ANNUAL REPORT
ACCELERATOR & FUSION RESEARCH DIVISION

Fiscal Year 1978
October 1977 - September 1978

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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# TABLE OF CONTENTS

Forward

I. Accelerator Operations
   A. SuperHILAC
   B. Bevatron/Bevalac
   C. 184-Inch Synchrocyclotron

II. Magnetic Fusion Energy
   A. Basic Plasma Theory
   B. TORMAC Confinement Theory
   C. TORMAC Magnetic Confinement Research Project
   D. Atomic Physics Studies
   E. Ion Source Research
   F. Neutral Beam Development

III. Advanced Accelerator Development
   A. PEP
   B. ESCAR
   C. Accelerator Theory

IV. Heavy Ion Fusion
On October 1, 1977, the beginning of the period covered by this report, the Accelerator Division was joined by the Magnetic Fusion Energy Group to become the Accelerator and Fusion Research Division. With this addition the scope of the Division's activities has increased considerably. However, an essential unity is provided by the fact that the science and technology of particle accelerators is basic to all our activities. The Accelerator and Fusion Research Division now numbers 130 persons, but additional support staff from the Engineering and Technical Services Division brings the total to 440 persons who work on our programs. One-third of these are professionals.

Accelerator operations continue in a funding-limited mode. The demands for time are higher than we can meet, and machine availability, while improving, inevitably suffers from marginal crew strength. Nonetheless, it has been a productive period as detailed in this report.

Preparations for the start of clinical radiation trials at the Bevalac were advanced with a regular schedule of treatment to begin in early FY79.

A major change in the direction of the advanced accelerator program was made. With the completion and testing of one-half of the accelerating ring, ESCAR was discontinued. Preparations were made to launch two new programs in FY79. The first is development of high field (> 70 kilogauss) superconducting accelerator magnets, and the second is a study of the physics and techniques of stochastic beam cooling.

The other programs of the Division--PEP, Heavy Ion Fusion, the Uranium Beam upgrade of the SuperHILAC and Bevalac, and the Magnetic Fusion Energy program--continue to make very favorable progress as described in this report.

Edward J. Lofgren
Division Head
**ACCELERATOR DIVISION**
Professional Staff
E. J. Lofgren, Head

<table>
<thead>
<tr>
<th>Research Staff</th>
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<tr>
<td>W. Abt</td>
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<td>K. Shav</td>
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<td>J. Glatz</td>
<td>J. H. Shiloh</td>
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<td>G. R. Gray</td>
<td>L. J. Skvarla</td>
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</table>
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R. P. Warren
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R. B. Yourd

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R. K. Tegen
I. ACCELERATOR OPERATIONS

SUPERHILAC/BEVALAC OPERATION AS NATIONAL FACILITIES

The SuperHILAC and 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. With the now-standard time-share operation, either of two different ion beams can be selected for delivery on any SuperHILAC pulse 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 up to 2.1 GeV per nucleon.

MANAGEMENT PHILOSOPHY

Several advisory groups function at the two accelerators to consult with accelerator management and advise the Laboratory director. Meetings of the Program Advisory Committees for the SuperHILAC and the Bevatron/Bevalac, including the latter's nuclear science and biology and medicine committees, were each held twice during FY78 to advise the Director of LBL on research proposals. In addition, a scientific director was named for each accelerator to give programmatic guidance. R. M. Diamond fills this role for the SuperHILAC, while at the Bevalac the counterparts are A. M. Poskanzer for the nuclear

STAFF

Hermann Grunder in charge

science program and for the biology and medicine program, E. J. Ainsworth.

The users' associations at both accelerators held a joint meeting in January 1978 to share research results. Monthly telephone conferences among the users' associations' executive committees and accelerator management were instituted to facilitate regular communications.

Finally, the Fourth Summer Study on High Energy Nuclear Collisions was held July 24-28, 1978, at LBL attracting nearly 150 participants from around the world.

