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MASTER

ANNUAL REPORT

ACCELERATOR & FUSION RESEARCH DIVISION

Fiscal Year 1979
October 1978 - September 1979

Lawrence Berkeley Laboratory
University of California, Berkeley

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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March 1980

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FOREWORD

The Accelerator and Fusion Research Division, which was expanded to include the magnetic fusion program only three years ago, represents an ambitious combination of projects in basic research, technological advancement and facility operation. Formally, the division is organized into four programmatic groups: Accelerator Operations, Advanced Accelerator Development, Magnetic Fusion Energy, and Heavy Ion Fusion. While distinct program goals are pursued within these groups, the various elements of the division's activities strongly influence and complement each other. During the past year, these goals and their collective impact on the division's role, have been strengthened by carefully evaluating the facilities and expertise at our disposal in relation to the nation's research needs.

An important event in the division's history took place this past year. Edward J. Lofgren, who had led the Accelerator Division and then the combined Accelerator and Fusion Research Division from their beginnings, stepped down on July 1, 1979 to return to research. As the new head of the division, I wish to express the division's enormous gratitude to Ed Lofgren. His wise guidance of the division's efforts, and his personal friendship and counsel to me and so many of his colleagues, have produced one of the laboratory's strongest programs. We are privileged that he will continue his contributions as a member of the division's senior scientific staff.

Because this division is blessed with an impressive record of achievements, the prospects for the future are exciting. A sense of continuity with the pioneering brilliance which has characterized the growth of this laboratory is reflected in the accomplishments and research philosophy of the division's outstanding staff, and undergirds our confidence in meeting the demanding tasks we have set before us.

Hermann A. Grunder,
Accelerator and Fusion
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ACCELERATOR OPERATIONS

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R. Yourd, M. Zisman,
E. Zajec.

SuperHILAC/Bevalac Operation

The SuperHILAC and the Bevatron/Bevalac are operated as National Research Facilities for studies in nuclear physics, biophysics, nuclear chemistry, biomedical studies and astrophysics. Ions from lithium to lead are accelerated to energies up to 8.5 MeV per nucleon at the SuperHILAC. Beams of two different ions can be produced on alternate pulses and delivered to one or two SuperHILAC experimenters plus the Bevalac. At the Bevalac, beams from hydrogen to iron are delivered to researchers at energies from approximately 70 MeV to 2.1 GeV per nucleon. Five major beam lines, with 13 target areas designed for various studies are currently in operation at the SuperHILAC. At the Bevatron, experimenters are served by eight beam lines, with several specialized target areas.

Outside users account for approximately half the research time at each accelerator. The Accelerator Research Coordination Office, augmented by a group of physicists, 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 communicate user concerns to accelerator operations staff, and also hold annual meetings to share research results and discuss future directions.

The capability to deliver intense very high mass beams is now being developed with the construction of the High Intensity Uranium Beams line item. When completed in FY 82, the SuperHILAC will produce

1 p A of all masses at up to 8.5 MeV/amu. The Bevalac will be capable of delivering relativistic beams of all mass numbers including uranium, in addition to high intensity intermediate energy beams between 40 and 200 MeV/amu.

Continual effort is given to improving the two accelerators, both in machine operation and experimental facilities, so that they remain relevant tools at the forefront of scientific investigation. User input regarding future research requirements form the basis of these development efforts.

Management Philosophy

Proposals for research time are submitted twice a year to program advisory committees (PACs, one for the SuperHILAC and one each for the nuclear science and biomedical programs at the Bevatron/Bevalac).

BBC 754-2502A

Top: The proximity of the SuperHILAC and the Bevalac permits a combination of accelerator capabilities which is available nowhere else in the world. In this aerial photo, the path of ions from the SuperHILAC to the Bevatron/Bevalac is superimposed on the site view.

Left: From the injection end, one can view the main portion of the SuperHILAC, which consists of two Alvarez-type tanks separated by a foil stripper.

BBC 799-12346

MEETINGS: 1979

January 11-12
Bevalac Biomed PAC
May 17
Bevalac Users'
Association Meeting
May 18
HIS Users' Group
Meeting
May 18-19
Bevalac Nuclear
Science PAC
May 21-24
Workshop on Ultra-
Relativistic
Nuclear Collisions
July 25-26
SuperHILAC PAC
October 11-12
Bevalac Biomed PAC
Nov. 30 - Dec. 1
Bevalac Nuclear
Science PAC

These expert panels meet and make recommendations for allocation of research hours to the Laboratory director; as a rule, their recommendations have been 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 research on the floor and to coordinate long-term improvements. Howel Pugh holds this post at the Bevalac, and Richard Diamond is scientific director at the SuperHILAC. The Biology and Medicine division appoints a scientific director for the biomed program at the Bevalac; E. John Ainsworth serves in this capacity.

The Accelerator Research Coordination Office (ARC Office), located in the Bevatron building, serves as the focus for user services, with particular attention to the needs of outside users. Three of its staff are also experimenters who serve as scientific liaison or coordinators for the programs at each accelerator. Gary Westfall performs this function for Bevalac nuclear science users, and Jerry Howard serves as liaison for Bevalac biomed users; Michael Zisman is the SuperHILAC 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. The scientific directors may allocate 10% of the research hours on a discretionary basis.

SuperHILAC PAC

P. Bond, Brookhaven Nat'l. Lab.
J. Cerny, LBL, ex officio
L. Cocke, Kansas State U.
H. Grunder, LBL (ex officio)
R. Stokstad, ORNL, Chairman*
W. Swiatecki, LBL
D. Ward, Atomic Energy of Canada
M. Zisman, LBL, Executive Sec'y.

* Dr. Stokstad recently (Feb. 80) joined the LBL staff.

Bevalac Nuclear Science PAC

J. Cerny, LBL (ex officio)
 H. Feshbach, M.I.T., Chairman
 H. Grunder, LBL (ex officio)
 S. Koonin, Cal. Tech.
 H. Pugh, LBL (ex officio)
 J. Schiffer, ANL
 R. Stock, GSI, Germany
 W. Wenzel, LBL
 G. Westfall, LBL, Exec. Sec'y
 T. Yamakazi, U. of Tokyo

Bevalac Biomed PAC

E. Ainsworth, Exec.
 Secretary, LBL.
 E. Alpen, LBL
 W. Glass, Batelle
 Pac. Northwest
 H. Grunder, LBL (ex
 officio)
 R. Kallman, Stanford
 S. Rossi, Columbia
 University
 H. Suit, Mass. Gen.,
 Chairman
 G. Whitmore, Ontario
 Cancer Inst.
 H. Withers, M.D.
 Anderson Hosp.

MEETINGS: 1980
 February 22-23
 Bevalac Users'
 Association Meeting
 March 26-27
 SuperHILAC PAC
 April 14-15
 Bevalac Biomed PAC
 May 30-31
 Bevalac Nuclear
 Science PAC

The experimenters at each accelerator belong to users groups which hold annual meetings to share research results. An executive committee of each group conducts monthly telephone conferences with accelerator management.

SuperHILAC
Users' Association
Executive Committee

Bevatron/Bevalac
Users' Association
Executive Committee

E. Ainsworth, LBL (ex officio)	J. Cerny, LBL (ex officio)
J. Cerny, LBL (ex officio)	S. Curtis, LBL
R. Diamond, LBL	M. Garcia-Munoz, U. of Chicago
H. Grunder, LBL (ex officio)	H. Grunder, LBL (ex officio)
B. Harvey, LBL	P. Kirk, LSU, Chairman
N. Johnson, ORNL, Chairman	J. Leith, Rhode Is. Hosp.
M. Kaplan, Carnegie-Mellon U.	H. Pugh, LBL (ex officio)
L. Moretto, LBL, Secretary	J. Slater, Loma Linda University
R. Vandenbosch, Univ. of Washington	G. Westfall, LBL, Liaison
M. Zisman, LBL, Exec. Sec'y	K. Wolf, Argonne

In addition to the annual users meetings and the semiannual meetings of each PAC, at least one major scientific workshop in connection with SuperHILAC-Bevalac research is generally conducted every year.

Publications

A Microcomputer Control System for the SuperHILAC Third Injector, W. D. Lancaster, et al, LBL-9763.

Operation of a High-Current Xenon Source, W. Chupp, D. Clark, R. Richter, J. Stapler and E. Zajec, NIPAN-75 (LBL-8859), (PAC paper), March 1979.

Prospects for High Energy Heavy Ion Accelerators, C. Leemann, LBL-08899, presented at the Particle Accelerator Conference, San Francisco, CA, March 12-14, 1979.

Charge-Changing Cross Sections for Heavy Ions at Energies to 8.5 MeV/amu, J. Alonso D. Dietrich, and H. Gould, LBL-08932, presented at the Particle Accelerator Conference, San Francisco, CA, March 12-14, 1979.

Computed Tomographic Reconstruction of Beam Profiles with a Multi-Wire Chamber, J. Alonso, C. Tobias, and W. Chu, LBL-08947 presented at the Particle Accelerator Conference, San Francisco, CA, March 12-14, 1979.

Highlights

Over the past year, research results from the nuclear science programs at the SuperHILAC and the Bevalac have generated worldwide interest. At the same time, the heavy ion therapy program at the Bevalac has begun full-scale patient trials on a four-day-a-week basis. Installation and development of new experimental beam lines and facilities has been a particularly consuming task for the operations staff. The table on the next page summarizes the operating experience for FY 79. The percentage of research time devoted to outside users was 53% at the SuperHILAC and 48% for Bevalac nuclear science experimenters; 19% of the Bevalac Biomed program was devoted to outside users. An important element of accelerator operations which is not reflected in the table is the versatility of beam delivery and scheduling: typically three ion, energy and/or beam line changes were made at the Bevalac every day to accommodate a variety of research needs. At the SuperHILAC, the routine operating mode was two ion beams delivered to two SuperHILAC experimenters and the Bevalac.

ACCELERATOR OPERATION SUMMARY FY79
SuperHILAC and Bevatron/Bevalac

Machine Operation for Research	SuperHILAC Hours	Bevatron/Bevalac Hours
Nuclear Science	2557.00	1856.50
Biology & Medicine	---	1046.00
Machine Studies	400.25	298.50
	2955.25	1201.00
Tuning	440.50	918.75
TOTAL OPERATING HOURS	3495.75	4119.75
Unscheduled Maintenance	1444.25	787.25
TOTAL SCHEDULED OPERATION	4850.00	4907.00
Shutdowns	3910.00	3853.00
<u>Beam Utilization (Experimental Hours)</u>		
Nuclear Science	3210.00	2209.50
Biology & Medicine	---	1046.00
<u>Multiplicity (Experiment Hrs/Research Operation Hrs)</u>		
Nuclear Science	1.26	1.19
Biology & Medicine	---	1.00
Combined	1.26	1.09

EXPERIMENT SUMMARY
FY 79

	SuperHILAC	Bevatron/Bevalac	
Experiments Operated	NuclearSci. 30	Nuclear Sci. 30	Biomed 20
Completed	30	15	
Institutions			
Universities	10	13	7
Others	6	6	4
	16 +LBL	19 +LBL	11 +LBL
Percent time to LBL	47	52	81
Percent to others	53	48	19

The focus through FY 80 to spring of FY 81 will be steady operation for the final round of research before the availability of very high mass beams, up to uranium, that will maintain the position of these two machines as technological leaders in the field of heavy ion physics.

SuperHILAC FY 79		Bevatron/Bevalac FY 79	
Ion	Ave. Intensity at* post-stripper exit (particle amperes)	Ion	Ave. Intensity on target
Lithium 6	0.4 pA	Protons	1x1011
Carbon 12	8 pA	Alphas	1x1010
Oxygen 16	3 pA	Carbon	5x109
Neon 20	7 pA	Nitrogen	5x108
Argon 40	2 pA	Oxygen	5x108
Calcium 48	0.2 pA	Neon	1x109
Iron 56	0.2 pA	Argon	1x108
Krypton 86	0.1 pA	Calcium-48	1x107
Niobium 93	30 pA	Iron	1x106
Xenon 136	30 pA		
Holmium 165	0.5 pA		
Lead 209	0.2 pA		

Outside Users Support

Several mechanisms exist to assist outside users in designing, proposing and conducting experiments at the SuperHILAC and the Bevalac. Although the entire Accelerator Operations Group is ultimately dedicated to serving the needs of the research users, the focus of this support is the ARC Office. However, additional technical support is required by outside users to increase their research productivity.

A core of physicists, computer specialists and technical support personnel at each accelerator is available for assistance in designing or modifying beam lines for specific performance characteristics, interfacing data collection systems and maintaining delicate equipment. At the SuperHILAC, the principal staff contacts for outside user support are Michael Zisman (physics, experiment coordination), Creve Maples (data collection systems), Eleanor Potter (supplies), Bill Elwood (machinist), and Richard Diamond (scientific director). For Bevalac users the primary technical staff for outside user support for nuclear physics are Jose Alonso, Hank Crawford and Roichi Wada (physics, beam lines), Gary Westfall (physics, experiment coordination) and Howel Pugh (scientific director). The biomed outside user community is assisted by Jose Alonso (physics, instrumentation), Jerry Howard (radio-biology, operations), Tom Criswell (radiotherapy, hardware, computer systems), Bill Chu (physics, beam delivery) and John Ainsworth (scientific director). Scheduling assistance is provided by Fred Lothrop. Considerably more effort is necessary for user support, but is difficult under current funding and manpower constraints.

