits an edge sharpness of 6 mm between the 90 and the 10 percent dose contours. The sharpness improves to 3 mm for a depth of 8 cm. The beam used to treat ocular melanoma at a depth of 2 cm has a sharpness better than 1.7 mm.

The cyclotron’s reliability remained excellent. Downtime for the year was only 1.9 percent. Such high availability is encouraging for our design of a dedicated facility (see "Dedicated Heavy-Ion Medical Accelerator").
ADVANCED ACCELERATOR STUDIES
<table>
<thead>
<tr>
<th><strong>Superconducting Magnets</strong></th>
<th><strong>Beam Cooling</strong></th>
<th><strong>Accelerator Theory</strong></th>
<th><strong>Administrative Assistance</strong></th>
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<tr>
<td>C. Taylor (group leader)</td>
<td>G. Lambertson (group leader)</td>
<td>L. Smith (group leader)</td>
<td>L. Egeberg</td>
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<td>R. Althaus</td>
<td>A. Arthur</td>
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<td>C. Peters</td>
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The Division's advanced accelerator studies focused primarily on activities to produce a large flux of cooled antiprotons in the Fermilab collider project (TeV I) e^+e^- to develop superconducting magnets for both Isabelle and future accelerators. Besides these major programs, which are discussed below, work continued toward completion of documentation for certain PEP components, design of septum magnets for a Stanford Linear Collider (SLC) damping ring, application of rare earth cobalt (REC) permanent magnets to future accelerators, and pursuit of a variety of advanced accelerator concepts, many of which are described in the "Special Projects" section of this report. In addition, theoretical support for the Division's programs was provided in the form of short-term assistance at the request of program leaders, long-range studies aimed at future accelerator possibilities, and extensions of basic accelerator problems to new parameter ranges.

HIGH-FIELD SUPERCONDUCTING MAGNETS

The main goal of the Superconducting Magnet Program is to design and develop superconducting magnets for a next-generation accelerator. However, in FY81, in response to requests from DOE and the Brookhaven National Laboratory (BNL), our major effort was to design an alternative dipole magnet for the Isabelle accelerator and to build and test a series of 1-m-long model magnets based on 23-strand, Fermilab-type cable.

Starting in July 1980, we built and tested five two-layer, 76-mm-bore magnets (the D-7 series) to develop winding methods. We then built two three-layer magnet models (D-8A and D-8B) that have the same bore as the Isabelle magnet (132 mm). By July 1981 we had successfully tested the three-layer D-8A, which has aluminum rings, and reached a central field of 5.6 T at 4.2 K. The D-8B, which has iron flux return, reached 6.5 T at 4.2 K. Subsequently, at 1.8 K, both magnets reached 7.6 T, a world record for accelerator-type magnets. These model magnet tests are summarized in Table 3.

Cyclic energy loss was determined by calorimetry in the helium II bath during the tests. Cycling between 0.6 T and 6.0 T at 0.42 T/s (25-s period) produced 40 W of magnet heating.

The two large-bore magnets, D8-A and D8-B, are 1.3-m long and are wound with Fermilab cable in three concentric layers; however, unlike Fermilab, we use an epoxy-free construction method. The cable insulation consists of 25-μ Kapton and 50-μ Mylar with no fiberglass. Figure 6 shows the D8-B model with its 495-mm-diameter "cold iron" yoke.

All objectives of the development program were met, including design studies of a full-length magnet with a laminated structure that would ensure precise location of the three coil layers. Continuation of this program proved unnecessary after BNL successfully tested its two-layer "Palmer" magnet, which can utilize much of the existing Isabelle parts and tooling.

Test Facilities

LBL's Isabelle model magnets were tested in our newly improved test facilities. The magnet cryostat was modified to allow testing of the D-8 model in a horizontal position. The new CCI refrigerator, commissioned in June 1981, delivers 360 W at 4.4 K or 80 liters per hour as a liquifier. As a closed-loop 1.8 K refrigerator, with a vacuum pump operating as a low-pressure compressor, the system has a capacity of about 35 W.

An HP-1000 minicomputer and a CAMAC data acquisition system were installed to more completely monitor the magnets during tests. This computer allows rapid data acquisition at the time of a quench (superconducting-to-normal
Table 3. Summary of test results on five two-layer, 76-mm-bore magnets (the D-7 series) and two three-layer magnet models (D-8A and D-8B) that have the same bore as the Isabelle magnet (132 mm).

<table>
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<tr>
<th>Magnet</th>
<th>Iron</th>
<th>$B_{0\text{max}}$ (Tesla)</th>
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<tr>
<td></td>
<td></td>
<td>4.2 K</td>
</tr>
<tr>
<td>D - 7A</td>
<td>No</td>
<td>4.6</td>
</tr>
<tr>
<td>7B</td>
<td>No</td>
<td>4.3</td>
</tr>
<tr>
<td>7C</td>
<td>No</td>
<td>4.5</td>
</tr>
<tr>
<td>7D</td>
<td>No</td>
<td>4.1</td>
</tr>
<tr>
<td>7G</td>
<td>No</td>
<td>4.8</td>
</tr>
<tr>
<td>D - 8A</td>
<td>No</td>
<td>5.6</td>
</tr>
<tr>
<td>8A</td>
<td>Yes</td>
<td>6.1</td>
</tr>
<tr>
<td>8B</td>
<td>Yes</td>
<td>6.5</td>
</tr>
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Figure 6. The DB-B alternative Isabelle magnet model (132-mm bore) shown with its 495-mm-diameter "cold iron" yoke. The magnet reached 6.5 T at 4.2 K and 7.6 T at 1.8 K—a world record for accelerator-type magnets (CBB 819-9179).
transition). With the output from this system, we have been able to measure the velocity of propagation of the normal region and pinpoint the region where the quenches are initiated.

High-Field Magnet Program

Although a next-generation accelerator has yet to be specified, our long-term program is developing the technical base which will be critical to its success. We are investigating promising magnet designs with the general goals of 10-T central field and 4-7 cm bore diameter, and we are developing suitable conductors for such magnets.

During the year, we completed a system study of accelerator magnet costs and made preliminary design studies of two different approaches for 10-T central fields. The first approach is based on technology and materials now used at lower fields: Nb-Ti cable, 2-K refrigeration, and layer (shell) design. Figure 7A shows a six-layer, 70-mm-bore design of this type. We are continuing to evaluate techniques for layer winding of this design and have examined small-bore versions. The second design uses a much

![Diagram of magnet designs](image)

Figure 7. Cross sections of three 10-T magnet designs: (A) a six-layer, 70-mm-bore shell design that uses NbTi cable and 2 K refrigeration; (B) a six-block, 70-mm-bore design; and (C) a four-block, 40-mm-bore design. Block designs (B) and (C) use a developmental Nb$_3$Sn conductor but more conventional 4.5 K refrigeration (XBL 822-8023).
more developmental Nb<sub>3</sub>Sn conductor but has more conventional 4.5-K refrigeration. Figure 7B shows a six-block, 70-mm-bore design of this type, and Fig. 7C shows a four-block 40-mm-bore version. In preparation for winding a 1-m-long Nb<sub>3</sub>Sn model, we started tests of insulation methods and mechanical properties of epoxy-impregnated cabled conductors.

In collaboration with LBL's Materials and Molecular Research Division, we continued to study the effects of multiple heat treatments on critical current of "commercial" Nb<sub>3</sub>Sn conductor between 8 and 15 T. Heat treatment of two days at 700°C followed by 2 days at 730 to 750°C produced significantly higher critical current than did heat treatment at any single temperature. Independently, an evaluation of the microstructure of the Nb<sub>3</sub>Sn layer shows that this improved performance may result from a combination of maximum layer width, minimum grain size, and more optimum stoichiometry.

We are working with several U.S. superconductor manufacturers to develop a high-current-density Nb<sub>3</sub>Sn cable for winding into final coil shape prior to the reaction heat treatment.

**STOCHASTIC BEAM COOLING**

LBL is the principal U.S. laboratory pursuing stochastic beam cooling—a technique used to increase the phase-space density of a captured batch of rare particles such as antiprotons, or, in a combined action, to continually cool and accumulate many batches into a single intense beam. Collaboration with Fermilab on the design of a source of cooled antiprotons for the colliding beam project (TeV I) dominated the year's activities. TeV I is a project to upgrade Fermilab's Energy Saver to a 2-TeV colliding beam facility with two experimental areas. To reach such unprecedented energies at good luminosities is an ambitious goal. In addition to our TeV I work, we continued to perfect and test the advanced electrical components needed to sense random fluctuations in the beam and to apply corrective forces (Fig. 8). For example, experimental measurements of the response of traveling-wave pickup electrodes installed at the 200-MeV Fermilab Cooler Ring were completed.

