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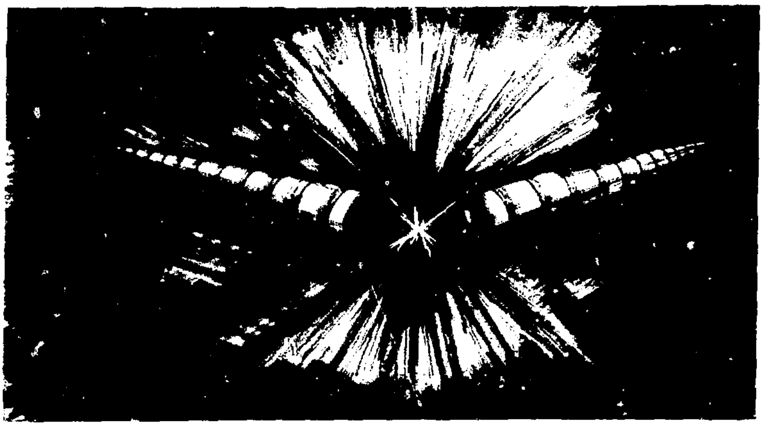
ACCELERATOR & FUSION RESEARCH DIVISION



March 1981

Lawrence Berkeley Laboratory
University of California

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ANNUAL REPORT
ACCELERATOR & FUSION RESEARCH DIVISION

Fiscal Year 1980
October 1979 - September 1980

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

March 1981

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FOREWORD

The Accelerator and Fusion Research Division made substantial progress during the year in its experimental and theoretical research activities as well as in its service to other programs through operation of LBL accelerators as national facilities. These achievements are chronicled in this report by program within the division; however, the underlying unity of the four programs can best be seen by examining highlights from each in terms of their impact on physics, biomedicine, and energy-related technology.

The division has a good record of providing researchers the powerful tools needed to probe the physical world. This year, the $78-million PEP colliding beam facility was completed, and experiments began, culminating four years of work by LBL and SLAC researchers. Meanwhile, the pioneering development of relativistic heavy ion beams continued at LBL in the High Intensity Uranium Beams Project, and existing beams were adapted to a full program of cancer radiotherapy at the Bevatron/Bevalac. Reflecting the international flavor of nuclear physics, West German researchers perfected the GSI-LBL Plastic Ball--Plastic Wall detector system in the Bevalac target area, while their American colleagues worked to complete the Heavy Ion Spectrometer System.

Other division researchers continued to pursue both the magnetic and inertial approaches to fusion energy. A milestone was reached in our support of the U.S. magnetic fusion energy program when the large R&D neutral beam sources for the TFTR and the Doublet III were first tested. These facilities are being improved, and the transition has begun from positive-ion-based neutral beams to the more efficient negative-ion-based beams. In the development of heavy-ion accelerators for use as ignitors in inertial fusion systems, the 1-A cesium injector was completed, and many of its design features were verified. Systems studies resulted in potentially much less costly designs.

The division has a strong sense of continuity with the pioneering spirit that started the laboratory and has sustained its excellence through a strong commitment to basic science and the development of advanced technologies. With an eye to the future, division scientists are laying the groundwork for tomorrow's accelerator concepts, some of which are featured in a separate section of this report. Our achievements during this year inspire confidence that we can meet these and the other tasks in the years ahead.

Hermann A. Grunder
Accelerator and Fusion Research Division

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ACCELERATOR OPERATIONS

The Accelerator and Fusion Research Division operates the SuperHILAC and the Bevatron/Bevalac as National Research Facilities for studies in nuclear physics, biophysics, nuclear chemistry, biomedicine, and astrophysics.

The SuperHILAC is an Alvarez-type linear accelerator designed to provide heavy ion beams of lithium through lead at energies from 1.2 to 8.5 MeV per nucleon. Currently, its two injectors can supply two different ion species to five different beamlines 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 lighter ion beam to the Bevalac for further acceleration to relativistic velocities, and the use of 2 pulses/second of either beam—at a different energy if desired—for a parasitic experiment at the SuperHILAC. As of January 1981, the SuperHILAC experimental area contains 13 beamlines housed in 9 target caves. In addition, a transfer line provides a beam for injection into the Bevatron—LBL's venerable weak-focusing synchrotron—as part of the Bevalac facility, in which beams from hydrogen to iron are accelerated and delivered to researchers via eight beamlines at energies from approximately 50 MeV to 2.1 GeV per nucleon.

Continual effort is given to improving the two accelerators, both in machine operation and experimental facilities, so that they remain useful tools at the forefront of scientific investigation. During FY80, considerable progress was made in upgrading the SuperHILAC to produce ions of all masses, including uranium, at energies up to 8.5 MeV/amu. When this work is completed in 1981, the Bevalac will then be able to deliver relativistic beams of all mass numbers in addition to high-intensity intermediate-energy beams between 40 and 200 MeV/amu. These and other developments are discussed further below in this section of the report (see "High Intensity Uranium Beams").

Outside User Support

The SuperHILAC and Bevatron/Bevalac are National Research Facilities operated by LBL for the nuclear physics community. Outside users account for approximately half the research time at each accelerator (Table 1). Of these non-LBL research groups, about 70% (that is, 41% of the total research program) come from various universities.

There is a growing interest among members of the international physics community in LBL's pioneering development of relativistic heavy ion beams. This interest is manifested in fruitful collaborations with foreign scientists, notably the Japanese collaboration in Beam 30 of the Bevalac as well as several collaborative efforts with researchers from GSI, Darmstadt, West Germany--the GSI-LBL-ANL search for heavy fragments, the GSI-LBL Plastic Ball/Plastic Wall detector system in the Bevalac target area, and the joint effort to make the LBL streamer chamber a reliable and efficient tool to search for exotic nuclear phenomena.

To deal effectively with predominantly user communities, various committees and support groups have been set up. The Accelerator Research Coordination Office (ARC Office), augmented by a group of physicists,

TABLE 1. Summary of SuperHILAC operations by recent calendar year shows the increase in non-LBL use and the decrease since 1978 in operating hours as a result of steadily rising energy costs.

	LBL users		Non-LBL users		
Year	Hours[a]	%	Hours	%	Total hours
1975	998.25	60	675.00	40	1673.25
1976	950.50	59	650.25	41	1600.75
1977	1174.25	46	1352.50	54	2526.75
1978	1217.75	44	1527.50	56	2745.25
1979	1036.60	42	1438.40	58	2475.00
1980	883.00	41	1287.75	59	2170.75
	6260.35	47	6931.40	53	13191.75

[a]Hours = target hours + (tune and setup) hours--time chargeable to experimenters. On average, there are 6 such hours available during each 8-hour shift.

engineers and support staff, is dedicated to assisting users, particularly those from other institutions, in successfully mounting their research. The SuperHILAC and Bevatron/Bevalac Users' Associations (Table 2) communicate user concerns to the accelerator operations staff and also hold annual meetings to share research results and discuss future directions.

The ARC Office, located in the Bevatron building, serves as the focus for user services. Three of its staff are also experimenters who serve as scientific coordinators for the programs at each accelerator. Gary Westfall performs this function for Bevalac nuclear science users; Jerry Howard serves as liaison for Bevalac biomed users; and Michael Zisman is the SuperHILAC

TABLE 2. Membership in the Users' Associations Executive Committees.

Member	Affiliation
<u>SuperHILAC</u>	
N. Johnson, chairman[a]	Oak Ridge National Laboratory
M. Blann[b]	Lawrence Livermore National Laboratory
J. Cerny (ex officio)	Lawrence Berkeley Laboratory
R. Diamond	Lawrence Berkeley Laboratory
H. Grunder (ex officio)	Lawrence Berkeley Laboratory
M. Kaplan[c]	Carnegie-Mellon University
L. Moretto[a]	Lawrence Berkeley Laboratory
M. Nitschke[b]	Lawrence Berkeley Laboratory
R. Vandenbosch	University of Washington
M. Zisman, executive secretary	Lawrence Berkeley Laboratory
<u>Bevatron/Bevalac</u>	
S. Curtis, chairman	Lawrence Berkeley Laboratory
R. Poe, chairman elect	UC Riverside
E. Ainsworth (ex officio)	Lawrence Berkeley Laboratory
J. Cerny (ex officio)	Lawrence Berkeley Laboratory
H. Grunder (ex officio)	Lawrence Berkeley Laboratory
H. Pugh (ex officio)	Lawrence Berkeley Laboratory
J. Slater	Loma Linda University
G. Westfall (liaison)	Lawrence Berkeley Laboratory
K. Wolf	Argonne National Laboratory

[a]Term expired January, 1981.
[b]Term began January, 1981.
[c]Chairman for 1981.

experimental coordinator. The ARC Office also supports researchers in the processes of designing and submitting proposals, mounting experiments, arranging for the loan, construction or repair of detection and data collection equipment, and providing administrative support. Finally, the ARC Office produces and distributes experimenter handbooks and scheduling information.

Long-range scheduling is performed by a staff committee, with periodic notices sent to all users. The immediate operating program is arranged in weekly scheduling meetings among staff and users. Although the task of scheduling is a complex one, especially at the Bevalac where the nuclear science program is allocated two-thirds of the research time and the biomedical program one-third, every effort is made to accommodate users' preferred running schedules.

Because there are usually twice as many shifts requested as are available, proposals for research time are reviewed twice a year by program advisory committees (PACs). 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 3) and one each for the nuclear science and the biology and medicine programs at the Bevatron/Bevalac (Table 4). These expert panels recommend the allocation of research hours to the LBL director, and, as a rule, their recommendations are implemented.

A scientific director for the nuclear science program at each accelerator is appointed by the LBL Nuclear Science Division to provide leadership for the

TABLE 3. Membership in the SuperHILAC program advisory committee.

Member	Affiliation
P. Bond, chairman	Brookhaven National Laboratory
J. Cerny (ex officio)	Lawrence Berkeley Laboratory
L. Cocke	Kansas State University
C. Gelbke	Michigan State University
H. Grunder (ex officio)	Lawrence Berkeley Laboratory
J. Randrup	Lawrence Berkeley Laboratory
D. Ward	Atomic Energy Commission of Canada
M. Zisman, executive secretary	Lawrence Berkeley Laboratory

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 scientific director (presently E. John Ainsworth) for the biomed program at the Bevalac. The scientific directors may allocate 10% of the research hours on a discretionary basis.

FY80 Operations

Research efforts at the SuperHILAC and Bevatron/Bevalac proceeded briskly during FY80 despite urgent efforts to conserve energy, which limited operation

TABLE 4. Membership in the Bevalac program advisory committees.

Member	Affiliation
Nuclear Science	
H. Feshbach, chairman	Massachusetts Institute of Technology
J. Cerny (ex officio)	Lawrence Berkeley Laboratory
H. Grunder (ex officio)	Lawrence Berkeley Laboratory
S. Koonin	California Institute of Technology
H. Pugh (ex officio)	Lawrence Berkeley Laboratory
J. Schiffer	Argonne National Laboratory
R. Stock	GSI, Darmstadt, West Germany
W. Wenzel	Lawrence Berkeley Laboratory
G. Westfall, executive secretary	Lawrence Berkeley Laboratory
T. Yamazaki	University of Tokyo
Biology and Medicine	
H. Suit, chairman	Massachusetts General Hospital
E. Ainsworth, executive secretary	Lawrence Berkeley Laboratory
E. Alpen	Lawrence Berkeley Laboratory
R. Fry	Oak Ridge National Laboratory
W. Glass	Batelle Pacific Northwest Laboratory
H. Grunder (ex officio)	Lawrence Berkeley Laboratory
R. Kallman	Stanford Medical School
G. Whitmore	Ontario Cancer Institute

to the equivalent of less than six of the available twelve months for the nuclear science programs. Cancer therapy trials at the Bevatron/Bevalac, begun last year, were continued as exceptional operation of the Bevatron during some of the time that the nuclear science program could not run, and as part of standard operation of the Bevatron/Bevalac during the normal operating portion of the year (March through July).

Table 5 shows the operating experience for the two accelerators. Of particular interest is the small amount of unscheduled maintenance time this year, typically less than 15%. Such a low figure results from outstanding diligence of the operating staff in keeping the accelerators in top form.

Techniques introduced last year at each facility for rapid beam changes and multiple-beam operation were refined this year. At the SuperHILAC, an average of at least two simultaneous users was maintained, which resulted in a beam utilization 26% greater than machine operating time for research. Because of the radiotherapy program scheduling at the Bevatron/Bevalac, three ion, energy, or beamline changes were made every operating day, on the average.

At the SuperHILAC, 30 nuclear science experiments were completed during the year, 16 of which were done by non-LBL researchers who accounted for 53% of the operating time. At the Bevatron/Bevalac, 29 nuclear experiments were

TABLE 5. Summary of SuperHILAC and Bevatron/Bevalac operations during FY80.

	Hours	
Mode of operation	SuperHILAC	Bevatron/Bevalac
Research		
Nuclear Science	3113.75	1926.50
Biology & Medicine	---	1518.25
Machine Studies	562.75	420.00
Subtotal	3676.50	3864.75
Tuning	438.50	971.50
Unscheduled maintenance	1321.00	681.75
Total scheduled operation	5436.00	5518.00

conducted, and 21 were completed. Outside users accounted for 54% of the machine research time. Biomedical experiments at the Bevatron/Bevalac were another matter--43 experiments were conducted and 2 completed by mostly (81%) LBL researchers. Table 6 shows the ion species and intensities used during the year.

The first half of 1981 will be spent in steady operation of both facilities for the final round of experiments prior to very-heavy-ion research. Included in this round will be the first operation of the Plastic Ball--a 4π detector being built at LBL by researchers from GSI, Darmstadt, West Germany (Fig. 1)--and the Heavy Ion Spectrometer System (HISS).

Bevatron/Bevalac Highlights

The first part of FY80 saw extensive running of the Bevatron/Bevalac for nuclear science experiments and cancer radiotherapy. Commissioning and debugging of a new beamline, B43, was a highlight of the nuclear science

TABLE 6. Ion species and intensities delivered to experimenters during the year.

SuperHILAC		Bevatron/Bevalac		
Ion	Average intensity[a] (particle microamperes, pμA)	Ion	Average intensity (ions/pulse)[b]	Percent of total pulses
Carbon 12	8	Protons	1.5×10^{10}	7.1
Oxygen 16	3	Alphas	1.5×10^{10}	7.5
Neon 20	7	Carbon 12	1.2×10^{10}	29.6
Silicon 28	1.7	Nitrogen 14	1.0×10^{6}	0.2
Argon 40	2	Oxygen 16	3.5×10^{8}	1.8
Calcium 48	0.2	Neon 20	4.5×10^{9}	41.4
Iron 56	0.2	Silicon 28	2.6×10^{8}	0.6
Krypton 86	0.1	Argon 40	3.0×10^{8}	8.9
Xenon 136	30.0 pnA	Calcium 48	1.0×10^{7}	0.3
Holmium 165	0.5 "	Iron 56	1.0×10^{5}	1.8
Lead 208	0.2 "			

[a]At poststripper exit.
[b]On target.

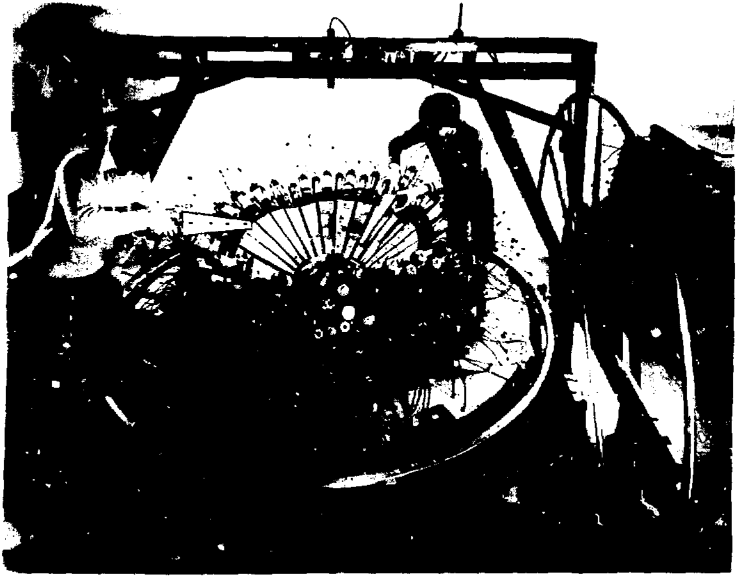


FIG. 1. GSI researchers at LBL install two of more than 800 CaF_2 plastic scintillator modules in an array called the Plastic Ball. When completed in mid-1981, the Plastic Ball spectrometer system will cover nearly 98% of a full 4π solid angle, allowing experimenters to measure and identify nearly all fragments produced in central nuclear collisions. (CBB 811-822)

program. Careful attention to beam optics, magnet alignment, and collimation produced an ultrapure beam (total background halo outside the beam envelope of less than one part in 10^7). This experience will be valuable in preparing beam-delivery systems for the upcoming nuclear science experiments that require large, sensitive, area-detector arrays (Fig. 1) which cannot tolerate excessive background generated by the beam. Later in the year, efforts in the experimental hall centered on the construction of the HISS facility, scheduled for initial operation in the spring of 1981 (see "HISS," below).

New tactics were adopted to substantially improve the effective use of our beam. Rapid switching of the beam to different caves in the intervals between patient treatments, and reinstituting the septum split at F1 to allow the beam to reach simultaneously experiments in both channels I and II, have resulted in about 10% more time for experiments than actual machine time for research.

Experiments with "mezzanine" operation—providing two flat zones during each magnet cycle, thus allowing for beam extraction at two different energies for each pulse—proved successful. This mode of operation will help in the sharing of beam between experimenters with different energy needs, and in permitting experimental runs to continue through short interruptions for patient treatments.

The new ModComp computer control system worked well, offering excellent reliability, reproducibility of day-to-day tunes, and convenient operator communications. Connection of the multiwire beam-monitoring system to the computer gave the operators greater flexibility in monitoring and displaying beam profiles. Since magnet current and beam diagnostics are both on the same system, automatic tuning of external beam lines is now a real possibility. A good start in this direction has been the implementation of an autotune program for the Bevalac transfer line. Although not as efficient as a trained operator, the program does a creditable job.

An additional amplifier was added to the local injector, improving linac reliability and boosting operating gradients enough to accept Ne^{+6} ions—a major step toward local radiotherapy support capability.

The vacuum pumping in the external beam lines is being upgraded to a fully diffusion-pumped system. All beam diagnostic instrumentation is being placed in vacuum boxes, with plunging mechanisms to allow for retraction of all material from the beam path. To be completed in early 1981, this work is in preparation for the delivery of partially stripped very heavy ions.

From mid-August 1980 to January 1981 the Bevatron was shut down. In preparation for the installation of the new vacuum liner, the west tangent tank was removed (for the first time in 25 years) to obtain access to the extraction channel. Stanchions and vacuum skins were modified to allow space for liner components. Additionally, guides and rollers for the liner were installed around the ring, and several old beam-exit ports were removed to reduce the potential hazard of vacuum leaks. This latter work was performed then, since internal access to these areas will be impossible once the liner is installed in mid-1981 (see "High Intensity Uranium Beams").

Bevalac Biomedical Facilities

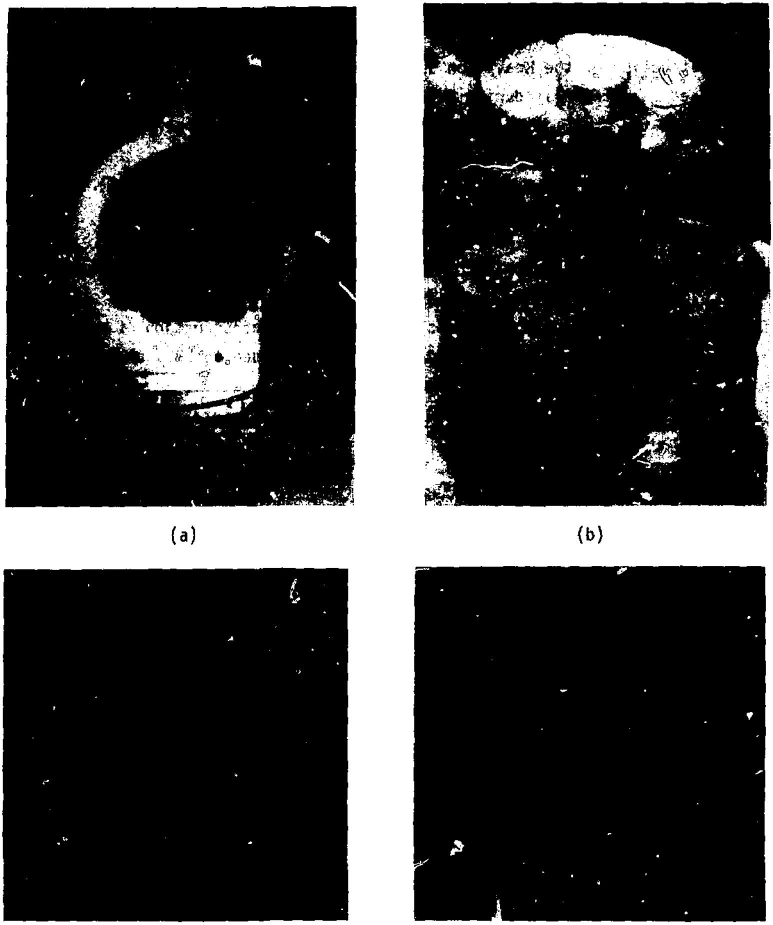
In addition to a full radiobiology program, patient treatment with carbon and neon ions went into full swing during the past year. From November 1979 through August 1980, 50 cancer patients received a total of 520 treatments. As many as 12 treatments were delivered on any single day. Crucial to this successful effort were the highly reliable Bevalac operation, the excellent operation of the new computer control system, and the beam switching techniques discussed above. The control system was improved during its first full year of operation. Monitoring, logging, and safeguarding are all satisfactory, and there are ample redundancies and system interlocks.

The rapid switching of beams between therapy and biology areas substantially increased effective experimental on-target hours, since each therapy treatment requires almost 30 minutes of setup time and 2 minutes of actual beam time. During patient setup, the beam is used for biology experiments, then is switched, typically in 30 seconds, to the therapy room. Reproducible beam positioning is ensured, and routinely obtained, by cycling the beam line magnets through saturation and back to their required settings.

Radioactive beams of ^{11}C and ^{19}Ne were used frequently. A modification in the beam tuning improved the delivered intensity—^{19}Ne activity deposition is now approaching 1 microcurie per pulse, a level adequate for all the localization and implantation studies performed.

The modified EMI 7070 CT scanner was delivered and installed in the medical building (Bldg. 55). We anticipate scanning patients by mid-February 1981. Use of this instrument is expected to greatly improve the accuracy of the treatment plans. Less involvement of normal tissue and a higher dose to the tumor are expected to improve the results of treatments.

A new technique for tomographic imaging of solid objects was developed using the Medical Dose Uniformity Sampler (MEDUSA), a 16-plane multiplane wire chamber originally developed to ensure uniform heavy-ion beams for radiotherapy. This technique involves a double reconstruction: the first produces the ionization intensity at each (x,y) coordinate in the chamber placed behind the object; the second uses these ionization data at different orientations of the sample to produce a full three-dimensional image of the object (Fig. 2). Further development will improve image quality, and eventually this technique should aid in patient diagnostic applications and in patient alignment and tumor localization during therapy.



(a) (b) (c) (d)

FIG. 2. MEDUSA, a multiwire proportional chamber (a), was tested as an imaging device. A lucite-and-teflon model of the human thorax (b) is presented as 64 2-D reconstructed slices (c) which are combined to reveal "spinal column" and "lungs" (d). (CBB 809-10443, CBB 800-13561, XBC 800-13459, XBC 800-13458)

HISS

Construction of the Heavy Ion Spectrometer System (HISS, Beam 42), progressed substantially during FY80. This flexible dedicated user facility is designed for high momentum and spatial resolution and large solid angle. HISS consists of

- A large-volume (1-m gap, 2-m diameter), high-dispersion (30 kG) superconducting dipole magnet that weighs 525 tons (Fig. 3);
- A highly versatile, automated beam-preparation system;
- A computer system for experiment control, data collection, and on-line experiment monitoring and staffing for multiuser support.