SuperHILAC Program Advisory Committee
R. Stockstad, Chairman, Oakridge Nat'l Lab.
P. Bond, Brookhaven Nat'l. Lab.
W. Swiatecki, LBL
D. Ward, Atomic Energy of Canada
M. Zisman, LBL, Executive Sec'y.

Bevatron Program Advisory Committee: Nuclear Science Panel
H. Feshbach, Chairman, M.I.T.
L. T. Kerth, LBL
S. Koonin, Cal. Tech.
A. Poskanzer, LBL (Ex officio)
B. Povh, Max-Planck-Institut fur Kernphysik, Heidelberg
J. Schiffer, Argonne Nat'l Lab.
R. Stock, GSI, Germany
G. Westfall, LBL Exec. Secretary

Biomedical Panel
M. M. Elkind, Chairman, Argonne
E. L. Alpen, LBL
E. J. Ainsworth, Exec. Sec'y, LBL
E. J. Hart, Argonne Nat'l Lab.
H. H. Rossi, Columbia Univ.
G. Whitmore, Ontario Cancer Inst.
H. R. Withers, M.D. Anderson Hosp.

SuperHILAC Users' Association Executive Committee
H. Britt, Chairman, LASL
R. M. Diamond, LBL
H. A. Grunder, LBL
B. G. Harvey, LBL

N. Johnson, Oak Ridge Nat'l Lab
M. Kaplan, Carnegie-Mellon U.
L. G. Moretto, Secretary, LBL
F. Plasil, Oak Ridge Nat'l Lab.
M. S. Zisman, Exec. Sec'y, LBL

Bevatron/Bevalac Users' Association Executive Committee
J. C. Castro, (Med.Sci.) Chairman, LBL
K. Fu (Med. Sci.), UC San Fran.
M. Garcia-Munoz (Cosmic Rays), U. of Chicago
H. Gutbrod (Nuclear Sci.), GSI (currently at LBL)
P. Kirk, Chairman Elect
Louisiana State Univ.
J. T. Leith (Bio. Sci.)
Rhode Island Hosp.
J. Carroll, Liaison Officer, LBL.

The Accelerator Research Coordination Office (ARC Office) continued to be the focal point for interaction between the accelerators and users. All matters of interest to the experimenters are handled, including experiment proposals, staging and scheduling.

OPERATIONS SUMMARY
Following the precedent established in 1977, the machines were scheduled for maximum operation and scientific output, although budgetary constraints limited the running period to 8.5 months. The year began as California's drought was coming to an end; we were able to anticipate slight reductions in the cost of power, as PG&E converted back to hydroelectric generation from fossil fuel electric generation. The summary of machine operations appears in the accompanying table.

SUPERHILAC:

Ion Source Development
Improvements were made to the cryogenic pumping equipment at the ADAM source test stand. A methodical analysis and modification of the system cold fingers led to a
OPERATIONS SUMMARY FY 1978  
(8 Months Operation)

<table>
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<tr>
<th>Research</th>
<th>SuperHILAC</th>
<th>Bevalac</th>
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<td>Nuclear Science.</td>
<td>4273 hours</td>
<td>2397 hours</td>
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<td>Biomedical Studies</td>
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<td>1231</td>
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<td>Accelerator Devel.</td>
<td>612</td>
<td>129</td>
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<tr>
<td>Total Research</td>
<td>4785*</td>
<td>3757</td>
</tr>
<tr>
<td>Tuneup</td>
<td>715*</td>
<td>898</td>
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<tr>
<td>Total Operation</td>
<td>4570</td>
<td>4655</td>
</tr>
<tr>
<td>Multiplicity</td>
<td>1.05</td>
<td>1.09</td>
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<tr>
<td>Multiplicity with Bevalac (3445 hours)</td>
<td>1.67</td>
<td></td>
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<tr>
<td>Availability (Actual Research/Scheduled Research)</td>
<td>0.82</td>
<td>0.78</td>
</tr>
<tr>
<td>Experiments served</td>
<td>32</td>
<td>29 Nucl. Sci ; 26 Biomed</td>
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<td>Institutions served</td>
<td>LBL + 20</td>
<td>LBL + 16; LBL + 18</td>
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<tr>
<td>% LBL</td>
<td>50%</td>
<td>65%</td>
</tr>
<tr>
<td>% other</td>
<td>50%</td>
<td>35%</td>
</tr>
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</table>

*Time share operation with 2 ion beams increases total research hours. Tuning hours cover tuning for two beams to two or three beam lines.