A major upgrade of the expected flux of cooled antiprotons for the Fermilab collider was undertaken at mid-year and entailed a change from

![Figure 3](image_url). Stochastic beam cooling equipment senses a deviation of beam particle position and sends a correcting impulse to those particles at a downstream kicker electrode (XRL 8110-7186).
batch pre-cooler technology to an all-stochastic accumulator. Physics design and hardware efforts were redirected to match this more demanding task. To provide greater flux capability, a larger rf bandwidth is needed and, consequently, higher-frequency equipment must be used. Development work, previously in the range below 500 MHz, was shifted to evaluate operation as high as 8 GHz. Physics design and theory are also more complex in the accumulator application. The highlights of our FY81 activities in the areas of design, component development, and theory that are discussed in this report are listed below.

- Initial pre-cooling design for use with subsequent electron cooling.
- Design work for an all-stochastic system with high yield.
- Measurements of traveling-wave electrodes with 200-MeV protons.
- Development of a cryogenically-cooled wide-band preamplifier with exceptionally low noise.
- Radio-frequency model measurements of loop-type electrodes in the 1- to 4-GHz range.
- Fabrication and dc electron beam tune up of an electrode test facility.
- Theory of the slotted beam coupler with non-synchronous signal velocity.
- Development of Schottky-feedback theory and application to accumulator systems.
- Analysis of bunched-beam cooling.

Cooling System Designs

Fast momentum cooling of batches of antiprotons prior to their deceleration, further cooling, and accumulation by an electron beam was a feature of the collider design until mid-year. Electronics in the 100- to 500-MHz range were intended for this precooler, which had a low repetition rate and a correspondingly limited throughput of antiprotons.

The upgraded design under study at year end will provide a higher flux of cooled antiprotons. An 8-GeV accumulator ring will contain a complex cooling and stacking system with advanced, high-frequency cooling equipment. Frequent visits to Fermilab by LBL staff members to discuss designs and goals led to our proposal of a conceptual design based on operating frequencies of 2-4 GHz and 4-8 GHz. LBL beam-transport specialists have generated ring lattice arrangements to accommodate the evolving needs of the cooling system plan.

Component Development and Testing

Electrical noise from the thermal motion of electrons is a limiting factor in the low-signal electronics of stochastic cooling. The operation of input circuits at low temperature promised reduced noise, but wide-band preamplifiers had not been developed. At low temperature, the electrical characteristics of transistors are changed, and a complete circuit redesign was needed. We developed a preamplifier that is usable over the band 100-500 MHz at 20 K and that has a noise figure of 0.5 dB (room temperature preamplifiers in this range have a 2-dB noise figure).

The performance of pickups and kickers that last year had made possible the satisfactory cooling experiments on 200-MeV protons was the subject of an experimental session early in the year. The response of these traveling-wave electrodes and the final cooling results were reported at the Particle Accelerator Conference in March, 1981. Response of the helical, sum pickup was quite understandable, but the twin-line vertical electrode displayed some as-yet unexplained spectral structure.

The rf characteristics and the sensitivity of loop-type pickups and kickers are being studied in a modeling program. A quarter-wave-
length loop electrode at 2-4 GHz is only 2.5-cm long, but it provides the same coupling to the beam as a longer electrode at lower frequency. Compactness is an advantage because hundreds of loops will be installed in the accumulator, their tiny signals being combined to raise the signal level above background noise. The development program will define a geometry for these structures that avoids distortions in amplitude and phase throughout the octave bandwidth. Beam diameter at the electrodes also affects the response and is an important specification in the accumulator ring design.

Wires and electrical instruments do not accurately simulate a beam for the testing and calibration of pickup electrodes. This is especially true at high frequencies where the effects of small capacitances and inductances are relatively greater. Consequently, a test facility that provides a modulated electron beam is under fabrication at LBL. A 2-MeV Van de Graff accelerator has been attached to a 10-ft test tank in which model electrodes may be mounted. At yearend, the electron beam at 1.7 MeV had been focused, centered, and passed through the test tank. A modulator to chop the beam current at 400 MHz was prepared but was not installed because of the recent shift toward gigahertz frequencies. A new modulator for the new range of interest is under development.

Theory

An analysis has been completed of the response of a beam electrode in which the beam couples to a coaxial line through slots in the wall of the coax. This slotted coupler, a form of traveling-wave electrode, has been developed and used at CERN. In attempting to gain a general understanding of such electrodes, LBL theorists treated the case in which beam and wave may be of unequal velocities. This analysis provides a design guide and an evaluation relative to other electrodes.

Expressions for Schottky signal suppression for transverse and longitudinal cooling in the presence of band overlap were derived from a Vlasov equation approach. These results take into account the character of the feedback system in each harmonic band and the distinction between devices sensitive to energy or to frequency. The formulation predicts possible large-gain instabilities which correspond to coherent overdamping. The stability thresholds derived apply as well to any localized feedback system or impedance, and the analysis can be extended to any spatially-varying impedance structure. For stochastic cooling, it appears that systems with energy-dependent gain variation are significantly less susceptible to such instabilities than are systems with substantial filter-derived gain variation.

Computer codes were developed to evaluate the signal suppression numerically and were introduced into existing Fokker-Planck equation solvers. Single-particle longitudinal damping with transversely varying gain was analyzed in the presence of betatron oscillations, and a relatively simple expression was derived for the effective gain.

Transverse and longitudinal Fokker-Planck coefficients have been derived for the time evolution of the phase-space distribution of a bunched beam undergoing stochastic cooling, including amplifier noise and signal suppression effects. A general expression for signal suppression, including band overlap, is obtained. The analysis has been extended to coupled, three-dimensional cooling and to non-linear pickup-kicker devices. Analysis has progressed to the point of numerical analyses of realistic cooling scenarios.

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The Magnetic Fusion Energy program at LBL is devoted primarily to the research and technological development of systems for heating and maintaining plasmas in mirror and tokamak experiments. Part of this work involves the development of neutral beam components and systems, including large test facilities. At the same time, basic studies are underway to improve our understanding of the atomic physics, plasma characteristics, and general theory of neutral beams. We also have an active research program in basic plasma theory, developing and applying modern mathematical techniques to plasma physics problems. In pursuit of these activities during FY81, we

- Demonstrated operation of the TFTR neutral beam modules at their design specifications (120 kV, 65 A, 0.5 s) on the Neutral Beam System Test Facility (NBSTF).

- Operated a fractional-area (7 cm x 10 cm) advanced positive-ion source at 80 kV with 30-s pulses and at 120 kV for several seconds (pulse lengths limited by test facility).

- Completed design and construction of a full-size (10 cm x 40 cm) 30-s pulse accelerator for MFTF-B Tandem Mirror development.

- Demonstrated a "magnetic filter" concept for reducing the molecular-ion component in a neutral beam system.

- Produced a 1-A, 34-keV, 7-s H⁻ beam with a surface-production source.

- Completed the initial design of an injector system for the proposed ZEPHYR tokamak in Germany.

- Obtained 80 percent H⁺ ion component from a "hybrid" plasma source.

- Demonstrated long-pulse operation of a beam-stop panel in a neutral beam system at a power density of 2 kW/cm².

- Started procurement and construction of components for our major new test facility, the Neutral Beam Engineering Test Facility (NBETF).

- Completed a computer-model analysis of the physics of our conventional ion sources.

- Completed measurements of H⁻ production by double charge exchange in alkali and alkaline-earth metal vapors.

- Extended the theory of interacting particles and waves to general geometry with possible application to plasma instability, turbulence, and wave-heating of plasmas.

- Showed computationally that intense 3-mm microwave beams can be generated with good efficiency in a 4-MeV (electron beam energy) free-electron laser.

The official programmatic elements of our neutral-beam research and development activities are Positive-Ion-Based R and D, Negative-Ion-Based R and D, and Test Facilities, the latter including a Major Device Fabrication (NBETF). In this section, we report on the progress made during FY81 in each of these program elements, and we also report on our work in atomic physics, plasma theory, and microwave heating.
NEUTRAL BEAM DEVELOPMENT

Positive-Ion Beam Research and Development

Present neutral beam activities at LBL in support of magnetic fusion experiments at the Lawrence Livermore National Laboratory (LLNL), Princeton Plasma Physics Laboratory, and General Atomic Company involve the production, acceleration, and neutralization of 80- to 120-keV positive hydrogen and deuterium ions. During the past year we have devoted a substantial part of our research to long pulse lengths (from 30 s to dc), and we have emphasized the composition and purity of the beams. The results of this research will be applied to experimental devices built and operated between 1985 and 1995.

During FY81, we continued testing of neutral beam sources for the TFTR (120 kV, 65 A) and for the Doublet III (80 kV, 80 A), both designed for 0.5-second pulse lengths. In addition, we completed the fabrication of a large advanced positive-ion accelerator for the MFTF-B mirror machine experiment at LLNL. This water-cooled assembly (Fig. 9) will be capable of accelerating a 40-A deuterium beam to 80 keV, with a 30-s pulse length.