During FY80, the following progress was made in the construction of HISS:

- The superconductor was tested, completed, shipped to LBL, and wound into coils;
- An additional 200 tons of steel for the yoke was obtained, machined, and installed;
- The hydraulic rotatable base was completed and rotated successfully with full load exceeding 500 tons;
- Coil bobbins were made, coils wound, and pressure tests completed;
- Cryostats were designed, built, and installed. Cryogenic supply systems were modified and connected;
- Control and instrumentation facilities and equipment were completed and installed, as were vacuum systems;
- Power supplies and dump resistors were completed and tested.

By February 1981, the HISS magnet was ready for pumpdown and a final safety check. The first cooldown and powered operation is expected in March, and full-scale nuclear science experiments are scheduled for June.

SuperHILAC Highlights

On the whole, the SuperHILAC performed smoothly and reliably during the year, and experimenters had beams available to them about 75% of their scheduled time. Unfortunately, budgetary constraints have limited accelerator operation to only 6 to 8 months per year recently (See Table 1). Beamline construction in the SuperHILAC experimental area focused on provision for

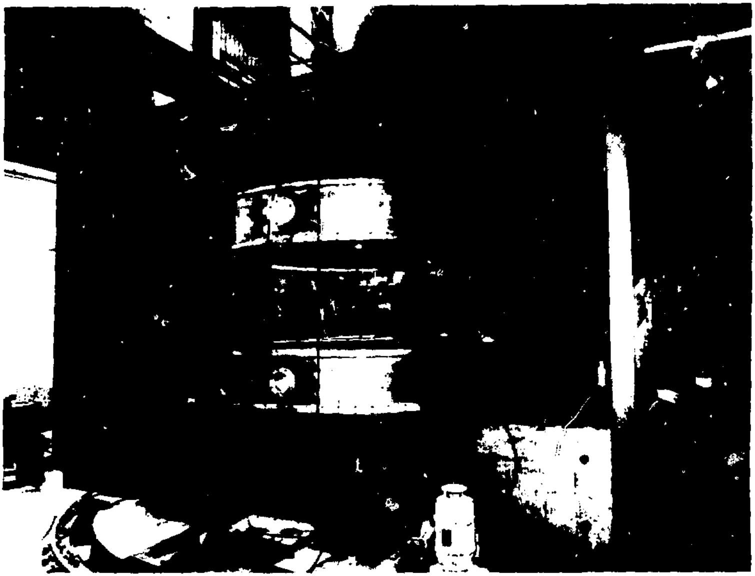


FIG. 3. The HISS superconducting dipole magnet coils were completed, tested, and then positioned within the magnet frame. (CBB 811-846)

three new caves in the north section. Although the primary focus was on the construction of the new third injector for the very-heavy-ion beams project discussed below, other progress was made during the year, including:

- Duty-Cycle Improvement. In the past, coincidence and gamma-ray experiments using the heavy ion beams at the SuperHILAC have frequently been count-rate limited by the low duty cycle (maximum 16%). The rf system is being upgraded to provide a 33% duty cycle for all masses. This includes a replacement of the final amplifier tubes, modifications of the final amplifier carts, and installation of additional cooling to the amplifiers, drive lines and linac tanks.

• Post-Accelerator Buncher. Fast-timing experiments often require subnanosecond beam bunches. To achieve this, a new buncher cavity was designed for installation in one of the existing beam lines to provide beam bunches with a time spread of less than 0.5 ns FWHM. In a further step, another buncher will be put in a dedicated beam line (probably in the presently unused South Cave Area) to provide beam bunch widths of about 0.25 ns FWHM. A full-scale model of a triple-gap buncher has been built to study its rf behavior, and the actual buncher is now being designed (Fig. 4).

• Liquid Film Stripper. High-intensity heavy-ion beams, which will soon be available, will reduce drastically the lifetime of the carbon foils presently used to strip the ions at 1.2 MeV. The idea of a constantly regenerated liquid film is being pursued, and a stable, free-standing oil film of about 30-cm^2 area and a thickness between 20 and 80 $\mu g/cm^2$ has been achieved. Actual beam tests are in preparation.

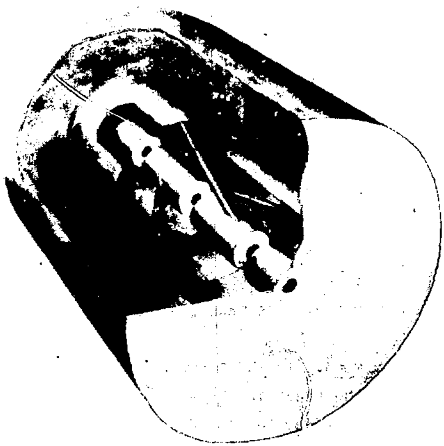


FIG. 4. A cavity with three series gaps was designed to operate as a SuperHILAC postacceleration buncher. A unique cross-coupling scheme enables the buncher to achieve the same energy gain as an Alvarez cavity twice as long and three times the diameter. (XBB 808-9620)

- Nondestructive Beam Monitoring. Nondestructive beam monitoring equipment is highly desirable for the timesharing operation. Recently, a new type of energy monitoring system was successfully implemented. These capacitive pickup probes (phase probes) allow a nondestructive measurement of the average beam velocity with an overall accuracy of ~0.25%. Work is now being done on the design of similar devices for beam position monitors.

- Energy Increase. Studies are continuing to find the best means to at least double the SuperHILAC beam energy. We are currently considering replacing the existing linac structure with one that accelerates more efficiently, drawing upon recent advances in linac technology.

High-Intensity Uranium Beams

Design and fabrication work continued during FY80 on the High Intensity Uranium Beams Project, which the the U.S. Department of Energy authorized in June 1979. The project entails the following modifications:

- A new (third) injector for the SuperHILAC consisting of a preinjector, a Wideröe linac, and beam transport lines;
- An ultrahigh vacuum (10^{-10} torr) at the Bevatron to permit acceleration of very heavy ions in a variety of charge states and minimize loss of ions due to charge-exchange interactions with residual gas atoms;
- An upgraded transfer line to the Bevalac.

When the modifications are completed in 1981, the SuperHILAC will be able to accelerate all ions through uranium with beam intensities increased by a factor of 100 over those now available. The Bevalac will use these SuperHILAC beams, and accelerate them to the maximum Bevatron operating field which, in the case of uranium, will yield 1.0 GeV/amu with intensities as high as 10^8 particles per second. Lighter ions will have maximum energies up to 2.1 GeV/amu and intensities constrained only by the space charge limit of the machine. Highlights of progress toward these capabilities are chronicled below.

SuperHILAC Third Injector

The final assembly, installation, and testing of all parts of the new SuperHILAC injector were well underway at the end of FY80. The addition to the SuperHILAC building was completed early in the year, and installation of preinjector components and power supplies began in mid-April (Fig. 5). The first beam delivery to the SuperHILAC is anticipated in the spring of 1981. Important milestones during the year include the following:

- High-voltage tests were started on the 750-kV preinjector section. The Cockcroft-Walton power supply was operated at full design voltage and tested to 890 kV on the new terminal house shell in September. The 200-hp motor and two generators--one rated at 75 kW at 60 Hz, and the other 25 kW at 400 Hz--that will power the new power supplies, vacuum equipment, and electronics units were installed in the high-voltage terminal house.

- The 7500-lb ion source magnet, its vacuum chamber and equipment were assembled and tested in Building 53 early in the summer, and were installed in the terminal house in October. The ion source magnet power supply, and the six special high-voltage ion source power supplies were fabricated and assembled in the fall, and were tested under load in December.

- The ion source assembly was developed and underwent preliminary tests in Building 53, where the first ions of U^{+5} were studied. The new source features two electrically separate anode chambers (Fig. 6). In December, the source assembly was moved to the new terminal house and tested with the new power supplies (Fig. 5). Initial operation produced approximately 4 mA of peak Xe^{+3} current, and subsequent runs provided 3 to 5 mA of gold and lead beams for study.

The Wideröe Linac

The Wideröe linac tank was installed in June and underwent preliminary vacuum tests in August. Internal components were fabricated and copper plated and then installed in November. The outer drift tube quadrupole magnet

FIG. 5. Construction of the new SuperHILAC preinjector was nearly completed during the year. Workers (left) lower the Cockcroft-Walton high-voltage terminal house onto its supports inside the new addition to the SuperHILAC facility. (CBB 805-7790) Inside the shell (below) a researcher adjusts the ion-source extractor position during tests in December. Ion-source high-voltage power supplies are at right, magnet power supplies and vacuum controls at left. The ion source magnet is in the rear. (CBB 811-870)

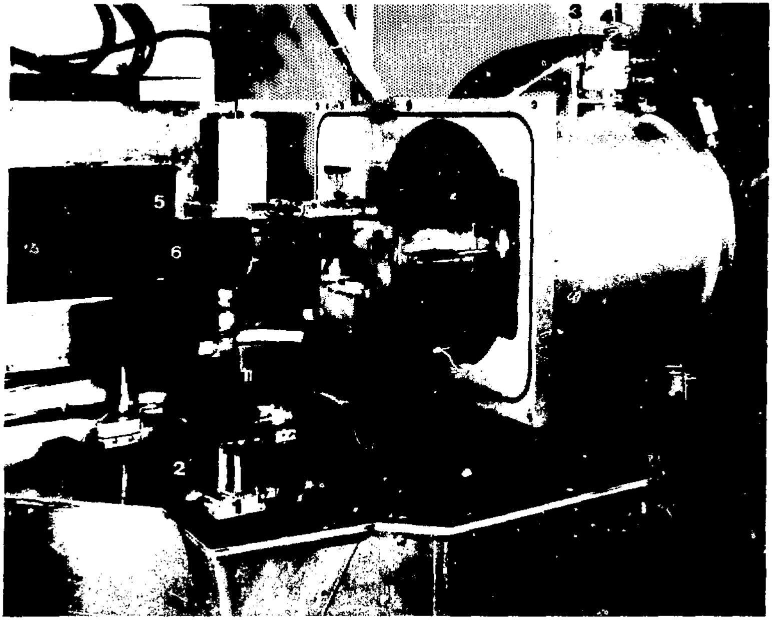


FIG. 6. The new sputter-ion source. Its source head, which has two electrically separate anode chambers (1) and (2) that can be selected by remote control, is easily removed from the assembly as shown. Also shown are (3) the gas inlet, (4) gas switching valve, (5) magnet opening, and (6) extractor and short dee. (CBB 811-884A)

fabrication was underway at year's end (Fig. 7). The 18 quadrupole magnets were found to fully meet anticipated magnetic performance needs of 97.5 kG integrated strength with a satisfactorily low harmonic content. The power supplies for the quadrupole magnets were each tested and installed in the new power supply building. The rf system was tested to full peak power under dummy load in June, and the final power amplifier was attached to the Wideröe tank.

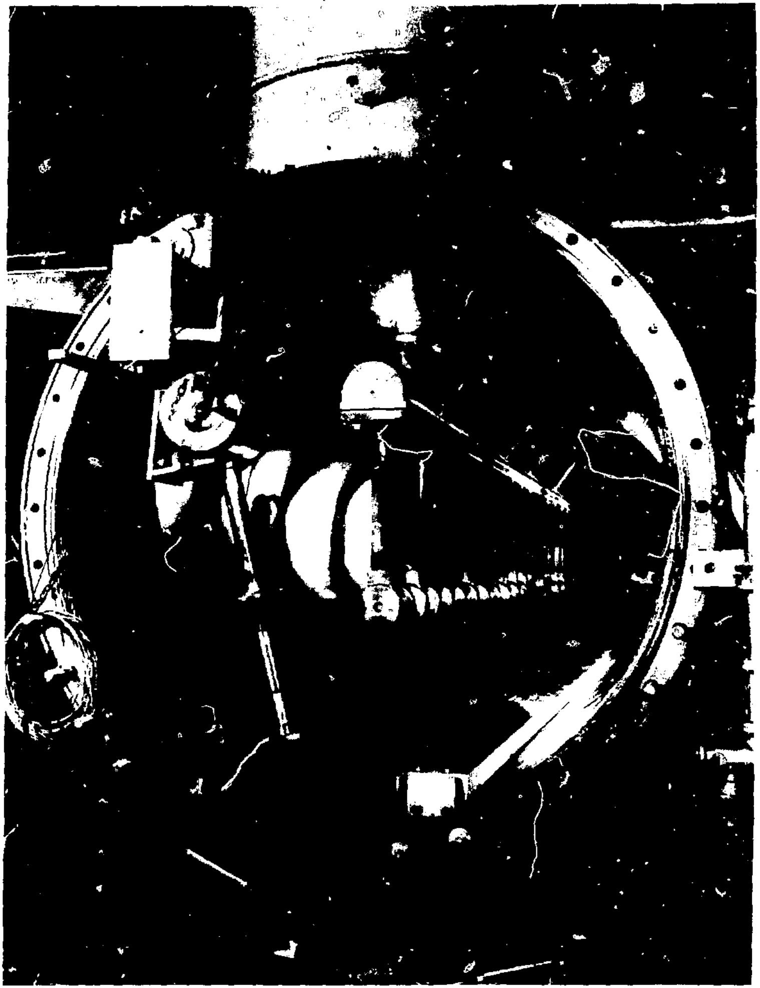


FIG. 7. At the end of the year, the inner drift tube array was in place in the Wideröe, and installation of the outer drift tube quadrupoles had begun.
(CBB 811-888)

Conventional Beam Transport

Component fabrication for the conventional beam transport portions of the third injector line was also completed. Quadrupole, dipole, and steering magnets were all assembled and tested. A fluorocarbon oil-vapor stripper, needed at the exit of the Wideröe to match the q/A required by the SuperHILAC prestripper, was fabricated and checked for equilibrium thickness using an ^{40}Ar beam from the EVE injector. The beamline instrumentation for the new injector transport lines also was developed and tested in the EVE injector line to confirm the suitability of both the wire profile monitors and the beam transformer probes.

Control System

A high-performance computer control system tailored to the requirements of the third injector is being implemented. Dynamically assigned and labeled knobs together with touch-screens provide a flexible and efficient operator interface. An x-y vector graphics system allows display and labeling of real-time signals as well as general plotting functions. The control system provides for attachment of a powerful auxiliary computer for scientific processing and access to accelerator parameters.

A prototype of the system was installed in the EVE injector beamline in March for three months. The reliability and enhanced operator console reponse time agreed with our calculations, which gave us confidence in the soundness of our design approach:

- Multiple microprocessors operate in parallel to collect and transmit data.
- Each processor repeatedly executes a single task, thereby reducing programming complexity and software costs.
- Fiber-optic data links increase bandwidth and reduce noise.
- Distributed data base permits stand-alone operation of accelerator subsystems.
- All programming is in a high-level language.

Testing of the accelerator using the control system is scheduled to begin in February 1981, and full operation is planned for March.

Bevatron Vacuum Improvement

The concept of using a triple-walled vacuum liner to provide an ultrahigh vacuum in the curved portions (quadrants) of the existing Bevatron magnet pole gap was thoroughly tested in 1980. The prototype worked effectively—quickly pumping down to below 10^{-10} torr pressure while requiring acceptably low amounts of cryogenic coolants.

This cold-bore concept holds the inner liner of the rectangular cross section insert 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 (Fig. 8). An activated charcoal pump operates at the same temperature to remove the remaining gases, particularly hydrogen. The inner cold-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.

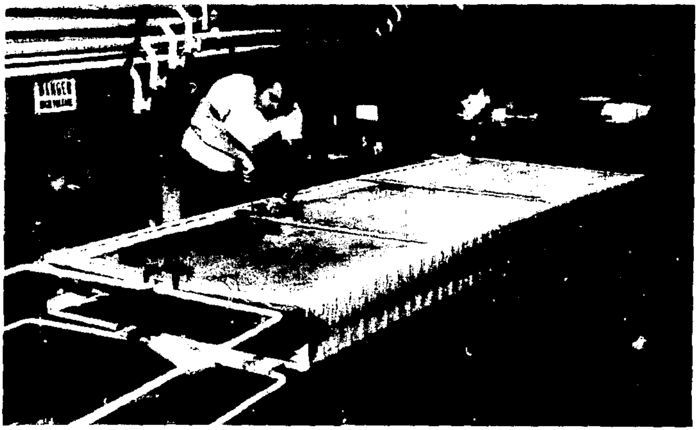


FIG. 8. Freezing out of moisture in the air on a test section of the cold-bore inner box demonstrates the uniform heat-transfer property of the piping and circuit-board material. (CCB 809 10297)

Copper-clad printed circuit board material is used for the inner and middle liners. Circuit board material for the complete cold bore was etched during 1980. The material 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.

The design of the north, south, and east tangent section liners, which are made of stainless steel and will operate at liquid-nitrogen temperature, was almost completed, and some fabrication work began. The north tangent tank liner was tested for stress damage by pumping liquid nitrogen through all cooling tubes. No damage resulted. Material was supplied for the west tangent liner, which is similar in design to the quadrant liners.

Concentrated design work on the cryogenics equipment and on the instrumentation will start in 1981. The goal for the project is to have all liners ready for installation during the Bevatron shutdown in 1981. Installation of all equipment will be complete, and operations and testing will begin by the end of December 1981.

184-Inch Synchrocyclotron

The 184-Inch Synchrocyclotron continued to operate as a dedicated medical accelerator, providing helium ions for both patient radiotherapy and biological experiments. During FY80, 126 patients received 1880 treatments for cancer and other diseases. Most patients were in the ongoing program (sponsored jointly by the National Cancer Institute and the Department of Energy) to compare helium and heavier ions with conventional radiotherapy in the treatment of cancer. Taking advantage of the rapid fall-off in dose beyond the Bragg peak, one patient with skin metastases was exposed to scattered helium ions that penetrated only about 2 cm. Rotation of the seated patient about a vertical axis ensured a uniform dose to the entire thorax. Nine patients with pituitary gland disease were treated, using the customary moving-port technique, and full-energy ions on the Bragg plateau.

A new beamline arrangement was devised for patients afflicted by arteriovenous malformation (AVM) and internal carotid artery-cavernous sinus fistula (CCF). The well-defined treatment volume, which lies deep with n the brain, may vary from <1 to ~ 60 cm^3. The Bragg peak is used for the radiotherapy, and the beamline geometry is chosen to minimize damage to the surrounding tissue. The first AVM and CCF patients were treated in September and October 1980.

The reliability of dedicated operation and the small operating staff needed for the facility (one crew chief and two operator-technicians) offer encouragement for the proposed dedicated medical accelerator (see "Dedicated Heavy-Ion Medical Accelerator"). In the past three years, availability of the 184-Inch Synchrocyclotron averaged 99%; most failures were repaired in less than two hours; and not one patient treatment was lost because of an accelerator-related failure.

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ADVANCED ACCELERATOR STUDIES

The Advanced Accelerator Studies Group conducts research and development of particle accelerators in order to

- Improve the design and operation of existing accelerators
- Extend the frontiers of accelerator theory and technology as the basis for future physics applications.

The group's efforts were concentrated in four programs during FY80--PEP research and development, high-field superconducting magnets, stochastic beam cooling, and accelerator theory. Each activity is discussed in detail below.

Positron-Electron Project (PEP)

Fiscal year 1980 marked the completion of the Positron Electron Project (PEP, an electron-positron colliding beam facility) after four years of concerted effort by LBL and SLAC research teams. The PEP project was the most significant high-energy physics construction activity in the United States since Fermilab was completed in 1972. In November 1979, beams were injected for the first time into Regions 7 and 8 of the PEP main ring. The first circulating beams were achieved in April 1980, the date projected in the 1975 PEP proposal schedule. Particle physics experiments began in late June. Formal dedication ceremonies were held on September 5, 1980. The project was completed within its total projected cost of $78 M. Various aspects of PEP and related research and development activities are described below.

PEP in Brief

PEP is located at the end of the two-mile-long linear accelerator (linac) at SLAC. The major component of PEP is a six-sided storage ring in which beams of electrons and positrons that have energies up to 18 GeV per beam circulate in opposite directions for several hours. The ring tunnel scribes a circumference of approximately 1.4 miles and varies in depth between 20 and 80 feet below ground. The short curved sections contain the bending magnets, which constrain the beams to their closed orbits, while the straight sections hold the radiofrequency cavities, injection magnets, and assorted instruments.

The beams are produced in the linac and injected into the ring via two beam transport lines. The counterrotating beams can be made to collide head-on inside the six interaction halls located at the mid-points of the six straight sections. A typical interaction hall has two sections, one constructed of heavy concrete walls, the other an outer metal frame building. A concrete block shielding wall and a movable crane-operated concrete curtain separate the two areas. Experiments are located within the shielded enclosure that intercepts the PEP tunnels. The outer structure allows heavy equipment access for assembly and repair of experimental devices while the storage ring is in operation.

Conventional Facilities

Fiscal year 1980 marked the completion of all PEP conventional facilities and a systematic turnover of the interaction halls, support buildings, and beam housing to experimenters (Fig. 9). The following systems were completed and tested in the final phases of completion:

- Fire-detection/protection system (smoke and heat detectors, a sprinkler system, and the elaborate system for remote control of the beam housing ventilating fans from outdoor stations around the PEP ring to be used in the event of a fire),
- Permanent power network,
- Phone system that will provide critical computer links as well as communication lines,
- Distribution system for domestic and cooling water,
- Heating, ventilating, and air-conditioning systems,
- Reinforced-concrete-block wall systems required for radiation shielding of each on-line experiment in the five experimental interaction halls.

Interaction Hall 6, constructed separately from the rest of the conventional facilities, progressed from a basic foundation slab at the beginning of FY80 to a finished facility by the end of the second quarter. The four counting houses around the ring, which contain the control equipment for each experiment, were also completed and accepted.

Landscaping, which included the planting of approximately 1200 trees, shrubs, and ground-cover plantings, along with an automatic irrigation system, was accepted. Final paving of the PEP site roads was begun and completed within the first half of FY80.

FIG. 9. The experimental hall (left) and support building (right) for Region 12--one of six such facilities located at the mid-points of the six straight sections of the PEP storage ring.

Beam Transport and Injection Systems

A major LBL responsibility was the design and construction of the beam transport and injection system for switching the appropriate electron and positron beams out of the many beams emerging from the linac, transporting them to the PEP tunnel, and injecting them into the storage ring. Two beam lines were built--one to the south of the linac for electron beams and the other to the north for positrons. Seventeen different magnet designs were used for a total of 108 magnets. Also, some 120 devices were made for monitoring, analyzing, and controlling the beams.

A major PEP milestone was achieved in November 1979 when the south injection line was completed and successfully tested (Fig. 10). In each test, the beam was quickly and easily steered through the line and delivered with good transmission and correct optical quality. A steady, high-intensity 10-GeV

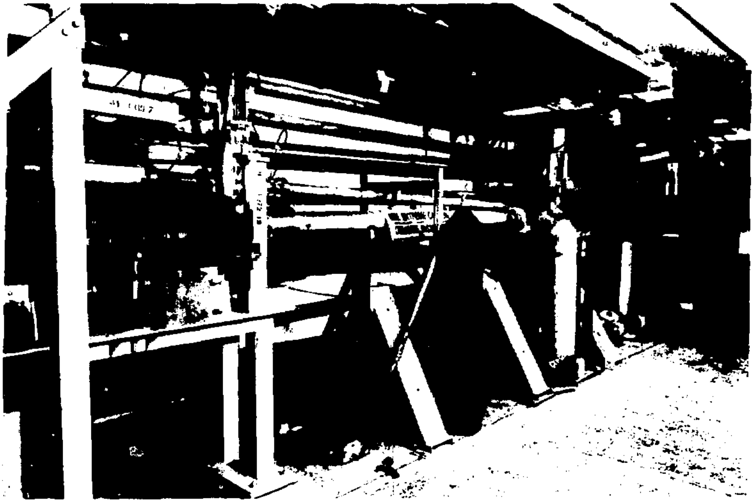

FIG. 10. Region 8B of PEP, where the injection beam line (seen descending from left to right) joins the main magnet ring at the right of the photograph. (CBB 801-900)

positron beam was delivered via this line for the beam-launch tests in the PEP ring in November and December.

The north injection line was completed in February 1980, but beam tests were not begun until April when the PEP ring was completed. Like the south line, the north line worked well from the start.