Publications

High Purity Radioactive Beams at the Bevalac, J. Alonso, A. Chatterjee and C. Tobias, LBL-951, presented at the Particle Accelerator Conference, San Francisco, CA, March 12-14, 1979.

The Bevalac Radiotherapy Facility, J. Alonso, J. Howard, and T. Criswell, LBL-08961, presented at the Particle Accelerator Conference, San Francisco, CA, March 12-14, 1979.

A Study of Microwave Instabilities by Means of a Square-Well Potential, R.-J. Kim, LBL-9741, presented at the ISABELLE Workshop, September 1979.

Longitudinal Dynamics of Bunched Beams in a Model Linac, R.-J. Kim, LBL-10250, November 1979.

Preliminary Design Report, High Intensity Uranium Beams from the SuperHILAC and the Bevatron, Accelerator Staff, Pub. 5014, Feb. 1979, rev. Nov. 1979.

The VENUS Project, Accelerator Staff, Pub-5025, June 1979.

SuperHILAC/Bevatron Computer Control Status

Over the past several years, a network of Mod-Comp computers has been created at the SuperHILAC and the Bevatron to control all accelerator parameters at each machine and permit the complex time-sharing operations that are now standard. Although they currently operate independently, the two computer systems will be linked in FY 81. They are discussed here together because much of their development is shared.

The basic improvement program was nearly completed by the end of FY79. At the SuperHILAC, three operator consoles are now in use. Vacuum and rf status displays have been added.

At the Bevatron, the transfer of all PDP-8 functions to the Modcomps was completed; the old computers and their associated interfacing hardware were

The ModComp room at the Bevatron houses the computers which control all accelerator parameters, as well as the operator displays in the main control room. A similar set-up exists for the Mod Comp installation at the SuperHILAC.

BBC 799-12350

removed. The Modcomp hardware now has reached its design goal of five processors in a star-network, driving three operator consoles and a summary display. All major components of the accelerator that are presently suitable for computer interfacing have been provided with software. All parameters from every section of the accelerator are easily accessible from FORTRAN programs in the central computer. A number of additional components will be added this year.

The basic layer of software upon which the applications are built, the OPERATING SYSTEM, has been

completely updated to the latest Modcomp version. All the LBL-created enhancements have been speeded up and their memory requirements sharply reduced. It is now about twice as fast on the average, and peak overloads are handled by a roll-out/roll-in technique. The use and layout of disc space has been rearranged to support full accelerator program and data archiving needs while allowing 3-5 users to perform simultaneous programming or other utility operations. About 12 people or groups share the facility at each site, including operators, engineers and physicists engaged in beam-line design and development; and hardware engineers and technicians from the electronics shops (for testing and inventory).

Among the recent improvements installed at both sites is an ALARM SCANNER, which compares actual and desired parameters for selective presentation to the operators when deviations are detected. STATE SAVE provides automatic recovery of all parameters if any computer (central or satellite) fails or halts.

SuperHILAC Facilities Developments

The SuperHILAC now supports five major beam lines, plus the Bevalac transferline, and 13 target areas, as illustrated in the experimental layout. Two more caves are being completed. Several additions to the SuperHILAC beam switchyard are providing increased operating flexibility among these beamlines. Two simultaneous experiments may receive different particles on alternate pulses, or share

BBC 759-12360

At the exit of the SuperHILAC, pulsed switching magnets direct beam to 13 target areas, plus the Bevalac transfer line.

LEGEND

QUADRUPOLE SINGLET

QUADRUPOLE DOUBLET

DIPOLE BENDING MAGNET

PULSED MAGNET

PULSED ALIGNMENT MAGNET

QS

QD

M

PM

PAV

SUPERHILAC EXPERIMENTAL AREA

(JANUARY 1980)

each pulse of the same ion. The first case is time-sharing, in which duty cycle is reduced, but maximum intensity is preserved for each ion. In the second case, beam splitting, duty cycle is conserved, and beam intensity is variable between the two users.

To make these modes possible, a new three-channel septum magnet (M3) was installed in the E2 line in cave A. In conjunction with the new PM5 pulsing magnet, this configuration permits time-shared beams to be delivered to three new beam areas. Parasitic use of beams for experimental set-up purposes is now possible in all major cave areas at the SuperHILAC. A splitter magnet (M2), which is duty-cycle-conserving, has also been built for this line to split the beam at the entrance of M3. The advantage of split beams over pulsed beams is that each experimenter receives the maximum pulses per second and beam intensity is variable. The magnets and power supply underwent final testing at the end of 1979, and will be installed in January 1980.

A new cave area designed for radioactive targets (S cave) was installed on the SuperHILAC zero degree beam line (E31) and was used for several actinide target irradiations during the year. The E31 line transmits maximum beam intensity for the target irradiations, and includes a fast-acting (3 msec) "slammer" valve to insure the containment of active material in the event of an accidental target rupture. A small scatter chamber, glove box, and newly-designed beam interlock system are other components of this facility.

A major expansion was implemented in the coulomb excitation counting area with the addition of a fifty foot trailer. The resulting increase in the

Opposite:
Layout of beam lines in the Super-HILAC experimental area.

Below left:

The 30-inch scattering chamber located in SuperHILAC Cave G is heavily used by outside researchers for nuclear reaction experiments ranging from elastic scattering to heavy ion-neutron coincidence work.

Below right:

One of the most heavily used research areas at the Super-HILAC is the Cave J multi-purpose target area. Four experiments are currently set up here, but a new cave (K) is nearing completion to relieve the crowding.

BBC 772-1217

KSB 799-12344

counting area space relieved the very congested conditions in this heavily used facility. Design and specification for the experimental requirements in the new E87 line were completed. Magnets were built late in FY 79; final installation of elements is expected by February 1980. The Moretto group will move their equipment to a new cave on this line (cave M) to relieve another very crowded area, cave J, presently being shared by Moretto and three other groups.

The concrete pad between Bldg. 71 and the shop building, designed to accommodate a major new experimental facility, was completed last year. A roof and craneway have been drawn up for this area and await plant funding approval.

SuperHILAC Accelerator Improvements

The new phase probe energy measurement system, designed and installed over the past few years, was augmented with more detector probes over the last year, particularly in the post stripper linac tank and the diaphragm areas between rf tanks. When fully functional, these will allow non-destructive measurement of phase differences between tanks for optimization of rf tuning. By the end of 1979, phase probe energy measurements were possible in the E2, E15, E11 and the E33 lines. The present manual system has a threshold beam current of about 250 nA peak. Planned improvements to the system should allow measurement of peak beams of about 25 nA.

Experiments using time-of-flight techniques rely on short beam bunches (less than 0.5 ns). Various post-accelerator buncher schemes are under investigation to satisfy this requirement. Experiments were carried out to measure the longitudinal phase space and its dependence on rf parameters. Typically, full energy HILAC beams were found to fill a phase space area of 70 keV-ns/amu. In order to do these measurements, the existing energy crystal (XTL) system has been expanded to allow for fast timing measurements and two-parameter data acquisition. Electronic time resolution better than 60 ps has been achieved.

Finally, feasibility tests on a liquid film stripper are underway to avoid the anticipated problem of short stripper foil lifetimes with higher intensity beams.

Bevatron/Bevalac Nuclear Science Facilities Developments

Two issues were dominant at the Bevatron/Bevalac last year: continuation of the major reorganization of the experimental hall, and preparation for the launching in fall 1979 of full-scale cancer treat-

Opposite:
Layout of the
Bevatron/Bevalac
experimental floor.
At upper left is the
new HISS (Heavy Ion
Spectrometer System)
facility; at lower
right, Beam 39 is the
low energy nuclear
physics beam line.

ment trials on a four-day-a-week therapy schedule. Significant successes were realized on both of these fronts.

In the Low Energy Beam Line (Beam 39), all the magnets were installed, along with the scattering chamber, the cave area and the control house. The line was used for preliminary experiments, but further debugging will render it completely operational this year, when it becomes an important outside user facility.

The new Zero-Degree Spectrometer Line (Beam 40) was reinstalled and operating as a very successful experimental facility. In one of its most spectacular runs in 1979, over a dozen new isotopes were discovered in a 24-hour period with a calcium-48 beam, itself a challenge to produce. This area is heavily used for fragmentation studies and cosmic ray calibrations.

The Plastic Ball-Plastic Wall line (Beam 43) received concentrated attention toward the end of the year, in preparation for its initial runs in Fall 79 for the German-American collaboration (GSI-Marburg, LBL) which conceived it. Additional refinements in 1980 will improve beam purity.

HISS

Construction of the Heavy Ion Spectrometer System (HISS, Beam 42), progressed substantially during FY 79. This flexible dedicated user facility, designed for high momentum and spatial resolution and large solid angle, will consist of a large volume (1 m gap, 2 m diameter), high dispersion (30 kGauss) superconducting dipole magnet (525 tons); a highly versatile, automated beam preparation system; computer system for experiment

Below:

The Low Energy Beam Line (Beam 39) is designed to accommodate the transitional energy range from 20 to 200 MeV/nucleon which connects traditional nuclear physics to relativistic heavy ion physics.

Below right:

The Plastic Wall, being assembled here by a collaboration of German and American researchers, consists of 160 time-of-flight detectors. It will be used in concert with the Plastic Ball, to be installed in FY 80, which adds another 815 modules to detect central collision fragments, while the particles emerging with small forward angles are identified in the wall.

BBC 799-12305

XBC 799-12372

XBC 790-14564

XBL 799-12036

control, data collection and on-line experiment monitoring and staffing for multi-user support

The rotating assembly and the majority of steel for the large aperture HISS magnet were installed. Tests of the rotating mechanisms were successful. The first phase of HISS, the straight-through momentum-recombined transport line, will be ready for research in mid-80. Phase 2, the high dispersion isotope loop, will be installed later.

Bevalac Biomedical Facilities Development

The patient therapy program began in small scale in the spring of 1979. Treatment delivery techniques, dosimetry, field shaping and instrumentation were liberally borrowed from the successful development efforts over the past years at the 184-Inch Synchrocyclotron. Considerable support from the accelerator operations staff was focused on achieving the necessary beam reliability for reproducible patient treatments. An example of such reliability was the successful completion of a 24 week schedule of fractionated irradiations delivered for one radiobiology experiment. An advanced computer control system, brought on line in summer 79, provides for fast switching between two irradiation areas to allow simultaneous patient treatment and radiobiology, sophisticated data logging and operator interaction, and great flexibility for control and modification. Intensive accelerator staff support contributed to the inauguration of full scale patient trials in the fall.

Above:

The HISS spectrometer is a joint effort by Bevalac researchers to create and staff a dedicated user facility capable of precisely identifying and measuring the directions and momenta of many particles from one interaction. At the heart of HISS is a large volume (1 m gap, 2 m diameter), 525 ton superconducting dipole magnet, augmented by an automated beam preparation system and a data collection and monitoring system.

Left:

installing the HISS magnet steel on its rotating base in Fall 79 was a major accomplishment.

Right:

In the radiotherapy room of the Bevalac Biomedical Facility, the beam passes through dosimetry and range-modifying apparatus on the optical rails before entering the patient. A collimator, shaped to the treatment field prescribed by the radiotherapist, is located directly in front of the patient. With four treatment days per week, patients receive their full course of heavy ion therapy in fractionated doses.

Below:

In the biomedical control room, all beam delivery, dose monitoring, and record-keeping is handled by computer. However, redundant, computer-independent controls are used to insure that the correct dose is delivered. Rapid beam switching between the two biomed irradiation areas permits patient treatments in one room, while biology experiments are conducted in the second room.

Below right:

A comfortable patient waiting and examination area has been created in the Bevalac Biomedical Facility.

BBC 798-10683

A new radioactive beam - neon-15 - was successfully produced during the year. It joins carbon-11 as a tool for potential treatment verification techniques and other applications under study.

A much needed X-ray CT scanner, funded by a grant from National Cancer Institute, was ordered from EMI for installation in Bldg. 55. Delivery is promised for mid-1980. This unit will be rotatable through 90° to permit tumor imaging in the actual treatment position. Its use on-site will facilitate the operation of the treatment program and make possible standardization of treatment planning techniques.

BBC 788-10243

BBC 788-10247

Bevatron/Bevalac Accelerator Improvements

Dramatic improvements in the output of the Bevatron local injector have become extremely important in permitting flexibility in scheduling different ions to various experiments. Successful operation with a new extractor source geometry now produces currents of carbon up to 400 μ A peak; all carbon radiotherapy is now done with this injector. Higher rf amplifier gradients and installation of new injection line quadrupoles have improved operational dependability. During FY 80 we will extend efforts directed at obtaining an acceptable neon beam from this injector.

BBC 794-4866

Ion source development to improve the output of carbon ions from the local injector is a continuing activity at the Bevatron.

An important continuing project is to implement hardware and software changes necessary to speed switching of beam particle, energy and/or beam line. Realization of significant progress in fast beam switching was essential for inauguration of the daily patient treatment schedule; typically, one ion, usually carbon or neon, is delivered to biomed four day shifts per week, while a different beam and energy is produced for nuclear science users during many evening and night shifts.