In developing large sources, we test the concepts first on fractional-area sources, which produce 10- to 15-A beams and duplicate the geometry of the large accelerating structures in all respects except total area. Consistent with this philosophy, we tested a fractional-area (7 cm x 10 cm beam cross section) water-cooled accelerator. This accelerator has operated well with 80-kV, 30-second pulses, and at 120 kV for several seconds; the pulse length at 120 kV was limited by the test facility capability. Heat loads were carefully measured by water-flow calorimetry and found to be comfortably small. Each of the four sets of electrodes, all at different potentials, received only a few tenths of one percent of the beam power, well within the cooling capability of the hollow water-cooled molybdenum rails of the accelerator.

Figure 9. The 10 cm x 40 cm Advanced Positive-Ion Source steady-state accelerator, presently configured for MFTF-B. The accelerator "rails" are specially shaped hollow molybdenum tubes, individually sprung and water-cooled (CBB 810-10861).
For many fusion applications, an essentially monoenergetic beam of neutral atoms is desirable. Neutral atoms in the beam at less than full energy do not penetrate as far into the magnetically confined plasma as do full-energy atoms. Also, they adversely affect the electric potential distribution. Therefore, one of our highest priority goals is to develop ion sources that produce nearly pure D beams, with only a small component of D and D~ molecular ions that break up in the gas target that serves as a neutralizer and produce neutral atoms with one-half and one-third of the full energy, respectively. Source modeling studies indicate that the surface-to-volume ratio of the source is an important factor—the larger the source, the larger is the D~ fraction. This has been borne out in practice. Operated with a modified TFTR accelerator structure, our large "magnetic bucket" plasma source—which has rows of permanent magnets on the walls to improve the electron and ion confinement—produced a 120-keV, 65-A beam of deuterium ions in which the D~ fraction was 78 percent. This is substantially higher than the 65 percent D obtained at the same current from smaller-volume "field free" sources.

The original magnetic bucket source was difficult to operate in the proper mode, so a "hybrid" source was built and tested; this module combines our "field-free" plasma generator and a magnetic-multipole confinement wall. It operates well and gives an atomic-ion fraction of 80 percent.

The ion fractions (D~, D^+, D_2^+) are determined, in part, by the electron energy distributions in various parts of the plasma. We have shown experimentally that it is possible to affect the ion composition in a dramatic way by changing the electron energy distribution. The experiment is shown schematically in Fig. 10. Energetic electrons from the cathodes (filaments) produce a dense plasma containing D^+, D_2^+, and D_3^+ ions. To minimize the accelerated D_2^+ and D_3^+ fractions that reach the accelerator, a transverse magnetic field ("magnetic filter") was applied which helped degrade the electron energies as the plasma diffused through the filter. When electron energies on the accelerator side of the magnetic filter are low enough that D_2^+ ions are not produced in this region, then both the D_2^+ and D_3^+ components are attenuated more than is the D^+ ion density. The result was

![Figure 10. This "magnetic filter" arrangement was used to increase by 90 percent the atomic-ion fraction from a 10 cm x 10 cm source (XBL 823-8223).](image-url)
that the atomic-ion fraction from a fractional-area (10 cm x 10 cm) source could be increased to as much as 50 percent. The principle has not yet been incorporated in a full-size source.

There is a price that must be paid for the improvement in ion species: the atomic-ion fraction is increased by raising the magnetic field in the filter, which in turn requires more arc power. However, the cost that results from the additional arc power will not be more than about a percent of that of the total system. (As an indication of the economic incentive for increased atomic-ion fraction, the Princeton TFTR tokamak requires eighteen megawatts of full-energy neutral beam; this is obtained from the atomic rather than the molecular ions: This power input can be achieved with four beam lines operating with 65 percent O°, or three beam lines with 85 percent D°. The difference in hardware cost is about ten million dollars.)

For possible application to MFTF-B, we assembled an optimized, fractional-area accelerator that has only three electrode sets, not the four electrode sets that our 80- to 120-kV accelerators normally have. If this device works well, the current from a given-size module could be larger, and the cost lower. The main question is whether the optics will be good enough.

In June 1980 we began a study to produce a conceptual beamline design for the German ZEPHYR project, a proposed tokamak to study the physics of an ignited plasma. The U.S. fusion program contributed to this project, in part by supporting our conceptual beamline design study. The ZEPHYR project was terminated by the German government, but the conceptual beamline design study was carried far enough that elements could be useful in the design of injectors for the next generation of U.S. experiments (e.g., the Fusion Engineering Device tokamak). An important feature of this design is that all critical components—all cryopanels, the ion and neutral dumps, the magnet, and the three source assemblies—are directly and independently accessible by overhead crane and remote handling equipment.

Negative-Ion Beam Research and Development

Future fusion experiments and reactors may require the injection of very energetic neutral beams to heat large-diameter, high-density plasmas. For example, the use of monoenergetic beams in the end plugs of tandem mirror machines can increase the Q-value significantly. Also, very-high-energy neutral beams (0.5-1.0 MeV/amu) may be used for driving currents in tokamaks, thereby providing a mechanism for obtaining steady-state operation. At energies of about 200 keV the neutralization efficiency for positive ions decreases drastically, whereas the relatively easy stripping of the electron from a negative ion can result in higher efficiency. Therefore, the development of efficient, long-pulse (dc) negative-ion-based neutral beam systems has been an important aspect of our research.

Recently, we have been investigating the operation of an ion source to produce continuous or long pulses of self-extracted, surface-produced negative ion beams with large currents but at modest current densities.

Figure 11 shows the 1-A negative-ion source—a cylindrical multiline cusp geometry with magnets placed on all sides—mounted in Test Stand I. This stand had previously been used for negative ion production by the double-charge-exchange method, and it was completely rebuilt, mechanically and electronically, during FY81 for the surface-production tests. By the end of this period we had accelerated a 1-A beam to 34 keV in 7-second pulses. The electron component of the beam was very small, about 4 percent. (Note: the principle of operation of this source is described in the FY80 annual report.)

With this very encouraging progress we were able to carry out a preliminary conceptual design of a 10-A, 200-kV, long-pulse injection system with some confidence. We would like to raise the H- current density by about a factor of three above the initial value of 20 mA/cm² at the maximum density point in the accelerator.
Figure 11. The 1- to 2-A source for accelerating an H⁻ ion beam to an energy of 40 keV with pulse lengths from 5 s to steady state. Visible are (a) the exit aperture region where the negative ions self-extract, (b) the converter, which is curved to geometrically focus the ions at the aperture, and (c) the tungsten filaments which are the cathodes for the discharge (the entire outer wall is the anode) (CBB B15-4267).

TEST STAND FABRICATION/OPERATION

Large facilities are required to test the ion sources and accelerators developed for neutral beam injection. These facilities consist of multimegawatt power supplies capable of being switched off in a few microseconds, large vacuum systems to handle the gas load from the neutralizer, beam dumps that can handle power densities of several kilowatts per square centimeter, and the associated controls and beam diagnostics.

There are three major facilities for positive-ion injector testing at LBL. Test Stand IIIA is for beams up to 120 kV, 15 A, and 30 s at 5-percent duty factor, and it is used for the development of fractional-area modules. Larger injector modules are tested for voltage-holding and beam optics on Test Stand IIIB (120 kV, 65 A, 30 ms, 1-percent duty factor). The pulse length is limited by the capacitor-bank power supply, so that we cannot investigate properties that may vary with time.

The largest neutral beam facility at LBL is the Neutral Beam System Test Facility (NBSTF—120 kV, 65 A, 1.5 s, 1-percent duty factor) built and operated for the Princeton Plasma Physics Laboratory to test system concepts for the TFTR injection system. This facility will undergo a major upgrade in FY82-83 to permit long-pulse (30-s) module development for the MFTF-B and other large experiments. The unique new facility will be called the Neutral Beam Engineering Test Facility (NBETF). Some parameters of these facilities are given in Table 4. The NBETF will be built in two stages, with Phase I limited to 120 kV, to be operational in April 1983.
Table 4. A comparison of power supply and neutral beam module specifications for the Neutral Beam System Test Facility (NBSTF) and the Neutral Beam Engineering Test Facility (NBETF), a substantial upgrade of the NBSTF scheduled for completion in April 1983.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NBSTF</th>
<th>NBETF Phase I</th>
<th>NBETF Phase II</th>
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<tr>
<td>Accelerator Voltage (kV)</td>
<td>120</td>
<td>120</td>
<td>170\textsuperscript{a}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150</td>
<td>120</td>
</tr>
<tr>
<td>Accelerator Supply Drain (A)</td>
<td>80</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>65</td>
<td>65</td>
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<tr>
<td></td>
<td></td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Pulse Length (s)\textsuperscript{b}</td>
<td>1.5</td>
<td>30</td>
<td>30</td>
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<td></td>
<td></td>
<td>30</td>
<td>30</td>
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<tr>
<td>Duty Factor (percent)</td>
<td>1</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>10</td>
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<tr>
<td>Arc Supply (V/A)</td>
<td>70/4000</td>
<td>80/3000</td>
<td>80/3000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>160/1500</td>
<td></td>
</tr>
<tr>
<td>Filament Supply (V/A)</td>
<td>18/6000</td>
<td>18/6000</td>
<td>18/6000</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Variable from 10 to 170 kV.
\textsuperscript{b}Maximum at indicated currents.