Radiation Studies

The LBL Health Physics Group investigated the long-term effects of synchrotron radiation on electronic cables and magnet cooling hoses both in the laboratory and at the PEP site. A ^{60}Co source in LBL's Building 6 was used to irradiate samples of Synflex water hose (for magnet cooling systems) and RG-142 B/U signal cable. At 10^7 R the teflon-insulated double-shielded signal cable became less flexible, and at 10^8 R its outer cover flaked and the teflon fractured and crumbled. Following irradiation, the hose samples were hydrostatically tested at 500 psig. The hoses failed at exposures between 10^8 and 10^9 R.

At PEP, LBL and SLAC physicists began a program to measure the intensity of synchrotron radiation in the tunnel, primarily to monitor such components as electronic cables and magnet cooling hoses. Preliminary measurements were made during July runs that involved a mixture of two beam energies (0.27 A-hr at 11 GeV and 0.02 A-hr at 14 GeV). The dose rate on the outer radius of an unshielded section of beam pipe near Magnet 7B2B1 was found to be 2×10^6 rad, in rough agreement with previous calculations. As a result, lead shielding was added to those pipe sections that were previously unshielded. Synchrotron radiation monitoring will continue in 1981, and a series of attenuation measurements to determine the effective energy of the synchrotron radiation will begin.

Interaction Region Quadrupole Magnets

The quadrupole magnets for the PEP insertion regions must have excellent field quality, otherwise the luminosity will suffer. LBL designed and built 24 insertion quadrupole magnets, which were installed in the main ring system near each of the six interaction regions. Previously, these magnets were magnetically measured and found to have the required field uniformity (approximately 1 part in 10,000). From the subsequent beam tests during the past year, it appears that the insertion quadrupole magnets are performing as intended, thereby establishing a new standard for excellence.

Experimenters at PEP are interested in converting one (and possibly two or three) of the six PEP interaction regions into "low-beta" regions to achieve higher luminosity than is presently available. This improvement could be achieved by adding an additional insertion quadrupole magnet at ±6 m from the interaction point. In conjunction with the existing Q1 and Q2 magnets, the new magnets would form a pair of triplets that would strongly focus the circulating bunches at the interaction point. The axial space available for experimental equipment would necessarily be reduced from the present ±10 m to approximately ±5 m.

The new magnets must operate at ~90% greater excitation than that of the existing magnets (Q1 and Q2). LBL is assessing the feasibility of operating the Q2-style magnets at this higher excitation level. Initial indications look promising. Magnetic measurements for the equivalent of 22-GeV operation indicate that the required field quality can probably be achieved.

Survey and Alignment

At the start of FY80, approximately half of the beam elements in the PEP ring had been aligned, and the remaining alignment task was completed during the first half of the fiscal year. A crucial element in this success was the Laser Surveying System that LBL developed for PEP to provide automatic data acquisition and analysis (Fig. 11). Operable by minimally-trained technicians, the system was important in providing adaptability to schedule changes during PEP construction. Proof that the alignment requirements had

FIG. 11. A technician using the Small Automatic Micrometer measures the vertical distance from a bend magnet to a laser beam. At the left are the electronic instruments and the on-line computer that provide automatic data acquisition and analysis. (CBB 803-3079)

been met came in mid-year during the process of starting up PEP. Measurements showed that the closed orbit distortions caused by misaligned quadrupole magnets were well within expectations.

Late in FY80, data taken with the PEP Liquid Level System showed that some portions of PEP, mainly near experimental halls, had settled up to a millimeter. As a result, beam elements in these areas were realigned.

Magnet Power Supplies

The PEP magnet power supply system represents a significant departure from previous technology with the goal of excellent performance at low cost. In all 20 magnet systems around the ring, "chopper" power supplies are used. The many choppers are powered from two 2-MW supplies and control the average power to the various magnet loads by pulse-width modulation at a 2-kHz repetition rate. Each chopper utilizes SCR's for switching and stores sufficient capacitive energy for turn-off on command. Most of the energy is recirculated, resulting in high efficiency. The 2-kHz chopping rate allows a 1-kHz unity-gain bandwidth in the current-regulator loop, and this wide bandwidth, coupled with low drift components in the error-detection system, provides high performance. The chopper supplies, rated either 840 kW or 300 kW, are all located in Region 8 (Fig. 12). There are two additional 840-kW booster supplies for the bend magnet system located in Regions 12 and 4. The dc supplies are powered directly from distribution transformers on the outside utility pad. These distribution transformers and their associated secondary circuit breakers are the only ones in the chopper power supply system, resulting in a substantial saving in cost and floor space. The construction cost for this 5-MW system with 20 separately-controlled magnet-currents was $442,000, a cost of $88/kW.

The performance of the choppers during the first year of operation has been excellent. During running periods, the wide-bandwidth and low-drift characteristics have provided better than ±0.01% performance over both the short and long term. Operational difficulties have occurred more from the standard dc supplies, circuit breakers, transformers, and water circuits than from the choppers. Previous concern over high-frequency "cross-talk" between the choppers did not prove to be a problem. The electromagnetic noise from the magnet cables entering the tunnel detected by the experimenter in Region 8

FIG. 12. Chopper power supplies located in Region 8 are rated either 300 or 840 kW and supply magnet power to all 20 magnet systems around the PEP ring. (CBB 801-904)

was reduced by adding small air-core chokes in series with some of the choppers.

The remainder of the 240 separately-controlled power supplies in the PEP system are of a more conventional nature, with phase-back, ac-line-commutated supplies used for all the injection-transport supplies, and transistor-actuators used for the 180 trim-and-steering power supplies.

Computer and Control Systems

Software for the PEP control system had already been started, but had to be fitted to the PEP operating system and the database in FY80. By PEP startup, a basic set of orbit programs was available for the ModComp computer to

- Initiate scanning of the beam position monitoring (BPM) system and convert raw data to orbit position and corrector strengths,
- Display the closed orbit in local and global format on color monitor displays,
- Print relevant orbit and corrector information for measured orbits and corrected orbits,
- Control the activation and deletion of monitors and correctors,
- Display displacements and divergences of the orbits at interaction points,
- Predict corrector changes to reduce the global rms position errors, and set corrector strengths using this information.

During the early stages of PEP commissioning, new functions were added to the system to

- Compare orbits (hence, measure the dispersion function),
- Control the orbit at the interaction points by means of a combination of local symmetric and antisymmetric orbit bumps,
- Convert the current monitor program on the new VAX computer to use photodiode detectors to monitor the intensity of the synchrotron light emitted by the bunches of positrons and electrons.

During the summer shutdown, existing programs were transferred from the ModComp to the VAX computer, and a new graphics display package was written for the VAX computer to speed up the displays, particularly for the current monitoring program. Later, modifications were made to control local bumps with knobs by using software to gang together the correctors. A calculator program was written that allows flexible handling of orbit data. Another program allows operators to correct vertical dispersion globally by using a combination of single correctors, or by using local symmetric and antisymmetric bumps (not yet programmed).

Development of Rare Earth Cobalt Magnets

LBL researchers continued to pioneer the use of permanent magnet material, especially rare earth cobalt (REC) material, in the design of accelerator magnets. In certain applications, permanent magnets can be made compact without a reduction in magnetic field strength or difficult cooling and power problems that are inherent in small conventionally powered magnets. Two novel designs are discussed below--quadrupole magnets for the SLAC Single Pass Collider and an undulator for SPEAR. Though not discussed here, REC and ferrite materials are also being studied for use in the electron and positron damping rings of the SLAC Linear Collider project to reduce the emittance of positron and electron beams. The feasibility of using REC or ferrite magnets for the main dipoles of the damping rings is also being pursued.

An REC Undulator for SPEAR

Undulator magnets are of great interest in electron storage rings because they generate quasimonochromatic synchrotron radiation with higher brightness than can be obtained using the ring bending magnets or wigglers. An undulator has an alternating periodic transverse field designed so that the maximum angular deflection of the electron is of the order of γ^{-1}, which is also the natural opening angle for emission of synchrotron radiation. Ring bending magnets and wigglers produce angular deflections much greater than γ^{-1}; hence, the intrinsic high brightness in the plane of the deflection is lost. Furthermore, because only a small deflection is wanted in an undulator, it is possible to have a large number of periods in a given length. Interference effect in the radiation emitted at a large number of essentially colinear source points result in enhancement of the radiation at certain wavelengths and suppression at other wavelengths.

In a collaborative effort with the Stanford Synchrotron Radiation Laboratory (SSRL), an REC undulator magnet was designed, constructed and tested at LBL for use at SSRL.[1,2] The 30-period, 1.95-m-long, variable-gap undulator was fabricated with $SmCo_5$ magnet blocks (Hicorex-90B, Hitachi Magnetics, Edmore, MI) oriented and positioned as shown in Fig. 13 to produce the alternating periodic field. The variable gap is achieved with four right-hand and four left-hand ball screws driven through an arrangement of gears and shafts by a stepping motor.

The undulator was installed at the SPEAR storage ring at SLAC on December 10, 1980, and the first radiation from it was measured a few days later. The device produces high-brightness, tunable, quasimonochromatic synchrotron radiation with first harmonic peaks at photon energies up to about 2 keV. Higher harmonics (up to the 5th harmonic) have been observed with reduced intensity. Preliminary measurements of the radiation produced by the

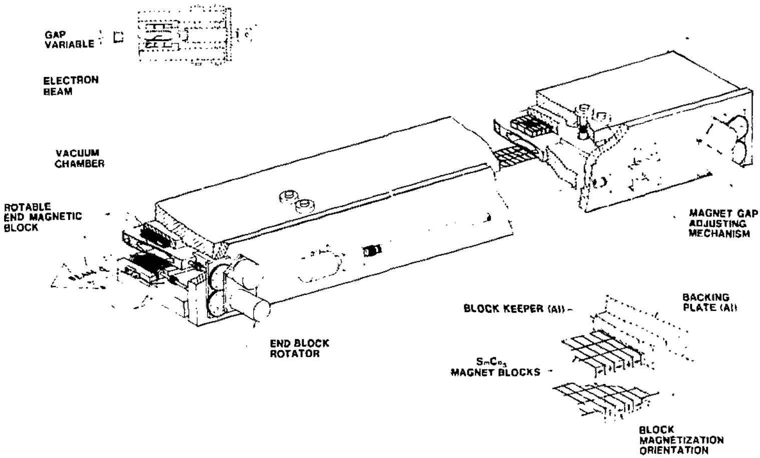

FIG. 13. A 30-period, 1.95-m-long, variable-gap undulator magnet was fabricated with $SmCo_5$ magnet blocks oriented and positioned as shown to produce an alternating periodic field. The variable gap is achieved with four right-hand and four left-hand ball screws driven through an arrangement of gears and shafts by a stepping motor. Gap adjustment range is 2.7 to 6.0 cm, which corresponds to a peak field range of 2808 to 504 Gauss. A set of magnetic blocks at each end of the undulator can be rotated in opposite directions to symmetrically null the field integral. A tuning range of 3500 Gauss-cm is obtained with one rotator pair at a 2.7-cm gap. A total of 726 $SmCo_5$ magnet blocks are contained in the 20 keepers and four end magnetic blocks. (XBL 804-9277)

undulator indicate that it performs as predicted. At photon energies around 1 keV the undulator provides a brightness that is about 2 orders of magnitude higher than that produced by the ring bending magnets. The higher brightness and flux provided by the undulator will have a major impact on several types of studies in soft x-ray microscopy and surface physics.

Results of the project show that the properties of REC material are ideally suited to the design and construction of short-period undulators resulting in high performance with considerably less construction cost and complexity as well as operations simplicity and economy (e.g. no power required) compared to other approaches. Effort is now underway to develop an in-vacuum permanent magnet undulator and permanent magnet wiggler system.

SLAC Single Pass Collider Magnets

Pure REC quadrupole systems promise to satisfy a set of rather unusual conditions in the final focusing system for the SLAC Single Pass Collider:

- To obtain the desired spot size of approximately 1 μm at the interaction point, the final lens system must be well within the solenoid of the experimental detector system.
- Outside the physical boundary of the final lens, the solenoidal field of the detector should not be strongly perturbed by the focusing lens, which precludes specifically the use of steel.
- Even though the good-field region of the lens needs to be only very small, the much larger disrupted beam that emerges from the interaction point has to be accommodated within the aperture of the final lens as well, taking into account the focusing and defocusing of the disrupted beam by that lens.

Two different approaches are under investigation. One--the use of segmented REC quadrupoles with essentially circular aperture--involves fairly straightforward design, and a detailed cost analysis is underway.[1,2] The other--use of segmented REC quadrupoles that have either a strong elliptical aperture, or are completely open in one dimension--is being investigated. A previous design study indicated that such REC quadrupole magnets could be built cheaply when compared to quadrupoles with a circular aperture.

Stochastic Beam Cooling

Reaction rates between the particles in a colliding beam system depend on the densities of the two beams and optical parameters of the colliders. The rates are generally low because relatively few particles can be contained in the interaction system in comparison to a solid target. An increase in the reaction rates will increase the utility of colliding beam facilities for rare particles.

Through stochastic beam cooling, the efficiency of the colliding beam technique is improved by reducing the momentum and angular spreads of the beam, which has the effect of increasing the beam density and thus increasing the reaction rate. The motions of the particles in a beam due to differences in their momenta and directions are analogous to the thermal motions of gas molecules; thus the reduction of these motions is termed "beam cooling."

Experiments at Fermilab

To advance the theoretical and technological base for stochastic cooling designs and applications, experiments were run during the year at a 200-MeV proton storage ring at Fermilab. Initiated at CERN, the technique involves the use of a pickup electrode located at one point in the storage ring to detect the random (stochastic) fluctuations that occur in the particle density as the beam circulates and the faster particles overtake the slower ones. The amplified and processed signals from the pickup are then applied to the beam as a corrective impulse by a downstream kicker electrode.

The program requires the development of extremely sensitive wide-band pickup electrodes; kicker electrodes; state-of-the-art, low-noise, wide-band preamplifiers; and wide-band, minimum-delay power amplifiers.

During FY80, complete systems for vertical and longitudinal cooling were taken to Fermilab and installed at the 200-MeV proton cooler ring. The pickups and kicker electrodes, developed at LBL, employ traveling-wave structures tuned to match the proton velocity of 0.56 times the velocity of light. For this velocity range, these structures offer comparatively high coupling impedances to the beam, low noise, and simplicity. The longitudinal pickup is a 1.75-m-long helix. The vertical pickup has twin ladder lines, 3.8 m long.

In tests, the longitudinal pickup gave the predicted response, and it has become a generally useful beam-monitoring device at the cooler ring. The vertical pickup generally responded as expected, but some unexplained signal modulations as a function of frequency remain the subject of further measurements. These anomalies did not detract from the initial intent and satisfaction of being able to see vertical Schottky signals with only 10^6 protons circulating in the ring.

Initial trials based on preset, measured characteristics of the components served to point out the need for diagnostics. Adjustments of the system parameters to achieve cooling were successful only after making and interpreting measurements of Schottky acceleration. Future work will include development of techniques for measuring system response.

The longitudinal system produced a minimum cooling time constant of 18 s and reduced the initial momentum spread a factor of 13 to 0.018%. This action is apparent on Schottky scans (Fig. 14).

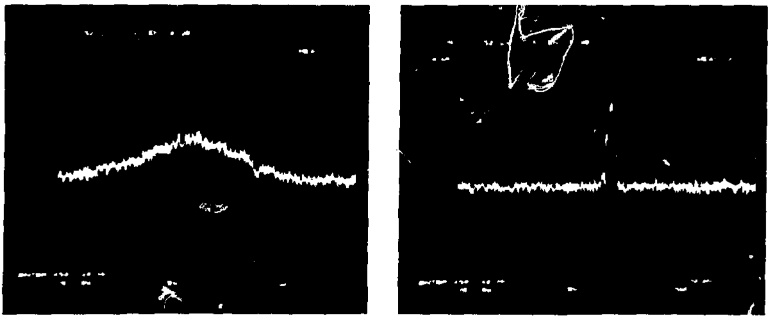

Fig. 14. Longitudinal Schottky scans before and after cooling show a 13-fold reduction in momentum width in tests at the Fermilab 200-MeV proton storage ring. (XBB 805-6627)

Despite the inherently weak signals and some questions regarding the pickup electrode operation, vertical cooling achieved a reduction in beam width of a factor of two in 20 s--a record rate for transverse cooling. A secondary reward was the increase of beam lifetime by one to two orders of magnitude, making this system a useful addition to the cooler ring beam-handling equipment.

Later in the year, effort was directed toward the application of beam cooling in the Fermilab $\overline{p}p$ Collider Facility. This included the evaluation of the current costs and performance of applicable electrode structures, preamplifiers, power amplifiers, and filters. The use of higher frequencies and simpler electrode structures seems desirable; in particular, pickup and kicker structures above ~500 MHz need to be developed. Electronics are already available for these higher frequencies. Hence, the initial design basis for the collider system precooler is now based on the 150-to-500-MHz range, with the possibility of extending the range later. The precooler parameters were the subject in part of a week-long design study at Fermilab and of ensuing collaborative design work. The details of a precooler lattice have been established that will accommodate the required momentum cooling, offer early operation alone at reduced collider luminosity, and be extendable in performance.

Electrode Test Facility

A means of accurately measuring the response of beam pickups was desired during the development of the traveling-wave electrodes. This need has become more apparent as a result of our experimental work and evaluation of electrode technology. Hence, an electron beam facility for electrode testing is being constructed. An electron Van de Graaff accelerator with energy variable from 0.2 to 2 MeV has been overhauled and assembled in a radiation-shielded enclosure. The beam will pass through a 10-ft-long electrode test chamber. Initially, beam current will be modulated at a rate between 200 and 600 MHz. The beam modulator is under development, and most of the other components are on hand for assembly and operation in 1981.

High-Field Superconducting Magnets

The development of reliable high-field magnets (from 7 to 10 T) for future high-energy physics accelerators is the major long-range goal of LBL's developmental efforts in superconducting magnets. During FY80, we

- Analyzed new magnet designs for efficiency and stress to determine the mechanical properties required of the conductor and coil structure,
- Developed and tested a new epoxy-free winding method,
- Made a preliminary design of a dipole magnet suitable for ISABELLE.
- Upgraded our magnet testing facilities,
- Advanced the technology of high-field dipole magnets.

Stress Testing

To reach magnetic fields appreciably greater than 5 T, thick superconducting coils and new design approaches are required. Because some of these new designs result in high local stress in the conductor, we are measuring the deformation and creep characteristics of coil materials at stresses above 15,000 psi. Tests on magnets to determine the relationship between magnet training and initial coil prestress are major goals of our research activities. Minimal training was observed in two well prestressed 7.6-cm-bore, 5-T magnets (D-7A and D-7B).

Stress vs strain measurements were made for a variety of coil structures with our 2.5-ton Instron test machine. A 25-ton Instron test machine, and a [illegible]-ton MTS machine, located in the Materials and Molecular Research Division laboratory, are now being used to extend these data to higher stress levels on larger samples. Cable with various insulation combinations of Kapton, Mylar, fiberglass tape and epoxy were characterized (Fig. 15). Equipment to measure long-term creep under high prestress was also built.

Epoxy-Free Winding Method

During the year, we developed and tested a new epoxy-free winding method. Usually, epoxy is used in coil construction to hold the winding in a precise shape so that the coil parts can be transferred from the winding fixtures to the final magnet configuration. In the new winding scheme, the magnet is

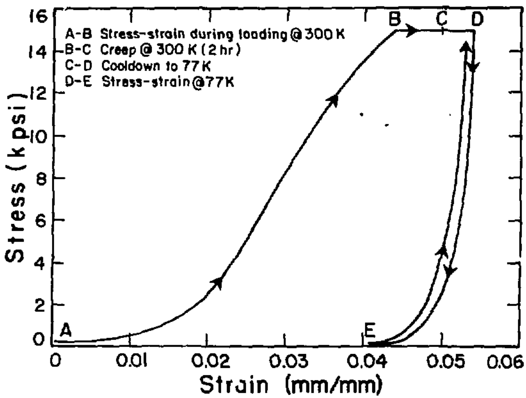

FIG. 15. A typical stress-vs-strain measurement on a 23-mm-high test stack of 16 cables, each insulated with a layer of 25-μm-thick Kapton plus a layer of 50-μm-thick Mylar. During initial compression (A-B), the stack is "soft," and both the cable strands and the insulation yield locally. At higher stress, some creep occurs (B-C). During cooling to 77°K (C-D), thermal contraction appears as an additional total strain. However, after initial compression, creep, and cooldown, the stack is much "stiffer" and can be repeatedly cycled between D and E with very little subsequent change in stress-vs-strain behavior. (XBL 812-355)

built up, layer by layer, into its final form so that no epoxy or other adhesive is required.

Figure 16 shows the winding fixture used for the first models: 76-mm-bore, 5-T, 1-m-long dipoles (D-7 series) that are similar in winding geometry to the doubler magnets at Fermilab. No fiberglass tape or epoxy is used, and external aluminum structural rings replace the Fermilab stainless-steel-collar structural system. The first two test magnets performed to short-sample levels with minimum training.

At the request of the Brookhaven National Laboratory, we made a preliminary design of a dipole magnet suitable for ISABELLE. A program was started to construct and test several 1-m-long models to verify the design principles, which are based on the new epoxy-free winding method. The design is based on a "Rutherford" cable, which contains much more superconductor than the ESCAR cable previously used at LBL. To accommodate the larger conductor,

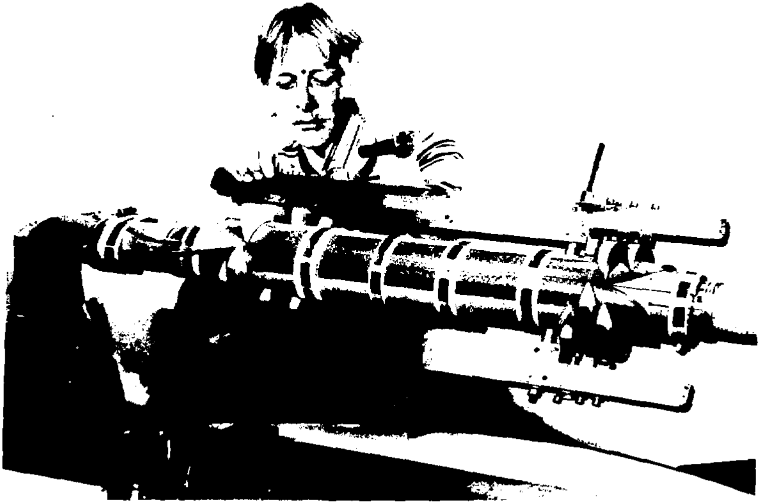

FIG. 16. A D-7B 76-mm-bore dipole magnet that has two layers of 23-strand superconducting cable is being wound in the fixture developed for the new epoxy-free winding method. (BBC 808 9604)

the magnet test facilities were upgraded from 3000 to 7000 A and the CTI-1400 refrigerator is being replaced by a 400-W (at 4.2°K) CCI unit which will increase the cooling available at 1.8°K from 5 to 30 W. A new horizontal cryostat is being fabricated to connect to the 1.8°K superfluid system to permit testing of large magnets with iron flux return and with horizontal magnetic-field measuring coils.

Other activities begun during the year and still continuing include:

- Short-sample measurements, mechanical tests, and construction of test magnets using 23-strand cable.
- Development, in cooperation with industry, of the first 27-strand cable made in the United States. Wider cable is needed for multilayer high-field magnets.

- Tests on "bronze-process" Nb_3Sn conductor supplied to us as unreacted 23-strand cable. We reacted this material and measured its short-sample performance to 10 T. Mechanical tests revealed low compressive strength, which may make the material unsuitable for use in a simple layer-wound dipole magnet; therefore, we are investigating alternative magnet designs and methods of reinforcing the windings.

Accelerator Theory

Although the completion of PEP, the beam-cooling experiments at Fermilab, and the advancement of superconducting magnet technology were proud experimental accomplishments for the Advanced Accelerator Studies Group, theoretical advances were often vital to the success of these activities, and, perhaps more importantly, they form the cornerstone for future experiments. In addition to the topics discussed in this section, the following theoretical subjects are discussed in the "Heavy Ion Fusion" section of this report:

- Final focusing
- Electrostatic quadrupoles
- Longitudinal stability
- Transverse-longitudinal coupling
- Beam break-up mode.