### TYPICAL BEAMS

<table>
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<th>SUPERHILAC</th>
<th>BEVATRON/BEVALAC</th>
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<tbody>
<tr>
<td>Particles</td>
<td>Average Intensity*</td>
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<tr>
<td>Lithium 6</td>
<td>.4 puA</td>
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<tr>
<td>Carbon 12</td>
<td>8 &quot;</td>
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<td>Oxygen 16</td>
<td>3 &quot;</td>
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<tr>
<td>Neon 20</td>
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<td>Argon 40</td>
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<td>.2 &quot;</td>
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<td>Niobium 93</td>
<td>30 puA</td>
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<td>Xenon 136</td>
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<tr>
<td>Holmium 165</td>
<td>2 &quot;</td>
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<tr>
<td>Lead 208</td>
<td>2 &quot;</td>
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*Measured at post-stripper exit
Fig. 1. SuperHILAC Experimental Area proposed arrangement for FY 1979 operation.
A reduction in the time required for warm-up and cool-down.

A modified sputtering geometry was examined and a number of different cathode materials tested. This work has not turned up a more favorable source construction. Holmium, palladium, germanium, silicon, and niobium were tested and the technical problems of cooling resolved. These elements are ready for on line use.

Special effort has been given to the optimization of a lead ion beam. A pioneering sputter timing procedure has led to a factor of two improvement of the intensity of Pb17+. A peak beam of two electrical microamperes was recorded at the entrance to the SuperHILAC poststripper in July 1978 utilizing this delayed pulsing technique. Unfortunately, the lifetime of the lead sources are at present about seven hours, substantially less than for other heavy ions such as xenon or holmium.

The design, fabrication and testing of a new improved extraction system from the ADAM source has been completed, and should lead to an improved source emittance match to the HILAC.

ADAM beams were measured in vertical emittance space; beam oscillations and other characteristics were related to specific source parameters.

Construction of a new high power test stand was begun to permit the development of a larger, more intense source for use in the Third Injector. Substantial modifications to source power supplies were undertaken. Considerable time and design effort were saved by borrowing a GSI source which formed the basis for the first test source. Important ideas were also gained from the GANIL effort. This development work will be of prime importance in the following year.

Experimental Area Improvements

The experimental status is shown in Fig. 1. A new beam line E89, was installed in the north cave area. The distribution magnet M8 was instrumented to provide magnetic analysis of beam rigidity (to ± 0.2%) using line E82.

A concrete pad for the south cave area was started. Cave S, intended for bombardment of radioactive targets, was also started and will be finished in early 1979.

Beam Velocity Measurement by Time-of-Flight

For the purpose of non-destructive beam energy determination by the time-of-flight method, a measuring system was designed employing wide-band electric pick-up stations for beam bunch detection (similar to the UNILAC phase probes). Probes for velocity measurement were installed in all major beam lines. Improvement work on the pick-ups is in progress and the electronics to allow digital processing of signals (sampling method) is under development. Data processing and operator control will be handled by the SuperHILAC computer control system; as an interface to it a serial CAMAC system was purchased and put into operation.

Bevalac/SuperHILAC Computer Systems

Major improvements were implemented in both control systems. Central processors were replaced with Modcomp IV-35s, with double the core memory (now 256K). Also greatly improved network software was installed, to allow a substantial increase in usable core and to remove restrictions on the number of controlled devices as well as on the number of operator displays.

A third operator control station, used for parasitic beams and beam development, was installed at the SuperHILAC.