High Intensity Uranium Beams Line Item Progress

Authorization of construction for the High Intensity Uranium Beams line item was received on June 18, 1979. A thirty month overall construction

and installation schedule is anticipated. The project is described in the Preliminary Design Report: High Intensity Uranium Beams from the SuperHILAC and the Bevalac, Pub. 5014, Feb. 1979 (rev. 11/79). The project consists of two major parts, a new very high mass injector for the SuperHILAC and an ultra high vacuum system for the Bevatron, plus modifications to the transferline from the SuperHILAC to the Bevalac.

SuperHILAC Third Injector

Construction work on the conventional facilities for the new injector (a Cockcroft-Walton pre-injector tower enclosure, a power supply building, and an elevated beam transport deck) started on July 16, 1979 and is scheduled for completion by April 1980.

An intense design effort for the third injector special facilities and equipment has continued throughout most of the year. Fabrication of most of the long-lead-time items had been initiated by summer 1979. Construction work was also started for the beamline bending magnets, quadrupoles and trim/alignment magnets, and orders were placed for the quadrupole and trim magnet power supplies. Most of the components for the Cockcroft-Walton pre-injector and the beamline to the Wideroe linac will be fabricated in FY 80 and many of them assembled in the new building. The main tank and stubs of the Wideroe linac will also be built and installed.

Although in FY 79 the ADAM injector test stand

The SuperHILAC third injector system, consisting of a Cockcroft-Walton pre-injector, two transport lines, and a low velocity Wideroe linac, is shown in the layout. It is scheduled to begin operating in 1981.

XBL 7910-12105

was used for preparation of a rhodium beam and for ion source debugging, the central thrust of our ion source development work currently lies with the operation of the uranium test stand for the third injector. A GSI source was adapted, and pulsed supplies were added or upgraded, all to probe the low charge to mass heavy ion species, such as U^{+5} , which this injector is to supply. Acceptable emittances of solid and gaseous ion beams were measured with intensities of several electrical milliamperes, peak.

Control requirements for the third injector include stand-alone control capability for the Cockcroft-Walton, Wideroe, and transport lines, and display of a large amount of beam-related information for operator use. Considerable effort was directed to the planning, design and development of the new microcomputer control system for the third injector, and specific design work was initiated in detailing the operator control console, graphics and displays, and a new fiber-optic communication link. The overall system requires control of up to 80 analog and 300 boolean devices and will consist of commercially available hardware (20 microcomputer boards with 700 kilobytes total memory), in a star type architecture. Considerable R&D effort has provided a sound basis for final design and implementation of this approach to the entire third injector control system with the potential for expansion to control the other two injectors. In FY 80, components will be purchased and installation will be partly completed for the third injector control system.

The transfer line between the SuperHILAC and the Bevatron will have much of the engineering completed and construction will have started on the magnets which must be rebuilt. Many of the minor modifications to power supplies and cooling systems will be completed.

Bevatron High Vacuum Improvement

The objective of the Bevatron Vacuum Improvement portion of the HIUB program is to achieve a vacuum of 10^{-10} torr in the Bevatron to prevent significant loss of the accelerated ion beam due to collisions with residual gas molecules. A new and improved means of achieving this goal was conceived during FY79 and was formally adopted after careful investigation.

The new approach is to install a cryogenically-cooled liner (cold bore) through which the beam will circulate inside the existing Bevatron vacuum chamber. The tangent regions will be maintained at 77° K, while the innermost part of the quadrant tanks will be cooled to 120° K. At these tempera-

tures, the outgassing of the cryo-cooled surfaces is virtually zero. The resulting gas load within the beam circulation region of the Bevatron will be very significantly reduced. The 77° K surfaces will effectively "pump" CO₂, water and organic vapors, while the 12° K surfaces will pump N₂, O₂, CO and some other gasses. H₂, and to some extent He, will be pumped by activated charcoal surfaces maintained at 12° K. The net effect is an enormous increase in pumping speed over the present system.

The quadrant liner will consist of a curved, triple-walled rectangular tube with multi-layer superinsulation between each layer to minimize heat transfer. The outer box will be exposed to the existing Bevatron vacuum in the 10⁻⁷ torr range. The intermediate box will be cooled to 77° K, and the inner box to approximately 12° K. The cryo-cooled boxes will be constructed of copper-clad printed circuit fiberglass-reinforced plastic sheets. The copper surface is etched in a striped pattern to provide thermal conduction, yet permit the time-varying magnetic field of the Bevatron to penetrate easily. Tests conducted on a simulated

The cold bore tank for the curved sections of the Bevatron ultra-high vacuum liner consists of three concentric boxes, separated by superinsulation. The outer box is exposed to the existing Bevatron vacuum, the middle box is cooled to 77° K and the innermost box to 12° K to reach a vacuum of 10⁻¹⁰ torr in the main ring.

CBS 7910-13841

A test section of triple-walled liner proved that the vacuum goal will be reached with the cold-bore approach.

section of the Bevatron liner confirmed that this concept readily achieves the vacuum goal. During the first part of FY 80, we will refine the final designs for the quadrant sections of the vacuum chamber. A full-size prototype section of the cold-bore quadrant liner will be tested in a vacuum chamber. The circuit board material will be purchased and etching and assembly will begin.

Concentrated layout and design work will be completed on each tangent area, with fabrication beginning as each set of detailed drawings is finished.

Advanced High Charge State Ion Source R&D

The Accelerator and Fusion Research Division and the Nuclear Science Division of LBL are planning the construction of an advanced high charge state heavy ion source, to be used at the 88-Inch Cyclotron. Detailed studies have been made of the potential of two sources - the Electron Beam Ion Source (EBIS) and the Electron Cyclotron Resonance (ECR)

source - which have been the subject of considerable development in laboratories in France and the U.S.S.R. The EBIS source has been selected as having the greater capability for producing the highest charge states, especially for the medium mass ions, to extend the performance of the 88-Inch in the 10-30 MeV/amu range.

We have begun an intense R&D effort to build an experimental EBIS, with the goal of providing optimum design specifications for final construction of an EBIS source for the 88-Inch Cyclotron. Preliminary design work, and observation of the EBIS operation at Saclay, France were conducted last year.

Effort in FY 80 will be concentrated on building up a small EBIS test stand to serve as the developmental facility for the final device. Critical parameters to be investigated include electron beam alignment in the solenoid, magnetic field influence on the electron gun and the effect of space charge neutralization. The high electron beam compression inferred from the French experiments will permit high charge state production at 50 pulses/second and duty factors as high as 50%.

The final EBIS will be funded as an equipment line item for FY 81, 82 and 83. A formal proposal will be submitted in September 1980.

184-Inch Synchrocyclotron

The 184-Inch synchrocyclotron operates as a dedicated medical accelerator. Helium ions accelerated to an energy of 230 MeV per nucleon are used to treat pituitary gland diseases and various cancers in human patients, as well as for parallel dosimetry and biology experiments. The uniform treatment field may be as large as 27 cm in diameter, and the Bragg peak extended to as much as 14 cm. The dose rate exceeds 150 rads per minute, yielding typical treatment times of one minute.

During FY 79, the accelerator operated for 1009 hours to provide 1,673 treatments to 102 patients. Reliability has continued to be excellent, with a total down time of 13-1/2 hours. Of the 18 failures during the year, 9 resulted in less than 1/4 hour delay for the medical program. Overall reliability was 98.7%.

VENUS Project

Looking toward the future research needs of the nuclear physics community, studies of a versatile heavy-ion facility have been underway at LBL for several years. The VENUS (Variable Energy Nuclear

V E N U S **RELATIVISTIC HEAVY ION ACCELERATOR** **AND STORAGE RING**

CBB 801-431

Synchrotron) dual ring superconducting accelerator/storage ring concept has been devised as the most versatile and economic solution to post-SuperHILAC/Bevalac research priorities. 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 2 on 2 to 20 on 20 GeV/amu (approximately 1 TeV/amu fixed target equivalent) for colliding beam interactions. The 230 meter diameter VENUS rings fit comfortably into the Laboratory site, with the SuperHILAC used as injector.

In FY 79, a preliminary description of the VENUS concept was circulated (The VENUS Project, Pub. 5025, June 1979), and several workshops among the heavy ion physics community have been or are being held, with the aim of refining performance requirements. A construction proposal will be prepared in the near future. If construction began in FY 84, VENUS could be operating by 1988.

Schematic layout of the VENUS concept, with the rings separated to illustrate versatile transfer, reinjection and extraction operations.

Aerial view of the
PEP site at the end of
the Stanford Linear
Accelerator shows
work in progress.

Lower yard region
of the Experimental
Hall at Region 8 gives
access for large
equipment.

BBC 801-456

ADVANCED ACCELERATOR STUDIES

The Advanced Accelerator Group conducts programs in high energy physics accelerator R&D in pursuit of two objectives. The first is to support current accelerator needs for design and operational improvements; the second is to push the frontiers of accelerator theory and technology to supply the foundation for new principles and techniques for future high energy physics applications. Currently, this group's efforts are represented by four programs: PEP research and development, high field superconducting accelerator magnets, stochastic beam cooling, and accelerator theory.

Positron-Electron Project (PEP)

The fiscal year 79 marked the third year of construction for the PEP (Positron-Electron-Project) project with major components of the facility nearing completion. All conventional facilities were completed, installation and testing of all technical components was in maximum progress, and the various experimental detectors were being assembled in the interaction halls.

First tests of the injected beam transport system took place in the early part of the year. In November beam was injected successfully into the PEP main ring. The first circulating beam is expected in March 1980. Although this is several months behind the working schedule of the past year, it is on-schedule with respect to the April 1980 date projected in the original PEP proposal schedule. The project has been maintained within its total projected cost of \$78 M. Various aspects of the PEP project and other research and development activities are described below.

PEP in Brief

PEP, a joint venture by scientists and engineers from LBL and SLAC, is a six-sided storage-ring facility currently being constructed at the end of the two-mile-long linear accelerator at SLAC. Basically, the project will provide a storage ring in which counter-rotating beams of electrons and positrons will circulate for several hours and collide head-on with energies up to 18 GeV per beam. The collisions take place at six points spaced symmetrically around the ring. Various experimental devices will surround these collision points to analyze the reaction products.

ADVANCED ACCELERATOR STUDIES GROUP

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The ring tunnel scribes a circumference of approximately 1.4 miles and varies in depth between 20 and 80 feet below ground. The 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 various instrumentation. The interaction halls (and beam collision points), which partially protrude above ground, are at the mid-points of the six straight sections.

In a typical interaction hall, half of the building is above ground and half below. The hall has two sections: the below-ground portion, constructed of heavy concrete walls, and an outer metal frame building. A concrete block shielding wall and a movable crane-operated concrete curtain separate the two areas. Operational experiments will be 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 beam is in operation.

Progress of PEP Conventional Facilities

During FY79, the last three of five conventional facilities subcontracts were essentially completed. The major Beam Housing Subcontract was finished after completion of the last of four concrete interaction halls (at Region 2) and the remaining beam tunnel structure in Regions 9 through 11. Excess ground water in the area of the newly-mined tunnel from Region 9 to 11 required the installation of additional water collectors and

The beam tunnel from region 9 to 11 was the last portion to be completed.

water sealant to control undesired seepage. In each interaction/assembly hall a radio-controlled 50-ton overhead traveling crane was installed, followed by a 107-ton concrete shielding curtain which was formed and poured on the hall floors and then hoisted into place 40 feet in the air. The movable curtains are mounted on rails near the hall ceiling. A system of shielding blocks is first stacked up to the limit of the crane hook height. The movable curtain is then towed by the crane into place directly above the blocks to completely seal off the experimental area and effect a safe radiation barrier.

Except for minor items, the Support Facilities Subcontract was finished with the construction of seven steel-framed support buildings, ranging in size from 440 to 12,300 sq. feet, and three assembly buildings. One support building is located at the upper yard of each interaction area and houses various combinations of instrumentation and control, rf and magnet power supply equipment. The seventh and smallest building is located at the symmetry point of Region 7 and houses equipment for monitoring beam luminosity. PEP's main control and computer room is housed on the Region 8 building along with upstairs offices and laboratory space. The interior framing of support buildings 4 and 12 allows for the future economical addition of a 2,650 sq. foot second floor mezzanine.

Two of four counting houses were nearing completion at the fiscal year's end. These 50' x 50' two story buildings, located at the lower yards of Regions 12, 2, 4 and 6, will house computers and electronic equipment that will control and monitor the various PEP experiments.

Installation of all conventional utilities including lighting, electrical power, fire detection and sprinklers, cable trays, vacuum and magnet cooling water, compressed air and a liquid level system was completed last year for all 2.2 kilometers of the PEP Beam tunnel. The mechanical systems include pumps, ion and heat exchangers, surge tanks, filters and controls. The electrical portion includes transformers and switchgear that service all PEP technical systems.

Paving and landscaping, while not essential for beam turn-on, were also completed in FY79. The access roads and lower yards of each region received four inches of asphaltic paving to support the heavy loads of experimental detectors outside the experimental areas while the Ring Road and upper yards received a double seal coat surfacing because of the more normal traffic loads expected.