Proton-Antiproton Collider Activities

Work is underway at Fermilab to build a complete ring of superconducting magnets in the main-ring tunnel plus refrigeration and rf equipment adequate for sustained operation of the ring at a peak energy of 500 GeV. As a next step in boosting energy, the Tevatron Phase I project has the goal of providing sustained operation of the superconducting magnet ring at 1 TeV (1000 GeV) and proton-antiproton colliding beams at up to 2 TeV (center of mass) with a luminosity of 10^{30} cm^{-2} s^{-1}. The LBL Accelerator Theory Group is participating in the Fermilab project in three ways:

- Consultation on beamline designs,
- Study of alternative lattices for the superconducting Tevatron,
- Design of the precooler/decelerator/accelerator ring.

The proposed Tevatron must function both as an accelerator and a colliding-beam storage ring; yet, it is constrained by the geometry of the conventional-magnet main ring that was designed purely as an accelerator. The design problem that results from this constraint primarily concerns the long straight sections, especially those to be used for the collisions. To overcome this problem, two alternative lattice schemes were proposed that differ qualitatively from those proposed previously by other investigators. The first, worked out in detail, is a ring with two low-β long straight sections for collisions and four relatively high-β straight sections.[3] All insertions are matched to the normal cells both in beta function and dispersion, unlike either the conventional main ring or previous designs. The low-beta sections have $\beta^* = 1.5$ m and dispersion of 0.5 m at the center of the 24.5-m-long interaction regions. The high-beta straight sections are similar to those in the main ring. The second scheme proposes a way to make Tevatron insertions symmetric (FDLDF) even though those of the main ring are antisymmetric (FDLFD).[4] This is done by reversing the polarity of the quadrupoles in the intervening areas.

LBL theorists devoted a great amount of effort to the design of the precooler ring. Antiprotons from the target will be injected into this ring at 4.5 GeV and stochastically cooled in momentum, decelerated to 200 MeV for transfer to the electron cooling ring, cooled and accumulated there, then accelerated in the precooler to 8 GeV and injected into the main ring. An alternative scheme replaces the electron cooling accumulator with a stochastic cooling accumulator.

LBL work on the precooler ring has included four phases:

- Collaboration in the design of a ring using magnets from the Zero Gradient Synchrotron.
- Design of a comparatively strong focusing ring that has four zero-dispersion straight sections.[5]
- Design of rings with variable transition energy. This feature would be especially useful with boxcar-style injection near transition, followed by cooling after the transition energy had been shifted.
- Design of a ring, likely to be adopted, with two zero-dispersion straight sections and two nonzero-dispersion straight sections, each with 20-m clear space. This configuration is suitable for injection, extraction, and momentum and transverse cooling. Orbit properties such as tunes, maximum beta values, chromaticity, and transition energy appear quite favorable.

Stochastic Cooling

Stochastic cooling is an essential feature of proton accumulation schemes for high-energy physics experiments (see "Beam Cooling"). In addition, cooling systems may significantly increase the lifetime of stored particle beams. The theoretical effort in stochastic cooling has focused both on extending the understanding of the stochastic cooling process for coasting and bunched beams, and on designing practical systems for proton accumulation.

The basic theoretical description of stochastic cooling is in terms of a Fokker-Planck equation, which includes both multiple particle effects and amplifier noise, and signal suppression factors that are directly related to the dispersion integrals of beam instabilities. From this basic framework moment equations have been written that include the effects of finite notch filter depth and provide simple formulas to aid in the design process. The Fokker-Planck equation has been rewritten in a form which emphasizes the interrelation between Schottky noise and signal suppression and more directly addresses the limitations on the magnitude and frequency domain shape of the system transfer functions. Simple criteria have been developed to optimize cooling rates and avoid instabilities.

The cooling of bunched particle beams would provide additional flexibility in designing accumulation scenarios. For example, continuous cooling and deceleration may lead to faster cooling than sequential methods.

An LBL computer simulation addresses the difficulties encountered in understanding system feedback effects, which are analagous to those found in bunched beam instability theory. It appears that spread in synchrotron frequency for bunches is the analogous mixing mechanism to revolution frequency spread for coasting beams. In the simulation, a perfectly harmonic bucket does not sustain cooling after times of the order of a synchrotron period. However, the natural nonlinearity of the usual rf bucket allows cooling to proceed past one synchrotron period. Various nonlinear forces have been included in the simulation and are currently being studied.

In parallel with the simulation effort, a theoretical formulation of bunched beam cooling is underway. The basic Schottky spectrum as sampled by cooling particles has been analyzed. The feedback or signal suppression effect is more complicated for bunches since finite length effects couple coherent modes. Some methods from finite plasma theory appear to be useful in understanding this phenomenon.

Single-Pass Collider Studies

A computer simulation to study beam-beam interaction for the SLAC Single-Pass Collider was developed.[6] The collision of an intense bunch of electrons with an intense bunch of positrons was simulated using a macroparticle code in which the interaction between each two macroparticles is calculated directly. The simulation reveals the pinch effect of one bunch upon the other, the luminosity enhancement that results from the pinch effect, the attraction between offset bunches, and the large opening angles of particles in the disrupted bunches. Finally, the effects of synchrotron radiation emitted during the collision are simulated.

The particle simulation code was used along with envelope theory in a study to facilitate parameter choices that maximize luminosity and minimize bunch disruption and detector background.[7] We first considered hypothetical infinite streams of counterrotating electrons and positrons, which would focus one another through space-charge focusing if the proper radius is selected. If collider bunches were to meet with the same linear density and radius as these infinite equilibrium streams, they might maintain this radius during the collision and suffer no disruption. This cannot be achieved perfectly, however, because all particles do not first enter the opposing bunch at the same longitudinal position. By scaling, however, we were able to reduce the five intrinsic variables to only two dimensionless phase advances and still treat all possible collisions. A series of computer runs verified the scaling and showed that luminosity is greatest and bunch disruption least at a certain ratio of the two dimensionless quantities.

Cited References

1. K. Halbach, "Physical and Optical Properties of Rare-Earth Cobalt Magnets", Nucl. Instr. and Meth. (in press).
2. K. Halbach, IEEE Trans. Nucl. Sci. NS-26, 3882 (1979).
3. A. A. Garren, Tevatron Lattice with Partly Symmetrical Low β Long Straight Sections, FNAL P-note 65 (April 1980).
4. A. A. Garren, Symmetric Long Straight Sections for the Doubler, FNAL P-note 63 (April 1980).
5. Tevatron Phase I Design Report, Fermi National Accelerator Laboratory (Feb. 1980).
6. R. C. Sah, "A Beam-Beam Simulation for the Single-Pass Collider," Proc. of the 11th Int. Conf. High-Energy Accelerators, Geneva, Switzerland, July 7-11, 1980, pp. 736-740.
7. A. A. Garren, "Choice of Bunch Parameters in Single-Pass Colliders," Proc. of the 11th Int. Conf. High-Energy Accelerators, Geneva, Switzerland, July 7-11, 1980, p. 725.

MAGNETIC FUSION ENERGY

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MAGNETIC FUSION ENERGY

The Magnetic Fusion Energy Program at LBL is devoted primarily to the research and technological development of neutral beam 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, aimed at a better understanding of the atomic physics, plasma characteristics, and general theory of neutral beams. In addition, we are actively researching basic plasma theory by developing and applying modern mathematical techniques to plasma physics problems. In pursuit of these activities during FY80, we

- Obtained a 0.5-A, low-energy, steady-state H^- beam from a surface-production source.

- Operated three TFTR-type injector modules at 120 kV on the Neutral Beam System Test Facility (NBSTF).

- Operated a fractional-area advanced positive-ion source at 90 kV with 5-s pulses (pulse length limited by test facility).

- Upgraded Test Stand IIIA to 150-kV, 15-A, 5-s capability.

- Developed a successful technique for the brazing of large ceramic insulators required for injectors in reactor-like environments.

- Developed a plasma-source computational model that is consistent with experimental observations.

- Discovered a method for integrating Hamiltonian systems through resonance regions, in which perturbation theory breaks down.

- Developed a theory to predict backscattering of 100-eV to several-keV hydrogen nuclei from alkali-metal surfaces as negative ions and performed an experiment that supports the theory.

Neutral Beam Development

The concept underlying present neutral beam activities at LBL and elsewhere is the production, acceleration, and neutralization of positive hydrogen and deuterium ions for injection into a confining magnetic field device. Figure 17--a schematic of the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory--illustrates this concept. Initial work, which began ten years ago, was directed toward developing neutral beam currents of hundreds of amperes at 20 keV, in 20-ms pulses. For the new magnetic fusion experiments about to start at Lawrence Livermore National Laboratory (LLNL), Princeton Plasma Physics Laboratory (PPPL), and General

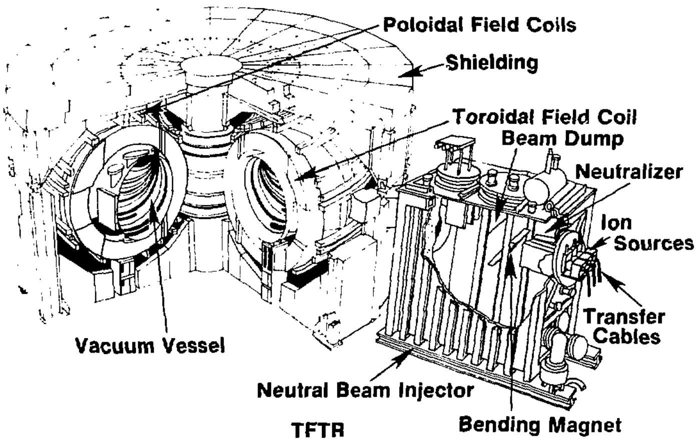

FIG. 17. A schematic of one of the four neutral beam injectors developed at LBL for the Tokamak Fusion Test Reactor. Electric power enters the ion sources, which consist of a plasma source and accelerator. The resulting high-power ion beam then moves (right to left) through a rectangular gas-filled "neutralizer" where some ions are converted to neutral atoms of the same speed. The remaining ions are deflected upward by a bending magnet and stopped on water-cooled beam dumps. The neutral beam injector box is lined with cryopanels at liquid-helium temperature, to pump the slow deuterium gas emerging from the neutralizer. (XBL 787-9619)

Atomic Co., our research is directed to higher energies (80 to 120 keV) and longer pulse lengths (0.5 to 1.5 s). During the past year we have devoted a substantial part of our research to yet higher energies (80 to 170 keV) and longer 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. Each step in energy and pulse length has required additional atomic and plasma physics research, as well as substantial advances in such technologies as high-power electronics, heat transfer, and brazing of metals to ceramics.

Starting in the 1990s, mirror-machine and tokamak experiments that will use neutral beams with energies above 170 keV are planned. Although the efficiencies of positive-ion-based neutral beams are unacceptably low at such energies, negative-ion-based beams appear to be useful at arbitrarily high energies. Consequently, we are developing negative-ion sources and accelerator concepts to meet the needs of this next generation of experiments.

Our research activities require the operation and improvement of large test facilities. Our most ambitious project is the Neutral Beam Engineering Test Facility (NBETF). It is a substantial upgrade of our present largest facility, the Neutral Beam System Test Facility (NBSTF), now operated for the Princeton Plasma Physics Laboratory, and will be fully operational in April 1983. Some of the parameters of the NBSTF and NBETF are given in Table 7.

TABLE 7. 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 mid-1983.

Parameter	NBSTF	NBETF		
Accelerator Voltage (kV)	120	170[a]	150	120
Accelerator Supply Drain (A)	80	65	65	80
Pulse Length (s)[b]	1.5	30	30	30
Duty Factor (%)	1	10	10	10
Arc Supply (V/A)	70/4000	80/3000		160/1500
Filament Supply (V/A)	18/6000	18/6000		

[a]Variable from 10 to 170 kV.

[b]Maximum at indicated currents.

Positive-Ion Beam Research

Our primary near-term program is directed to the development of advanced ion sources and systems suitable for current magnetic fusion experiments. During FY80, we completed initial testing of the large R&D neutral beam sources for the TFTR (Fig. 17) and for the Doublet III. The performance characteristics of these sources are shown in Table 8. We are continuing to test these sources to demonstrate their performance at longer pulse durations. In addition, we nearly completed the fabrication (but not the assembly and alignment) of a large advanced positive-ion source, gapped for the MFTF-B mirror-machine experiment at LLNL. When completed in FY81, this water-cooled source will be capable of accelerating a 50-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

TABLE 8. Performance requirements for large R&D neutral beam sources.

Parameter	TFTR	Doublet III
Gas	D_2	H_2
Energy (keV)	120	80
Current (A)	65	77
Pulse Length (s)	0.02	0.025
Divergence (1/e halfwidths)	0.95 x 0.32	1.3 x 0.5
Composition ($D^+:D_2^+:D_3^+$ or $H^+:H_2^+:H_3^+$)	78:18:4	60:28:12
Plasma source	Large "bucket"	"Field-free"

with this philosophy, we completed and began testing a fractional-area (7 x 10 cm beam cross section) water-cooled accelerator. When completed, these tests will verify the concepts employed in the 10 x 40 cm source being built for the MFTF-B. By year's end, this accelerator had reached 90 keV for a 5-s pulse of deuterium. Heat loads were carefully measured by water-flow calorimetry and found to be comfortably small. Each of four sets of electrodes, all at different potentials, received only a few tenths of one percent of the beam power. A reasonable extrapolation indicates that the heat loads at 120 keV will be well within the cooling capability of the hollow water-cooled molybdenum rails of the accelerator (Fig. 18).

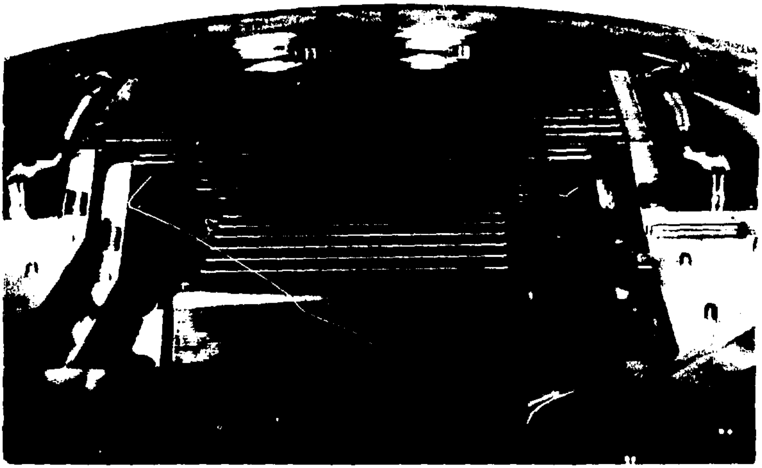

FIG. 18. The fractional-area (7 x 10 cm beam cross section) water-cooled accelerator, built to test the concepts employed in the 10 x 40 cm source being built for the MFTF-B. The acceleration "rails" are specially shaped hollow molybdenum tubes, individually sprung and water-cooled. (CBB 790-14496)

For many fusion applications, it is desirable to produce an essentially monoenergetic beam of neutral atoms because 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. The slower atoms tend to heat the surface, which is undesirable. One of our highest priority goals is, therefore, to develop ion sources that produce nearly pure D^+ beams, with only a small component of D_2^+ and D_3^+ 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. To test this hypothesis, we built and operated a large "magnetic bucket" plasma source and put rows of permanent magnets on the walls to improve the electron and ion confinement. This source, operated with a modified TFTR accelerator structure, produced a 120-keV, 65-A beam of deuterium ions, in which the D^+ fraction was 78%. This is the highest D^+ fraction that we have ever achieved with a full-size source, but it still falls short of our goal of 85% D^+. Therefore, we are pursuing several new ideas to further improve the D^+ fraction and are also working to improve the reliability of these sources.

In other developments, we designed and constructed, but did not assemble, an optimized fractional-area, 120-keV accelerator that has only three electrode sets, not the four electrode sets that our accelerators for this energy normally have. In collaboration with LLNL, we developed a new inexpensive technique for producing the shaped hollow molybdenum electrodes needed for the water-cooled sources (see Fig. 18). All test stands were upgraded toward higher energies and longer pulse lengths.

In June 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 is contributing to this project, in part by supporting our conceptual beamline design study and a competitive study by researchers at the Oak Ridge National Laboratory. The injection requirements for ZEPHYR are similar to those of the next generation of U.S. experiments (e.g. the Fusion Engineering Device Tokamak), so this design effort complements some work in the U.S. fusion program. A schematic of the proposed injector, including a new kind of reflection magnet, is given in Fig. 19.

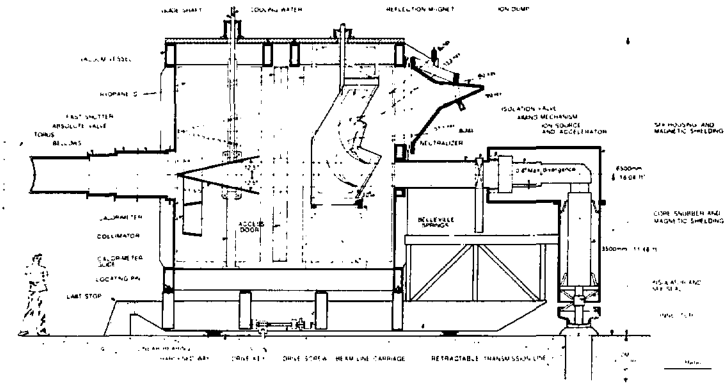

FIG. 19. Schematic of the ZEPHYR beamline. (XBL 813-8482)

Negative-Ion Beam Research

Future fusion experiments and reactors may require the injection of very energetic neutral beams to heat large-diameter, high-density plasmas. At high energies 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 (Fig. 20). For tandem mirror machines, the use of monoenergetic beams in the end plugs can increase the Q-value significantly. Very-high-energy neutral beams (0.5 to 1.0 MeV/amu) based on negative ions may be used for driving currents in tokamaks, thereby providing a mechanism for obtaining steady-state operation. Therefore, the LBL neutral-beam R&D program includes the development of efficient, long-pulse (dc) negative-ion-based neutral beam systems.

Prior to FY80, our joint effort with LLNL was geared to generating negative ions by conversion of low-energy positive ions to negative ions by means of double-charge-exchange reactions in a metal-vapor cell (Fig. 21). This program was completed during the year, and the potential of this approach is being analyzed.

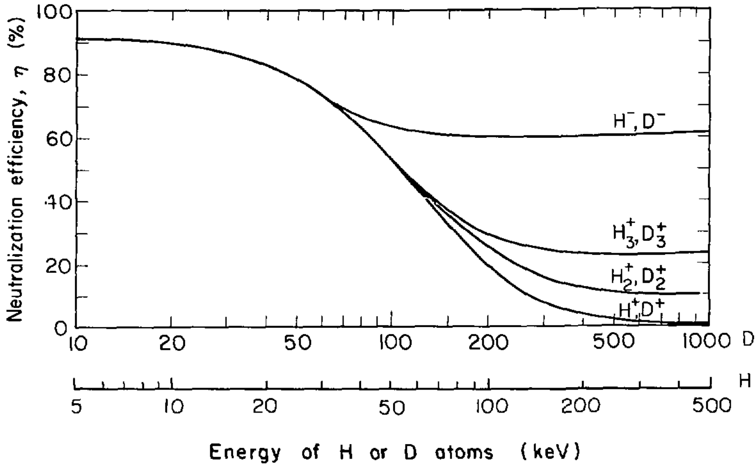

FIG. 20. Neutralization efficiency vs energy shows that positive ion beams are far less efficient than negative ion beams at energies above about 100 keV. (XBL 751-2059)

The accomplishments of this program include:

- More than 2 A of D^- at 10 keV were obtained.
- The angular divergence is excellent (0.75° x 2.75°).
- The sodium jet was measured to be highly directional, as was calculated for the design.
- The loss of sodium downstream was measured to be 2×10^{-11} g/cm^2-s in the idle mode (system hot, jet off), and 9×10^{-8} g/cm^2-s with the jet on. Spectroscopy indicates a sodium density in the beam channel of 10^9 cm^{-3} (3×10^{-7} torr).
- Gas loads, which agree with those calculated, are shielded from an accelerator by the sodium vapor and can be pumped.
- In our previous experiment with cesium, 100 mA of D^- was accelerated to 60 keV, demonstrating electron control.
- We have an accelerator design for our present beam which could easily be extended to higher current beams.

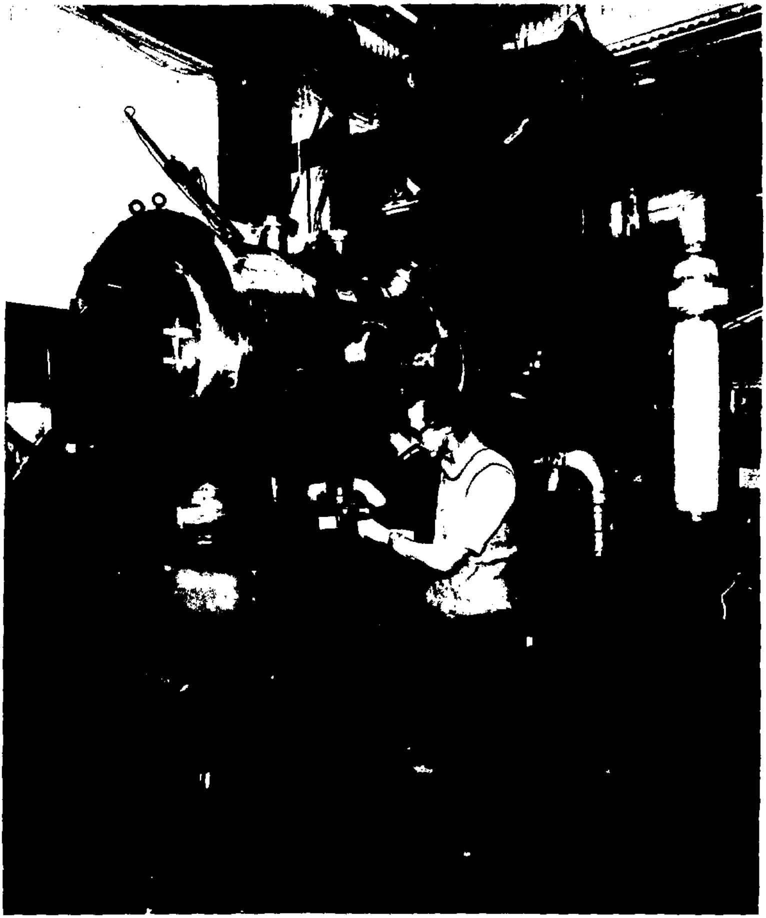

FIG. 21. The double-charge-exchange experimental assembly. A standard LBL 50-A, 20-kV positive-ion source (not visible in the figure) is operated in the 5- to 10-kV range to produce a 10-ms beam of about 26 A at 10 kV. The beam passes (from right to left) through a supersonic sodium jet mounted inside the rectangular, stainless-steel vessel. The negative beam emerges and passes into the cylindrical beam-dump tank, which has a calorimeter and ports for the many diagnostics. (CBB-793-4076)

The program produced enough data with both cesium and sodium metal vapors that we can calculate and confidently extrapolate our results to other charge-exchange media. A detailed report and manuscript for publication are in preparation.[1] The reports will include analysis of charge-exchange systems in general, considering all media, to provide a guide for future work.

With the conclusion of the double-charge-exchange experiment, we have shifted our effort to investigate the operation of an ion source geometry to produce continuous or long pulses of self-extracted, surface-produced negative ion beams at modest current densities. Because the useful current density will not be high (~50 mA/cm^2), large exit apertures will be required to obtain the multiampere beams desired, and this, in turn, means that the source operating pressure must be low. The basic source geometry was devised with this requirement in mind, and for all tests thus far source pressure has been limited to 1 mtorr or less.

Figure 22 shows the geometry of the new >1-A negative-ion source, which is conceptually similar to its predecessor—a cylindrically shaped, multiline cusp geometry with magnets placed on all sides. In the exit aperture region where the negative ions are to self-extract, the magnet spacing is increased so that the magnetic field is high enough to confine all energetic electrons, yet weak enough not to seriously perturb the trajectories of the emitted energetic negative ions. The tungsten filaments are the cathodes for the discharge, and the entire outer wall is the anode. Electrons leave the plasma only at the cusp points of the magnetic configuration.

To produce negative ions, the converter is biased negative to the potential of the plasma by several hundred volts. Positive ions from the plasma strike the converter surface with this potential. Any negative ions produced are then accelerated back through the plasma sheath that forms at the converter by the same potential, and they pass through the plasma and the exit aperture. This self-extraction feature is desirable because no external extraction electric fields are needed and the beam is not contaminated with large numbers of electrons.