The new counting area for SuperHILAC experimenters was also
completed with 2 Modcomp IV's available for data collection and data reduction.

At the Bevatron, computer control was being transferred entirely to the Modcomp system, replacing the PDP-8's in a phased process. Two operator control consoles were established, and enhanced software implemented. Conversion of the EPB area advanced, with fully integrated control of 38 magnets the initial goal, and ultimate provision for 140 magnets.

BEVATRON/BEVALAC

During 1978 ten different ion beams were delivered, with the allocation of research time continuing as one-third to the biomedical program and two-thirds to nuclear science. NASA calibrations run this year occupied about 7% of the nuclear science time.

An effort is underway to improve the multiplicity for the machine, that is, the number of experimenter hours per machine research hour, by splitting the beam and sending it to two experimenters at once. Multiplicity at the Bevatron has risen from 1.06 last year to 1.09 in FY78. Further gains can be made only with added staff to support simultaneous operation of magnets and components in two beam lines. The result, however, would be a substantial drop in the cost per research hour.

Ion Source

The Bevatron injector uses a PIG source to generate $^{12}\text{C}^4+$ ions, which are in turn accelerated to 5 MeV per nucleon and stripped with a 50 $\mu$g/cm$^2$ foil to $^{12}\text{C}^6+$. Three years ago, a typical carbon beam injected into the Bevatron was 1.5 $\mu$A peak. Best operation at year's end was 70 $\mu$A injected into the Bevatron. Four separate factors are involved in this increase:

1. Installation of a 6kV, 6 amp current regulated arc supply.

2. Additional pumping at the source end of the terminal with an LN cold trap and a Ti-ball pump.

3. Optimization of the cathode geometry and installation of a movable extraction electrode.

4. Placement of the stripper foil nearer the beam waist, which has reduced the emittance to give a gain in transmission.

More improvement in beam is expected in the future through the addition of a 1500 l/sec turbo pump in the source terminal, and optimization of the source exit and extraction apertures.

The continued use of this injector is important because it relieves dependence upon the SuperHILAC for the light ion beams and thus improves overall Bevalac reliability.

RF Improvements

On the 20 MeV linac, a single 2.5 MW amplifier and RF manifold have been installed, operating for the last year with a temporary driver and modulator. The new system, which is driven from a master oscillator and allows easy tuning to the correct linac mode, replaces ten self-excited oscillators and a pre-exciter that were exceedingly difficult to tune up and maintain. A new permanent drive system and modulator are being built to complete the system, and are expected to greatly increase the reliability of the 20 MeV injector.

For the main ring, a new wide band driver has been installed, since tubes for the old drive amplifier are no longer manufactured. We expect to replace the low level amplitude control chassis with a more
reliable and more versatile version designed specifically to match the wide-band drive system.

Bevatron Resonant Extraction

Work is in progress to design a large aperture resonant extraction system to achieve good extraction efficiency with low energy large emittance beams. This includes the design of the required large aperture perturbation magnets as well as a detailed analysis of the resonant extraction process. The problem is complicated in the Bevatron due to the field nonlinearities which result in both a large tune spread across the aperture and substantial amplitude-dependent tune shifts. Existing analyses and computer codes are being extended to handle this task.

Bevalac Experimental Area Facilities

Major changes were underway in the experimental area, with work on the installation of three new facilities (Fig. 2): the Low Energy Beam Line (Beam 39), the HISS Beam Line (Beam 41), and a rebuilt Zero Degree Spectrometer (Beam 40 now). Beam 26 has been modified and beams 37 and 38 removed to accommodate these additions.

The Low Energy Beam Line (Beam 39) was partially installed, and will be concluded this year. This line, capable of bending beams of up to 250 MeV/amu through a total angle of 150°, will afford exceptionally high dispersion for high precision spectroscopy and related experiments.

To replace the Beam 33 Zero Degree Spectrometer, which must be removed to make room for HISS, a new spectrometer will be assembled, consolidating the present Beam 33 and Beam 38 lines. The facility will accommodate projectile fragmentation studies, NASA instrument calibrations, fragment clustering studies, and other experiments presently done on these lines.