NEUTRAL BEAM ATOMIC PHYSICS STUDIES

The development of neutral beam systems is, in part, based on knowledge of atomic physics processes. During FY81 we investigated:

- Production of negative hydrogen ions in metal vapors and on low work function surfaces.
- Interactions of negative hydrogen ions with highly-ionized plasma targets.
- Diagnostic techniques for studying the composition of intense neutral beams.

We continued our systematic study of the yields of negative hydrogen ions in vapors of the alkali and alkaline-earth elements in search of a suitable material for producing intense negative ion beams by double electron capture. Theoretical considerations indicated that strontium may give the highest yield, and we showed experimentally that strontium indeed is the best charge exchange medium for deuterium ion energies of about 400 eV/nucleus (Fig. 12). The important energy range around and below 100 eV has not been investigated.

Energetic heavy neutral atoms injected into fusion plasmas can cause technical problems or prevent the confinement experiments from achieving their goals. It has not been possible to set reliable limits on permissible impurity currents, but it has been estimated for both the MFTF-B and TFTR experiments that not more than about $10^{-4}$ of the injected particle current should have a $Z$ greater than that of oxygen. We do not know how to measure the impurity components yet, so an important part of our program is the development of suitable diagnostic techniques. The one that is farthest along involves...
the detection of low-energy x-rays produced when the heavy ions and neutrals in the beam strike xenon atoms inserted into the beam. We will make the cross section measurements required for interpretation of the data.

NEUTRAL BEAM PLASMA RESEARCH

We are conducting research to better understand the physics of neutral beam plasma sources and neutralizer plasmas. The results of this research may help to improve the efficiency of neutral beam systems and the reliability of long-pulse neutral beam systems, as well as to reduce beam divergence. Our approach is to

- Develop the measuring techniques required.
- Develop computer models of the plasmas.
- Conduct experiments to validate the models.
- Use the validated models to recommend modifications to the neutral beam ion sources and neutralizers.

Two examples of the work carried out in this program are neutral beam ion source modeling and neutralizer plasma studies, both of which are discussed below.

The objective of the modeling program is to develop a computer model of a positive ion source that can predict the D+, D2+ and D3+ currents produced and the gas efficiency. For a specified geometry, we solve the simultaneous rate equations for the surface and volume production and loss of relevant neutral and charged atomic and molecular species. The electron distribution function is calculated self-consistently. We improve the model until agreement with experimental data is obtained. Model predictions agree well with experimental data for all LBL positive ion sources, as shown in Fig. 13—a plot of the calculated and measured D+ fractions for LBL plasma sources as a function of the volume-to-surface ratio. Moreover, relevant atomic molecular processes have been identified, and suggestions have been made for improving source performance.

In this research program we also want to develop an understanding of the plasma processes occurring in the neutralizer section of a neutral beam line, and determine any possible effects on beam operation. The plasma density and tempera-
ture are measured by Langmuir probes, and plasma flows are measured using ion-acoustic waves. These numbers are compared to predictions of a computer model being developed. So far, the density profiles agree reasonably well with the model predictions.

**BASIC PLASMA THEORY**

The study of interacting particles and waves has been extended to general geometry by using the concepts of action density $J(x,k)$ in six-dimensional (position, wave vector) space, and guiding-center density $f(x,u,u)$ in five-dimensional (position, parallel velocity, magnetic moment) phase-space. Nonresonant interactions, leading to ponderomotive effects, are obtained from an energy functional: $H(f,J)$. The particle Hamiltonian and wave frequency are respectively the first functional derivatives: $\partial H/\partial f$, $\partial H/\partial J$. The mixed second functional derivative $\partial^2 H/\partial f \partial J$ yields simultaneously the ponderomotive Hamiltonian and the linear susceptibility.

Local gyroresonant interactions yield quasi-linear diffusivity in guiding-center phase space:

$$df/dt = \sum_k \alpha_k D_k \hat{\mathbf{a}} \hat{\mathbf{f}}$$

and linear wave growth:

$$dJ/dt = 2 \sum_k \gamma_k J.$$  

The coefficients, $D_k$ and $\gamma_k$, and the operator $\hat{\mathbf{a}} \hat{\mathbf{f}}$ are related by the requirement of energy conservation: $dH(f,J)/dt = 0$. Each contains the gyroresonance condition:

$$\omega(k,x) = \epsilon \Omega(x) + k \cdot \hat{\mathbf{a}} \hat{\mathbf{f}} (x,u,u),$$

where $\hat{\mathbf{a}} \hat{\mathbf{f}}$ is the guiding-center velocity.

Application can be made to plasma instability, to turbulence, and to wave-heating of plasmas.

**RADIO-FREQUENCY PLASMA HEATING**

Although neutral beam heating of confined plasmas is the presently used technique, there is strong motivation for supplementing neutral beams with high-power radio-frequency (rf) techniques. At least two of the approaches to magnetically confined plasmas for fusion power—the tandem mirror with thermal barriers and the Elmo bumpy torus—require "hot" electrons for their successful operation. One way to heat the electrons is using electron cyclotron resonance heating (ECRH).
We are exploring some aspects of rf heating technology, although still at a very modest level of activity. In a small experiment we are generating a plasma in a "magnetic bucket" geometry with about 1 kW of 10-GHz steady-state power. The goal is to produce a quiet, uniform, and dense \(10^{12}\) cm\(^{-3}\) steady-state plasma using microwaves. Such a plasma generator could then be specialized to become an ion source (either positive or negative) or a plasma neutralizer.

We are also investigating ways to generate microwave power, with emphasis on high average power for long-pulse or steady-state applications. One possibility is the free-electron laser. In a joint program with LLNL we used a model which tracked 500 electrons of specified mean energy and energy spread through various wiggler configurations, self-consistently calculating both space charge fields and radiation fields. Effects of emittance and transverse magnetic field gradients were approximated by including an "equivalent" energy spread. Collective effects (Raman instabilities) were not included in the simulation. All of the amplifiers considered utilized an electron beam with a large enough energy spread to cause severe Landau damping of any collective oscillations.

Our studies indicated that a wiggler with a large period (10 cm) would be the best choice for ECRH because this would enable us to extract energy from an electron beam with a large cross section. A 4-MeV accelerator is required, but extraction efficiencies of 40 percent are then predicted for a properly tapered wiggler. On the other hand, a non-tapered wiggler has a conversion efficiency of only a few percent. Figure 14 shows the results of one of the calculations, with the microwave power density growing to 1 GW in a distance of about 3 meters. These promising results can be tested at LLNL.

Because rf generator test facilities have much in common with neutral beam test facilities, LBL can also contribute to the national program by making its high-power facilities available for R and D.

![Figure 14. Radiation intensity vs amplifier length calculated using a one-dimensional simulation code for a 3-mm (100 GHz) free electron laser. The electron beam energy is 4 MeV, the energy spread is 11 percent, and the electron beam current density is 500 A/cm\(^2\) (XBL 823-8672).](image-url)
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<thead>
<tr>
<th>STAFF</th>
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<tbody>
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HEAVY ION FUSION

The AFRD Heavy Ion Fusion group continued its work toward a better understanding of high-current heavy-ion accelerators that eventually could be used to generate electrical power via inertial confinement fusion (ICF). LBL's program is focused on the induction linac as the basis for a conceptually simple single-pass ICF scheme in which heavy-ion beams are accelerated to high current and then focused onto a small pellet of deuterium and tritium fuel. The beams would heat the pellet surface, creating a rocket-like ejection of the surface material that compresses and heats the fuel to the point where a thermonuclear burn occurs.

Induction linac development currently involves design and cost studies of multiple-beam linacs to verify their potentially significant technical and cost advantages. The conceptual computer design program LIACEP was augmented to enable systematic consideration of the acceleration of multiple beams focused either by electric or magnetic quadrupoles at any point in the machine. The current results point towards a system minimum cost for between 4 and 16 beams throughout the accelerator and transport lines, with perhaps a larger number of smaller beams in the source region.