To increase negative ion production, the converter area is increased by making the converter longer than the extraction aperture. The converter is curved to geometrically focus the ions at the aperture.

In tests of the first such ion source, the production of negative ions increased when alkali metals were added to the discharge—by a factor of 10 over the yield of a plain copper converter when lithium was added, by 50 when

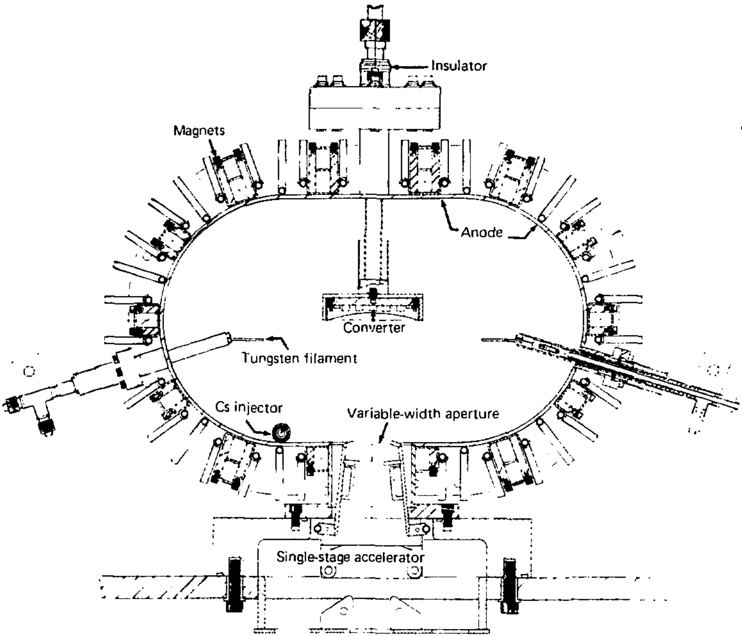

FIG. 22. Cross-sectional drawing of the 1- to 2-A source for accelerating an H^- ion beam to an energy of ~50 keV with pulse lengths from 5 s to steady state. To provide uniform plasma illumination of the converter surface, feedthroughs for eight 0.15-cm-diam tungsten filaments are located four at the top and four at the bottom of the chamber. Initially, cesium from an oven will be sprayed into the discharge through a single, resistance-heated coaxial tube located below the ion exit slit, which is electrically isolated and mechanically adjustable from 3 cm to nearly closed--narrow enough to reduce the gas flow rate without impeding optically useful negative ions. (XBL 808-11259)

sodium was added, and by 100 when cesium was introduced. Moreover, the experimentally observed narrowing of the energy spectrum when cesium is introduced suggests that the negative ion production mechanism changes.

We built a gridded Faraday cup with which to read the total negative ion current. This unit also incorporates a small, permanent-magnet mass spectrometer for determining the percentage of high-Z impurity negative ions that are produced. Upon initial startup with a new conve-' ' the impurity content in the beam is quite high (~75%). The source is operated until the impurity content drops well below the H^- level, and then cesium is introduced from a valve-controlled oven through a heated tube to the discharge. The H^- current increases greatly, but the impurity level does not increase. Thus, the impurity content of the beam is a strong function of the amount of discharge cleaning that the system exeriences, and it decreases with time. We generally see impurity content less than 1%.

We investigated several converter materials, particularly those with high Z which might resist sputtering. Although we found rhenium, uranium, and tungsten to be useful, molybdenum seems to be the most productive, reproducible, and practical converter material. In general, with proper cesium coverage, optimum converter potential is about 200 V.

With tne small test source, stable H^- beam currents of 450 mA and an impurity content of less than 1% were obtained with dc operation. This source has a curved 6 x 10 cm molybdenum converter electrode and operates with a plasma density of about 10^{12} cm^{-3}.

The program goals, as established by the review panel of the recently convened Negative Ion Program Review, are to accelerate an H^- ion beam of >1 A to an energy of ~50 keV with pulse lengths from 5 s to steady state. To meet these goals, we are constructing the larger source (Fig. 22), accelerator, and vacuum system. The vacuum system will be pumped by two turbomolecular pumps and two auxiliary liquid-helium cryopumps (~12,000 l/s each). The new ion source is designed to be scalable in both directions to obtain larger negative ion currents than are possible from the single converter shown. By increasing the vertical height and maintaining the magnet spacing for the single exit aperture, add tional ion exit apertures could be added, along with additional converter electrodes, which would be placed above and below the single one shown. The test stand that was used early in the year for the double-charge-exchange experiment (Fig. 21) has been completely dismantled and is being rebuilt to accept the new surface-production source.

Neutral Beam Test Stand Fabrication and 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 injector testing at LBL. Test Stand IIIA (TS IIIA) is for beams up to 150 kV, 15 A, and 5 s at 5% duty factor and is used for the development of fractional-area modules, which are tested before larger, more expensive structures are built. TS IIIA was commissioned for 5-s operation during FY80. A cryopump system, with a hydrogen pumping speed of about 500,000 l/s, was brought on line for the long-pulse development. Local neutron shielding around the beam dump is provided to allow operation with deuterium beams.

Larger injector modules are tested for voltage-holding and beam optics on TS IIIB (120 kV, 65 A, 30 ms, 1% duty factor). The pulse length is limited by the capacitor-bank power supply. During the year, TS IIIB was used to develop a new plasma source with higher atomic fractions in the beam, and to qualify the 80-kV, 80-A injector for the Doublet III tokamak.

The largest neutral beam facility at LBL is the Neutral Beam System Test Facility (NBSTF--120 kV, 65 A, 0.5 s, 1% duty factor) built by the Engineering and Technical Services Division as a prototype of the beamline for the TFTR. Operation of the NBSTF was transferred to the Accelerator and Fusion Research Division in mid-1980. Source operation at the design parameters was achieved with several TFTR accelerators, and preliminary measurements to check the overall beamline performance were made. Components to upgrade the facility to 1.5-s-pulse capability in FY81 were fabricated. Because of the high power in the beam (~8 MW), an extensive diagnostic system is required. A portion of the NBSTF operator's console is shown in Fig. 23.

FIG. 23. Operator's console of the Neutral Beam System Test ac,lity, operation of which was transferred to the Accelerator and Fusion Research Division in FY80. (CBB 791-581)

Neutral Beam Atomic Physics Studies

The development of neutral beam systems is, in part, based on a knowledge of atomic physics processes. During FY80 we investigated

- Production of negative hydrogen ions in gases, 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, starting with ~10-keV positive ions. Theoretical considerations indicate that strontium may give the highest yield, and we have begun experimental studies to verify this. We are also investigating calcium, barium, and rubidium.

We concluded initial studies [illegible] duction of negative ions by backscattering of positive ions [illegible] aces. A theoretical model was developed for thick alkali metals and for nickel and other surfaces with thin alkali-metal coatings. Test results for normal incidence of hydrogen nuclei with energies of 100 eV to a few keV agreed well with the theoretical predictions.

Our first experiment on interactions of a 250-keV D^- beam with a partially ionized hydrogen plasma was completed. As shown in Fig. 20, high-energy negative hydrogen ions can be converted to uncharged atoms in an optimized gas target with an efficiency of about 60%. From experiments with crossed e^--H^- beams we can infer neutralization efficiencies of 80% to 90% in fully-ionized plasma targets. Our experiment used a pulsed hydrogen discharge as the target. The percentage ionization varied up to a peak of 50%, and calculated and experimental results agreed reasonably well (±25%).

Neutral Beam Plasma Research

We are conducting research to understand better 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.

We completed an experimental, parametric study of a "bucket" source plasma. We extended the plasma source model to include plasma sources of the type now being developed and obtained good agreement with experimental data (ion current density, beam composition, and electron temperature, all as functions of arc power and gas flow). We used the source model to evaluate five different proposed variations of a standard "bucket" source to determine the most promising approach for optimizing the D^+ fraction. The variations, with the calculated D^+ fractions, are shown in Table 9. Recommendations based on this study are being included in the current planning of the neutral beam development program.

As part of the experimental study of neutralizer physics, we measured the electron temperature and ion density in the neutralizer plasma on Test Stand IIA (both at the wall and in between the beamlets) for various gas flow rates and beam energies. These measurements were compared with a theory developed in the Plasma Theory program. We concluded that there appears to be anomalous heating of the electrons in the neutralizer plasma by the beam, and we are working to understand this anomaly.

TABLE 9. Variations in calculated D^+ fraction from a parametric study of "bucket" source plasmas.

Variation	Calculated D^+ Fraction (%)
None (reference design)	76 (same as measured)
Predissociate the D_2	77
Inject 16-eV electrons to enhance D_2 dissociation	83
Heat all walls except the front to enchance D_2 dissociation	94

Neutral Beam Theory

We developed a theoretical model to describe the plasma in the neutralizer of a positive ion beam. Using a free-fall ion confinement model, a relationship was found between plasma ion current density and beam current density which suggests that an experimental measurement of plasma ion current density as a function of beam volume at various points along the neutralizer can be developed as a neutral gas diagnostic. An experimental program has begun to develop a Langmuir probe diagnostic of the neutralizer plasma.

Basic Plasma Theory

We are studying stochastic or chaotic behavior in nonlinear dynamical systems.[2] Much of the work concentrates on Hamiltonian systems, but some of the techniques have wide application to answering fundamental questions about the stochastic properties of dynamical systems. We discovered a method for integrating Hamiltonian systems through resonance regions. Perturbation theory breaks down in precisely this domain; hence, our method will permit us to connect regimes where perturbation theory is adequate.

The essence of the idea can be explained in the context of the following Hamiltonian

$$H(\underset{\sim}{I},\underset{\sim}{\theta},t) = H_0(\underset{\sim}{I},t) + \varepsilon \sum_{\underset{\sim}{\ell}\neq 0} h(\underset{\sim}{\ell},\underset{\sim}{I}) \cos \underset{\sim}{\ell}\cdot\underset{\sim}{\theta}$$

in action angle variable. $\underset{\sim}{\ell}$ is an N-vector of integers; ε is small. The equations of motion

$$\underset{\sim}{I} = \varepsilon \sum_{\underset{\sim}{\ell}} \underset{\sim}{\ell}\, h(\underset{\sim}{\ell},I) \sin \underset{\sim}{\ell}\cdot\underset{\sim}{\theta}$$

$$\underset{\sim}{\theta} = \underset{\sim}{w}(I,t) + \varepsilon \sum_{\underset{\sim}{\ell}} \frac{\partial h}{\partial \underset{\sim}{I}} (\underset{\sim}{\ell},\underset{\sim}{I}) \cos \underset{\sim}{\ell}\cdot\underset{\sim}{\theta} ,$$

with

$$\underset{\sim}{w}(\underset{\sim}{I},t) = \partial H_0(\underset{\sim}{I},t)/\partial \underset{\sim}{I},$$

change their character at times t_j when $\underset{\sim}{\ell}\cdot\dot{\underset{\sim}{\theta}}(t_j) = 0$; that is, at resonances. Perturbation theory in ε breaks down, and $\underset{\sim}{I}(t)$ calculated as a power series in ε becomes secular. We observe, however, that near t_j, $\underset{\sim}{\ell}\cdot\ddot{\underset{\sim}{\theta}}(t_j) \neq 0$ in general. Expanding, near $t = t_j$,

$$\underset{\sim}{\ell}\cdot\underset{\sim}{\theta}(t) = \underset{\sim}{\ell}\cdot\underset{\sim}{\theta}(t_j) + \frac{1}{2}(t - t_j)^2\, \underset{\sim}{\ell}\cdot\ddot{\underset{\sim}{\theta}}(t_j) + \ldots$$

The equation for $\underset{\sim}{I}(t)$ is now expressible in terms of Fresnel integrals, is never secular, and has no small denominator problem.

We are also studying finite-Larmor-radius corrections to magnetohydrodynamic theory for the geometry of a field-reversed-mirror, near the vortex. A full Vlasov model for the plasma is used.

TFTR Support

In addition to our research activities in support of neutral beam technology, LBL is supplying critical components for the neutral beam injectors of the TFTR at the Princeton Plasma Physics Laboratory. The designs for these components stem from the development of the prototype beam line of the Neutral Beam Test Facility, now in operation at LBL. These activities were carried out by the Engineering and Technical Services Division. Three TFTR support activities progressed during FY80:

- Thirty of the 42 copper chevron panels for the cryogenic pumping systems were manufactured and shipped.
- Four ion deflection magnets for the beam dumps—along with stands, scrapers, lifting fixture, and spare coils—were delivered.
- One of four helium dewars was delivered. (This activity also included LBL's development of a remotely controlled multifunction diverter valve.)

The above activities will all be completed by the end of FY81. Two new activities—the fabrication of four 1.5-s ion beam dumps and nine ion sources for the TFTR—are scheduled for completion in FY82.

Cited References

1. E. B. Hooper, Jr., P. Poulsen, and O. A. Anderson, "Optimized System for D^- Production from Charge Exchange in Alkali Metals," submitted to Nuclear Fusion.
2. H. D. I. Abarbanel, C. Grebogi, and A. N. Kaufman, Multiple Resonance Crossing in the Eikonal Model of Plasma Turbulence, presented at 22nd Annual Meeting, Division of Plasma Physics, November 10-14, 1980, San Diego. Also Lawrence Berkeley Laboratory Report No. LBL-11217-4.

HEAVY
ION
FUSION

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HEAVY ION FUSION

Work continued during FY80 in the Heavy Ion Fusion Group toward a better understanding of the physics of high-intensity heavy-ion accelerators to assess their promise as ignitors for inertial fusion systems. Major accomplishments during the year include:

- Operation of the large-aperture Cs^{+1} contact-ionization source. The full system--source plus three drift tubes--began operation early in April 1980. Beam profiles and current measurements indicate that the system performs close to design specifications.

- Study of multiple-beam systems, in addition to single-beam systems.

- Development of beam diagnostic techniques, especially resonant laser scattering, electron beam probes, and scintillator systems.

- Development of a Zeolite source, with major emphasis on source stability and lifetime.

- Design and construction of an electrostatic quadrupole array capable of handling 49 parallel beams.

- Development of a model for the longitudinal resistive wall instability, which indicates that an induction linac beam should be stable to the first order in resistance.

- Theoretical development of the transport of space-charge-dominated beams through periodic focusing structures.

These developments are discussed in the sections below. Additional details can be found in Refs. 1, 2, and 3.

High-Current Cesium-Ion-Beam Experiment

During FY80 we continued development of the large-aperture Cs^{+1} injector and used it in various experiments (see the FY79 Annual Report for a complete description of the device). In late 1979, the source and the first pulsed drift tube were operated in conjunction with a diagnostic tank—a Faraday cup, beam profile probe, and a KBr scintillation plate—to provide an optical measure of beam quality. Experiments with 1-A, 6-μs pulses of Cs^{+1} ion beams verified that ion current is proportional to $V^{3/2}$ over a wide range of voltage (180 kV to 1 MV, the design maximum) and that the beam envelope corresponds to EGUN[4] calculations for a space-charge-dominated beam.

Other experiments showed that the space charge of the beam could be neutralized by slow secondary electrons generated by a ribbon grid placed in the leading end of the drift tube. The grid intercepted a small fraction of the beam. Thus, transport of considerably more beam through a given structure than in the unneutralized case now seems possible.

A one-dimensional computer simulation and, later, an analytic treatment were used to study the transient behavior of the beam during the first and last 1.5 μsec of the pulse, during which the Child-Langmuir steady-state condition is not satisfied. Two results were obtained:

- Transients in beam energy and current died out in a time on the order of the transit time of a particle in the Child-Langmuir limit (for the actual system with a gap of 0.5 m and 1 MV potential this time is ~1 μs).
- The calculated and observed beam pulses are nearly identical, which indicates that longitudinal forces, especially space charge, determine the beam profile.

In April 1980, operations of the Cs^{+1} injector began with all three drift tubes in place (Fig. 24). In June, movable radial probes were installed at the entrance to all three drift tubes for following the beam envelope through the accelerator. Measurements of the envelope are represented by the vertical bars in the schematic of Fig. 24 and should be compared with the envelope calculated with the EGUN code (shaded region of Fig. 24). The density profile and beam emittance were also studied extensively. At 1 MeV energy, normalized emittance ($\pi\epsilon_n$) was measured at $<2\pi \times 10^{-6}$ m-rad.

Steps were taken to eliminate insulator sparking damage and speed up the voltage conditioning process. One drift tube housing and drift tube insulation support assembly was tested to determine the maximum voltage-

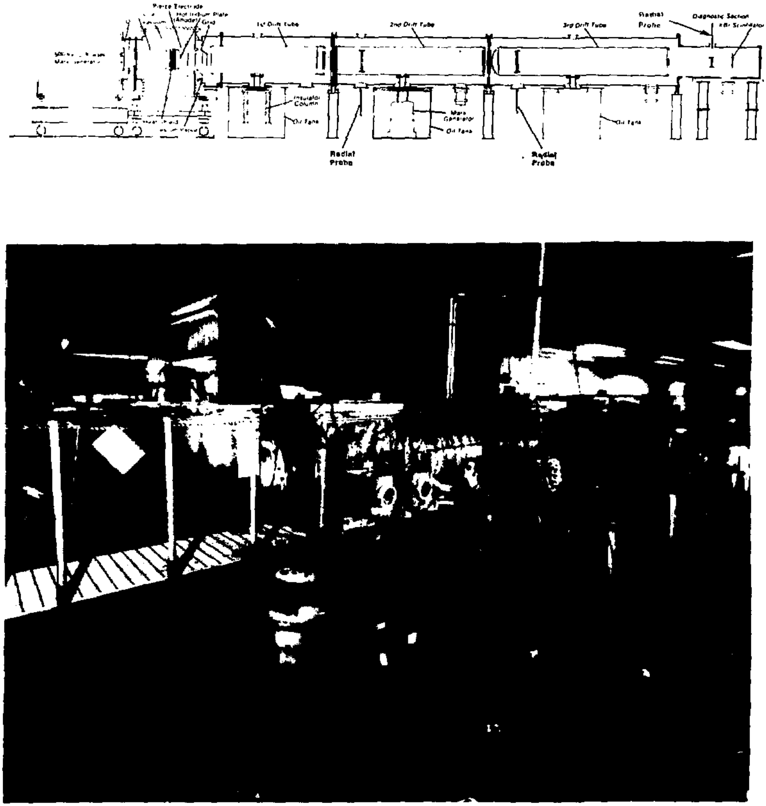

FIG. 24. Schematic and photograph of the complete 1-A Cs^{+1} injector, which began operating in April 1980. The shaded area of the schematic represents the beam envelope calculated using the EGUN code; vertical bars represent measurements. (XBL 8010-12495, CBB 809-11234)

holding capability of the drift tube insulator column. Spark damage to the insulator surface was greatly reduced by adding cylindrical stainless steel insulator shields to both gradient rings. We also found that degassing the insulator column assembly with an argon gas glow discharge speeded up voltage conditioning and greatly reduced both the high-voltage breakdown rate and x-ray production. Argon glow discharge was made a standard procedure. As a final result of the tests, the modified insulator columns can hold 600 kV for >20 μs.

Beam Diagnostic Developments

Beam diagnostic techniques, especially nondestructive ones, are important at every stage in the development of an ion-beam driver. Several different lines are being pursued to provide the program with the necessary tools for rapid accurate diagnosis--laser techniques, electron beam probes, and scintillation techniques.

Laser Diagnostic Techniques

Resonant laser scattering provides a way of measuring the ion velocity distribution in an ion beam in a given direction. By shining the laser light transversely to an ion beam and observing the Doppler broadening (~0.5 Å) of the spontaneous emission at an angle of 90°, the transverse emittance can be measured. Corresponding measurements with the laser shining along or against the beam give the longitudinal energy spread. Thus, the six-dimensional emittance may be measured.

We are studying this technique at our laser diagnostic test facility, which consists of

- A 6-in.-diameter, 2-ft-long vacuum tank evacuated with a turbomolecular pump,
- An ion source that generates a barium ion beam of variable energy up to 20 kV,
- A 100-kW tunable dye laser of 300-ns duration which illuminates the ion beam and excites the valence electron to the first excited level,
- A Fabry-Perot interferometer for measuring the line shape of the resulting spontaneous emission.

Electron Beam Probes

The strong space charge associated with the Cs^{+1} ion beam and the uncertain state of neutralization greatly affect the beam dynamics; therefore, we need better ways to measure the beam space-charge distribution as a function of time. One such technique, which is nondestructive, is based on an electron beam probe. In this scheme, a beam of electrons (1-mm diameter, 1 to 10 μA, 1 to 10 keV) is injected perpendicular to the ion beam at an angle with respect to the center of the beam. The space charge forces in the beam deflect the electrons, and the resulting trajectories vary as a function of initial position, angle, and energy. The electron beam is chopped in time and detected on a standard phosphor, from which both spatial and temporal information can be inferred.

We first developed a computer program to determine the electron trajectories, given the ion-beam and electron-beam parameters, and then we wrote another program to derive the space charge from the experimental data. We also designed and tested an electron gun to probe the Cs beam.

Scintillation Techniques

Scintillation techniques give spatial and temporal information simultaneously and provide easy optical transmission of signals from high-voltage locations. The problem has been to find scintillators characterized by fast response time (<<1 μs), high sensitivity, and good resistance to radiation damage. Several candidates were eliminated, but we are still investigating materials based on CaF_2 (both pure and doped with europium) which seem to have the best combination of properties.

Induction Module Development

Work continued on the design and construction of prototype induction modules and associated pulsers. The pulsers will probably be based on ignitrons because of their low cost compared to thyratrons, but jitter concerns us. We measured the jitter and firing delay of Type-A ignitrons from both English Electric Valve and Varian/National as functions of temperature and igniter voltage. At a tube temperature of 40°C, jitter of less than

100 ns was achieved. We are studying further the required temperature stability and examining tubes with dual igniters from both manufacturers to see if they have less jitter than the single-igniter version that we tested.

We are constructing an ignitron pulser with a lumped-element pulse-forming network to drive a dummy load--two packages of silicon steel toroids made of 2-mil-thick ribbon. Driven in parallel, the packages will receive 39×10^{-3} V-s each. This load will provide a good representation of the electrical behavior of a core for evaluating jitter, delay, and life of the pulser under realistic operating conditions.

Evaluation of Core Materials

Magnetic cores are a central item in the design of an induction accelerator, affecting the design of many other components and strongly influencing total cost. Our ongoing materials study was extended to include toroid samples of amorphous magnetic glass materials produced by Allied Chemical Corporation and TDK Industries. We hope to stimulate the commercialization of such material for use in induction linac cores.

The toroid from Allied Chemical was made of their Metglas 2605 SC in a 1-in.-wide ribbon (the net weight of Metglas was 290 g). At a packing fraction f = 0.77 we measured a magnetization swing %B of 1.44 T (i.e., 1.86 T in the Metglas itself) and a core loss of 400 J/m^3 at a pulse width, t_p = 2 μs. As a core material, Metglas is already cost-competitive with $Ni_{50}Fe_{50}$ alloys, and mass production might lower its cost.

The material from TDK was in the form of tiny test toroids, 31 mm OD and 6 mm high. This material also performed well--%B was 1.5 T at f = 0.9, and core loss was ~400 J/m^3 at t_p = 2 μs.

Zeolite Source Development

We are examining Zeolite ion sources as possible emitters in future induction linacs. Above ~1200°C, Zeolite starts to evaporate and its lifetime is reduced. Nevertheless, we achieved a current density of 100 mA/cm^2 of Cs^{+1} for 5-μs pulses at 0.5 Hz without noticeable decrease in current from pulse to pulse. Thallium and barium ions were also produced. We are continuing lifetime measurements and also measuring ionic conductivity inside the Zeolite.

Induction Linac System Studies

System studies were directed to search for concepts that might reduce the ultimate cost of a fusion driver and permit feasibility testing of small-scale modules. An induction linac design based on multiple beams and combined electrostatic and magnetic focusing emerged as one such concept.

Computer code LIACEP was modified to permit evaluation of the cost of the accelerator section of a magnetically focused driver as a function of the number of beams. We studied a U^{+1}, 3-MJ driver at 1 Hz for 1, 4, 8, and 16 beams and found that at 225 μC charge, an accelerator with 4 beams (each with 1.5×10^{-5} m-rad normalized emittance and 56.2 μC of charge per bore) would cost approximately 30% less than a single-beam accelerator with a normalized emittance of 3×10^{-5} m-rad and 225 μC of charge. Additional savings would show up in the final beam transport for a 4-beam accelerator because the 4-way beam splitter at the end of the accelerator is not required.