Rapid Beam Switching

With the start of regular, daily radiotherapy at the Bevalac in Fall 1978 great emphasis was placed on developing techniques to quickly switch the beam between experiments. Two major switches per day are required; to therapy in the morning and back to nuclear science in the evening; with the possibility of different beam particles and energies for each mode. The thrust of this project has been mainly in developing procedural techniques, and isolating areas where improved hardware and instrumentation are required to expedite changeovers.

Notable successes in 1978 included a two week run where biomedical and nuclear science experiments alternated twelve hour shifts, with particle and energy changes occurring in as little as 30 minutes, and a nuclear science excitation function experiment where many energy changes per shift were accomplished in as little as fifteen minutes each.

The completion in FY 79 of the new EPB computer control system, which features 14 bit monitoring and control, will greatly aid in performing these rapid beam line changes.

HISS

The Heavy Ion Spectrometer System (HISS), on which construction began in 1978, is designed to permit experiments which require high momentum resolution, high spatial resolution and large solid angle. HISS will be a dedicated user facility, with the flexibility to accommodate a wide variety of experimental interests. The facility itself 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; powerful computer system for experiment control, data collection and on-line experiment monitoring; common experiment floor area and housing to facilitate resource sharing; and staffing and manuals to support multi-user participation. Completion is scheduled for early 1980.

BEVALAC BIOMEDICAL OPERATIONS

The two achievements of the past year most important to Biomed operations are improved reliability of beam delivery to the Biomed area and increased amount of beam delivered. Biomed operational efficiency reached the mid-eighty percent level. Beam intensities for carbon, neon and argon are more than sufficient for therapeutic use. The radiobiology program, which uses reduced beam intensities, has run smoothly. During the year, a patient with Kaposi sarcoma on the leg was treated with carbon ions and another with leiomyosarcoma of the chest with neon ions. Beam delivery was so reliable that 10 daily fractions were given for therapy as well as 16 hourly fractions for radiobiology whenever desired.

The staff has stabilized at three permanent operators, with two physicists handling 24 hour radiological support.

Radiotherapy Preparation

The Radiotherapy Treatment Room was completed in September with the installation of a Philips treatment table, a device which permits precise patient positioning in three dimensions.

A beam-flattening system, modeled after the 184-inch therapy beam system, is being prepared to produce the large field, uniform dose profile beams required for radiotherapy.

Verification of the dose distribution and flatness quality will be performed by a newly completed multi-plane, multi-wire proportional chamber dubbed MEDUSA. Data from this chamber, which has 16 signal planes of 64 wires each, with each plane rotated by 11.25°, are collected by the microprocessor system and handled by standard tomographic reconstruction algorithms to yield beam profile distributions in pixel sizes as small as 3 x 3 mm.

CT Scanner

This past year a grant proposal was submitted to and approved by the National Cancer Institute to purchase and install an X-ray CT scanner in the Medical Building (Bldg. 55). The scanner will be modified by rotating the scanning plane 90° to permit scanning patients in the actual treatment position. The availability of an on-site scanner will vastly facilitate the conduct of the therapy program and allow standardization of treatment planning efforts. This capability should be realized in about a year.

Radioactive Beams

The feasibility of producing and separating ¹¹C beams from primary ¹²C beams was demonstrated this past year. A 400 MeV/amu beam of ¹²C was passed through 8.5 cm of beryllium at F1 (first focus in both planes outside accelerator), and emerging ¹¹C fragments were focused and transported to the Biomedical Cave II area. The difference in rigidities between ¹²C and ¹¹C allowed a high degree of purification; careful dosimetric measurements revealed less than 1% ¹²C contamination in the beam. The production and transport efficiency was about 0.17%. Bragg peak measurements (peak width around 2mm), and positron camera measurements confirmed the beam purity. The high production efficiency obtained indicates that dose rates
of the order of a few tens of rads per minute for modest beam spot sizes are possible, thus opening up a whole range of diagnostic and dose-delivery verification possibilities for heavy ion beams.