The landscaping work involved the planting of approximately 1200 native trees and shrubs including

Publications

PEP

A Proposed Orbit and Vertical Dispersion Correction System for PEP, E. Close, M. Cornacchia, A. King, and M. J. Lee, IEEE Trans. on Nuclear Science, Vol. NS-26, PEP-271, June 1979.

A Beam-Beam Simulator for the Single-Pass Linear Collider, R. Sah, AATF/80/14, February 1980.

A Superconducting Proton Storage Ring for PEP, A. Garren, E. Moisshever, J. Peterson, and R. Sah, Ibid, p. 3261.

The upper beam line, emerging from the south injection tunnel, is one of two mirror-image 220 meter long transport lines for positrons and electrons. The line descends toward the PEP storage ring below, and joins the main ring some 35 meters downstream.

BBC 001-019

oaks, willows and California redwoods. This new greenery will help blend the PEP facility into the surrounding topography and create a pleasant environment for the facilities.

PEP Beam Transport and Injection Systems

Another of LBL's responsibilities is the beam-transport and injection system. Here the task was to design and build a system to switch the appropriate electron and positron beams out of the many beams emerging from the two-mile linac, to transport them to the PEP tunnel, and there to launch their orbits in the storage ring.

Two beam lines are required, one for electron beams and the other for positrons, totaling over 400 m in length. Seventeen different magnet designs were used for a total of 108 magnets. Also, some 120 devices were made for monitoring, analyzing, and controlling the beam. Threading through the entire beam-transport line is a vacuum system made up of several hundred components.

The first installed beam line magnets were powered in January 1979. This major PEP milestone was achieved a full month ahead of schedule. Beam tests using electron and positron beams from the linac began in February and were immediately successful, operating almost exactly as designed. The south injection line was extended to the 2/3 point and successfully tested with beam in June.

In November the complete south line was tested. In each test, the beam was quickly and easily steered through the line and delivered with good transmission and correct optical quality. These tests proceeded so well that beam operation was soon transferred to the Main /Control Center staff. A steady, high intensity 10 GeV positron beam was delivered via this line for the successful November/December beam-launch tests in the PEP ring.

The north line was completed to the 2/3 point, and it, too, was ready for beam in November, although beam tests were delayed because the personnel protection system in that area of the PEP tunnel was incomplete.

The PEP beam lines have been useful also for monitoring and analyzing other linac beams. The use of a scintillator screen at a point of high energy resolution allowed the first (unplanned) detailed observation of the phenomenon of beam breakup during the testing of the south beam line. A subsequent run was scheduled for just this purpose. The line was also used as a convenient monitoring point for tests related to the proposed single pass collider system.

PEP Survey and Alignment

The development of the PEP Laser Surveying System was completed early in FY79, and was put into operation after a short period of testing. After a surveying crew was trained, most of the 700 magnets in PEP were aligned in the second half of the fiscal year. The Laser Surveying System is unique in that the recording and analysis of survey data are entirely computerized. Even the operation of the specially built surveying instruments is cued by an on-line computer.

Early in the year, a network of approximately twenty survey monuments were constructed on the surface of the PEP site and were accurately surveyed. Twelve primary survey monuments in the PEP tunnel were then located by surveying through vertical penetrations and by tying these monuments to the surface networks. Subsequently, ninety additional survey monuments in the PEP tunnel were surveyed and then used as reference points in aligning beam elements horizontally. The use of sophisticated instruments and computers makes the Laser Surveying System very easy to operate and has resulted in unusually rapid and accurate magnet alignment.

A special instrument, the PEP Liquid Level, consisting of a series of half-filled water containers, which are connected by a water-filled pipe, was permanently installed around the entire PEP Ring. During operation, the levels of the

Publications

On Setting Magnets in the PEP Beam-Transport Line, J. M. Peterson, PEP-306, June 1979.

water surfaces within the various containers are used as reference elevations in the alignment of beam elements. The Liquid Level was found to be very accurate and easy to use, with typical accuracy of 0.1 mm or better.

Theory and Computation

The LBL/SLAC alignment program ALIGN was further developed on the SLAC IBM triplex system and used to simulate and develop a beam alignment system for the PEP storage ring. The use of ALIGN to correct simulated survey and position errors led to the development of an appropriate orbit correction scheme and the determination of the corresponding corrector strengths. The program was also used in conjunction with the SYNCH program to study the orbit properties of the corrected machine and compare it with those of a perfect machine.

At the request of the ISR division at CERN, ALIGN was brought from SLAC to CERN and appropriate modifications were made to enable it to run on their IBM computer. ALIGN was then updated to handle the large number of magnetic elements in their proposed electron-positron colliding machine LEP.

The construction of Isabelle produced a renewed interest in the beam-beam problem in colliding beam storage rings. A report summarizing much of the unpublished work done at LBL was written and papers pertaining to the beam-beam phenomena were presented at a Symposium on Non-Linear Dynamics and the Beam-Beam Interaction at Brookhaven National

Below right:

The electronic components of the PEP Laser Surveying System are transported and operated around the site via an electric vehicle.

Below:

Over 100 Liquid Level readouts, connected by water-filled pipe for reference elevations, are permanently installed around the PEP ring.

BBC 790-15104

BBC 791-860

Laboratory. Experiments at SPEAR and analyses have been made in collaboration with SLAC toward the understanding of the "flip-flop" beam-beam effect. The phenomena occurs at high shift values where one of the two equal intensity (e^+ and e^-) beams blows up vertically more than the other beam. Various adjustments (e.g. rf cavity phase difference) cause the beams to reverse their roles. A detailed investigation has summarized the contributing factors to this effect.

Considerable attention was directed to the PEP computer control systems. The two control computers as well as the seven regional computer systems were installed and put into operation. Work is in progress on the various control and diagnostic programs. Efforts will continue into FY80 on debugging the control systems as PEP comes into full operation.

A new lattice design for a potential electron-proton system for PEP was made in which the proton ring vertically crosses the current electron ring system. This avoids the substantial synchrotron radiation from vertical bends in the electron-positron lattice. Separation of the beams is achieved with septum dipoles and quadrupoles in this design.

Magnet Power Supply Systems

The PEP Magnet-Power-Supply Group was in the production, installation, and testing phase of the project during the last year. The major production contracts and internal lab installation work proceeded as planned, within budget and delivery constraints. This is largely the result of adequate prototype debugging and testing after the development phase was completed. Testing of all production units was done at both LBL and SLAC before the equipment was installed.

In the two "turn-on" dates successfully met during the year--the South Injection Transport system (SIT) beam tests in March and the partial Main-Ring beam tests in November--the power supply equipment performed according to expectations, with a minimum of down-time due to failures. The final turn-on date to be achieved is scheduled for the end of March 1980, when the North Injection Transport system (NIT) and the whole ring will be tested.

All of the main ring power supply equipment had to be fabricated and tested in order to run the partial ring beam tests in November because the various types of supplies are built as production runs, and some of each type were needed for the tests. The major component of the ring power supply system, the 26 "chopper" supplies fed from two 2 MW

Publications:

Orbit Properties in PEP with Magnetic Misalignments, E. Close and A. Garren, PTM-157, 1979.

SPEAR I At 1.5 GeV e^+e^- Beam-Beam Limit Simulation, E. Close, UCID-8055, 1979.

Beam-Beam Limit Simulation of SPEAR I, A Summary of Results, E. Close, LBL-9683, 1979.

General Properties of Beam-Beam Interaction Orbits, A Look at Their Sensitivity to Parameter Changes, E. Close, LBLID-006, 1979.

Electric Fields for Beam-Beam Force Calculations, Subroutine DVXYLS, E. Close, LBL-8903, 1979.

An Investigation of the "Flip-Flop" Beam-Beam Effect at SPEAR, M. Donald and J. M. Paterson, LBL-8941, presented at 1979 PAC in San Francisco, March 12-14, 1979.

DC supplies, were completely installed in the Region 8 Surface Building. The 2 dipole and 12 quadrupole magnet supplies were used in the test, so only the 11 sextupole supplies and 1 wiggler supply remain to be operated with the ring magnets in March. Because only 1/12 of the ring was used for the November tests, the DC and chopper supplies had to operate at low voltage levels to achieve the required 10 GeV operating currents. Their performance at the 0.01% current regulation level under low voltage operating conditions was very encouraging in looking toward full ring operation.

While the chopper system represents the bulk of the power used in the main ring magnet system, the 182 trim and steering power supplies account for the majority of the 242 power supplies fabricated for the whole PEP system. They power all the vertical and horizontal steering magnets throughout the ring and injection systems and "trim" the magnetic fields of the insertion quadrupole magnets used at each interaction region (IR).

The trim and steering supplies were fabricated and assembled by contractors on three separate purchase orders to our specifications. The design and development work was done at LBL so the specific units were already known to perform to the required 0.1% current regulation level. All the units for PEP have the same power ratings. The magnets were designed to match their capabilities. From an oper-

RBC 705-6456

Among the 242 power supplies designed and fabricated for the PEP beam lines are 24 "chopper" modules, like this one, used to supply the 18 separately-controlled ring quadrupole and sextapole magnet circuits.

ating and maintenance point-of-view, the advantages of only one type of T&S unit outweigh costs due to an imperfect match between power source and load. The units have a 60 KHz unity gain bandwidth to provide high performance, wideband current regulation.

The chopper power supply system represents a major thrust into new technology in the high performance, current regulated, magnet power supply field. This is the first application in which multiple choppers, operating at a 2 KHz repetition rate, with a combined power capability of 4 MW, have been operated from only two DC sources. The performance advantage of this new system is that it is as power efficient as existing multiple phase, phased back, AC line commuted power supplies, but without the disadvantages of limited bandwidth, poor power factor, and 6 Hz sub-harmonic ripple in the magnet current caused by three phase line voltage imbalance, or firing circuit imbalance. The chopper system performance instead approaches that of a transistor bank system, but without the high cost and maintenance problems associated with multiple transistors. The results so far are very encouraging, with no problems from electrical noise from the fast switching "chopped" magnet voltage.

The cost per KW of the chopper system, including the large DC supplies, extensive protective apparatus, and 26 separate choppers with 16 bit computer control, was \$60/KW. This is less than the cost of lower-performance standard three-phase, full-wave bridge supplies, which are currently at least \$100/KW in this size and quantity.

PEP Interaction Region Quadrupole Magnets

The PEP storage ring has six interaction regions equally spaced around the ring, at which experiments can be performed. A pair of quadrupole magnets is located on both sides of each interaction region. These magnets focus the circulating electron/positron beams to small size at the interaction point.

Achievement of high event rates for the experiments requires that the circulating beams be focused very accurately. This means that the magnetic field pattern in these magnets must be very precise. Specifically, for any ray within the beam envelopes, the line integral of the magnetic field value must agree with the theoretically correct value within approximately two parts in a thousand. This is comparable to the magnetic field accuracies associated with spectrometer magnets.

Development of magnets of this precision required special considerations in computation,

Publication

PEP Interaction Quadrupole Design Features, R. Avery, T. Chan, K. Halbach, R. Main, and J. Tanabe, IEEE Trans. on Nuclear Science, Vol. NS-26, (LBN-8340, PEP-291), p. 4033, 1979.

Measurements and Corrections of the PEP Interaction Region Quadrupole Magnets, R. Main, J. Tanabe, and K. Halbach, IEEE Trans. on Nuclear Science, Vol. NS-26, p. 4030, 1979.

The B2 bending magnet directs electron and positron beams from the linac into the two PEP injection lines. The straight-through line delivers beam to the SLAC experimental area.

BBC 787-9429

A close-up end view of a PEP insertion quadrupole shows the precisely contoured pole tips and the water and power connections. A pair of these high precision magnets is located at each side of the six interaction regions to focus the beams to small size.

This typical section of the PEP ring includes dipole magnets to bend the beam (rear and foreground), and a quadrupole and sextupole magnet for focusing.

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CBB 801-828

design, fabrication, inspection and magnet measurement. Initial magnet measurements guided trimming of the poletips to achieve better field quality. Field errors can be expressed as harmonic coefficients; all of the coefficients are well below one part in a thousand.

Radiation Studies

In order to assess long-term aspects of synchrotron radiation near the PEP ring elements, cooling water hoses and various electrical and signal cable elements are being irradiated with exposures from 10^8 to 10^9 rads via ^{60}Co sources. Dosimetry studies are being planned in the PEP tunnel with a system of LiF chips. The radiation-induced increase in optical absorption at several wave lengths is used as a measure of the absorbed dose over a range from 10^4 to 10^9 rads.

Rare Earth Magnets

A new design principle has been developed that allows the construction of strong rare earth cobalt (REC) multipole magnets. Taking advantage of the specific properties of commercially available REC material, quadrupoles with good field quality can be made with a field of 1.2 tesla at the magnet aperture. A prototype quadrupole, to be used in a linac, has been built by industry, and it performs exactly as predicted by analytical calculations and computer evaluation with the program PANDIRA. The most prevalent anticipated application is in linear accelerators, since these quadrupoles can produce gradients in small apertures that are not achievable in any other way.