Meanwhile, physics issues relating to the stability of high-current beams are being investigated theoretically and experimentally, and innovative diagnostic systems are being developed. The major accomplishments during FY81 that are reported in this section are summarized below. Additional detail can be found in Refs. 1 and 2.

- The single beam transport experiment—which will test theoretical predictions about transverse instabilities in a heavy ion beam with large space-charge effects in a long quadrupole transport system—was partially built and operated.

- The Cs\(^+\) pulsed drift tube injector model was used to study beam optics\(^\text{3}\) test components in an intense ion-beam environment, and develop diagnostics such as the electron-beam probe which yielded time-resolved charge density data for the Cs\(^+\) ion beam and revealed the existence of an electron halo around the beam.

- Theorists supported the HIF program by working out many of the details of the single beam transport experiment, by advancing the theory of longitudinal instabilities, and by investigating a system of octupoles that might be better suited than an all-quadrupole system for the transport of high-intensity beams.

SINGLE BEAM TRANSPORT EXPERIMENT

Theoretical predictions about the dynamics and stability of a space-charge-dominated heavy-ion beam in a long periodic focusing channel can only be tested through experiment. As a result, fabrication and assembly of the single beam transport experiment became the major experimental effort of the HIF program during FY81. The completed device will consist of an ion source with associated high voltage and focusing elements, a matching quadrupole section (for smoothly fitting the round beam from the source into the alternating gradient transport line), a transport channel consisting of 82 electrostatic quadrupole lenses in seven vacuum tank sections (Fig. 15), and associated control and diagnostic systems.

During FY81, the 200-keV injector, in which both current density and emittance can be varied, was built, and the three matching quadrupoles were successfully tested at voltage while being flooded with Cs\(^+\) ions from the existing Cs\(^+\) injector. At year's end, the ion source and
ratcheting section were operated together. The first of the seven sections of the transport channel will be ready in early 1982, and the complete channel is expected to be ready by the end of FY82.

BEAM DIAGNOSTIC SYSTEMS

Scintillator Development

Our effort continued to develop a long-lived, fast scintillator for heavy-ion beam imaging at high current densities such as those expected in the single beam transport experiment. Europium-doped calcium fluoride, CaF$_2$(Eu), was found to work well except that the light output diminishes exponentially with Cs ion dose with a mean lifetime of 900 pulses at a current density of 0.8 mA/cm$^2$. Sintered Al$_2$O$_3$ proved to have more than four times greater resistance to damage than the calcium fluoride, but we are still trying to develop a technique for making transparent Al$_2$O$_3$ scintillators. Rf-sputtered Al$_2$O$_3$ on glass appears to result in a good quality transparent surface, but we have yet to test it in the ion beam. Sapphire (pure single crystal Al$_2$O$_3$) emits only ultraviolet light, and we are examining the possibility of using wavelength shifters to convert the UV to visible light.

Electron Beam Probe

Information on the charge density distribution of the Cs$^+$ ion beam was obtained by a newly developed electron beam probe. The probe has an electron gun that produces a low current (5-50 μA), thin (< 3 mm diameter) electron beam at 5-10 kV. The beam can be rotated transversely from 0° (electron beam aimed vertically down) to 50° inside the diagnostic tank. The e-beam passes through the ion beam, is deflected by the space charge, and strikes phosphor-coated plates. The trace resulting from the deflection of the
The electron beam was chopped into temporally-short (50 ns) pulses every 100 ns to give good time resolution of the deflection. This capability is particularly important for study of longitudinal charge density distribution and beam neutralization in time.

THEORETICAL STUDIES

AFRD theorists supported the single beam transport experiment, for example, by carefully studying quadrupole electrode shapes to minimize non-linear aberrations. Other work, described below, pursued the well-known but poorly understood longitudinal instability, which could have serious consequences for an induction linac approach to ICF. This possibility has stimulated a new attack on the problem, combining analysis and particle simulation codes.

Longitudinal Stability

A longitudinal simulation code was used to investigate the stability of bunched beams under the influence of the resistive impedance of the accelerating modules. The simulations were performed to understand better two analytic predictions reported in 1980. One analysis, which used a square well model for containment of the bunch, predicted stability, while the other one, which started from a parabolic charge distribution with no velocity spread, also indicated stability to first order in the resistive component of the impedance. The latter analysis suggested that the criterion for stability is that the e-folding distance for a space-charge perturbation running along the bunch should be long compared to the length of the bunch.

Our simulation runs were for the case of a parabolic charge distribution, which is simpler to study than the more realistic square-well model. By varying the resistance through the range suggested by theory, bunch behavior appeared to be qualitatively different above and below the suspected threshold. If the resistance is high, a perturbation does not reflect readily from the end of the bunch but rather chews the bunch apart starting from that end. With a low resistance, the end is perturbed but seems to recover as the wave reflects.

Work continues to determine if it is the e-folding distance that matters or if the absolute magnitude of the disturbance might be more important. We anticipate that a square distribution will be better behaved, as the square-well analysis predicts, but we have not yet tested the reliability of the code in handling abrupt discontinuities at the ends.

We also modeled as realistically as possible two example cases of full-scale drivers that had been developed for cost and systems studies without regard to longitudinal stability. The first case proved to be unacceptable, while the second case, involving multiple beams, was acceptable for the specified length of accelerator. Eventually, a fully three-dimensional code will be needed for a satisfactory modeling of bunch behavior.

Octupole Focusing

Since the advent of alternating gradient focusing there has been occasional speculation on the possible advantage of using alternating-polarity non-linear lenses for beam transport. Until now, the matter was never pursued because of the mathematical simplicity of linear systems. Because space-charge forces can be highly non-linear, this simplicity loses much of its advantage for the transport of intense beams, and it
becomes worth asking if a system of alternating gradient octupoles, for example, might be more practical than a system of quadripoles. Work during the year indicates that single-particle motion in an octupole system is stable, provided that the amplitude is not too large. There is some indication that a hybrid quadripole-octupole combination might be better in current carrying capacity than either single system.

CITED REFERENCES


SPECIAL PROJECTS
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SYNCHROTRON LIGHT FACILITY

In a joint effort with the Stanford Synchrotron Radiation Laboratory (SSRL) and Exxon Corporation, LBL began the conceptual design of a dedicated beam line that will add striking new capabilities to SSRL. The new facility will provide an intense beam of polarized photons in both the vacuum ultraviolet (VUV) and x-ray regions. The line is to be fed by a powerful new wiggler design based on hybrid concepts involving rare earth cobalt (REC) permanent magnets and steel pole pieces. The wiggler can be operated as an undulator to further enhance spectral peaks in the VUV region. The REC-steel hybrid can deliver fluxes roughly 30 times larger and with much less angular divergence than those from the conventional bending magnet sources at SSRL. Such an intensity is so far unprecedented, and it will remain unique until the European Synchrotron Light Facility based on all-wiggler concepts materializes.

The proposed beam line will add significantly to the various research areas utilizing synchrotron radiation. The newly available high-energy photons (up to 30-40 keV) will be useful in investigating the radial distribution function of molecules in an amorphous solid. A 20- to 30-fold increase in photon flux will mean shorter data collection time, better statistics, and higher resolution for various established synchrotron radiation experiments. Such VUV research as the photoemission study of the chemisorbed system and the study of photostimulated desorption processes will be enhanced. In the x-ray region, the increased intensity will make possible:

- Time-resolved extended x-ray absorption fine-structure spectroscopy studies of dynamical systems for monitoring the evolution of catalytic actions, studying the change of the binding site coordinations for enzyme-substrate interactions, etc.
- Surface diffraction experiments in which x-rays are incident on a surface with a glancing angle less than 1° to probe a surface layer less than 20-50 Å thick.
- The study of light atoms on a substrate of heavier atoms.
- Inelastic x-ray scattering experiments to explore the structure of vibrational excitations in the solid. Such experiments have not been carried out yet because the required intensities and/or resolutions are higher than those provided by the usual sources.

The source for the proposed beam line is a newly-developed powerful wiggler based on a REC-steel hybrid concept which has several advantages for this application over the pure REC approach used in the SPEAR undulator described in last year’s annual report. First, the hybrid can produce magnetic fields which are about 50 percent stronger than those obtainable with the pure REC devices. Second, the field distribution in the hybrid wiggler is mostly controlled by the shape of the steel pole surfaces. Even though the steel is driven into saturation, its permeability is still large compared to unity, which makes the field strength and distribution much less dependent on material properties than in the case of the pure REC undulator. In addition, it will be fairly easy to fine-tune the excitation of individual steel poles by using a variable flux shunt at each pole. Figure 16 is a sketch of the hybrid wiggler design showing how the poles and REC blocks are arranged.