Uranium Capability Line Item
Research and Development

A revised Conceptual Design Report (LBL Publication 96) was issued in June 1978. The scope of the third injector portion of the project was slightly upgraded to more easily meet the performance goals. The pre-accelerator voltage was increased from 400 kV to 750 kV, and the required charge-state of the ion reduced. A 1:7 scale R.F. model was constructed, as was a prototype drift-tube focusing quadrupole. A new type of high molecular weight (Fomblin) gas stripper was designed and investigated. Its excellent stripping efficiency for high charge states at very low particle velocities makes it an attractive choice for the third injector. Ion sources for high current and relatively low charge state were pursued. Accelerating column development progressed with a new large computer code to model the non-linear dynamics and with high-voltage tests on a prototype NEC sample section of the column. Finally, engineering designs were developed for complex and long lead time items of the accelerator structure. Much fruitful work has resulted from collaboration and scientist exchanges with GSI in Darmstadt.

Turning to the Bevatron vacuum improvement side of the project, at the beginning of the fiscal year a new approach was evolved to meet the 10-10 torr vacuum requirements in the Bevatron main ring. The quadrant (curve) tank will consist of a rectangular convoluted bellows that can withstand atmospheric pressure, yet have sufficiently low induced eddy-currents that no new trim windings will be needed. It can be assembled and tested ahead of time as a full-length quadrant tank. Then, because of its flexibility, it can be slid into the magnet gap from the tangent region without disassembling the Bevatron magnet.

A flexible cryopanel design was conceived for the curve tank that will permit "snaking" the cryopanel into or out of the quadrant through the tangent region. New smaller tangent tanks fabricated of stainless steel are planned. All of the probes, magnets and other components inside of the new vacuum chamber will be redone to satisfy ultra-high vacuum (UHV) requirements.

184-INC SYNCHROCYCLOTRON OPERATION

The 184-inch synchrocyclotron is operated year round, four days a week, as a dedicated medical accelerator, supported by the Biology and Medicine Division. During calendar 1978 the emphasis at the 184" was to develop reliable and efficient procedures to treat patients with the helium beam. Sixty-five cancer patients received 1,097 treatments, and 23 pituitary patients received 92 treatments. Actual beam time for the cancer patients is one minute per treatment, and the total setup time ranges from fifteen to thirty minutes. In vivo dosimetry measurements using diode detectors were performed on selected patients to aid in helium ion penetration calculations. Film stacks were also used to verify penetration and depth compensater design.

A beam line was developed to treat ocular melanomas. Typical penetration is about 2 cm, and field size about 0.5 cm diameter. The edges of the field must be
very well defined to permit low radiation dose to the lens and eyelid during the treatment. Typical dose fall-off (90%-10%) at the edge of the field is 1.5 mm or less. The beam energy modulator used to broaden the Bragg peak to about 1.3 cm is a simple plastic paddle. Closed circuit TV is used to monitor the position of the patient's eye during treatment. Dose rate is about 1000 rad/min. A small amount of biological studies were also performed. Physical measurements were made of edge effects within the treatment volume, depth dose measurements, and effects of tissue inhomogeneities.

The maximum number of patients per day was 16 (10 cancer plus 6 pituitary), with 10 or 12 the usual member by the end of the year.

A former breezway between Bldg. 6 and 10 was enclosed to make an entry/waiting/consultation room for families and the social worker. Indoor/outdoor carpet and several plants make the area quite pleasant.

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II. MAGNETIC FUSION ENERGY

INTRODUCTION

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

1. Basic Plasma Theory
2. TORMAC Confinement Theory
3. TORMAC Experiments
4. Atomic Physics Studies
5. Ion Source Research

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 Development and Technology Project. It is carried out as a joint program with the Lawrence Livermore Laboratory, 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 restricting our report to the work done at LBL. Only very brief summary statements are made because a description of this project appears in the annual report on magnetic fusion energy issued by LLL.