More recently, the REC quadrupoles have been proposed as interaction region final focusing elements for the Single-Pass-Collider program. They are uniquely suited for this application as they can be placed inside a detector solenoid without significantly perturbing the detector field outside of the quadrupole. They can thus be placed very close to the interaction point to achieve maximum luminosity. In addition, the REC quadrupoles have three-dimensional fringe fields that are intrinsically free of unwanted harmonics, and therefore maximum field quality can be maintained - an essential aspect of the single-pass-collider system. In collaboration with Stanford, a linear REC array is being designed and fabrication at LBL for use as an undulator at SPEAR.

Publications

Rare Earth Cobalt Magnets, K. Halbach, IEEE Trans. on Nuclear Science, Vol. NS-26, p. 3882, LBL-8906, presented at 1979 PAC in San Francisco, March 12-14, 1979.

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Rare Earth Cobalt Permanent Magnets, K. Halbach and R. F. Holsinger, Proc. 4th International Workshop on Rare Earth Magnets and Applications, p. 37, (to be published), 1979.

High Field Superconducting Accelerator Magnets

HIGH FIELD SUPER- CONDUCTING MAGNET STAFF

G. Lamberton (in charge), A. Borden, S. Caspi, J. Cox, G. Doscher, W. Eaton, W. Gilbert, J. Hohl, K. Katayanagi, C. Kim, E. Knight, A. Kruser, R. Meuser, H. Meyer, E. Molishever, J. O'Neill, T. Purtell, J. Rechen, R. Schafer, R. Warren, W. Wilson.

This was the first year of the LBL high field superconducting magnet program that began shortly after the completion of systems tests on the ESCAR project. That work on total superconducting synchrotron systems based on rapidly pulsed 4.5 tesla magnets provided a realistic and comprehensive background for the magnet development group.

The creation of high field magnets, from 7 to 10 tesla, for future high energy physics accelerators is the goal of LBL's development efforts in superconducting magnets. This effort is a response to the heavy reliance of the overall U.S. HEP program on superconducting magnet technology and the need to develop maximum fields, high reliability for accelerator systems, and minimum capital and operating costs. Other labs are fully occupied with specific practical goals in the 4-5 tesla region. LBL is in a unique position to pursue the R&D necessary for the next generation of accelerator magnets in the 7-10 tesla range. The addition of a comprehensive research effort in new superconducting and structural materials, conducted by experts in LBL's Materials and Molecular Research Division, adds to our confidence in reaching these high field goals.

Test facilities for measuring materials properties, conductor characteristics, and magnet

A new magnet coil structure for fields above 5.5 tesla is being wound for testing by the high field superconducting magnet development group. The wrap of Mylar strips separates coil layers to allow complete permeation with liquid helium.

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models have been set up for use in the new range of field levels and forces. A 5000 pound mechanical test machine has been equipped to measure at 4.2°K ; it has already been used at this temperature to measure the mechanical moduli of coil composites used in existing magnets and some new coil structures for higher-field models. Short sample measurements are being made, and solenoids testing future windings have been measured in fields up to 8 tesla. The magnet test stand previously used for ESCAR dipoles has been operated with added mechanical and electrical instrumentation.

Magnet Coil Pre-Stress and Training

Dipoles from the ESCAR project exhibited premature quenching when first excited, required many quench cycles to reach 4.0 tesla, and failed to reach their short sample limit of 4.56 tesla (some magnets attained 4.3 to 4.4 tesla after training). Detailed analysis of the coil structure after mechanical pre-stress applied in assembly led us to conclude that insufficient pre-stress had been built into the magnet series. We systematically increased the pre-stress on existing coils, retested the

Above left:

Liquid helium (helium II) has been the standard cooling medium for superconductors and superconducting magnets for over 50 years. At LBL, superfluid helium II at 1.80 K and atmospheric pressure is being investigated as a superior coolant that will permit the superconduction at 8 tesla to carry twice as much current as it can at 4.2°K . This 1 meter long test magnet coil will be lowered into the helium II dewar at left.

Above right:

Mechanical properties of coil assemblies and structural materials are studied in a 5000 pound test machine modified to permit operation at 4.2°K .

Publications

HIGH FIELD SUPERCONDUCTING MAGNETS

Eight-Tesla Synchrotron Dipoles -- Design Alternatives, W. Gilbert, G. Lambertson, R. Meuser, IEEE Trans. on Nuclear Science, Vol. NS-26, LBL-8410, SUMAG-7, March 1979.

Snapshot #2 of Superconducting Magnet Program, J. Rechen, SUMAG-8, April 1979.

Coil Deflection Measurements on a Modified ESCAP ESCAR Magnet, S. Caspi, SUMAG-10, July 1979.

Systems Analysis of Superconducting Bending Magnets - A Mini-Computer Program, R. Meuser, SUMAG-16, March 1979.

Programmed Winding Tension for a Thick Solenoid, R. Meuser, SUMAG-25, August 1979.

LBL Superconducting High Field Accelerator Magnet Development Program for High Energy Physics, W. Gilbert, SUMAG-27, October 1979.

Conductor Position Errors Due to Friction, R. Meuser, SUMAG-29, November: 1979.

magnets, and correlated the training behavior with the initial state of coil pre-stress. At the final design pre-stress, short sample performance of the magnet was achieved. This confirmation of the coil pre-stress theory serves as a base for our higher field designs.

Mechanical Measurements of Coil Structure

A 2.5 ton Instron mechanical test machine has been instrumented to record both compressive stress and strain to $\pm 0.1\%$ from room temperature down to liquid helium temperature. Extensive compressive tests have been made on samples of our coil structure under various combinations of compression (as during magnet assembly) and cooling. Since the coil structures are compound and contain organic materials, in addition to the superconductors, the mechanical responses are most complex and history-dependent. New coil structures have been fabricated and a broad measurement program is planned.

A 25 ton mechanical test machine has been purchased and personnel from the Materials and Molecular Research Division will carry out an expanded materials test program.

Higher Field Dipoles

Using one of the newer, more rigid, coil structures mentioned above, a dipole, called D-5, has been fabricated. This magnet is physically similar to the older dipole series (D-4) but the short sample limit has been raised from 4.5 tesla to 5.5 tesla at 4.20 K and to 7 tesla at 1.80 K. Designs for smaller bore dipoles with 4.20 K short sample limits ranging from 7 to 8.5 tesla have been evolved and preparation of fabrication tooling has begun.

Filamentary Nb₃Sn, made by the bronze process by Airco, Inc., has been purchased in unreacted wire form. An additional contract has been let to Airco to cable this wire into a Rutherford cable. In FY 1980, we will start fabrication tests aimed toward use of this material in a wind and react process.

Superfluid Helium II Facility — 1.8°K Operation

A major new area for superconducting research has been opened by the successful operation of our pressurized Helium II facility which came into operation at the end of FY 1979. The helium II vessel is approximately 1.4 meters high by 0.4 meter in diameter and accepts one of our full size dipoles, without the return iron. With the dipole in place,

90 liters of helium are in the low temperature Dewar. Working with superfluid helium II at 1.8°K, the system is pressurized to one atmosphere with greatly improved heat transfer and energy absorption characteristics.

Initial training experiments with an existing dipole show dramatic improvement in performance if the magnet is first energized at 1.8°K rather than at 4.2°K. Training can be greatly accelerated, or possibly even avoided, by this method.

Beam Cooling

A program of experiments and studies on stochastic beam cooling was started early in FY 79. The term "beam cooling" refers to any process that increases the phase-space density of particle beams. The stochastic method is a rapid electronic feedback scheme in which statistical fluctuations in the motions of a circulating stream of particles are detected, amplified, and reapplied to the beam as corrective forces. The process was pioneered in Europe, and the LBL work is intended to establish expertise in the technique in the United States, as well as to advance technology. The goals of the continuing program are now expanded to include specific design and development work for the utilization of stochastic cooling in the Fermilab p-p Collider Project.

A plan was defined early in the year to carry out a series of experiments in cooling the 200 MeV proton beam at the Fermilab cooling ring. Hardware components of advanced design were fabricated during the year in preparation for their shipment to Fermilab. Two complete systems were built, one for longitudinal (momentum) cooling and one for rapid transverse (vertical) cooling.

The amplifier systems are characterized by very low effective noise level, high gain, large

BEAM COOLING STAFF
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The beam path in the Fermilab cooler ring is curved while the signal follows a straight path. This allows the signal from a pickup electrode to reach its kicker in coincidence with the beam.

bandwidth, and short delay. Two similar systems with remote controls for gain and delay have been assembled from carefully evaluated components to provide a gain of 140 dB over a frequency band from 50 to 300 MHz. The amplifiers are all solid state and deliver 70 watts with 55 nanoseconds overall system delay. Power amplifiers of a new type, utilizing electron-bombarded semiconductors, promise to provide more power with reduced delay; attempts are in progress to obtain these for evaluation. The preamplifier must operate with signals at or below thermal noise level, about 10-12 watts. A wide-band preamplifier with a 1.8 dB noise figure has been employed. The design of preamplifiers operating at cryogenic temperature is being pursued to further reduce the noise level.

The longitudinal system requires an electronic filter to discriminate the signals of off-velocity particles. Cable for this filter has been procured and circuit networks are in design and evaluation. This filter must be stable and precise; development

Below:

The extremely weak signal (10-12 watt) from intensity variations in beam position must be increased through a chain of low-noise amplifiers. With careful selection of components, a final signal of 100 W after a delay of only 55 nsec has been produced.

Below right:

Continuous beam current, with normal random variations in intensity, passes through this longitudinal pickup. A signal from these variations grows as it progresses down the helical conductor at the same rate as the beam. The signal is then amplified and used in a downstream kicker to smooth out the beam current.

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of this component will be an important element in improving the cooling systems for the Fermilab antiproton precooling.

The performance of the stochastic cooling scheme is limited by the very low level of signals detected by the beam pickup electrode. To maximize this signal, pickups of traveling-wave principle have been devised at LBL for the Fermilab experiments. In traveling-wave electrodes, the phase velocity of the signal is made equal to the beam velocity; then, in a single, long structure a growing wave is generated and delivered to the preamplifier at the downstream end of the electrode. A vertical pickup of this type, 3.5 meters long, has been constructed to match the relatively low-velocity ($\beta = 0.57$) of the 200 MeV protons. This low-velocity structure will produce a signal power 100 times greater than would an equally long array of discrete pickups of the type used in the most recent cooling experiments at CERN. This enhanced pickup efficiency will be utilized to attempt dramatically reduced cooling times, in the neighborhood of 0.25 second. A helical traveling-wave pickup of 1.8 meters length has also been constructed for longitudinal signals. At year end, these pickups in bakeable high-vacuum enclosures were being vacuum checked before shipment to Fermilab. Efforts are underway to explore the extension of these pickup concepts to the higher-velocity range of the antiprotons to be cooled in the Fermilab precooling ring.

The signal pickup and kicker electrodes for the stochastic cooling experiment are enclosed in tanks which are cleaned by baking before replacing existing portions of the cooling ring.

Publications

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High Energy Electron Cooling to Improve the Luminosity and Lifetime in Colliding Beam Machines, D. Cline, A. Garren, H. Herr, F. Hills, C. Rubbia, A. Ruggiero, and D. Young, IEEE Trans. on Nuclear Science, Vol. NS-26, p. 472, 1979.

Stochastic Cooling at the Fermilab Cooling Ring, Proposal to FNAL, A&PRD Staff, November 1978.

A Transmission Line Model for the Transverse Pick-up Electrode, L. Smith, BECON-13, January 1979.

Low-Noise Wide-Band Amplifier Systems for Stochastic Beam Cooling Experiments, B. Leskovar and C. C. Lo, BECON-12, LBL-9841, October 1979.

Low-Noise Power Amplifier Considerations for Stochastic Cooling Systems, B. Leskovar, BECON-4, November 1978.

Design Report: The Fermilab High Intensity Anti-Proton Source, A. Garren, October 1979.

Kicker electrodes of traveling-wave design have also been fabricated. Here the greater efficiency reduces the required amplifier output power.

During the year, the LBL group has participated in design efforts at Fermilab to define the anti-proton collection systems of the Collier Project, particularly in the precooler lattice and stochastic cooling system. The experimental work will attempt to exercise the cooling parameters over a range that will test the theoretical and computational analyses.

Accelerator Theory

Stochastic Cooling

A particle simulation program was used to investigate the transverse cooling mechanism under extreme conditions of a small number of particles in good and bad mixing situations, for the purpose of providing clues to a proper analytical treatment of the process. Among other things, it was shown that the scrambling of longitudinal momenta necessarily accompanying the time varying transverse deflections by the kicker provides an effective mixing mechanism for small momentum spread, a point which had not been recognized in previous analyses. A theoretical model in which the Vlasov formalism was extended to include two-particle correlations was then developed to rigorously describe the various aspects of the problem in a consistent way; we believe the theory of cooling in the vertical plane is now complete.

Because of the increasing interest in accomplishing momentum cooling at an early date, a similar technique was applied to that case, and we now have a formalism to describe momentum cooling as well. The next step will be to compare theory with the results of the experiments, which will be underway in FY 80.

Synchrotrons and Storage Rings

A substantial amount of work has been done on the design of magnet configurations, both for LBL projects and in assistance to other laboratories. In addition to preliminary work on VENUS, which included a study of possible collective instabilities, a new design for a proton-electron option to be added to PEP was developed. Contributions were also made to the concept of the single pass electron-positron collider, which is currently favored as the next step in an expansion of the PEP facilities at SLAC.