To minimize vacuum difficulties in SPEAR, which has a ring vacuum of 10⁻⁹ torr, the wiggler is to be located outside the high-vacuum region, and a variable aperture vacuum chamber will be
Figure 16. Drawing of the wiggler/undulator design being developed for a dedicated beam line at SSRL, cutaway to show rare earth cobalt (REC) permanent magnets and steel pole pieces. Because the wiggler is to be located outside SPEAR's high-vacuum region, flexible omega joints will be used to enable the gap to be varied over 1.2 cm of motion while the vacuum is maintained. The design has a 7-cm period and a 1.93-m magnetic length with a nominal design field of 1.3 T at a 1.0-cm aperture. Wiggler output radiation at 1.3 T is 1.86 kW—some 30 times more power with smaller horizontal divergence than the typical SSRL bending magnet source now produces (XBL 823-8221).

Flexible omega joints will enable the gap to be varied over 1.2 cm of motion. We plan to use the spare omega bellows from SPEAR's 82-Inch Bubble Chamber in this device.

The present wiggler design has a 7-cm period and a 1.93-m magnetic length with a nominal design field of 1.3 Tesla (T) at a 1.0 cm aperture. Wiggler output radiation at the 1.3 T level is 1.86 kW (critical energy = 7.8 keV) with SPEAR operated at 3 GeV and 0.1 amps, (typical parameters for dedicated synchrotron light operation), which is some 30 times more power with smaller horizontal divergence than the typical SSRL bending magnet source now produces. Reducing the aperture to 0.6 cm will provide a radiation output of 3.37 kW (critical energy = 10.5 keV).

In the proposed wiggler-beam line complex, radiation from the wiggler will be split among three lines: the VUV line (0.03-2 keV range); the soft x-ray line (1-4 keV range); and the x-ray line (3- to 30-keV range). The present design has the core of the beam (hard x-rays) going straight ahead and upper and lower tails of the beam being horizontally deflected by vertically split mirrors—at a 2.5° grazing angle into the VUV line and, in the opposite direction, at a 1.5° grazing angle into the soft x-ray line. The x-ray line will be deflected vertically a maximum of 1° (0.5° grazing angle).

The overriding technical challenge for the beam lines and end station equipment (monochrometers) is to handle the increased radiation intensities (thermal loading) and simultaneously maintain high optical quality in the various reflecting components. Currently, the beam lines are at a preliminary design stage. Metal and silicon carbide are being considered as materials for the intensely radiated x-ray line mirrors, and fused silica may be a possible candidate for the other lines. A variety of heat removal and mounting schemes are being examined for the mirrors. The beam lines will be fabricated using ultra-high vacuum techniques.
HEAVY ION RFQ LINAC DEVELOPMENT

The radio-frequency quadrupole (RFQ) linac is a compact, low-beta structure that can efficiently capture, bunch, and accelerate ion beams. Because of its simplicity and compactness, it is particularly well suited to two ongoing programs at LBL. The RFQ linac is being incorporated into plans for upgrading the heavy ion capabilities of the Bevatron local injector and is being considered for the heavy-ion medical accelerator facility (see "Dedicated Heavy-Ion Medical Accelerator"). Both applications require an accelerator optimized for neon and silicon with the possibility of producing significant quantities of argon.

The RFQ consists of four vanes that run along the length of a resonant cavity. Unlike conventional linacs, which are accelerating structures with focusing devices added, the RFQ structure is intrinsically a focusing structure in which the tips of the four vanes are modulated so a longitudinal electric field is present for bunching and accelerating the beam. The alignment and stability of the vane tips in the RFQ structure must be held to 1- to 2-mil tolerances. Because the surface modulation is a complicated numerical function with no regularity, the function is first calculated on a computer and then translated to instructions that a numerically-controlled mill uses to cut the vane tip.

The RFQ concept originated in the Soviet Union, and it was demonstrated recently in the United States in a proof-of-principle experiment with a proton RFQ accelerator at the Los Alamos National Laboratory (LANL). For our applications, it is necessary to design for q/A ratios in the range 0.14 to 0.5, much lower than that for the proton RFQ. LBL has developed design procedures for an RFQ suitable for heavy ions in this mass range.

Considerable progress was made in FY81 preparatory to the fabrication and testing of a heavy-ion RFQ in FY82 as part of the Bevatron local injector upgrade program. Major accomplishments are described below.

• The necessary computer programs for the critical vane tip design and fabrication were developed or adapted for heavy ion RFQ structures. The general formulation of the beam dynamics problem at Los Alamos resulted in the widely used PARMTEQ program, from which we derived PARM2 which includes all the additions needed for the generation of heavy ion structures. Such RFQ structures will operate in a somewhat different beam dynamics regime without space charge and with a much smaller transverse focusing parameter than the LANL proton structure. PARM2 treats the beam dynamics in this regime accurately, taking into detailed account the longitudinal fields in the radial matching section. The entire buncher/capture section has been reformulated resulting in shorter designs with improved capture efficiency. The program GENRFQ prepares the input data to PARM2 from a simple list of structure specifications. After the desired structure is found with the GENRFQ/ PARM2 programs, a series of three programs translates the profile table to a set of instructions for a numerically controlled mill. The data from this set of programs are punched onto a paper tape which controls the three degrees of motion used by the mill.

• To establish the electrical properties of the resonator cavity, we used the computer program SUPERFISH and an analytical technique that we developed. The analytical solution agreed remarkably well with experimental measurements; moreover, it provided valuable insights into the parametric behavior of complicated resonators.

• A 2.4-m long RFQ structure operated at 200 MHz was designed in the central part of the Bevatron local injector upgrade project (see "FY81 Operations"). It will contain 367 cells and operate at a peak surface field of 1.85 times the Kilpatrick limit, similar to RFQ structures being studied and assembled at other laboratories. The small aperture radius of 0.267 cm requires very
accurate machining and alignment techniques. The normalized acceptance of this machine is $0.5 \times \text{mm-mrad}$. The structure will require 250 kW of peak rf power.

- A section of vane representing the Bevatron RFQ structure between cells 270 through 293 was successfully milled (Fig. 17). The dimensions of the vane tip were then verified with an optical comparator to the expected dimension, including the calculated cutting errors due to the finite tool radius. The accuracy on this first trial was within 0.0015 inches. Surface finishing techniques for the vane tip are currently being evaluated.

- Various cold models (low-power rf) of the accelerating structure were built to evaluate the stability of dimensional tolerances, the calculated resonant frequency, and the tuning problems (Fig. 18). Techniques were established for tuning the structure and balancing the fields in the four quadrants. The correct end-tuner geometry, not amenable to calculation, was established experimentally. The models demonstrated that simple loop coupling provides a satisfactory method for coupling rf power into the cavity, eliminating the need for a resonant rf power manifold used on most other RFQ structures. Experience with the models also demonstrated the need for a change in the mechanical design concept from three-point mounting of each of the four vanes to a rigid structure whose stability and adjustability are designed in from the beginning. We are investigating a structure for which only one set-up on the numerically-controlled milling machine is required to mill all critical surfaces. Easily produced and utilized reference points will be provided on all critical pieces to ensure alignment on assembly. The stability of the initial alignment in time will be ensured by the elimination of push screws in favor of easily-accessible shims and by maintaining an isothermal structure constructed of only one type of material.

DEDICATED HEAVY-ION MEDICAL ACCELERATOR

The National Institutes of Health funded a program in FY81 for the detailed design of a

Figure 17. A section of vane representing the Bevatron RFQ structure was milled to an accuracy of 0.0015 inches. Because the surface modulation is a complicated numerical function with no regularity, the function is first calculated on a computer and then translated to instructions for a numerically controlled mill (CBB 810-10960).
Because maximum safety, high reliability, and low operating cost are important design goals, we have designed conservatively and selected existing proven technology instead of pushing the state of the art the way we might in designing a new high-energy physics accelerator. In two areas, however, we believe that technical innovation will provide substantial advantages with only minimal risk: a high-performance control system can improve accelerator operations and provide partial automation, and a compact radio-frequency quadrupole (RFQ) linac can accelerate low-velocity, heavy-ion beams from the ion sources (see "Heavy Ion RFQ Linac Development"). In designing the accelerator control system we utilized experience gained from the new SuperHILAC injector control system (see "SuperHILAC Highlights"). Our approach calls for many microcomputers operating in parallel to collect and transmit data and a powerful minicomputer to perform high-level control functions requiring complex numerical computations.

Though subject to change, our preliminary design for the accelerator is now as shown in Fig. 19, while key parameters are listed in Table 5. The machine is designed to deliver heavy-ion medical accelerator dedicated to clinical and other biomedical uses of heavy ions. A joint effort with LBL's Biology and Medicine Division, the program is aimed at developing a complete preliminary engineering design that will form the basis of a construction proposal to be submitted in 1983. In designing the advanced heavy-ion medical treatment center, we will assess the needs and objectives of the medical community, incorporate associated biomedical and radiobiological requirements, and optimize machine performance, ease of operation, and reliability.