Present and future large tokamak experiments in the U.S., as well as abroad, and the current and future mirror confinement experiments at Livermore, depend on powerful and intense, low-divergence beams of neutral hydrogen (or deuterium) atoms for the production of their hot plasma. It is, therefore, not surprising that the neutral-beam injector problem has been given the highest priority within the Development and Technology category of the MFE program.

The major accomplishment in the neutral-beam development at LBL in 1978 has been the successful construction and testing of a 120 kV 65A deuterium beam system, such as will be needed for the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory.

The remaining five 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 concentrated on the development of computer models for the source, and in diagnostic work needed to supply experimental input data for

STAFF

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Visitors: B. Vaucher, R. Smith;
these models. The atomic physics is aimed at supplying missing data on fundamental 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 nonlinear processes in plasmas, of interest to controlled fusion because of their relevance to plasma heating schemes.

A separate portion of the theory effort is carried out in support of the Tormac Project. The latter is our only direct contribution to the magnetic confinement problem in controlled fusion research. The Tormac (toroidal magnetic cusp) is one of several so-called "alternate 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 economical fusion reactor.
A. BASIC PLASMA THEORY

INTRODUCTION
Our program in basic plasma theory is aimed at improving our understanding of plasma dynamics, including particle and wave dynamics and their interactions. As plasma phenomena grow more complex, the need arises for new analytic approaches to provide fresh insights and ideas. All aspects of plasma dynamics (confinement, stability, transport, heating) can be more efficiently predicted and controlled when our understanding is deepened.

Our theoretical work makes use of standard analytic tools (Vlasov equation, Hamiltonian dynamics, Fokker-Planck equation) and of novel, more sophisticated techniques (Lie transform, Darboux algorithm, non-canonical coordinates in phase space, resonance overlap). Analysis is complemented by numerical studies to solve equations, to test analytic approximations, and to develop intuition and understanding.

APPROACH
1. The Lie approach to perturbation theory offers a highly economical way to obtain results in nonlinear plasma dynamics, which otherwise require lengthy laborious calculations.

2. The concept of intrinsic stochasticity is being more fully appreciated as it relates to particle motion, magnetic field line configuration, and wave interaction. A new development is the study of stochastic ray trajectories, as well as semi-ordered trajectories; these arise both in radiative heating and in instabilities. In addition to relating standard stochastic methods to ray trajectories, the need arises to understand the physical optics (wave spectra and eigenfunctions) under such conditions.

3. A limited amount of understanding has previously been achieved for the critical problem of trapping transitions, i.e., the transitions of a particle between the untrapped and trapped states. This transition occurs across a stochastic layer. A useful theory for this process is greatly needed.

NONLINEAR WAVES
1. By the use of Lie transforms for non-resonant particle motion, a unified theory has been developed for the self-consistent nonlinear quasi static effects associated with a wave. In a uniform unmagnetized plasma, results include the self-generated magnetic field, and the self-precession of wave polarization. In a uniform magnetized plasma, we found that a low frequency wave could cause ponderomotive trapping (i.e., density enhancement); this idea was subsequently developed as a method of stabilizing the DCLC mode in a mirror, by confining low energy ions in the attractive ponderomotive potential of an
Alfven wave. Secondly, a study of the motion of particles trapped in a phase-modulated wave showed that the trapped particles tended to remain synchronized to the wave, so that weak phase modulation should not disappear by phase-mixing, contrary to previous belief.

3. A diagnostic tool for measuring wave-generated magnetic field has been the Faraday rotation of a test wave. We have shown that this method is invalid, in that the test-wave polarization is modified also by other competing effects.

4. Another problem being studied, by Lie transforms, is the induced scattering of waves in magnetoplasma. We have obtained a noise and quite general expression for this process, and further work is planned for its study.

5. In a separate study, the behavior of double-solitons under weak dissipation was investigated, following their evolution both analytically and numerically.