We built a multiple quadrupole structure suitable for insertion in the first drift tube of the cesium beam injector. Photographs taken during assembly show the simplicity of this 49-beam device (Fig. 25), which approximately matches the design performance of the original structure (i.e., 1.0-A current at 1.0 MeV, and current scales as $V^{3/2}$). The ratio of quadrupole length to usable aperture is about 30:1. Table 10 gives the expected performance of the structure when combined with a suitable matching system and multiple-aperture gun, which have yet to be designed. The advantages of this structure include:

- A simple design;
- A design concept that can be readily extended (i.e., more beams, higher currents, a longer structure permitting more charge);
- The presence of fields acting as clearing electrodes to eliminate trapped electrons;
- No further interception of the beam after initial beam collimation (in which considerable effective area of the emitting surface is lost).

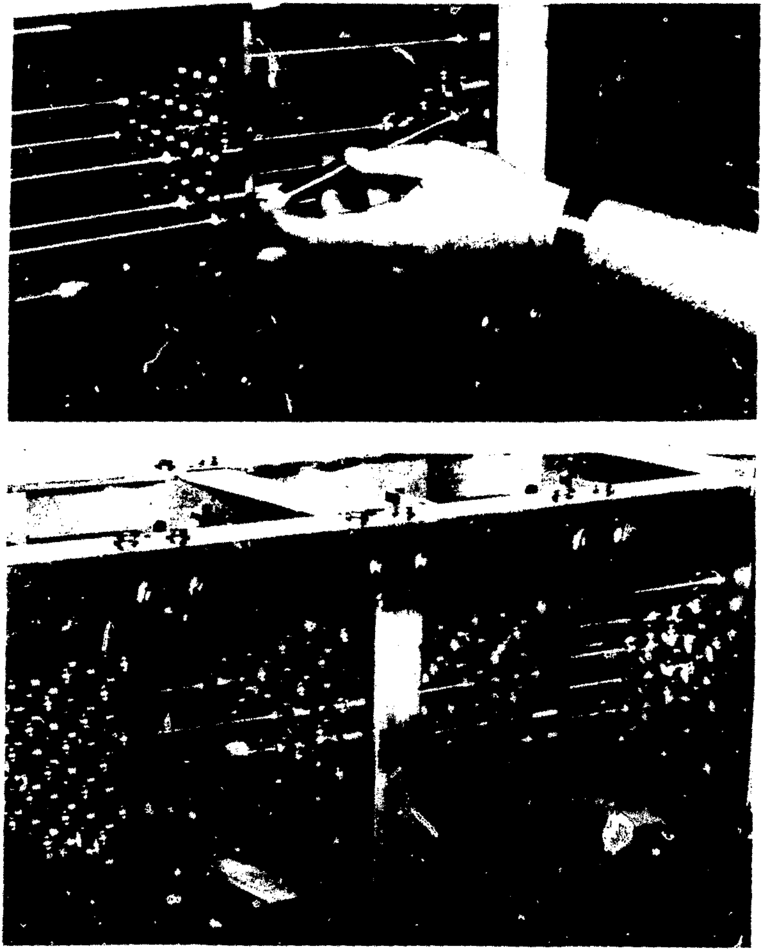

FIG. 25. Assembly of the 49-beam electrostatic quadrupole array. Alternate end plates are at the potentials of the quadrupole elements (short pieces of 1/2-in.-diameter aluminum tubing). The tubes are insulated at one end by a ceramic ball and held in place at the other end by a spring. (CBB 800 12014)

TABLE 10. Design performance of the 49-beam electrostatic quadrupole array *operating in drift tube No. 1 of the cesium-beam injec:·r.*

E (MeV)	β	Beam current[a] (mA)	Voltage (V)	Total current[a] (mA)
0.4	0.00255	5.4	3360	265
0.5	0.00286	7.6	4200	372
0.6	0.00313	10.0	5040	519
0.7	0.00338	12.6	5880	617
0.8	0.00361	15.4	6720	755
0.9	0.00383	18.4	7560	902
1.0	0.00404	21.6	8400	1058

[a]Currents represent space-charge-limited transport with the phase shift for a K-V distribution of 60° to 24°.

In October 1980 a workshop on multiple beams was held at LBL to define the problems and to assess the advantage of multiple-beam drivers in linear induction accelerators. The results of the study are presented in Ref. 3 and summarized below:

- Ion Source. High brightness and current densities will be :.eeded. Pulsed contact ionization sources and pulsed Zeolite sources ⌐hould produce the required ion beams at current densities up to 100 mA/cm^2.

- Electrostatic Focusing. Arrays of possibly several hundred electrostatically focused beams may be economical injectors for the accelerators. Becaus: of the ineffectiveness of electrostatic lenses at high energi⸗s, magnetic quadrupoles would take over at perhaps a few hundred MeV. Alternatively, a new concept proposed by Hogil Kim might provide electrostatic focusing for multiple beams, even at high energy, without having to set aside a large fraction of the accelerator length for focusing.[3] In a single-beam linear induction accelerator, there are gradient rings at the induction modules. In a multiple-beam accelerator, in which many beams pass through each induction module, these gradient rings might be redesigned as "gradient plates" with separate apertures for the individual beams. The new concept is to attach electrodes to the gradient plates so that when the acceleration voltage appears between two adjacent plates, an electrostatic quadrupole field also will be formed between the electrodes mounted on the same two plates.

- Magnetic Focusing. Both single-beam designs using superconducting quadrupole magnets and multiple-beam designs are being investigated to reduce the overall driver cost. Preliminary engineering designs and cost analyses have revealed two difficulties. First, magnetic focusing is relatively ineffective at low beam energies, which makes the injector of a magnetically focused accelerator costly, whether there is one beam or several. Second, the bores of the induction modules increase dramatically in size with more than about four beams, which tends to offset the cost advantages of multiple beams.

- Accelerator Alignment. Quadrupole lens misalignments in an accelerator would create transverse displacements of the beams. If the beam displacements caused by the misalignment of entire arrays of quadrupole lenses can be corrected, then the residual uncorrected beam displacements would stem from the relative misalignments of lenses within the arrays. If these residual beam displacements are left uncorrected, beam radii should be constrained to be no smaller than about 5 mm. Furthermore, the total number of beams should be limited to a maximum of several hundred, if a reasonable size for the beam array is to be maintained.

Theory

Final Focusing

A final focusing array was designed in late 1979 and used to study the transverse behavior of a non-K-V beam in the final focusing process. Because the design required the beam to expand and contract repeatedly, it was unable to overcome the effect of nonlinear space-charge forces. Accordingly, a new array was developed, consisting finally of three triplets, which allows the beam to expand gradually only once before converging on the target. This system is insensitive to variations in current of ±10% and in momentum of ±1%. Ninety percent of the computer-tracked non-K-V beam strikes the target.

Electrostatic Quadrupoles

In connection with proposals for an electrostatically focused accelerator, we are examining electrostatic quadrupoles, in which fields are nonlinear and particle kinetic energy is not constant. In an injector these effects are insignificant; however, at high energies, space-charge fields are comparable to the focusing fields, and beam emittances play only a minor role in determining the matched beam size. In this regime of near cancellation of external and self forces, slight deviations can markedly affect betatron frequencies and beam emittance, which could confuse a comparison of observed emittance growth with theoretical predictions based on a simple model.

To study this regime, EGUN was modified to accommodate a quadrupole geometry and provide an entirely self-consistent solution, including image forces. The code has accurately followed a beam for several periods (90 are proposed) at manageable expense in computer time. A self-inconsistent approach is also being pursued in which the space-charge force is taken as linear, the beam is matched by using the nonlinear external fields at the beam edge, and individual particle orbits are traced through the resulting total fields.

Longitudinal Stability

A serious threat to the induction linac concept is the possible resistive instability in the longitudinal degree of freedom. Energy-efficient acceleration requires a high shunt impedance for the accelerating modules, which implies high induced fields by the beam, which are resistive in nature. A proper solution to the problem requires following a bunch through the accelerator, shock-exciting successive modules in a manner analogous to the transverse beam-breakup phenomenon in an electron linac. So far we have resorted to a simple model in which the impedance of the modules is represented by a pure, steady-state resistance, resulting in a formalism identical with the familiar resistive-wall effect. Applied to circular machines, this model has been proven correct for continuous beams but not for bunched beams, for which approximate solutions predict stability whereas instability is observed.

LBL researchers developed a theory, starting from a bunch without velocity spread (cold beam), that predicts stability for an induction linac bunch in lowest approximation and an acceptably small growth rate in higher approximation.[5] The cold-beam assumption should be good in this situation because the intensity is so high that the velocity of space charge waves is much higher than the differential particle velocities; that is, a disturbance rattles back and forth along the bunch much faster than do the beam particles. The theory is being critically examined, and the search for alternative tractable models continues.

Another model for longitudinal motion has been pursued in which the ions are confined in a square well, which is appropriate to the induction linac. Individual particle motion is highly nonlinear, but in a special way that permits the application of the usual linearized perturbation treatment. The model predicts instability in the presence of a resistive wall when the characteristic oscillation time of particles in the well is of the order of the decay time of the surrounding wall currents. However, the model suggests stability for the anticipated induction linac parameters.

Use of the computer program developed by V. K. Neil and R. Cooper to solve the one-dimensional (longitudinal) Vlasov equation led to predicted unstable behavior for an induction linac in the presence of a resistive wall and parabolic confining well.[6] To check the validity of these results, we developed a one-dimensional simulation program that predicts the correct thresholds and linear growth rates for the resistive wall and negative mass instabilities. We are now examining the nonlinear saturation levels of velocity spread following unstable growth and applying the code to the bunched-beam case.

Transverse-Longitudinal Coupling

For intense beams, both transverse frequencies and the frequencies of longitudinal disturbances are characterized by the plasma frequency, in contrast to the more familiar case of high energy accelerators, in which space charge effects are a small perturbation on both longitudinal and transverse motion. In that case, most stability questions can be considered as purely longitudinal or transverse since the basic frequencies differ by orders of magnitude. We are studying the behavior of a continuous beam to see if the older concepts should be modified for intense beams.

Two approaches are being pursued--a fluid model based on a transverse distribution of approximately circular orbits with longitudinal and transverse temperatures, and a Vlasov treatment of a longitudinally uniform beam with a K-V transverse distribution. The fluid model proved too simple to describe instabilities of interest, which depend on detailed correlations in velocity space. However, we readily devised a closed algebraic formula for mode eigenfrequencies, assuming circular orbits in the transverse plane and including a longitudinal velocity spread. Though unrealistic in its description of transverse motion, the model provides insight into the influence of transverse motion on what are usually regarded as longitudinal stability questions. The case of a K-V transverse distribution is more difficult to treat mathematically because the eigenvalue equation takes the form of an infinite determinant. Numerical procedures are being used to approximate the eigenvalues for both longitudinal and transverse modes.

Beam Breakup Mode

A notorious instability in electron linacs is called the beam breakup mode. A slightly off-center beam excites a wave-guide mode that further deflects the beam. As a result, the tail end of the beam is lost because of the large induced transverse motion. This effect has been examined for the induction linac case and seems to be unimportant, largely because the deflecting mode in the induction modules have a sufficiently low Q-value that the deflecting fields do not build up to a dangerous level.

Cited References

1. Heavy Ion Fusion Group, Heavy Ion Fusion Half-Year Report--October 1, 1979 - March 31, 1980, Lawrence Berkeley Laboratory, Report No. LBL-10914 (1980).
2. Heavy Ion Fusion Group, Heavy Ion Fusion Half-Year Report--April 1, 1980 - September 30, 1980, Lawrence Berkeley Laboratory, Report No. LBL-11809 (1980).
3. R. Sah, E. Close, A. Garren, W. Herrmannsfeldt, E. Hoyer, D. Hunt, C. Kim, H. Kim, J. Shiloh, L. Smith, HIF Multiple Beam Arrays Workshop, October 22-28, 1980, Technical Summary, Lawrence Berkeley Laboratory Report No. HI-FAN-143 (1980).
4. W. B. Herrmannsfeldt, Electron Trajectory Program, SLAC 226 (1979).
5. P. J. Channell, J. S. Wurtele, and A. M. Sessler, Longitudinal Resistive Stability of an Intense Charge Bunch in a Linear Accelerator, Lawrence Berkeley Laboratory, Report No. LBL-11367 (1980).
6. D. Neuffer, Stability of a Self-Consistent Longitudinal Space-Charge Distribution under Space Charge Perturbations, Lawrence Berkeley Laboratory, Report No. LBL-9605 (1979).

NEW DIRECTIONS

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NEW DIRECTIONS

Although the division's resources are primarily devoted to the activities described above in this report, it is essential to chart new courses by investigating promising new technologies or proposing new uses of existing knowledge. During the year several such new initiatives were either continued or begun, including:

- Refinement of the VENUS concept,
- Design proposal for a dedicated heavy-ion medical accelerator,
- Construction of a small-scale test stand for investigating highly stripped ion sources,
- Examination of the feasibility of betatron operation with very high beam currents.

VENUS

Looking toward the future research needs of the nuclear physics community, LBL researchers have been studying a heavy-ion facility concept for several years. Called the Variable Energy Nuclear Synchrotron (VENUS), the facility would function both as a dual-ring superconducting accelerator and as intersecting storage rings. The concept is believed to provide a versatile and economical way to conduct post-SuperHILAC/Bevalac research. VENUS will offer beams of all ions through uranium at energies from about 10 MeV/amu to 20 GeV/amu (with protons to 50 GeV) in the fixed-target mode, and from 4 on 4 to 20 on 20 GeV/amu (approximately 1 TeV/amu fixed-target equivalent) for colliding beam interactions. The VENUS rings would fit comfortably into the laboratory site, and the SuperHILAC could be used as the injector.

During FY80, work on the VENUS concept involved lattice design, operating parameters, and injection systems for a system that could provide the 20 GeV/amu heavy-ion beams with intensity of about 4 X 10^{10} pps in a fixed-target mode, and luminosity of about 2 X 10^{28} $cm^{-2}s^{-1}$ in the colliding-beam mode.

A lattice was designed for the main rings--two vertically separated, 143-m-radius rings that cross vertically at 0.7 m-rad in six 16-m-long interaction regions, so that each beam is alternately in the upper or lower magnets in successive sextants. This crossing geometry would permit either coasting or bunched colliding-beam operation, though the former has been emphasized so far in the parameter selection. This geometry gives a straightforward magnet structure for the insertions containing the interaction regions. Each sextant consists of eight separated-function FODO cells with 4-T dipole magnets. The interaction-point beta-function values, magnet lengths, apertures, etc. are consistent with a choice of transverse and longitudinal stacking for the fixed-target and colliding-beam modes, respectively. This strategy appears to be highly efficient, especially in minimizing beam current and magnet apertures.

Several different injection-system designs were examined. All start with the SuperHILAC and have one or two booster synchrotrons. A few use a recirculating loop. The possible boosters range in energy from 0.5 to 4 GeV/amu and in sizes of 1/7, 1/2 and 1 times that of the main ring. While a final choice has not yet been made, there has been considerable progress. Thus, it is decided that the ions should be accelerated in a booster to at least 0.5 GeV/amu and completely stripped before injection into the main rings. The principal problems encountered in this work involve choosing transfer energies, ring sizes, and stacking numbers so as to have reasonable rf voltages and magnet power, avoid space-charge limits, and retain reasonable main-ring apertures, particularly in the interaction-region quadrupoles.

Dedicated Heavy-Ion Medical Accelerator

In FY80, a proposal was submitted to the National Institutes of Health for the detailed design of a heavy-ion medical accelerator dedicated to clinical and other biomedical uses of heavy ions. If approved, the proposed three-year design effort will generate detailed preliminary engineering drawings and lead to a complete construction proposal in the third year. The heaviest ion will probably be silicon-28 and the maximum energy ~700 MeV/amu; however, final specifications will be established early in the project by assessing user requirements and evaluating clinical and biological data.

In preparation for this design effort, several division staff members participated in a series of workshops held in Edmonton, Canada, to establish the specifications for a medically oriented heavy-ion accelerator facility planned for the Univeristy of Alberta. Other preparations include:

- Preliminary development of a synchrotron lattice,
- Studies of injection, extraction, rf, magnet, and power-supply requirements,
- Formulation of a control system philosophy,
- Conceptual design for a linac injector,
- Model of a beam delivery system.

These studies will enable us to make realistic projections of facility operating costs. Preliminary results indicate that all requirements, including patient safety, machine reliability, and cost effectiveness, can be readily met with available, proven technology.

Electron Beam Ion Source (EBIS)

A program is underway to develop a source of highly stripped heavy ions, primarily to upgrade the 88-Inch Cyclotron (the output energy per nucleon increases as the square of the charge state of the injected ion). The source will also have application to atomic physics. The program consists of two phases--construction of an EBIS test-stand, and design, construction, and installation of a full-scale EBIS source, which is in the planning stage.

Design of the test-stand (Fig. 26) began in January 1980, and construction was nearly complete at the year's end. Our aim was to build a low-cost test device in a short time, while incorporating those features that will allow for a complete survey of EBIS operation. Much of the equipment was either on-hand or borrowed.

The design avoids those features that might lead to poor and unreliable operation. For example, to reduce magnetic perturbations the vacuum vessel is made of Type-310 stainless steel, which is hard to obtain but has good magnetic susceptibility properties. To minimize magnetic field inhomogeneities stemming from imperfectly wound field coils, a series of soft iron annular rings, located between the vacuum vessel and the magnetic field coils, were precisely machined and positioned to 0.001-in. tolerance. These precautions yielded a magnetic field whose on-axis field line is straight to ±50 μ over the 65-cm distance between the iron pole pieces. A paper describing the technique is in preparation. By measuring with a telescope the position of the incandescent spot produced by letting a 10-μs beam pulse strike a 0.001-in.-thick tungsten plate that is moved axially, we found the beam trajectory is straight to the same ±50-μ tolerance. Such field and beam straightness is important to proper EBIS operation and is promising for the final device.

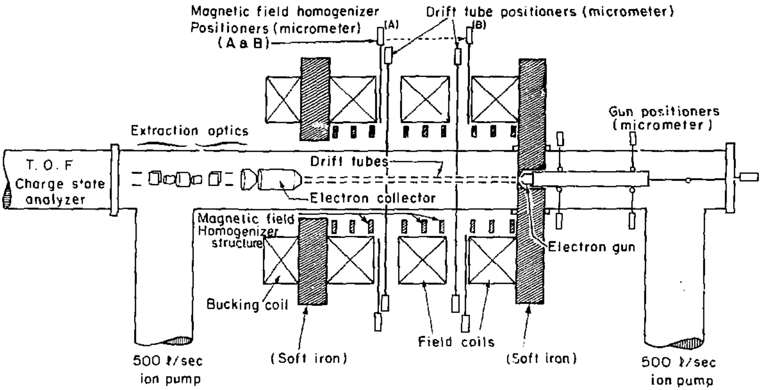
Another design feature is the ability to move and precisely locate the electron gun and the drift tube structure within the vacuum vessel, while operating at high vacuum. It will thus be possible to align the magnetic field axis, the beam trajectory, and the drift tubes axis to be colinear to within better than 100 μ. Preliminary measurements of the electron beam profile, as a function of gun position, gun voltage, and magnetic field, indicate that the central current density is up to 60% of the Brillouin current density. Further measurements and comparison with a beam envelope code are continuing.

High-Current Betatron

The feasibility of designing a betatron to operate with beam currents in the 10-kA range at energies of about 1 GeV is being investigated. Such high-current electron beams would prove useful to many areas of particle beam physics research and in the development of free electron lasers with potential application to inertial confinement fusion.

Betatrons operating at up to 300 MeV and beam currents of less than one ampere have been used successfully in high-energy physics research since about 1940. For higher energies, researchers turned to alternating-gradient synchrotrons because the magnets are more compact and the electron orbits are automatically synchronized despite the energy lost through synchrotron radiation. The synchrotron approach is impractical for producing the kiloampere beam currents because the power required to overcome synchrotron radiation loss is large, and the rf system and the beam are likely to interact in an unstable manner. Instead, a magnetic induction device seems more suitaole for accelerating very high current beams.

LBL has particular expertise in betatron design gained through the Electron Ring Accelerator (ERA) project. In ERA, magnetic induction was used to accelerate electrons to tens of MeV at beam currents of a few kiloamperes,



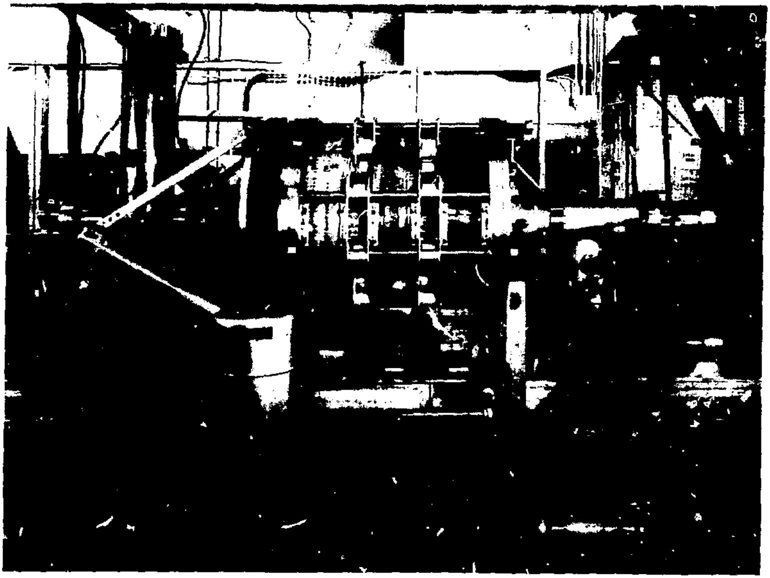


FIG. 26. Schematic and photograph of the EBIS test-stand, which was nearly completed during FY80. Preliminary measurements indicate good field and beam straightness (±50 μ tolerance), necessary features of a full-scale device for upgrading the 88-Inch Cyclotron. (XBL 808-1786, CBB 800-12340)

but the orbits were not constant as they would be in a conventional betatron. This expertise will be valuable in identifying and solving anticipated problems at high currents, including:

- Betatron detuning caused by space charge,
- Beam instabilities resulting from the longitudinal and transverse electromagnetic forces created by the beam,
- Intrabeam scattering observed in electron storage rings,
- Beam neutralization,
- Ion/electron-beam resonances,
- Synchrotron radiation power losses as high as 100 MW,
- Radiation hazards.

A conceptual design study is proposed for FY81 in collaboration with LLNL to explore the feasibility of a number of full-scale betatrons and to plan the experiments needed to broaden the technological base. In particular, an intermediate-level test accelerator composed of a betatron that would use the Advanced Test Accelerator at LLNL's Site 300 as an injector is being studied.

PUBLICATIONS

Accelerator Operations

Nuclear Science

J. M. Slater and W. T. Chu, "Leakage Radiation Regulations of High Energy Radiotherapy Machines," International J. Radiation Oncology Biol. Phys. 6, 251 (1980).

J. D. Williams, Air Flow into the LBL Bevatron, Lawrence Berkeley Laboratory, Berkeley, Calif., Report No. LBL-10972 (1980).

F. Lothrop, Bevalac Section of Research/Accelerators, Lawrence Berkeley Laboratory, PUB-300 (Sept.-Oct. 1979, Nov.-Dec. 1979, Jan.-Feb., 1980, Mar.-Apr. 1980).

H. D. Lancaster, S. B. Magyary, J. Glatz, F. B. Selph, M. P. Fahmie, A. L. Ritchie, S. R. Keith, G. R. Stover, and L. J. Besse, A Microcomputer Control System for the SuperHILAC Third Injector, presented at the 1979 Linear Accelerator Conf., Montauk, New York, September 10-14, 1979. Also Lawrence Berkeley Laboratory Report No. LBL-09763.

R. S. Stevenson, SuperHILAC Section of Research/Accelerators, Lawrence Berkeley Laboratory, PUB-300.

K. J. Kim, A Study of Microwave Instabilities by Means of a Square-Well Potential, presented at the 1979 Isabelle Workshop, Upton, New York, July 16-27, 1979. Also Lawrence Berkeley Laboratory Report No. LBL-09741.