In collaboration with other laboratories, a low-beta (i.e. small beam size) modification of an FNAL doubler straight section was designed for future use in a p-p colliding beam configuration,

ACCELERATOR THEORY STAFF

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BECON-9, October 1979.

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Design Study of a 22
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(LEP), The LEP Study
Group, CERN/ISR-LEP/
79-33,22, August 1979.

as well as a precooling-accumulator ring for collecting antiprotons. A small electron storage ring, applicable to both FNAL and CERN, was designed for the purpose of cooling high energy protons and/or antiprotons in a colliding beam storage mode.

Also cooperative assistance was extended to the University of Tokyo to provide them with our computational programs and assist in refinements of the design of the proposed 4.5 GeV/nucleon heavy ion synchrotron (NUMATRON).

Heavy Ion Fusion

Having completed considerable preliminary work on transverse stability in the transport of intense beams in advance of experimental results, attention has turned to the study of longitudinal motion and specific problems related to the design of the proposed test bed accelerator. A mode analysis of a self-consistent distribution in longitudinal phase space for a beam in a smooth, perfectly conducting pipe shows that all modes are stable, in contrast to the instabilities which appeared in the corresponding transverse problem. However, the accelerating modules in an induction linac present a strong resistive impedance to the beam, a situation which is known to cause instability for bunched beams in high energy circular accelerators but has not yet been demonstrated theoretically. Because the parameter range applicable to HIF is so different from that of high energy proton rings, we have tried (but have not succeeded) to find an analytic explanation of the effect and to make a computational study using our code for solving the one-dimensional Vlasov equation. This work is still in progress.

In connection with the test bed design, a procedure has been developed to determine the voltage wave forms on successive accelerator modules required to capture and bunch the injected beam while keeping the current profile in space and time as useful as possible. The bunching rate is constrained by transverse focusing requirements, both in maximum tolerable current and in the tolerance of the focusing system to an energy ramp in the beam. The program is being extended to describe realistic voltage wave forms and the effect of errors in timing and wave shape.

On the subject of final focusing, the work on third order aberrations was brought to a close with the formulation of a criterion specifying the tolerable emittance in the absence of octupole corrections. The problem of transporting the beam through a series of bending magnets to suppress chromatic aberrations received a first treatment with a simplified model for space-charge effects; this model will be developed further in the coming year.

Beam Transport and Matching for Experiments with a 2 MeV Cesium Beam A. Garren, HIFAN-95, October 1979.

Longitudinal Motion in High Current High Energy Heavy Ion Beams, D. Neuffer, HIFAN-77 (LBL-8387), (PAC paper), March 1979.

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Ribbon-Beam Drift-Tube Linacs, W. Herrmannsfeldt, HIFAN-69, June 1979.

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HEAVY ION FUSION

Induction Linac Drivers

High Current Cesium-Ion Beam Experiment

HIF STAFF

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E. Hartwig,
W. Herrmannsfeldt
(SLAC), E. Hoyer,
C. Johnson, D. Judd,
C. Kim, M. Lampel,
L. J. Laslett,
J. Meneghetti,
K. Mirk, R. Nemetz,
S. Rosenblum,
J. Shiloh, L. Smith,
M. Tiefenbach,
D. Vanecek, O. Wong,
J. Zelver.

In January 1979, the large-area Cs⁺ ion source suitable for an induction linac was successfully commissioned. This 1.2 A 500kV source has a repetition rate of 1 per second. In July, we installed the first of the three pulsed drift tubes (Fig. 1) and, since then, have been studying the beam behavior after this additional acceleration stage. For most of these studies the system has been operated somewhat below its full capability; typical operating parameters were the following: source voltage, 400 kV; first drift tube voltage, 400 kV; beam current, 0.7 amperes, and pulse duration, 2 μ sec.

The present experiments indicate that the source and acceleration system behave as designed. That is to say, the Child-Langmuir $V^{3/2}$ behavior follows over a wide range of voltages up to the design maximum, and the beam envelope follows the EGUN calculations of W. B. Herrmannsfeldt for a space charge dominated beam. It has also been observed that the installation of a 1/4" deep "honeycomb" grid in the drift tube nose produces slow secondary electrons which become trapped in the beam and thus neutralize the space charge. Under these conditions, the beam envelope decreases considerably in cross-section. Thus, at the expense of scattering a small fraction of the beam it appears possible to transport much more beam through a given structure than in the unneutralized case.

Although the measured pulse duration is 2 μ sec, the applied voltage pulse needs to last longer (3.5 μ sec) to compensate for the beam rise-time and the ion transit-time from the hot plate to the entrance of the first drift tube. The source and the first drift-tube voltages are turned on simultaneously to minimize the beam rise-time and, also, turned off simultaneously to minimize the generation of slow (low energy) ions. The beam envelope is independent of the two Marx generator voltages as long as they are kept at the same value. A one-dimensional simulation code was developed to enable us to better understand transient effects in the ion-gun when the voltage is first switched on.

CBB 801-425

Assembly of the drift tube sections for acceleration of the cesium ion beam.

CBB 801-423

The 1 MeV cesium beam experiment includes the source and three drift tubes. Here, the first two drift tubes are in place.

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A Self-Consistent Phase Space Distribution with an Envelope Equation for Longitudinal Motion, D. Neuffer, HIFAN-70, (UCID-8105), January 1979.

The Economics of ICF Power, W. Herrmannsfeldt, HIFAN-71, February 1979.

Ion Induction Linac Test Bed

A conceptual design and cost estimate for an Ion Induction Linac Test Bed, was developed and described in a report entitled "Ion Induction Linac" LBL PUB-5031, submitted in September 1979. This document presents the design of the Test Bed and the engineering development needed on crucial components, and describes the experimental and theoretical program that will answer uncertainties regarding beam behavior. The proposed Test Bed is currently being modified to coincide with available funding and still permit establishment of the technological feasibility of this approach. Considerable effort in basic physics and engineering design was devoted to refining the induction linac concept.

The desired bunch trajectory for the induction linac requires bunch shortening in length by about a factor of one-half during the transit of the bunch through the accelerator. This requirement translates into specific voltage-versus-time requirements at different locations in the machine, with the general trend that these voltages are steeply ramped at the low-energy end and essentially flat at the high-energy end, with a ramp that decreases with increasing energy at intermediate locations. The precise specification of these required waveforms is most easily handled with the help of a computer code "SAVE 1" developed last year; preliminary results are just now being obtained.

The waveform within any accelerating module will be generated by sequentially firing a small number of independent pulse-forming networks into independent core segments. The voltage seen by the beam will be the sum of the core segment voltages. The required number of pulsers will be 5-10 per

The five performance steps in the nation's inertial confinement fusion program. The LBL Ion Induction Linac Test Bed is step II.

Schematic layout of the Ion Inductive Linac Test Bed, with details of several elements.

CSD 803-3654

module, with the exact number to be determined by consideration of beam sensitivity to waveform errors and peak voltage constraints. One prototype pulser was constructed and operated at full power for more than 10^5 pulses at a 1 Hz repetition rate into a resistive load. This pulser will be used in conjunction with induction cores as soon as enough large cores become available. Some impedance tapering of the network will be needed to match the core. One large induction core, 91 cm outer diameter, 62 cm inner diameter, and 5 cm deep, was wound of 2 mil silicon steel with mylar insulation and was ready for testing.

Insulator development has started. A number of candidate materials for insulator assembly were surveyed, including the possibility of using Pyrex glass. Some test samples of glass bonded to stainless steel to form a graded column have been produced and will be tested for structural and voltage-holding properties.

Computations are currently underway to examine the proposed pulsed quadrupole magnet designs; in particular, the fringing field and the quality of the field within the bore are being studied.

Evaluation of Core Materials

Because the magnetic cores make up a large

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Large Aperture Contact Cs+ Ion Source for an Induction Linac, D. Keefe, et al, HIFAN-73, (LBL-8359), PAC paper, March 1979.

Design/Cost Study of an Induction Linac for Heavy Ions for Pellet-Fusion, A. Faltens, et al, HIFAN-74, (LBL-8357), PAC paper, March 1979.

Operation of a High-Current Xenon Source, W. Chupp, D. Clark, R. Richter, J. Staples and E. Zajec, HIFAN-75 (LBL-8859), (PAC paper), March 1979.

Comparison of performance characteristics of several possible materials for the induction modules.

Accelerator Module Materials Comparison Module specifications 15cm inner radius 0.5 volt-second flux change 1 meter length

part of the volume and cost of an induction linac it is important to pick a material for the core that strikes an optimum balance between its electrical behavior and its cost. A heavy ion induction linac needs to accelerate over a wide range of pulse widths, requiring several different types of core materials in the various parts of the accelerator.

The magnetic properties and core losses of a variety of material using a thyatron pulser were measured and are shown schematically in Fig. 4. Each sample is in the form of a tape-wound toroid with a single set of windings. Pulse durations have ranged from 500 ns to 100 s thus far and we plan, soon, to extend the range down to 40 ns. The materials to be studied to date thus far have included .001" thick molybdenum-iron, .001" Ni₅₀Fe₅₀, Stackpole C11 ferrite, .012" Silectron (Arnold Engineering) and three different amorphous magnetic materials--Allied Metglas 2826 and 2826 MB as well as General Electric Fe₈₂B₁₅Si₃.

The amorphous magnetic materials show great promise: they are inexpensive to manufacture (50¢/lb., projected) and have very attractive properties as a core material to replace Ni₅₀Fe₅₀ (\$10 - \$20/lb.). Fig. 5 shows the core loss for a possible induction module.

Publications

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System Studies

System studies for a Heavy Ion Driver using the Induction Linac have continued. The Induction Linac driver can be viewed as consisting of three systems: an injector, an accelerator and the final beam transport. Of these, the dominant cost system is the accelerator, so it has received the most attention to date.

Preliminary work with the computer code LIACEP (Linear Induction Accelerator Cost Evaluation Program) has been extended to Induction Linac accelerator systems for 100 kJ, 1 MJ, 3 MJ, and 10 MJ, with a wide variety of input assumptions. Information on accelerator cost, length, efficiency and detailed arrangement of magnets and accelerating modules was developed for the following matrix of parameters:

Ion Type: Cesium (133), Thallium (204), Uranium (238)

Charge State: 1+, 2+ and 4+ (1+ and only for Thallium)

Normalized Beam Emittance: 2, 3, 4, 6 ($\times 10^{-5}$ mrad)

Electrical Beam Charge: 25-1000 C (in ten suitable increments)

Betatron Tune Shift (due to space-charge): 60% 24%;

Repetition Rate: 1 Hz

The base-line induction linac concept is considered to have a superconducting quadrupole beam transport system and amorphous iron induction cores. In each case, the step-by-step design of successive parts of the accelerator used the minimum acceleration cost per megavolt to arrive at an overall minimum-cost accelerator. This criterion usually generates a design in which the beam current is not far from the space-charge limit throughout the length of the accelerator.

Some generalized results from our studies for a 1 MJ driver are as follows: (These results apply only to the accelerator portion of the driver.)

1. Considering a choice of particle, minimum accelerator cost is generally less for a lower atomic weight particle for a given charge state and normalized beam emittance.

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Proceedings of Clare-
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shop, October 1979.

2. For a particular particle, minimum accel-erator cost becomes less as the charge state of the particle is increased for the same normalized beam emittance.

3. Minimum accelerator cost was the least with particles of charge states 2+ and 4+ for the maximum normalized emittance examined (6×10^{-5} mrad) but for charge state 1+ a minimum existed in the $3-4 \times 10^{-5}$ mrad range of normalized beam emittance.

4. Accelerator lengths vary from 3 to 7 kilo-meters. Generally, a machine designed to transport higher emittance will be shorter.

5. Accelerator efficiency a 1 Hz varies from 7% to 12% for the minimum cost options obtained, and at higher repetition rates, more suited to a driver, range up to 30%. Higher efficiency is generally obtained with a higher emittance beam. There is a trade-off between capital cost and efficiency and the minimum cost accelerator is not necessarily the optimum choice.

6. Accelerator cost is sensitive to core material. Nickel- and silicon-iron cores show an increased accelerator cost and decreased efficiency.

For a 100 kJ driver, a cursory examination of an accelerator, using Cs, yielded the following results for a normalized beam emittance of 3×10^{-5} mrad. Silicon-iron was considered for the core material.

Charge State	Beam Charge (μC)	Accel. Cost (M\$)	Accel. Length (km)
+1	40	185	2.1
+2	80	145	1.7

RF Linacs and Storage Rings

High Current Xe¹¹ Ion Source for Conventional rf Linac Systems

A multi-aperture Ehlers-type source was constructed and operated to produce a 60 mA Xe¹¹ beam. This source utilizes 13 apertures closely spaced in a circular pattern to produce a beam 25 mm in diameter. The "accel-decel" extraction system delivered a 22.5 keV beam whose normalized emittance at 29 mA was 0.027 $\pi\text{cm-rad}$. The source was

mounted in the high-voltage terminal of a Cockcroft-Walton generator and the neutralized beam transported one meter through two magnetic quadrupole triplets to the entrance of the 20 cm long accelerating column consisting of five intermediate electrodes with a total voltage drop of 500 KV. The vacuum in the extraction region was held to 10^{-5} torr by using a puff valve and two 1500 l/sec turbo-molecular pumps. Multi-wire profile monitors just ahead of the column entrance measured the beam size, which was in good agreement with single-particle transport calculations, if one assumes the beam to be 97% neutralized. The normalized emittance of the full 500 KeV beam was measured to be 0.1 cm-mrad for 35 mA and the population of charge-state +1 ions was determined to be > 90%.