The design study was proposed at the end of FY80, and a site visit to review the proposal took place in mid-FY81. Actual funding began in August, 1981. In preparation for the site visit, tentative accelerator parameters were selected, and a "design example" was developed to indicate the general approach for achieving the project goals. Since the site visit, the primary efforts have been to investigate accelerator requirements more fully, set preliminary design parameters, develop a preliminary design for the accelerator, and begin the detailed investigation of all the technical systems.

Figure 18. A cold model (low power rf) of the Bevatron RFQ structure was built to evaluate the stability of dimensional tolerances, the calculated resonant frequency, and the tuning problems (CBB 810-10084).
ions up to silicon (mass 28). The injector consists of an ion source and its low-voltage stand (about 75 kV), an RFQ linac, two Alvarez linacs, and stripper foils. Fully stripped ions are injected into the synchrotron in a single turn at an energy of 8 MeV/nucleon. The synchrotron has 12 main dipole magnets and 18 quadrupoles, and its circumference is 91.8 meters. The circulating beam ($3 \times 10^8$ silicon ions, for example) is accelerated by the synchrotron to a maximum kinetic energy of 800 MeV/nucleon. A resonant extractor system then extracts the beam from the synchrotron, and the beam delivery system directs the beam to several research and treatment areas. The maximum cycle rate of the synchrotron is about 4 Hz.

ELECTRON BEAM ION SOURCE

Development of a source of highly-stripped heavy ions for cyclotron applications progressed satisfactorily in FY81 through full assembly of the test-stand device to its routine operation, which produced calcium ions of charge state up to 15$^+$. In an electron beam ion source (EBIS), a high-density electron beam is used to ionize a
Table 5. Medical accelerator parameters.

<table>
<thead>
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<th>Injector</th>
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<tr>
<td>Ion source stand voltage</td>
<td>75 kV</td>
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<tr>
<td>RFQ output energy</td>
<td>0.4 MeV/nucleon</td>
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<tr>
<td>Alvarez 1 output energy</td>
<td>1.75 MeV/nucleon</td>
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<tr>
<td>Alvarez 2 output energy</td>
<td>8.0 MeV/nucleon</td>
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<tr>
<td>Beam emittance</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Synchrotron</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring circumference</td>
<td>91.8 m</td>
</tr>
<tr>
<td>Max. dipole magnet field</td>
<td>1.6 T</td>
</tr>
<tr>
<td>Max. rep. rate</td>
<td>4 Hz</td>
</tr>
<tr>
<td>Ion species</td>
<td>Up to silicon</td>
</tr>
<tr>
<td>Beam intensity (silicon)</td>
<td>3 x 10^8 ions/pulse</td>
</tr>
<tr>
<td>Max. energy</td>
<td>800 MeV/nucleon</td>
</tr>
</tbody>
</table>

batch of ions in a solenoidal magnetic field. The ions are confined radially by the space charge field of the electron beam itself and axially by the electrostatic potentials applied to a set of drift tubes surrounding the beam. Feed material seeds the electron beam and is ionized by successive electron impact to a maximum charge state that is determined by the electron beam current density, the ion confinement time, and the background gas pressure. When maximum ionization is reached, the axial drift tube potential is changed from an ion-trapping distribution to an ion-expulsion distribution, and the ions are extracted, focused, and steered into the accelerator or experimental chamber. The cycle is then repeated.

During the year, we installed the drift tubes, ion extraction optics, time-of-flight charge state diagnostic, and atomic oven calcium injector, together with all the necessary electronics. The device was then used for EBIS research and development, which is needed because of the great paucity of information on EBIS behavior. Some highlights of this R and D follow.

We operated the device using the background gases nitrogen and argon and extracted species up to N^5⁺ and Ar^8⁺. Following considerable investigation, we chose calcium as the feed material and an atomic oven to inject it into the beam. (Feed materials must be solid at room temperature because the test stand drift tubes are not cryogenically cooled.) We have extracted calcium ions of charge state up to Ca^{15+}. The time-of-flight spectrum in Fig. 20 is typical of our results.

In normal operation the extracted ion pulse is up to about 30 microseconds wide (FWHM) and 5 μA in amplitude, for a total of nearly 10^9 charges per pulse. Because ions are lost within the non-optimized extraction optics, several times 10^9 charges per pulse are potentially available. However, for cyclotron application, we need a much longer pulse width, together with a high repetition rate. By appropriately tailoring the drift tubes' potential distribution in time, we have been able to stretch the extracted ion pulse width to a reasonably square 5 ms and

![Figure 20. Typical EBIS time-of-flight charge state spectrum which shows the delay between the 200-ns-wide gate pulse and the signals measured by the ion detector 2.3 m distant (XBB 821-628).](image-url)
to increase the repetition rate to 30 pulses per second, though we have yet to attempt both modes simultaneously.

Reproducibility and reliability are other characteristics that are very important to accelerator application, and for which the track record with other EBIS devices has been very poor. When properly aligned and tuned-up, our test-stand device is highly reproducible over both the short and the long term; that is, the shot-to-shot (one pulse per several seconds) variation in charge-state spectrum is minimal, say less than 10 percent, and the device can be switched on after a weekend and produce an output ion spectrum without any further tuning.

A phenomenon that must be involved in order to explain the very high charge states observed in the French experiments\(^1\),\(^2\) is that of beam space charge neutralization, due to the existence of the positive ion component, and the consequent collapse of the electron beam diameter and increase in current density by up to two orders of magnitude. Because of the importance of this behavior to the applicability of EBIS to cyclotron injection, where high duty cycle is needed, the investigation of beam collapse is one of our major goals. By comparing the maximum charge state observed with that calculated on the basis of the measured electron beam current density ("bare beam," with no ion loading), we can infer a beam collapse due to space charge neutralization of a factor of between 5 and 20 in current density. This is a very important result, and we will confirm and, hopefully, improve upon this.

EBIS test-stand R and D will continue in FY82 with the two-fold aim of (i) advancing the state of the art and increasing the understanding of EBIS operation, and (ii) answering specific questions, such as scaling, that will allow us to confidently design and construct an upgraded Mark II EBIS. For example, we have found that the number of ions generated per pulse varies linearly with the length of the trapping region, as is expected. We will next determine the variation in output with magnetic field strength and gun voltage.

### HIGH-CURRENT BETATRON DESIGN STUDY

A study of betatrons for accelerating high-intensity electron beams up to several hundred MeV was begun in FY81. Such high-current beams may be needed to develop free electron lasers for fusion energy. In such an application a weak-focusing betatron has two inherent advantages over other circular accelerators: (1) the low-impedance magnetic induction system is better suited than a radio-frequency system to the acceleration of kiloampere beams, and (2) the relatively large dispersion in beam orbits makes Landau damping more effective in combating various collective instabilities.

It soon became evident that normal design considerations are inadequate for relativistic electron beams in the kiloampere range. Severe space-charge detuning forces the injection energy up to 50 MeV or higher. Even with very large vacuum chamber apertures, at such injection energies the space-charge forces are image-dominated to a degree not experienced in any existing accelerator. In addition, the tune shift due to these forces varies appreciably over the volume of the beam, which is relatively broad because of the large momentum spread needed for Landau damping. The usual assumption of uniform conditions over the cross section of a beam is not applicable here, and beam stability criteria must be critically reviewed.

To relieve the image-force effects, a system of "image compensation" was invented. The method is to sustain the magnetic images that the beam tends to induce in a cage of conductors surrounding the beam. In most vacuum chambers the magnetic images redistribute and die away, leaving the electrostatic images to dominate the space-charge forces at the beam. If the magnetic images can be sustained, the net image forces will be reduced by the factor \(1/\gamma^2\).

Several types of betatron systems were examined: rapid-cycling, single-ring machines (up to 10 kHz); slowly-cycling, multi-ring systems; and multi-stage combinations. An example of the latter category is a two-stage system that uses a rapid-cycling (1 kHz) booster betatron whose
output pulses consecutively fill the several rings of a multi-stack, higher-energy betatron. When all the rings of the betatron stack are filled, they are simultaneously accelerated by the common accelerating flux and guide field. The several beams are stored at maximum energy and individually extracted on demand. A conceptual design has been made of a high energy betatron that uses the ATA induction linac at LLNL as an injector.

A novel two-ring, "push-pull" betatron was invented during this study. It consists of two rings that thread a common accelerating flux in such a way that beams can be accelerated in both the forward and the reverse directions of the magnetic flux. There are cost advantages for this configuration compared to the equivalent single-ring machine, especially in that a large and expensive bias choke is automatically eliminated.