S. Magyary, J. Glatz, H. Lancaster, F. Selph, M. Fahmie, A. Ritchie, C. Timossi, R. Sorensen, and R. Benjegerdes, "A High Performance/Low Cost Accelerator Control System," in Proc. of the 6th IEEE Conf. on the Application of Accelerators in Research and Industry, Denton, Texas, November 3-5, 1980 (in press). Also Lawrence Berkeley Laboratory Report No. LBL-11761.

B. T. Leemann, SuperHILAC Facilities, Contributed Poster Presentation to the August 1980 Meeting of the American Chemical Society, Las Vegas, Nevada.

R. C. Wolgast, V. A. Fletcher, A. M. Kennedy, and Y. Yajiyama, A Large Superconducting Dipole Magnet for the Heavy Ion Spectrometer System (HISS), Presented at the 1980 Applied Superconductivity Conference, Santa Fe, New Mexico, September 29-October 2, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11579.

Papers submitted for presentation at the 1981 Particle Accelerator Conference, Washington, DC, March 11-14, 1981:

K. C. Crebbin, Beam Energy Measurements at the Bevalac. Also Lawrence Berkeley Laboratory Report No. LBL-11692.

W. T. Chu, J. Alonso, and C. Tobias, Heavy Ion Beam Studies and Imaging with a Multiplane Multiwire Proportional Chamber. Also Lawrence Berkeley Laboratory Report No. LBL-11718.

F. Lothrop, J. Alonso, R. Force, H. Grunder, S. Lewis, R. Miller, and M. Tekawa, Physics and Medicine: The Bevatron/Bevalac Experience, 1979-1980. Also Lawrence Berkeley Laboratory Report No. LBL-11719.

J. R. Alonso, T. L. Criswell, J. Howard, W. T. Chu, R. P. Singh, and D. Geller, Operations Experience at the Bevalac Radiotherapy Facility. Also Lawrence Berkeley Laboratory Report No. LBL-11725.

R. Wada and J. R. Alonso, Metallic Wedge Degraders for Rapid Energy Measurement of Bevalac Heavy Ion Beams. Also Lawrence Berkeley Laboratory Report No. LBL-11726.

H. Pines and F. Selph, Automatic Tuning of the LBL Bevalac Transfer Line. Also Lawrence Berkeley Laboratory Report No. LBL-11580.

J. Hinkson, G. Behrsing, E. Hazelton, W. Hearn, and H. Lancaster, A New, Rugged, High Power Cockcroft-Walton Power Supply. Also Lawrence Berkeley Laboratory Report No. LBL-11715.

B. T. Leemann, A Liquid Film Stripper for High Intensity Heavy Ion Beams. Also Lawrence Berkeley Laboratory Report No. LBL-12268.

J. W. Staples, H. D. Lancaster, and R. B. Yourd, The LBL Wideroe-Based Heavy Ion Injector Project. Also Lawrence Berkeley Laboratory Report No. LBL-11693.

B. Gavin, S. Abbott, R. MacGill, R. Sorensen, J. Staples, and R. Thatcher, A High Current Pulsed Ion Source for Metallic Ions. Also Lawrence Berkeley Laboratory Report No. LBL-11706.

R. A. Gough, Use of a Small Off-Line Computer in the Operation of a Versatile Heavy Ion Cyclotron. Also Lawrence Berkeley Laboratory Report No. LBL-11709.

J. Fugitt, D. Howard, F. Crosby, R. Johnson, M. Nolan, and G. Yuen, A Simplified RF Power System for Wideroe-Type Linacs. Also Lawrence Berkeley Laboratory Report No. LBL-11713.

H. Kim, J. Fugitt, F. Crosby, and R. Johnson, A Unique Space Saving Accelerator Cavity Design. Also Lawrence Berkeley Laboratory Report No. LBL-11714.

S. Magyary, J. Glatz, H. Lancaster, F. Selph, M. Fahmie, A. Ritchie, C. Timossi, J. Hinkson, R. Benjegerdes, and D. Brodzik, Operating Experience with a New Accelerator Control System Based upon Microprocessors. Also Lawrence Berkeley Laboratory Report No. LBL-11724.

Biomedical Sciences

A. Chatterjee, E. L. Alpen, J. R. Alonso, J. Llacer, C. A. Tobias, "High Energy Beams of Radioactive Nuclei and their Biomedical Applications," J. Radiation Oncology (in press).

J. R. Alonso, Developments in Accelerators and Instrumentation Relevant to Imaging with Charged Particles and Positron Emitters, invited paper at Conference on Biological Imaging: Contributions from Contemporary Physics and Engineering, Scripps Clinic and Research Foundation, La Jolla, California, November 16-18, 1980. Also Lawrence Berkeley Laboratory Report No. 12074.

J. R. Alonso, J. Howard, T. Criswell, W. Chu, F. Lothrop, and C. Weber, "The Bevalac Biomedical Facility," pp. 11-20 in Biological and Medical Research with Accelerated Heavy Ions at the Bevalac, 1977-1980, M. C. Pirruccello and C. A. Tobias, Eds. (Lawrence Berkeley Laboratory, Berkeley, California, 1980), Report No. LBL-11220.

J. R. Alonso, E. V. Benton, W. Chu, J. Llacer, J. Richies, and C. A. Tobias, "Instrumentation for Measuring Heavy-Ion Fields," pp. 21-34 in Biological and Medical Research with Accelerated Heavy Ions at the Bevalac, 1977-1980, M. C. Pirruccello and C. A. Tobias, Eds. (Lawrence Berkeley Laboratory, Berkeley, California, 1980), Report No. LBL-11220.

J. T. Lyman, J. Howard, L. Kanstein, and J. R. Alonso, "Radiological Physics of Heavy Charged-Particle Beams used for Therapy," pp. 319-330 in Biological and Medical Research with Accelerated Heavy Ions at the Bevalac, 1977-1980, M. C. Pirruccello and C. A. Tobias, Eds. (Lawrence Berkeley Laboratory, Berkeley, California, 1980), Report No. LBL-11220.

J. Llacer, W. Chu, C. A. Tobias, J. I. Fabrikant, and J. R. Alonso, "Active Heavy-Ion Radiography and Computerized Tomography," pp. 367-374 in Biological and Medical Research with Accelerated Heavy Ions at the Bevalac, 1977-1980, M. C. Pirruccello and C. A. Tobias, Eds. (Lawrence Berkeley Laboratory, Berkeley, California, 1980), Report No. LBL-11220.

A. Chatterjee, E. L. Alpen, J. Llacer, J. R. Alonso, and C. A. Tobias, "High Energy Beams of Radioactive Nuclei and their Biomedical Applications," pp. 383-390 in Biological and Medical Research with Accelerated Heavy Ions at the Bevalac, 1977-1980, M. C. Pirruccello and C. A. Tobias, Eds. (Lawrence Berkeley Laboratory, Berkeley, California, 1980), Report No. LBL-11220.

Advanced Accelerator Studies

R. C. Sah, "A Beam-Beam Simulation for the Single-Pass Collider," in Proc., XI Int. Conf. on High Energy Accelerators, CERN, Geneva, 1980, pp. 736-740. Also Lawrence Berkeley Laboratory Report No. LBL-10755.

K. Halbach, Physical and Optical Properties of Rare Earth Cobalt Magnets, presented at the Int. Conf. on Charged Particle Optics, Giessen, W. Germany, Sept. 8-12, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11393.

G. Lambertson, J. Bisognano, W. Flood, L. J. Laslett, C. Leemann, B. Leskovar, C. C. Lo, R. Main, L. Smith, and J. Staples, Stochastic Cooling of 200 MeV Protons, International Accelerator Conference, CERN, Geneva, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10757.

J. Bisognano, Kinetic Equations for Longitudinal Stochastic Cooling, Lawrence Berkeley Laboratory, Berkeley, Calif., Report No. LBL-10753 (1980).

R. P. Warren, G. R. Lambertson, W. S. Gilbert, R. B. Meuser, S. Caspi, and R.V. Schafer, A Pressurized Helium II-Cooled Magnet Test Facility, presented at the 8th Int. Cryogenic Engineering Conf., Genoa, Italy, June 3-6, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10923 and SUMAG-31.

S. Caspi, Gravitational Convection of Subcooled HE I and the Transition into Superfluid HE II at Atmospheric Pressure, Lawrence Berkeley Laboratory, Berkeley, Calif., Report No. LBL-10928 (1980).

R. B. Meuser, Structural Analysis of Superconducting Bending Magnets, presented at the 8th Int. Cryogenic Engineering Conf., Genoa, Italy, June 3-6, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10950.

W. S. Gilbert, S. Caspi, W. Hassenzahl, et al., "Testing of Accelerator Dipoles in Pressurized Superfluid Helium," in Proc., XIth Int. Conf. on High Energy Accelerators, CERN, Geneva, 1980, pp. 858-862 . Also Lawrence Berkeley Laboratory Report No. LBL-10756.

A. Garren, "Studies of a Beam Line for Transport to a Target," Proceedings of the Heavy Ion Fusion Workshop, Claremont Hotel, Berkeley, Calif., October 29 - November 9, 1979, pp. 397-402 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10301.

A. Garren, "Final Transport in Vacuum--Summary," Proceedings of the Heavy Ion Fusion Workshop, Claremont Hotel, Berkeley, Calif., October 29 - November 9, 1979, p. 377 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10301.

S. Chattopadhyay and A. Faltens, "Investigation of Tolerances for the Parameters of the Proposed LBL Test-Bed Linear Induction Accelerator," Proceedings of the Heavy Ion Fusion Workshop, Claremont Hotel, Berkeley, Calif., October 29 - November 9, 1979, pp. 151-156 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10301.

K. J. Kim, "Longitudinal Dynamics of Bunched Beam in a Model Linac," Proceedings of the Heavy Ion Fusion Workshop, Claremont Hotel, Berkeley, Calif., October 29 - November 9, 1979, pp. 187-200 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10301.

K. J. Kim, A Study of Microwave Instabilities by Means of a Square-Well Potential, presented at the 1979 Isabelle Workshop, Upton, NY, July 16-27, 1979. Also Lawrence Berkeley Laboratory Report No. LBL-09741.

J. Bisognano, Kinetic Equations for Longitudinal Stochastic Cooling, Lawrence Berkeley Laboratory, Berkeley, Calif., Report No. LBL-10753 (1980).

A. Sternlieb, Particle Simulation of Longitudinal Instabilities in Heavy Ion Beams, 22nd Annual Meeting, Division of Plasma Physics, Nov. 10-14, 1980, San Diego, Calif. Also Lawrence Berkeley Laboratory Report No. LBL-11217-26.

B. Cork, T. F. Hoang, Multiplicity and Scaling of $e^+e^- \rightarrow$ hadrons, submitted to Phys. Rev. D., October 1979. Also Lawrence Berkeley Laboratory Report No. LBL-09958.

T. F. Hoang and B. Cork, Scaling, Multiplicity and Temperature of $e^+e^- \rightarrow$ hadrons, submitted to Physical Rev. D., November 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11806.

Papers submitted for presentation at the 1981 Particle Accelerator Conference, Washington, D.C., March 11-13, 1981:

T. Lauritzen and R.C. Sah, The PEP Liquid Level System.

J. M. Peterson and K. L. Brown, Design Features and Operational Characteristics for the PEP Beam-Transport Injection System.

K. Halbach, J. Chin, E. Hoyer, H. Winick, R. Cronin, J. Yang, and Y. Zambre, A Permanent Magnet Undulator for SPEAR.

J. J. Bisognano and S. Chattopadhyay, Stochastic Cooling of Bunched Beams--A Simulation Study.

G. R. Lambertson, J. Bisognano, W. Flood, K. Kim, C. Leemann, B. Leskovar, C. C. Lo, R. Main, R. Reimers, L. Smith, and J. Staples, Experiments on Stochastic Cooling of 200 MeV Protons.

E. Close, Numerical Simulation of Survey Misalignment Effects in the ATA Structure.

R. Althaus, S. Caspi, W. S. Gilbert, W. Hassenzahl, R. Meuser, J. Rechen, C. Taylor, and R. Warren, Performance of Dipole Magnets in Helium II.

W. V. Hassenzahl, A Comparison of NbTi, Nb_3Sn, and NbTiTa Superconductors for High Field Accelerator Dipoles.

C. Taylor, R. Althaus, S. Caspi, W. S. Gilbert, W. Hassenzahl, R. Meuser, J. Rechen, and R. Warren, A Novel Epoxy-Free Construction Method for Fabricating Dipole Magnets and Test Results.

J. J. Bisognano and S. Chattopadhyay, Stochastic Cooling of Bunched Beams--A Simulation Study.

S. Chattopadhyay, A. Faltens, and L. Smith, Study of the Beam Breakup Mode in Linear Induction Accelerators for Heavy Ions.

A. Garren, G. Krafft, and I. Haber, On Focusing of Heavy Ion Beams to a Target for Heavy Ion Fusion.

T. F. Wang and L. Smith, Transverse-Longitudinal Coupling in Intense Beams.

A. Sternlieb, J. Bisognano, L. Smith, T. F. Wang, and I. Haber. Numerical Studies of Longitudinal Instabilities in Bunched Beams.

Magnetic Fusion Energy

Neutral Beam Development and Technology

Review Papers

R. V. Pyle, Neutral Beam Development at the Lawrence Berkeley and Lawrence Livermore Laboratories, presented at the 4th American Nuclear Society Topical Meeting on Fusion Technology, King of Prussia, Pennsylvania, October 14-17, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11141.

K. H. Berkner, Advanced Neutral-Beam Technology, presented at the 2nd joint Grenoble-Varenna Int. Symposium on Heating in Toroidal Plasmas, Como, Villa Olmo, Italy, September 3-12, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11432.

W. B. Kunkel, "Neutral-Beam Injection," a chapter in Fusion, E. Teller, Ed. (Academic Press, New York, NY, in press). Also Lawrence Berkeley Laboratory Report No. LBL-10447.

W. B. Kunkel, Status of Magnetic-Confinement Fusion, presented at the AAAS Annual Meeting, San Francisco, Calif., January 3-8, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10202.

W. B. Kunkel, The Prospects of Fusion Energy as a Commercial Power Source, presented at the American Association for the Advancement of Science, San Francisco, Calif., January 8, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-09685.

K. H. Berkner, "Neutral Beam Technology: Accomplishments and Future Requirements," Bull. Am. Phys. Soc. 24 (1979).

R. V. Pyle, "The Neutral Beam Development Program at Lawrence Berkeley Laboratory," Bull Am. Phys. Soc. 25, 897 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-[illegible]-13.

Positive Ion Base

L. A. Biagi, K. H. Berkner, K. W. Ehlers, J. A. Paterson, and J. R. Porter, "The Design and Fabrication of a Large Rectangular Magnetic Cusp Plasma Source for High Intensity Neutral Beam Injectors," in Proc. of 8th Symp. on Engineering Problems of Fusion Research (Institute of Electrical and Electronics Engineers, New York City, 1980), IEEE Pub. No. 79CH 1441-5 NPS, p. 669. Also Lawrence Berkeley Laboratory Report No. LBL-10085.

K. H. Berkner, C. F. Burrell, W. S. Cooper, K. W. Ehlers, A. F. Lietzke, H. M. Owren, J. A. Paterson, R. V. Pyle, and J. W. Stearns, "Development of 120 keV Neutral Beam Injectors," in Proc. of 8th Symp. on Engineering Problems of Fusion Research (Institute of Electrical and Electronics Engineers, New York City, 1980), IEEE Pub. No. 79CH 1441-5 NPS, p. 214. Also Lawrence Berkeley Laboratory Report No. LBL-10086.

J. A. Paterson, G. W. Koehler, R. P. Wells, and L. A. Biagi, "The Mechanical Design and Fabrication of a Convectively Cooled Ion Accelerator for Continuously Operating Neutral Beam Systems," in Proc. of 8th Symp. on Engineering Problems of Fusion Research (Institute of Electrical and Electronics Engineers, New York City, 1980), IEEE Pub. No. 79CH 1441-5 NPS, Vol. 2, p. 1065. Also Lawrence Berkeley Laboratory Report No. LBL-10095.

K. H. Berkner, D. J. Massoletti, J. B. McCaslin, R. V. Pyle, and L. Ruby, "Neutron Production by Neutral Beam Sources," in Proc. of 8th Symp. on Engineering Problems of Fusion Research (Institute of Electrical and Electronics Engineers, New York City, 1980), IEEE Pub. No. 79CH 1441-5 NPS, p. 857. Also Lawrence Berkeley Laboratory Report No. LBL-10087.

D. B. Hopkins, W. R. Baker, K. H. Berkner, K. W. Ehlers, V. J. Honey, A. F. Lietzke, K. A. Milnes, and H. M. Owren, "Protection and Fault Detection for LBL Neutral Beam Sources," in Proc. of 8th Symp. on Engineering Problems of Fusion Research (Institute of Electrical and Electronics Engineers, New York City, 1980), IEEE Pub. No. 79CH 1441-5 NPS, Vol. 4, p. 2019. Also Lawrence Berkeley Laboratory Report No. LBL-9406.

C. F. Burrell, W. S. Cooper, R. R. Smith, and W. F. Steele, "Doppler Shift Spectroscopy of Powerful Neutral Beams," Rev. Sci. Instrum. 51, 1451 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10398.

L. A. Biagi, G. W. Koehler, and J. A. Paterson, "On Fabrication and Brazing of 15A, 120 keV Continuous Duty Accelerator Grid Assemblies," in Proceedings of the American Welding Society Conf. on Brazing (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10558.

J. A. Tanis, X-Ray Analysis to Determine Impurity Concentrations in Neutral Beams, presented at the Third Topical Conf. on High Temperature Plasma Diagnostics, Los Angeles, Calif., March 17-19, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10362.

C. F. Burrell, K. H. Berkner, W. S. Cooper, and W. F. Steele, Measurement of Neutral Beam Parameters on a Focused Neutral Beam System with Doppler Shift Spectroscopy, presented at the 1980 IEEE Int. Conf. on Plasma Science, Madison, Wisconsin, May 19-21, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10471.

K. N. Leung, Characteristics of Multi-Cusp Plasma Generators, presented at the 1980 IEEE Int. Conf. on Plasma Science, Univ of Wisconsin, Madison, Wisconsin, May 19-21, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10653.

A. P. Colliraino, J. F. Pipkins, L. Sevier, and K. H. Berkner, "Neutral Beam Tests for the Armor Plate for the DIII Vacuum Vessel," Proceedings of the 1980 IEEE International Conference on Plasma Science (1980).

D. L. Jassby, K. H. Berkner, P. L. Colestock, R. L. Freeman, H. H. Haselton, J. C. Hosea, J. A. Rome, J. A. Scharer, J. Sheffield, and L. D. Stewart, Plasma Heating R&D Assessment, U.S. INTOR Internal Report No. 5, (1979). Also Princeton Plasma Physics Laboratory Report PPPL-1610 (1-79).

K. W. Ehlers and K. N. Leung, "Characteristics of the Berkeley Multicusp Ion Source," Rev. Sci. Inst. 50, 1353 (1979).

K. A. Milnes, K. W. Ehlers, K. N. Leung, H. M. Owren, and M. D. Williams, "A Fast Langmuir Probe Sweeping Circuit," IEEE Trans. Plasma Sci., vol. PS-8, p. 124 (1980).

O. A. Anderson and W. S. Cooper, "High Current, Low Energy Neutral Beam Source," Bull. Am. Phys. Soc. 25, 982 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11217-16.

P. A. Pincosy, K. W. Ehlers, and C. F. Burrell, "Magnetic Bucket Ion Source Characteristics," Bull. Am. Phys. Soc. 25(8), 982 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11217-20.

K. H. Berkner, W. S. Cooper, J. H. Feist, D. J. Massoletti, H. M. Owren, J. A. Paterson, and R. P. Wells, "Performance Characteristics of a Long-Pulse Accelerator Configured for 120-kV, 10A (hydrogen), 5-sec Operation," Bull. Am. Phys. Soc. 25, 982 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11217-15.

Negative Ion Base

P. J. Schneider, K. H. Berkner, W. G. Graham, R. V. Pyle, and J. W. Stearns, "Negative-Hydrogen-Ion Production by Backscattering from Alkali-Metal Targets," in Proc. of the Workshop on Hydrogen Recycling, Dublin, Calif., October 17-18, 1979. Also Lawrence Berkeley Laboratory Report No. LBL-09992.

K. W. Ehlers and K. N. Leung, "A Multicusp Negative Ion Source," Rev. Sci. Instrum. 51(6), 721-727 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10013.

P. Poulsen and E. B. Hooper, Jr., Large Area Negative Ion Scource for High Voltage Neutral Beams, presented at the IEEE 8th Symposium on Engineering Problems of Fusion Research, San Francisco, Calif., November 13-16, 1979. Also Lawrence Berkeley Laboratory Report No. LBL-10081.

L. Ruby, Trace Identification of Cesium and Sodium in Neutral Beam Research, presented at the American Nuclear Society Meeting, Las Vegas, Nevada, June 8-13, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10367.

E. B. Hooper, P. Poulsen, P. A. Pincosy, C. F. Burrell, L. R. Grisham, and D. E. Post, "High Current Source of He^- Ions," Rev. Sci. Instrum. 51, 1066 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10448.

K. W. Ehlers and K. N. Leung, Electron Suppression in a Multi-Cusp Negative Ion Source, submitted to Appl. Phys. Lett., June 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11073.

P. J. Schneider, Negative Ion Production by Backscattering from Alkali-Metal Surfaces Bombarded by Ions of Hydrogen and Deuterium, Ph.D. thesis, University of California, Berkeley, Calif. (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10616.

K. N. Leung and K. W. Ehlers, "H^- Ion Formation from a Surface Conversion Type Ion Source," Brookhaven National Laboratory 2nd Int. Symp. on the Production and Neutralization of Negative Ions and Beams (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11638.

O. A. Anderson, "Large-Aperture D^- Accelerators," in Proc., 2nd Int. Symp. on the Production and Neutralization of Negative Ions and Beams (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11824.

K. W. Ehlers and K. N. Leung, "Low Energy Ion Beam Transport by Permanent Magnets," Rev. Sci. Instrum. 51, 500 (1980).

K. N. Leung, K. W. Ehlers, and E. B. Hooper, Jr., Low Energy Ion Beam Transport by Permanent Magnets, presented at the Low Energy Ion Beams--2 Conference, Surrey, England, April 14-17, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10217.

E. B. Hooper, Jr., P. Poulsen, and P. A. Pincosy, Large Scale Production of He^- Beam by Charge-Exchange in Na, presented at the Meeting of the American Physical Society for High Temperature Plasma Diagnostics, Los Angeles, Calif., March 17-19, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10310.

K. N. Leung, K. W. Ehlers, and P. J. Schneider, "He^- Ion Production for Alpha-Particle Distribution Measurement in Tokamaks," Bull. Am. Phys. Soc. 25(6), 698 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10361.

K. W. Ehlers and K. N. Leung, "The Self-Extraction Negative Ion Source," Bull. Am. Phys. Soc. 25(8), 981 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11217-21.

K. N. Leung and K. W. Ehlers, "On the Hybrid Production of H-Ions," Bull Am. Phys. Soc. 25(8), 981 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11217-22.

K. N. Leung, K. W. Ehlers, and E. B. Hooper, Jr., "Transport of Low Energy Positive and Negative Ion Beam by Permanent Magnets," in Proc., 2nd Int. Symp. on the Production and Neutralization of Negative Ions and Beams (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11636.

K. W. Ehlers and K. N. Leung, "Characteristics of Self-Extraction Negative Ion Source," in Proc., 2nd Int. Symp. on the Production and Neutralization of Negative Ions and Beams (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11637.

R. V. Pyle, "An Overview of the LBL/LLNL Negative-Ion Based Neutral Beam Program," Brookhaven National Lab 2nd Int. Symp. on the Production and Neutralization of Negative Ions and Beams (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11639.

Neutral Beam System Test Facility

A. F. Lietzke, K. H. Berkner, J. H. Feist, R. R. Smith, W. R. Baker, D. B. Hopkins, I. C. Lutz, D. Bereznai, and V. L. Jacobson, "Initial Operation of NBSTF, the Prototype Neutral-Beamline for TFTR," Bull. Am. Phys. Soc. 25, 982 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11217-14.