These achievements -- and subsequent comparably successful small-aperture ion-source work by Hughes Research Laboratories for ANL -- attest to the reliability of judgement expressed as long ago as the Claremont meeting in July 1976, that scaling to this level of parameters was readily achievable.

C&B 798-9617

Components of the multi-aperture source (based on Ehler's design). This source delivered 65 milliamperes of Xe^{+1} ions.

Status Report for Ion-Ion Cross Section ($Cs^{+1} + Cs^{+1}$) Measurements

Ion-ion charge-changing collisions may affect the lifetime of stored beams for heavy ion fusion drivers. Many ion species are presently under consideration; the final choice may be determined by the species with the smallest charge-changing cross sections.

The theoretical studies suggest that an important calibration point can be obtained by measuring the Cs^{+1} , Cs^{+1} cross sections. We have set up an experiment to measure the cross sections for both charge exchanges:

$$\text{Cs}^+ + \text{Cs}^+ \rightarrow \text{Cs}^{++} + \text{Cs}^0 \quad (1)$$

$$\text{Cs}^+ + \text{Cs}^+ \rightarrow \text{Cs}^{++} + \text{Cs}^+ + e \quad (2)$$

in the energy range 10 to 300 keV relative energy. Our experiment consists of a cesium plasma target (Q-Machine) through which a beam of Cs^+ ions is transmitted. Cross sections will be determined by measuring the growth in Cs^+ and Cs^{++} as a function of plasma density.

A measurement using the crossed-ion beam technique recently has been reported yielding a sum of the cross sections for (1) and (2) of $(1.5-2.8) \times 10^{-16} \text{ cm}^2$ in the 40-280 keV energy range (Ref. 1). This is in fair agreement with theoretical estimates by Olson (Ref. 2) of $\sim 4 \times 10^{-16} \text{ cm}^2$. Work by our group on the electronically similar system $\text{Cs}^+ + \text{Xe}$ gives ionization cross sections of approximately $2 \times 10^{-15} \text{ cm}^2$ (Ref. 3). We will complete measurements of (1) and (2) for comparison with Olson's calculations and the results of Ref. 1.

A surface ionization source for our accelerator was completed and used extensively for other experiments ($\text{Cs}^+ + \text{Xe}$) and systematic checks on the plasma target experiment. Upgrading of our accelerator from 150 kV to 300 kV was to be completed by November 1979. Preliminary measurements were being done with the 150 kV accelerator. We had originally planned (and set up) for longitudinal injection of the beam into the Q-Machine. However, we have discovered from the $\text{Cs}^+ + \text{Xe}$ experiment that large scattering cross sections will make it necessary to inject the Cs^+ beam transverse to the target (and magnetic field). The target has been rotated by 90° for transverse injection. This will result in a lower plasma line density and we are planning for a second cathode to increase the plasma density. Diagnostics include Langmuir probes, a microwave interferometer, and possible atomic beam probes. The analysis chamber has been completed and used for system checkout. Complete results from the operating system are anticipated in April 1980.

Theory

At the time of the Argonne Workshop (Sept. '78), we had made a preliminary comparison of our analytic work on a third-order instability, which occurs in the transport of a Kapchinskij-Vladimirskij beam through a quadrupole system, with

some of the results of Irving Haber's particle simulation calculation of the same instability. We were encouraged to believe that theory and computation were in agreement, but there remained a number of gaps and unresolved questions. Since then we have obtained the complete record of that run and find that over a range of about ten quadrupole periods, after the instability has grown out of the computational noise and before signs of non-linear saturation appear, the relevant moments of the distribution grow at the predicted rates to a remarkable accuracy. We are therefore quite confident in our double conclusion that the theory is correct and that the simultaneous computations are correct. We thus have reason to also believe that computational results for more realistic initial distribution functions that are beyond the capability of analytic treatment.

Our analytic work indicates that the maximum current that can be transported without emittance degradation is achieved by using a lattice designed for a zero-intensity phase advance of 60° (to avoid envelope and third order instabilities), depressed to 24° by space-charge forces (the threshold for higher-order instabilities). This criterion should be conservative, since the K-V distribution is somewhat more sensitive to instability than other more realistic distributions. The corresponding "figure of merit", $Q/u_m^{2/3}$, in the formula for current given in equation (3) of Ref. 1 depends on the fraction of transport channel occupied by quadrupoles, ranging from 0.76 for full occupancy down to 0.23 for 10% occupancy (see Ref. 2). This coefficient is not drastically different numerically from that proposed by Maschke at the time of the first HIF workshop (Ref. 3).

What is needed now to advance the study of beam transport is an analysis of the three-dimensional problem, including longitudinal forces and the resulting coupled motion. As a first step in that direction, we are using a one-dimensional code for longitudinal motion and developing an analytic approach to that problem. A distribution function has been found for which the space-charge forces are linear and which leads to an envelope equation similar to the familiar one for transverse motion (see Ref. 4). A perturbation analysis shows that this distribution is stable at all intensities if the (linear) external focusing force is continuous.

MAGNETIC FUSION ENERGY

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NEUTRAL BEAM

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NEUTRAL BEAM

DEVELOPMENT

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The Magnetic Fusion Energy Program at the
Lawrence Berkeley Laboratory is divided into five
projects:

1. Neutral-Beam Development and Technology
2. Atomic Physics Studies
3. Neutral Beam Plasma Research
4. Basic Plasma Theory
5. TORMAC Project

All of these are parts of the coordinated program of
Magnetic Fusion Energy Technology at the Department
of Energy.

By far the largest is the Neutral-Beam Develop-
ment and Technology Project. It is carried out as
a joint program with the Lawrence Livermore Labora-
tory, and in fact, is administered through LLL and
handled as a subcontract to LBL. We are including
it here for completeness sake, but we are restrict-
ing our report to the work done at LBL. Only sum-
mary statements are made because a description of
this project appears in the annual report on magnet-
ic fusion energy issued by LLL.

The remaining four projects listed above have
the following unifying features: both ion source
research and atomic physics studies are largely
serving the function of basic support for the
neutral-beam work. The first is concerned primarily
with the improvement of our understanding of ion
sources and similar matters of relevance to the
neutral-beam injectors. So far the effort concen-
trated on the development of computer models for the
source, and in diagnostic work needed to supply ex-
perimental input data for these models. The atomic
physics is aimed at supplying missing data on funda-
mental processes, such as certain charge transfer
cross sections or negative-ion production
mechanisms.

The theoretical effort has been diversified, but
as in previous years, the emphasis has been on non-
linear processes in plasmas, of interest to con-
trolled fusion because of their relevance to plasma
heating schemes.

The TORMAC Project has been our only direct con-
tribution to the magnetic confinement problem in
controlled fusion research. The TORMAC (toroidal
magnetic cusp) is one of several so-called "alterna-
tive concepts". The latter are being worked on in
the United States as backups, in case unexpected
difficulties arise in the mainline developments of
tokamaks or magnetic mirrors, or in case a new
concept is found leading to a superior or more eco-
nomical fusion reactor.

BBC 7511-8169

Above:

Neutral Beam
Injector System
(Schematic).

Left:

Ion Accelerator
Structure for 120 kV,
65 A (for TFTR). For
pulses up to 1.5 sec
the grid rails need
only end cooling by
conduction.

CBB 775-4693

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Electron Suppression in Negative Ion Beams, O. A. Anderson, E. B. Hooper, Jr., and P. A. Willman, Phys. Fluids 22(2334), 1979.

View inside a large ion source, showing coiled cathode filaments on long supports to clear surface magnetic multicusp fields.

LBL/LLL Neutral Beam Development

Positive Ion Base Program

The task of the Neutral beam Development Positive-Ion Base Program is the timely development and demonstration of principles and techniques needed for injection systems in the 80 to 200 keV range. (Above approximately 200 keV, the system efficiencies are unacceptably low for most applications. We are developing negative-ion based injectors for the higher-energy applications.) The development of components and techniques is carried far enough that confinement personnel can plan and design their neutral-beam injection systems with considerable confidence. In some cases, our staff and facilities participate in the design, construction, and testing of components and systems for specific confinement experiments.

Our primary near-term program is to develop advanced ion sources and systems suitable for MFTF-B, TFTR/TFM, DIII-U, ETF, MNS, etc. The generic focus for this development is the Advanced Positive Ion Source (APIS). The development of the long-pulse (1 to 30 seconds) capability of the APIS is directly applicable to all of the above systems, particularly ETF and MNS which will require the higher energy, full-energy fraction and availability, as well as the energy recovery capability of the APIS.

The development will continue to be carried out first on fractional-area (about 15 A), and then full-size (50-100 A) modules.

During FY 79 a 10 x 40 cm² magnetic-multiple

BBC 794-5218

LBL "65-AMP" NEUTRAL BEAM SOURCE MODULE
(65-Amp, 200-keV, 0.5-sec)

BBC 787-8076

("bucket") plasma source was completed, and first-phase species tests were conducted. A long-pulse, fractional-area, 15A, 120-150 kV module was designed and built. Testing and improvement of edge-cooled-electrode modules also continued, with some operation of a "TFTR" fractional-area source at 120 kV, 1.5 seconds. Research on long-life cathodes, including LaB₆ was carried out.

Design and construction of a full-size 120-150 kV module was started as a first effort toward an APIS source. In addition, 60% energy recovery from a 100-keV He⁺ beam was demonstrated, with 90 kV on the collector; energy recovery with hydrogen beams also was demonstrated.

Negative-Ion Base Program

Future mirror experiments and reactors may require efficient neutral-beam systems with injection energies of 150 to 200-keV and above. Therefore, the LLL/LBL neutral-beam R & D program includes the development of efficient long-pulse neutral-beam systems at these energies and higher. The present emphasis involves the production and acceleration of H⁻ and D⁻ ions, but other approaches may be added. Negative-ion-based beams with energies as low as 80 keV would be desirable.

Cutaway sketch of 120 kV 65 A ion source with "magnetic bucket" discharge chamber.

Publications

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Negative-Hydrogen-Ion Production by Low Energy Hydrogen Atom Bombardment of Surfaces, W. G. Graham, submitted to the Journal of Physics B, UCL-9511, July 1979.

Multicusp (magnetic bucket) dc negative-ion source with concave converter electrode. Addition of a little Cs results in 15% conversion from D^+ to D^- at -300 V bias on the converter electrode. The photo shows the magnetic field caused by the multipoles.

XBB 7912-15410A

There are several ways to generate and accelerate negative ions. Our main effort has been based on the conversion of a low-energy, positive-ion beam to a negative-ion beam in a metal vapor. During 1980 we expect to produce 2 amperes of D^- beam; at this point we will terminate this effort and pursue an alternate approach. Preliminary studies of volume-production processes also have been started. We are following and evaluating the other negative ion development efforts in the U.S. and U.S.S.R., with the expectation that a selection of the best negative-ion-generation and acceleration approach for a neutral-beam demonstration can be made in the second half of FY 81.

Specific activities during the past year included the modification of the test stand I to permit negative-ion-testing; the production of D^- ions by charge-exchange in a sodium vapor jet was then begun. The test stand jet, suitable for charge-exchange production of negative ions or conversion of D^- to D^0 , was diagnosed and shown to perform as calculated. A promising new approach to negative ion sources was demonstrated, that is, surface production on a biased electrode immersed in a plasma in a "magnetic-bucket" discharge.

XBL 792-8379

Test Stand Fabrication and Operation

Test stands are required for developing and testing neutral beam injection modules and system components. Our evolving test facilities serve in a sense as prototypes for neutral-beam injection systems for TMX, MFTF, TFTR, DIII, ETF, NMS, and other confinement experiments. They also serve as training facilities for scientists and technicians from confinement experiments. We expect them to be

vital to the national MFE effort as long as neutral-beam injection is an important part of the program.

Test stands have been, and continue to be, pacing items in neutral-beam development programs. For some users, they also will be pacing items for break-in and qualification of production neutral-beam sources. At present, two facilities at LBL, TS (Test Stand) IIIA, (150-kV, 15-A, 5-s) and TS IIIB (120-kV, 80-A, 20-ms) routinely operate at high power and particle energies up to 120 keV. The High Voltage Test Stand (HVTS) at LLL and the Neutral Beam System Test Facility (NBSTF) at LBL will operate in the same energy range, and with more total energy per pulse, in FY80. In addition, they have sufficient neutron shielding to permit regular operation with deuterium. All of these facilities will continue operation, with some modifications, for the next few years. TS IIIA, TS IIIB, and HVTS require substantial crews and budgets to operate and maintain them. We also use several smaller, but still high-power, test stands that can be operated by experimenters.