VARIABLE ENERGY NUCLEAR SYNCHROTRON

Studies of a versatile facility to serve the nation's heavy ion physics needs in the 1980's and beyond continued at LBL during FY81. Discussions and workshops regarding post-SuperHILAC/Bevalac research priorities point to the need for an accelerator with the following basic capabilities:

- Intense ion beams of all masses—protons through uranium.
- Low-energy beams from about 10 MeV/amu, overlapping the range of the 88-Inch Cyclotron.
- Intermediate-energy beams comparable to those at the Bevalac, but with much greater intensities.
- High-energy beams well above the Bevalac range, i.e., to 20 GeV/amu for the heaviest ions.
- Highest center-of-mass energies reached by colliding (opposing) beams of up to 20 GeV/amu nuclei, providing the equivalent of a fixed target accelerator of 1 TeV/amu.

The Variable Energy Nuclear Synchrotron (VENUS) promises to fulfill all of the above requirements by combining an accelerator and storage ring in a single facility without sacrificing the performance of either component. VENUS would consist of two identical superconducting rings located inside a single tunnel. As now envisaged, the two main rings would be about 300 m in diameter and would cross in six interaction regions. The elevation of the tunnel would be slightly below that of the Bevatron and its experimental hall.

In addition to the two main rings, a suitable booster scheme is needed. Present plans would use the SuperHILAC for the VENUS injector. For fixed-target operations, the experimental area would be extended, and many Bevalac user facilities, such as HISS, would be relocated and reused. For colliding beam experiments, three interaction halls would be built (Fig. 21). Both construction and operation of such a facility should be as economical as possible, and power consumption and staffing requirements should be kept low.

CITED REFERENCES


Figure 21. Planning for VENUS in FY81 centered on the scheme depicted here in which ions from the Super-HILAC would be injected into a booster synchrotron and then transferred to either of two identical rings of superconducting magnets inside a single tunnel. The countercirculating ion beams would be accelerated to energies as high as 20 GeV/amu and made to collide in three experimental halls to produce center-of-mass energies equivalent to a fixed-target accelerator of 1 TeV/amu. In addition, fixed-target experiments would be conducted at lower energies (XBL 823-8316).
## APPENDIX

### Table I. Membership in the Users' Association Executive Committees.

<table>
<thead>
<tr>
<th>Member</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SuperHILAC</strong></td>
<td></td>
</tr>
<tr>
<td>M. Kaplan, chairman</td>
<td>Carnegie-Mellon University</td>
</tr>
<tr>
<td>M. Blann</td>
<td>Lawrence Livermore National Laboratory</td>
</tr>
<tr>
<td>R. Diamond</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>M. Nitschke</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>R. Vandenbosch</td>
<td>University of Washington</td>
</tr>
<tr>
<td>M. Zisman, executive secretary</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>J. Cerny (ex officio)</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>H. Grunder (ex officio)</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td><strong>Bevatron/Revalac</strong></td>
<td></td>
</tr>
<tr>
<td>S. Curtis, chairman</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>R. Poe</td>
<td>University of California, Riverside</td>
</tr>
<tr>
<td>J. Slater</td>
<td>Loma Linda University</td>
</tr>
<tr>
<td>K. Wolf</td>
<td>Argonne National Laboratory</td>
</tr>
<tr>
<td>E. Ainsworth (ex officio)</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>J. Cerny (ex officio)</td>
<td>Lawrence Berkeley Laboratory</td>
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<tr>
<td>H. Grunder (ex officio)</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>H. Pugh (ex officio)</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
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### Table II. Membership in the SuperHILAC Program Advisory Committee.

<table>
<thead>
<tr>
<th>Member</th>
<th>Affiliation</th>
</tr>
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<tbody>
<tr>
<td>P. Bond, chairman</td>
<td>Brookhaven National Laboratory</td>
</tr>
<tr>
<td>L. Cocke</td>
<td>Kansas State University</td>
</tr>
<tr>
<td>O. Fossan</td>
<td>State University of New York, Stony Brook</td>
</tr>
<tr>
<td>C. Golbke</td>
<td>Michigan State University</td>
</tr>
<tr>
<td>J. Randrup</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>M. Zisman, executive secretary</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>J. Cerny (ex officio)</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>H. Grunder (ex officio)</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
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</table>
Table III. Membership in the Bevalac program advisory committees.

<table>
<thead>
<tr>
<th>Member</th>
<th>Affiliation</th>
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<tbody>
<tr>
<td><strong>Nuclear Science</strong></td>
<td></td>
</tr>
<tr>
<td>H. Feshbach, chairman</td>
<td>Massachusetts Institute of Technology</td>
</tr>
<tr>
<td>R. Klapisch</td>
<td>CERN</td>
</tr>
<tr>
<td>S. Koonin</td>
<td>California Institute of Technology</td>
</tr>
<tr>
<td>D. Scott</td>
<td>Michigan State University</td>
</tr>
<tr>
<td>W. Menzel</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>T. Yamazaki</td>
<td>University of Tokyo</td>
</tr>
<tr>
<td>J. Cerny (ex officio)</td>
<td>Lawrence Berkeley Laboratory</td>
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<tr>
<td>H. Grunder (ex officio)</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>H. Pugh (ex officio)</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td><strong>Biology and Medicine</strong></td>
<td></td>
</tr>
<tr>
<td>R. Kallman, chairman</td>
<td>Stanford Medical School</td>
</tr>
<tr>
<td>E. Ainsworth, executive secretary</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>M. Bagshaw</td>
<td>Stanford University Medical Center</td>
</tr>
<tr>
<td>R. Durand</td>
<td>Johns Hopkins Oncology Center</td>
</tr>
<tr>
<td>R. Fry</td>
<td>Oak Ridge National Laboratory</td>
</tr>
<tr>
<td>W. Glass</td>
<td>Batelle Pacific Northwest Laboratory</td>
</tr>
<tr>
<td>G. Whitmore</td>
<td>Ontario Cancer Institute</td>
</tr>
<tr>
<td>E. Alpen (ex officio)</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>H. Grunder (ex officio)</td>
<td>Lawrence Berkeley Laboratory</td>
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</tbody>
</table>
PUBLICATIONS

ACCELERATOR OPERATIONS


Paper submitted for presentation at the 1981 Linear Accelerator Conference, Santa Fe, New Mexico, October 19-23, 1981:

J. Fugitt, M. Nolan, and F. Crosby, Low Cost Megawatt RF Power Sources for Linear Accelerators to 70 MHz and Above. Also Lawrence Berkeley Laboratory Report No. LBL-13024.

ADVANCED ACCELERATOR STUDIES

High-Field Superconducting Magnets


57
R. B. Meuser, Structural Analysis of Superconducting Bending Magnets, presented at the 8th International Conference, Genoa, Italy, June 3-6, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10950 and SUMAG 39.


R. Meuser, S. Caspi, and W. Gilbert, Measured Mechanical Properties of Superconducting Coil Materials and Their Influence on Coil Prestress, presented at the VIIIth International Conference on Magnet Technology, Karlsruhe, Germany, March 30-April 3, 1981. Also Lawrence Berkeley Laboratory Report No. LBL-12438 and SUMAG 44.


Stochastic Beam Cooling


Other


MAGNETIC FUSION ENERGY


A. S. Schlachter, Production and Destruction of D- by Charge Transfer in Metal Vapors, presented at the U.S.-Mexico Joint Seminar on the Atomic Physics of Negative Ions, Galindo, Mexico, June 9, 1981. Also Lawrence Berkeley Laboratory Report No. LBL-12995.


K. Jimbo, Volume Production of Negative Ions in Reflex Type Ion Source, Ph.D. Thesis (in progress), Lawrence Berkeley Laboratory Report No. LBL-13769.


HEAVY ION FUSION


Poster: submitted for presentation at the 1981 Linear Accelerator Conference, Santa Fe, New Mexico, October 19-23, 1981:

L. Smith, Beam Dynamics in Heavy Ion Induction Linacs. Also Lawrence Berkeley Laboratory Report No. LBL-14131 and HIFAN 175.

A. Faltens and D. Keefe, Review of Induction Linacs. Also Lawrence Berkeley Laboratory Report No. LBL-14130 and HIFAN 176.


SPECIAL PROJECTS

RFQ

Papers submitted for presentation at the 1981 Linear Accelerator Conference, Santa Fe, New Mexico, October 19-23, 1981:

S. Yamada, Buncher Section Optimization of Heavy Ion RFQ Linacs*. *The main part of this work was done at Lawrence Berkeley Laboratory.

N. Tokuda and S. Yamada, New Formulation of the RFQ Radial Matching Section*. *The main part of this work was done at Lawrence Berkeley Laboratory.


H. Lancaster and D. Howard, Loop Coupling to a Radio Frequency Quadrupole Resonator (RFQ). Also Lawrence Berkeley Laboratory Report No. LBL-13008.

EBIS