Neutral Beam Plasma Research

K. F. Schoenberg, "Electron Distribution Function Measurement by Harmonically Driven Electrostatic Probes," Rev. Sci. Instrum. 51, 1159 (1980).

B. D. Billard, A New Mechanism of Spatial Resolution for Two-Beam Spectroscopy, submitted to J. Opt. Soc. Am., September 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11294.

K. F. Schoenberg, A Study of the General Plasma Characteristics of a High Power Multifilament Ion Source, Ph.D. thesis, University of California, Berkeley, California (1979). Also Lawrence Berkeley Laboratory Report No. LBL-08940.

K. F. Schoenberg, "Real Time Digital Spectral Analysis as a Plasma Fluctuation Diagnostic," Rev. Sci. Instrum. 51, 1151 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10112.

K. N. Leung and R. E. Kribel, "Rate of Electron Heating in a Multidipole Plasma," Phys. Fluids 23, 1923 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10363.

B. D. Billard, Evaluation of Two-Beam Spectroscopy as a Plasma Diagnostic, Ph.D. thesis, University of California, Berkeley, California (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10913.

N. E. Abt, C. F. Burrell, W. S. Cooper, and W. B. Kunkel, Studies on the LBL "10-Amp" Neutral Beam Neutralizer, presented at the 1980 IEEE Int. Conf. on Plasma Science, Madison, Wisconsin, May 19-21, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10468.

C. F. Chan, C. F. Burrell, W. S. Cooper, and P. A. Pincosy, "Model Calculations of Ion Source Performance Optimization," Bull. Am. Phys. Soc. 25, 982 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11217-19.

B. D. Billard, "Two-Beam Spectroscopy (TBS) as a Plasma Diagnostic," Bull. Am. Phys. Soc. 25, 939 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11217-11.

N. E. Abt, M. C. Vella, and G. Guethlein, "Neutralizer-Plasma Scaling Experiments," Bull. Am. Phys. Soc. 25, 982 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11217-18.

Experimental Atomic Physics

J. A. Tanis, S. M. Shafroth, J. E. Willis, and J. R. Mowat, Radiative Electron Capture by Cl Ion Incident C and Cu Foils, submitted to Phys. Rev. A, January 1980. Also Lawrence Berkeley Laboratory Report No. LBL-09848.

J. A. Tanis, S. M. Shafroth, J. E. Willis, and J. R. Mowat, Evolution of Projectile Double K Vacancy Fractions with Target Thickness in Ion-Atom Collisions, submitted to Phys. Rev. Lett., January 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10314.

J. A. Tanis, W. W. Jacobs, and S. M. Shafroth "Systematics of Target and Projectile K X-Ray Production and REC for 20-80 MeV Cl^{9+} Ions and Incident on 25-200 g/cm^2 Cu Targets," Phys. Rev. A 22(2), 483-495 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10641.

P. J. Schneider, K. H. Berkner, R. V. Pyle, J. W. Stearns, and W. G. Graham, "H^- and D^- Production by Backscattering from Alkali-Metal Targets," Phys. Rev. B 23 (1981). Also Lawrence Berkeley Laboratory Report No. LBL-10843.

A. S. Schlachter, K. H. Berkner, W. G. Graham, R. V. Pyle, P. J. Schneider, J. R. Stalder, J. W. Stearns, and J. A. Tanis, "Ionization of Rare Gas Targets by Collisions of Fast Highly Charged Projectiles," Phys. Rev. A (in press). Also Lawrence Berkeley Laboratory Report No. LBL-10944.

K. H. Berkner, R. V. Pyle, A. S. Schlachter, J. W. Stearns, and W. G. Graham, "Electron-Capture, Electron-Loss and Impact-Ionization Cross Sections for 103- to 3400-keV/amu Multi-Charged Iron Ions Colliding with Molecular Hydrogen," Phys. Rev. A (in press). Also Lawrence Berkeley Laboratory Report No. LBL-06823.

A. S. Schlachter, K. R Stalder, and J. W. Stearns, "D^- Production by Charge Transfer of 0.3-10 keV D^+, D^0 and D^- in Cesium, Rubidium and Sodium Vapor Targets," Phys. Rev. A (in press). Also Lawrence Berkeley Laboratory Report No. LBL-10255.

A. S. Schlachter, "D^- Production by Charge Transfer in Metal Vapors," Brookhaven National Lab 2nd International Symposium on the Production and Neutralization of Negative Ions and Beams (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11635.

A. S. Schlachter, K. H. Berkner, W. G. Graham, R. V. Pyle, J. W. Stearns, and J. A. Tanis, Collisions of Fast, Highly Stripped Carbon, Niobium, and Lead Ions with Molecular Hydrogen, submitted to Physical Review A: Comments and Addenda, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11732.

A. S. Schlachter, Collisions of Highly Stripped Ions at MeV Energies in Gas Targets: Charge Transfer and Ionization, presented at Sixth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 3-5, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11779.

P. J. Schneider, K. H. Berkner, W. G. Graham, R. V. Pyle, and J. W. Stearns, "Production of H^- and D^- by Backscattering from Low-Work-Function Surfaces," in Low Energy Ion Beams, I. H. Wilson and K. G. Stephens, Eds. (The Institute of Physics, Bristol and London, 1980), Conference Series No. 54, p 177. Also Lawrence Berkeley Laboratory Report No. LBL-10237.

W. S. Cooper, "Atomic Physics in Neutral beam Injectors Used in Fusion," Bull. Am. Phys. Soc. 24, 1193 (1979). Also Lawrence Berkeley Laboratory Report No. LBL-09772.

K. H. Berkner, R. V. Pyle, S. E. Savas, and K. R. Stalder, "Plasma Neutralizers for H^- or D^- Beams," Brookhaven National Lab 2nd International Symposium on the Production and Neutralization of Negative Ions and Beams (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11640.

A. S. Schlachter, Metastable Contamination of Fast He^{0} Beams Produced from He^{-}, presented at the Meeting of the American Physical Society for High Temperature Plasma Diagnostics, Los Angeles, Calif., March 17-19, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10256.

K. R. Stalder, K. H. Berkner, and R. V. Pyle, Plasma Target for Cs^{+} + Cs^{+} Charge Transfer and Ionization Measurements, presented at the Inertial Confinement Fusion Conf., San Diego, Calif., February 26-28, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-09873.

J. R. Hiskes, P. J. Schneider, A Model for H^{-} D^{-} Production by Hydrogen Backscattering from Alkali Metal Surfaces, presented at the 4th Int., Conf. on Plasma Surface Interactons, Garmisch, West Germany, April 21-25, 1979. Also Lawrence Berkeley Laboratory Report No. LBL-10184.

J. R. Hiskes and P.J. Schneider, A Model for H^{-},D^{-} Production by Hydrogen Backscattering from Alkali Metal Surfaces, presented at the Low Energy Ion Beams--2 Conference, Surrey, England, April 14-17. 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10236.

P. J. Schneider, K. H. Berkner, R. V. Pyle, J. W. Stearns, and W. G. Graham, Production of H^{-} and D^{-} by Backscattering from Low-Work-Function Surfaces, presented at the Low Energy Ion Beams—2 Conference, Surrey, England, April 14-17, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10237.

J. A. Tanis, K. H. Berkner, R. V. Pyle, A. S. Schlachter, P. Schneider, K. Stalder, and J. W. Stearns, Charge Exchange and Ionization by Highly Stripped Pb^{q+} Ions in Gas Targets, presented at the American Physical Society Meeting, Washington, D.C., April 21-24, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10413.

A. S. Schlachter, Collision of Highly Stripped Ions at MeV Energies in Gas Targets--Charge Transfer and Ionization, invited paper presented at the Sixth Conf. on the Application of Accelerators in Research and Industry, Denton, Texas, November 3-5, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11144.

J. A. Tanis, S. M. Shafroth, and J. E. Willis, Cross Sections for Radiative Electron Capture (REC) by 20-80 MeV Cl Ion Incident on C and Cu Foils, presented at the American Physical Society Meeting, Washington, D.C., April 21-24, 1980, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10412.

A. S. Schlachter, K. H. Berkner, J. W. Stearns, and J. A. Tanis, Charge-State Dependence of Electron Loss from Hydrogen by Collisions with Heavy Highly Stripped Ions, presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., November 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-12.

Neutral Beam Test Facility

LBL staff, Proposal to Upgrade the Neutral Beam System Test Facility (NBSTF) to a 170 keV, 65 A, 30 second, 10% Duty Factor Neutral Beam Engineering Test Facility (NBETF), Lawrence Berkeley Laboratory Publication No. PUB-5038, Rev. 1 (1980).

LBL staff, Neutral Beam Engineering Test Facility (NBETF) Administrative Plan (Addendum 1 to NBETF Major Project Proposal), Lawrence Berkeley Laboratory Publication No. PUB-5038, Rev. 1 (1980).

Plasma Theory

A. M. Sessler, Heavy Ion Inertial Fusion: The Driver, Invited Talk, 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., November 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-23 and HIFAN 129.

M. C. Vella, Optimization of EBT Annulus Power Drain with Respect to Core Properties, presented at the *Oak Ridge Workshop on EBT Ring Physics*, December 3-5, 1979. Also Lawrence Berkeley Laboratory Report No. LBL-10077.

J. R. Cary and A. N. Kaufman, Wave-Energy Density and Wave-Momentum Density of each Species of a Collisionless Plasma, submitted to Phys. Rev. A, November 1979. Also Lawrence Berkeley Laboratory Report No. LBL-10414.

H. D. I. Abarbanel, Non-Linear Diffusion in Hamiltonian Systems Exhibiting Chaotic Motion, submitted to Phys. Rev. D, April 1980. Also Lawrence Berkeley Laboratory Report No. LBL 10515.

A. N. Kaufman, H. D. I. Abarbanel, and C. Grebogi, "Statistical Analysis of a Deterministic Stochastic Orbit," in Proc., Int. Conf. on Plasma Physics, Nagoya, Japan, April 7-11, 1980 (in press). Also Lawrence Berkeley Laboratory Report No. LBL-10903.

E. Hameiri and J. H. Hammer, "Unstable Continous Spectrum in Magnetohydrodynamics," Phys. Fluids 22, 1700-1706 (1979). Also Lawrence Berkeley Laboratory Report No. LBL-09753.

H. D. I. Abarbanel, Classical Hamiltonian Perturbation Theory without Secular Terms or Small Denominators, submitted to Phys. Rev. D, October 1979. Also Lawrence Berkeley Laboratory Report No. LBL-09786.

M. C. Vella, Beam Electron Heating for High Density EBT Operations, abstract presented at the Oak Ridge Workshop on EBT Ring Physics, December 1979. Also Lawrence Berkeley Laboratory Report No. LBL-10076.

H. D. I. Abarbanel, C. Grebogi, and A. N. Kaufman, Stochastic Properties of the Chirikov-Taylor Mapping, presented at the 1980 Sherwood Meeting--Theoretical Aspects of Controlled Thermonuclear Research, Tucson, Arizona, April 23-25, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10727.

A. N. Kaufman, C. Grebogi, and H. D. I. Abarbanel, Resonant Diffusion in a Wave of Eikonal Form and its Relation to the Chirikov Mapping, presented at the 1980 Sherwood Meeting--Theoretical Aspects of Controlled Thermonuclear Research, Tucson, Arizona, April 23-25, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10728.

C. Grebogi and R. M. Kulsrud, Interpretation of the Collisionless Drift Mode in a Sheared Magnetic Field, presented at the 1980 Sherwood Meeting—Theoretical Aspects of Controlled Thermonuclear Research, Tucson, Arizona, April 23-25, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10600.

M. C. Vella, Neutralizer Plasma Particle and Power Balance Scaling, presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., November 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-17.

C. Grebogi, A. N. Kaufman, and H. D. I. Abarbanel, Statistical Analysis of Deterministic Orbits, presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., November 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-3.

H. D. I. Abarbanel, C. Grebogi, and A. N. Kaufman, Multiple Resonance Crossing in the Eikonal Model of Plasma Turbulence, presented at 22nd Annual Meeting, Division of Plasma Physics, November 10-14, 1980, San Diego. Also Lawrence Berkeley Laboratory Report No. LBL-11217-4.

H. D. I. Abarbanel, Non-Linear Diffusion of Stochastic Hamiltoian Systems, presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., November 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-5.

A. N. Kaufman and P. J. Morrison, Noncanonical Hamiltonization of the Vlasov Continuum, presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., November 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-1.

S. W. McDonald and W. M. Manheimer, Distribution Function for Regular and Stochastic Eigenfunctions, presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., November 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-2).

R. G. Littlejohn, Relativisitic Guiding Center Hamiltonian with Physical Variables, presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., November 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-6.

TORMAC

R. S. Shaw, B. R. Myers, and M. C. Vella, A Comparison of Spectral Data for Tormac T IV-a and T IV-c, September 1978, Lawrence Berkeley Laboratory, Berkeley, Calif., Report No. LBL-09696 (1979).

I. G. Brown, B. Feinberg, W. B. Kunkel, M. A. Levine, R. A. Niland, R. S. Shaw, and B. C. Vaucher, The Tormac V Experiment—A Summary, submitted to APS Twenty-first Annual Meeting, Division of Plasma Physics, November 12-16, 1979. Also Lawrence Berkeley Laboratory Report No. LBL-10082.

M. A. Levine and P. A. Pincosy, "Formation of a Compact Torus Using a Toroidal Plasma Gun," in Proc. of the Compact Torus Conference, PPPL, December 12-14, 1979. Also Lawrence Berkeley Laboratory Report No. LBL-10238.

B. R. Myers, M. A. Levine, and P. A. Pincosy, A Toroidal Plasma Gun, submitted to Phys. Fluids, December 1979. Also Lawrence Berkeley Laboratory Report No. LBL-09507.

R. S. Shaw, J. Coonrod, M. Greenwald, M. A. Levine, B. R. Myers, and M. C. Vella, Observation of Anomalously Broad Gaussian HeII 4686A Spectral Lines in Tormac, submitted to Plasma Phys., March 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10218.

B. R. Myers, M. A. Levine, and R. S. Shaw, A Fast Opening Toroidal Gas Valve, submitted to Rev. Sci. Instrum., February 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10459.

I. G. Brown, B. Feinberg, W. B. Kunkel, M. A. Levine, R. S. Shaw, R. A. Niland, and B. G. Vaucher, The Tormac V Experiment, submitted to Phys. Fluids, March 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10586.

B. Feinberg, R. S. Shaw, M. C. Vella, and B. G. Vaucher, Anomalous Toroidal Field Penetration in Tormac V, submitted to Phys. Fluids, March 1980. Also Lawrence Berkeley Laboratory Report No. LBL-10318.

R. S. Shaw, I. G. Brown, B. Feinberg, W. B. Kunkel, and M. C. Vella, Ion Line-Broadening in Tormac Discharges, presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., November 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-10.

Heavy Ion Fusion

Heavy Ion Fusion Staff, Heavy Ion Fusion Half-Year Report--October 1, 1979 - March 31, 1980, Lawrence Berkeley Laboratory, Report No. LBL-10914 (1980).

Heavy Ion Fusion Staff, Heavy Ion Fusion Half-Year Report--April 1, 1980 - September 30, 1980 (December 3, 1980). Also Lawrence Berkeley Laboratory Report No. LBL-11809.

Heavy Ion Fusion Staff, Ion Induction Linac 500 Joule Test Bed, Lawrence Berkeley Laboratory, Report No. PUB-5039 (1980).

A. Faltens, et al., Heavy Ion Induction Linacs for ICF, Lawrence Berkeley Laboratory, Report No. LBL-12144 (1980).

S. Rosenblum, et al., Ion Accelerators as Drivers for Inertial Confinement Fusion, Lawrence Berkeley Laboratory, Report No. LBL-12145 (1980).

J. Shiloh, W. Chupp, A. Faltens, D. Keefe, C. Kim, S. Rosenblum, and M. Tiefenback, "A Pulsed Vapor Source for Use in Ion Sources for Heavy Ion Accelerators," Appl. Phys. Lett. 36, 537 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-09601.

Heavy Ion Fusion Group, Year-End Report--Heavy Ion Fusion Program--October 1978 through September 1979, Lawrence Berkeley Laboratory, Report No. LBL-10291 (1980).

W. B. Herrmannsfeldt, T. F. Godlove, and D. Keefe, "Inertial Confinement Fusion Systems Using Heavy Ion Accelerators as Drivers," in Proc. 2nd Int. Conf. on Emerging Nuc. Energy Systems, 1980 (In press). Also Lawrence Berkeley Laboratory Report No. LBL-10878.

D. Keefe and A. Sessler, "Heavy Ion Inertial Fusion," in Proc. 11th Int. Conf. on High-Energy Accelerators, Geneva, 1980, and in Experientia Supplementum 40, 201 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-11146.

A. Faltens, E. Hoyer, D. Keefe, L. J. Laslett, L. Smith, R. O. Bangerter, and W. B. Hermannsfeldt, "Multi-Megajoule Heavy Ion Induction Linacs," in Proc. 8th Int. Atomic Energy Agency Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, Belgium, July 1-10, 1980 (In press). Also Lawrence Berkeley Laboratory Report No. LBL-11120.

D. Keefe, "Rapporteur Talk for IAEA Fusion Meeting," in Proc. 8th Int. Atomic Energy Agency Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, Belgium, July 1-10, 1980 (In press). Also Lawrence Berkeley Laboratory Report No. LBL-11429.

A. Faltens and D. Keefe, "Ion Induction Linacs: Reference Design and Proposed Test Bed," in Proc. of the Heavy Ion Fusion Workshop, Claremont Hotel, Berkeley, Calif., October 29 - November 9, 1979, pp. 157-181 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10301.

A. Faltens, "LIA Longitudinal Coupling Impedance," in Proc. Heavy Ion Fusion Workshop, Claremont Hotel, Berkeley, Calif., October 29 - November 9, 1979, pp. 182-186 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10301.

D. L. Judd, "Longitudinal Dynamics in Heavy-Ion Induction Linacs for Inertial-Fusion Power Plants," in Proc. of the Heavy Ion Fusion Workshop, Claremont Hotel, Berkeley, Calif., October 29 - November 9, 1979, pp. 201-231 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10301.

K. Brown and J. M. Peterson, "Chromatic Correction for the Final Transport System," in Proc. of the Heavy Ion Fusion Workshop, Claremont Hotel, Berkeley, Calif., October 29 - November 9, 1979, pp. 385-387 (1980). Also Lawrence Berkeley Laboratory Report No. LBL-10301.

M. Tigner, R. Diebold, K. Johnsen, D. Keefe, A. McInturff, F. Mills, W. K. H. Panofsky, C. Pellegrini, J. Sandweiss, R. Schwitters, L. Teng, A. Tollestrup, and W. Willis, Accelerator Research and Development in the U.S. High Energy Physics Program, A Report to the High Energy Physics Advisory Committee of the U.S. Department of Energy, DOE/ER 0067 (June 1980).

D. Keefe, Research and Development on Accelerators to Produce Very High Beam Currents, Appendix A in DOE/ERA 0067, pp. 61-79 (1980).

D. Keefe, High-Current and Collective Accelerators, Physical Dynamics Report PDLJ-80-226 (June 1980).

J. W. K. Mark, G. Krafft, and T. F. Wang, Space-Charge Limits in Beam Plasmas Revisited, presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., November 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-24.

J. Bisognano and J. W. K. Mark, The Warm Beam Equilibria and Some General Stability Considerations, presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., Nov. 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-25.

W. Chupp, A. Faltens, E. Hoyer, D. Keefe, C. Kim, S. Rosenblum, J. Shiloh, and W. Herrmannsfeldt, One Ampere Two MeV Cs^{1+} Ion Beam, Poster paper presented at the CLEOS/ICF 1980 Conference, San Diego, Calif., February 26-28, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-09858.

A. Faltens, E. Hoyer, D. Keefe, C. Kim, L. J. Laslett, S. Rosenblum, and L. Smith, Ion Induction Linac 500 Joule Test Bed, Poster paper presented at the CLEOS/ICF 1980 Conference, San Diego, Calif., February 26-28, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-09859 and HIFAN-104.

J. Shiloh, W. Chupp, A. Faltens, E. Hartwig, W. Herrmannsfeldt, D. Keefe, C. Kim, R. Nemetz, and S. Rosenblum, Cs^{+1} Injector for an Induction Linac, Poster paper presented at the 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., November 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11342.

J. Shiloh, W. Chupp, A. Faltens, E. Hartwig, W. Herrmannsfeldt, D. Keefe, C. Kim, R. Nemetz, and S. Rosenblum, Cs^{+1} Injector for an Induction Linac, Poster paper presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., Nov. 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-27.

M. Tiefenback, M. Lampel, and A. Faltens, Optimization of Current Pulse Shapes in a One-Dimensional Diode, Poster paper presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., Nov. 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-28.

Papers submitted for presentation at the 1981 Particle Accelerator Conference, Washington, D.C., March 11-13, 1981:

- W. Chupp, A. Faltens, E. Hartwig, E. Hoyer, D. Keefe, C. Kim, M. Lampel, E. Lofgren, R. Nemetz, S. S. Rosenblum, J. Shiloh, M. Tiefenback, D. Vanecek, and W. H. Herrmannsfeldt, Operating Experience with a High Current Cs Injector for Heavy Ion Fusion.

- S. Chattopadhyay, A. Faltens, and L. Smith, Study of the Beam Breakup Mode in Linear Induction Accelerators for Heavy Ions.

- A. Garren, G. Krafft, and I. Haber, On Focusing of Heavy Ion Beams to a Target for Heavy Ion Fusion.

- T. F. Wang and L. Smith, Transverse-Longitudinal Coupling in Intense Beams.

- E. Close, Numerical Simulation of the Transport of Intense Beams of Heavy Ions in an Electrostatic Quadrupole System.

- A. Sternlieb, J. Bisognano, L. Smith, T. F. Wang, and I. Haber, Numerical Studies of Longitudinal Instabilities in Bunched Beams.

New Directions

Edward L. Alpen, Advanced Design Research, Heavy-Ion Medical Accelerator, Lawrence Berkeley Laboratory, Berkeley, Calif., Publication No. PUB-5047 (1980).

R. A. Gough, J. R. Alonso, T. Elioff, and H. Grunder, "A Future Dedicated Medical Ion Accelerator," pp. 415-420 in Biological and Medical Research with Accelerated Heavy Ions at the Bevalac, 1977-1980, M. C. Pirruccello and C. A. Tobias, Eds. (Lawrence Berkeley Laboratory, Berkeley, California, 1980), Report No. LBL-11220.

J. R. Alonso, Considerations for Design Parameters for a Dedicated Medical Accelerator, invited paper at MARIA Workshop II: Optimal Parameters of Relativisitic Heavy Ions for Radiotherapy Research, Edmonton, Aberta, October 9-10, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11685.

R. A. Gough, Dedicated Heavy Ion Medical Accelerators, invited paper at MARIA Workshop III: Accelerator Systems for Relativistic Heavy Ions in Medical and Scientific Research, October 20-24, 1980, Edmonton, Alberta, Canada. Also Lawrence Berkeley Laboratory Report No. LBL-11808.

H. Grunder, R. Gough, and J. Alonso, Synchrotrons for Heavy Ions--Bevalac Experience, invited paper at MARIA Workshop III: Accelerator Systems for Relativistic Heavy Ions in Medical and Scientific Research, Edmonton, Alberta, Canada, October 20-24, 1980. Also Lawrence Berkeley Laboratory Report No. 12081.

I. G. Brown, B. Feinberg, and W. B. Kunkel, The Berkeley Electron Beam Ion Source, presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., November 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-7.

B. Feinberg and M. C. Vella, Space Charge Neutralized Beam Collapse in EBIS, presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., November 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-8.

C. Litwin, M. C. Vella, and A. M. Sessler, Electrostatic Stability of the Electron Beam Ion Source (EBIS), presented at 22nd Annual Meeting, Division of Plasma Physics, San Diego, Calif., November 10-14, 1980. Also Lawrence Berkeley Laboratory Report No. LBL-11217-9.

Paper submitted for presentation at the 1981 Particle Accelerator Conference, Washington, D.C., March 11-13, 1981:

I. G. Brown and B. Feinberg, The Electron Beam Ion Source (EBIS) Program at LBL. Also Lawrence Berkeley Laboratory Report No. LBL-11711.