In the previous year (FY 79) we operated and upgraded TS IIIA for long-pulse testing of fractional area source modules, and operated TS IIIB for short pulse testing of full-size source modules for TFTR and DIII. We also operated HVTS in a de-bug mode; prepared a proposal for upgrading the NBSTF (Neutral Beam Systems Test Facility) to a 150 - 250 kV R & D facility after 1981. Meanwhile, physics and operator staff for the NBSTF were trained.

Experimental Atomic Physics

The major part of the MFE effort at the Lawrence Berkeley Laboratory is concerned with the development and application of high-energy neutral beams

XBL 803-8610

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Comparison of experimental measurement and theoretical prediction for negative ion conversion coefficient I^-/I^+ on Cu target with thin Na coverage.

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for heating and fueling plasmas in fusion experiments. This development work is in part based on atomic collision data, some of which are known in insufficient detail, and some of which are still speculative.

During FY 79 the experimental atomic physics group measured the formation of H⁻ and D⁻ ions on clean and cesiated surfaces bombarded by thermal atoms from an oven. This work is related to negative ion formation processes in sources for neutral beam systems. By varying the oven temperature it was shown that the negative ion production probability is small at thermal energies, but rises rapidly with energy. H⁻ and D⁻ yield measurements and work functions for thin coverage of Cs measurements on Ca, Ni, Mo, and W substrates were continued, as well as Ti and Cu on W. Significantly higher yields for thin coverage vs. thickness have been obtained. A model to describe negative ion formation at surfaces based upon probabilities of reflection, H⁻ formation at the surface, and H⁻ survival leaving the surface has been demonstrated. The model fits the data for all the alkali metal targets and for both H and D incident. The model also correctly predicts the H⁻ yield from a Cu target with thin Na coverage, based upon the thick Na results. The first measurement of ³He⁻ and ⁴He⁻ on surfaces bombarded by low energy (> 300 eV) atoms and ions have been made, as well. The motivation is

Negative-ion (D⁻) yield by charge transfer processes for deuterium passing through thick targets of various metal vapors.

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development of diagnostic beams for measurement of energies in d-t plasmas.

The D^- yield from charge transfer in a sodium vapor target over the energy range 0.4 to 10 keV was also measured; the equilibrium yields have a broad maximum of about 10% at 3 keV.

The range of validity of an experimental/theoretical scaling rule for electron loss from hydrogen atoms colliding with highly-stripped heavy ions was extended with Nb^{+q} ions up to $q = 36$ and carbon ions in the E/q range 50 to 280 (keV/amu) / q .

Neutral Beam Plasma Research

Basic physics research is necessary to understand the operation of neutral beam plasma sources and the physics of the neutralizer plasmas, in order to improve the efficiency of neutral beam systems, improve the reliability of long-pulse neutral beam systems, and reduce the divergence of the beams obtained from neutral beam systems. The approach is to develop the measuring techniques required, develop relevant computer models of the plasmas, and use the models to predict how the neutral beam ion sources and neutralizers should be modified to achieve the desired results. This research feeds directly into, and is immediately useful to, the neutral-beam development program.

Technical progress in the past year includes the transfer of neutral beam plasma research to Test Stand IIB where work resumed. Experimental measurements of plasma properties (bulk electron temperature, plasma potential, and plasma density) were made as functions of position in a conventional LBL 10-ampere source (not a "bucket" source); the plasma discharge followed conventional collisionless gaseous discharge theory, and provided input for the source model. The bulk of the ionization in the discharge is done by the primary electrons, not by the bulk plasma electrons; the measured plasma properties indicate that the ion generation is approximately uniform in the source volume.

A study of fluctuations in the 10-ampere source indicated the existence of superthermal (by a factor of 100 or more) oscillations. Extensive studies indicated that these oscillations were due to ion acoustic waves, excited by a current-driven instability at the filaments. The frequency of the waves is determined by the spatial periodicity of the filaments. Although the fluctuation amplitudes are much larger than thermal, they do not appear sufficient to cause appreciable ion heating, and therefore, have no adverse effect on the beam divergence.

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Gross Ionization Cross Sections for Highly Stripped Carbon Ion Incident on H_2 , He, Ne and Ar, K. H. Berkner, M. G. Graham, R. V. Pyke, A. S. Schlachter, and J. W. Stearns, Conference on Atomic Processes in High-Temperature Plasmas, Colorado, January 17-19, 1979, LBL-9153.

Electron-Loss Collisions of Highly-Stripped Niobium Ions with Hydrogen and Argon, K. H. Berkner, M. G. Graham, R. V. Pyke, A. S. Schlachter, and J. W. Stearns, American Physical Society, April 23-26, 1979, LBL-9113.

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NEUTRAL BEAM PLASMA RESEARCH STAFF
W. Kunkel, W. Cooper (in charge), N. Adt, F. Burrell, C. Chan, K. Scheenberg.

Neutral Beam Plasma

Research Publications

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PLASMA THEORY STAFF

A. Kaufman (in charge), J. Cary, C. Grebogi, J. Hammer, R. Littlejohn, S. McDonald.

Plasma Theory

Publications

Wave Energy Density and Wave Momentum Density of Each Species of a Collisionless Plasma, J. Cary and A. Kaufman, *Physical Review A*, LBL-10414, 1979.

Strongly Mixed Stationary Turbulence, H. Abarbanel, submitted to *Physical Review A*, LBL-9198, June 1979.

Irregular nodal structure (top) and amplitude, in perspective, (bottom) of a typical eigenfunction of the Helmholtz equation within a two-dimensional race-track boundary, demonstrating an effect of ray stochasticity.

The source model was extended to include energy balance of the secondary electrons and inelastic collision processes that degrade the energy of the primary electrons. These features permit the self-consistent calculations of the bulk electron temperature in the source plasma. Model predictions (ion current density, beam composition, and electron temperature) agreed very well with measurements on four different field-free sources, with both hydrogen and deuterium, for variation of arc voltage, arc current and gas flow. This gives us confidence that the modeling to date is substantially correct.

Construction of a "bucket" source, identical to those in use in the Neutral Beam Development program, was completed. Measurements of the plasma properties of this source will be conducted in FY 80. An experimental program on TS IIIB was launched to measure the properties of the plasma produced in the neutralizer by the beam. This is the first step toward investigating the various beam-plasma instabilities that can increase the beam divergence in the neutralizer plasma.

Plasma Theory

Our program in basic plasma theory for application to MFE concerns the dynamics of particles and waves, and their interactions. The stress is on nonlinear and stochastic effects; the primary tool is Hamiltonian dynamics and its generalizations. The three primary areas of current study, which overlap each other are: 1) guiding-center theory

and its applications; 2) resonances and intrinsic stochasticity of particles; and 3) intrinsic wave stochasticity.

(1) Almost all previous work in plasma dynamics has been based on either physical variables in a non-Hamiltonian framework, or non-physical variables in a Hamiltonian framework. Realizing the great advantage of using both physical variables and a Hamiltonian, we are developing a new approach which bears fruit for a broad range of problems. The guiding-center Hamiltonian formalism developed by this group for nonrelativistic particle motion in a weakly nonuniform magnetostatic field of general geometry, has been extended in several directions. The study of linear wave propagation in a non-uniform Vlasov magnetoplasma is usually based on a local dispersion tensor, heretofore obtained from a two-point kernel, which is often difficult to calculate. We have developed an eikonal approach to solution of the linearized Vlasov equation, which leads directly to the local dispersion tensor in a simple and concise way. In addition, the guiding-center formalism has been generalized to the relativistic case, including finite electric field and covariant Euler potentials.

The role of geometric symmetries and their relation to action-invariants is being studied for application to (nearly) axisymmetric plasmas. The local guiding-center Hamiltonian formalism (in which gyro-phase is ignorable) is also being extended to the bounce and drift scales, with a view to higher-order action-invariants and to gyro-bounce-drift resonances.

(2) In relation to particle resonance and stochasticity, we developed a systematic perturbation theory to all orders for non-resonant particles, where adiabatic invariance is expected. This isolates the resonances and thus enables the overlap criterion for stochasticity to be applied, as well as elementary quasilinear diffusion in action-space. To develop a nonlinear theory of collisionless diffusion, the projection-operator technique of Zwanzig has been applied. Since the breakdown of adiabatic invariance and perturbation theory occurs in the neighborhood of a separatrix between orbits of different topology, we have studied a model problem involving separatrix crossing. We introduced the concept of "transition entropy" to characterize the spread in action due to the speed of crossing.

(3) On the subject of wave stochasticity and related problems, studies of the spectrum and eigenfunctions of the Helmholtz equation with "racetrack" boundary were extended. This model problem investigates a simple system for which the ray trajectories

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PLASMA THEORY

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Ray and Wave Optics of Integrable and Stochastic Systems, S. McDonald and A. Kaufman, Proceedings of Cargèse Workshop, Intrinsic Stochasticity in Plasmas, (Les Éditions de Physique, 1980), LBL-9462, 1979.

are known to be stochastic for almost all initial conditions. Two classes of eigenfunctions and eigenvalues have been found, one highly sensitive, the other insensitive, to variation of the aspect ratio.

Tormac Project

Comparable spectral data have been studied from the two versions of the Tormac IV experiment, a stuffed toroidal magnetic bicusps. In order to verify the high temperature inferred from line widths in the original device, T IV-a, a new vessel with much improved diagnostic access, T IV-c, was constructed. The additional diagnostics included Thomson scattering, magnetic probes, and a detailed He-Ne interferometric scan. Two spectral lines, HeII 4686 Å and D 4861 Å, were studied. Line of sight data were compared directly, and were also used as inputs to a computer assisted tomographic reconstruction. The evolution in time and the distribution in space of the total intensity of each of the spectral lines are found to be similar in both devices. Wide Gaussian HeII 4686 Å lines corresponding to Doppler "temperatures" of > 100 eV are noted in both versions of Tormac IV, while Thomson scattering shows the electron temperature to be < 10 eV in T IV-c. Since the energy equilibration time is on the order of a microsecond, the broadening of HeII 4686 Å was nonthermal.

Tormac V is a 1 m diameter toroidal magnetic cusp device in which the field is arranged to form cusps inside the vessel at some distance from the glass walls. The filling gas (~ 10 μ Torr H₂) is ionized and forms a toroidal z-pinch embedded in a toroidal bias magnetic field. The Tormac bicusps confining field configuration is then applied ($B \leq 5$ kG, 13 μ sec risetime).

Our observations indicate the following scenario. The pre-compression plasma is of density $\sim 5 \times 10^{14}$ cm⁻³ and temperature < 5 eV, and is embedded in a toroidal magnetic field ≤ 0.75 kG; it carries a toroidal current of magnitude up to ~ 100 kA. The Tormac confinement magnetic field is switched on and rises in 13 μ sec to a peak value of up to 5 kG. Plasma density rises with the field to a maximum of $\sim 2 \times 10^{15}$ cm⁻³. Although a part of the density increase must be due to compression, a substantial part of it is also due to ionization of residual gas, since the total number of electrons in the vessel ($\int n_e dV$) is observed to increase by a factor of several. The post-compression electron temperature is ~ 5 eV, and since the plasma is collisional for these parameters, the ion tempera-

ture is about the same. Diamagnetic plasma pressure measurements are consistent with this.

After the cusp field has peaked, density and temperature decay with a time constant

$\sim 20\text{--}30 \mu\text{sec}$. Magnetic probe measurements show that the poloidal component of the cusp field is not well excluded by the plasma but propagates radially inwards at several cm/ μsec ; the toroidal component of the cusp field is not excluded at all. Thus, the plasma formed was cold and a separation of interior plasma on closed field lines from exterior plasma or open field lines was not achieved. The sought for Tormac configuration was not established.

This does not imply that the Tormac concept has been invalidated, but indicates that this method of setting up the configuration is inadequate. One might speculate that a higher order cusp, possessing

TORMAC STAFF

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B. Myers, R. Miland,
P. Pincosy, R. Shaw,
M. Vella.

Schematic sketch of the toroidal plasma gun for the injection of a plasma ring into the TORMAC. The plasma is ejected radially outward by this "Puffer" gun and caught in the poloidal field of the toroidal magnetic cusp.

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only poloidal field components, together with hotter, more highly ionized pre-compression plasma and a lower background gas density, might show superior behavior. The Tormac concept itself remains intact and awaits confirmation via a different experimental approach.

Development of a plasma gun that accelerates a toroidally symmetric ring of plasma, containing $1-6 \times 10^{18}$ particles, to a radial velocity of $\sim 2 \times 10^7$ cm/sec, was a separate experiment. The device differs from the usual coaxial plasma gun in the use of a pulsed toroidal gas valve and a pair of annular accelerating electrodes. Enhanced gun efficiency is achieved by the use of a strong toroidal bias magnetic field. In addition, a technique was devised for generating a toroidal current of several kiloamperes in the plasma ring. The total number of particles in the ring can be varied over the range of 10^{18} to 10^{19} particles. The dynamics at the gun are such that the total kinetic energy of the plasma (200 Joules) remains roughly constant. The kinetics of the plasma gun are in good agreement with a modified "snowplow" model for the plasma acceleration. The plasma emerging from the 40 cm diameter gun has a minor diameter of about 3 cm. At least 60% of the accelerated particles are contained in this initial "ring", and little plasma is seen emerging from the gun after the first half cycle of driving current.