STRONG-SHEAR, LARGE GYRORADIUS EFFECTS

1. A self consistent slab model for realistic strong-shear equilibria has been developed.

2. A generalization of the magnetic-moment adiabatic invariant to the case of gyroradius comparable to cross-field magnetic scale length was derived for weak variation along the magnetic field.

3. A variational principle for linear instabilities of a strongly-sheared slab has been worked out and applied to the drift-cyclotron modes.

RAY HAMILTONIAN AND STOCHASTICITY

The solution of linear wave equations in 2 and 3 dimensional non-separable geometry is being studied in terms of a ray Hamiltonian derived from the differential or integral field equation via an eikonal expansion. First results have been obtained on the eigenfrequency spectrum and eigenfunctions for a wave equation whose ray Hamiltonian has stochastic trajectories. The spectrum is found to have a Wigner distribution of spacing, i.e., the same as that for a random Hamiltonian; while the eigenfunction exhibits isotropy in the distribution of local wave vectors. Both properties are in contrast to the standard case of ordered trajectories.

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INTRODUCTION
During the past year the Tormac Theory Group has investigated areas of concern to the Tormac concept including equilibrium, transport and stability. The major accomplishments were the development of a quantitative slab model to calculate the erosion rate from a Tormac edge, which confirmed previous estimates, and the development of a microinstability theory which shows that loss cone modes arise in the Tormac sheath even for shear lengths of the order of an ion Larmor radius. Some of the detailed problems studied are as follows:

ONE-DIMENSIONAL TORMAC EQUILIBRIUM
Using the exact invariants of motion, the equilibrium of a slab model with shear lengths of the order of an ion Larmor radius has been calculated numerically.

MHD TORMAC EQUILIBRIUM STUDIES
An MHD code has been used to construct Tormac equilibria with a sharp sheath and with poloidal flux enclosed in the bulk plasma. The Tormac sheath is compressed to zero thickness and the MHD jump conditions (continuity of \( p + B^2/8 \)) are applied at the plasma edge. The Tormac equilibrium is obtained by considering a straight pinch and then applying quadrupole fields. Successful high beta runs have been obtained.

STEADY TORMAC SHEATH MODEL
A quantitative model for the erosion rate of a Tormac sheath has been considered. The Tormac is modeled as a semi-infinite slab, and the equations for a steady erosion rate are studied. Careful attention is paid to the transition from closed to open field lines. The erosion velocity is found to be comparable to \( a_i v_i \), where \( v_i \) is the ion scattering frequency and \( a_i \) the ion Larmor radius, as had been predicted.

HYBRID CODE MODELING OF TORMAC
To understand the dynamics of a Tormac sheath where the sheath size is of the order of a Larmor radius, a one-dimensional hybrid simulation code has been used. In the code the electrons are a fluid, and the ions are particles obeying exact dynamics. Several numerical problems have prevented detailed study of a Tormac sheath, but the code has been used to compare with low temperature experimental data where a sheath has not formed.
SHOCK FORMATION OF TOKMAC

The conditions needed to form a Tormac sheath with rapid compression have been outlined in two separate reports. The studies are focused on attempting to form a plasma whose post-compression stage has a long mean free path and many ion gyroradii. Fast capacitor bank technology is required with rise times the order of a μsec producing magnetic fields of several kilogauss. Such technology is assessed to be feasible.

LOSS CONE INSTABILITIES

Studies of the loss-cone instability in the Tormac sheath have been carried out. As these instabilities have wavelengths short compared to an ion-gyroradius, WKB theory and straight line orbit approximations can be used. The result of the theory is that the loss-cone modes remain a serious instability problem even for shear lengths of the order of a gyroradius.

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Tormac (Toroidal Magnetic Cusp) is a high energy density system for confining a plasma for magnetic fusion. The high energy density confinement of this system is due to its absolute minimum-B characteristics. That is, the plasma is confined to a region in which the magnetic field intensity has a minimum even when the plasma is not present. It can be shown that any absolute minimum-B system must be surrounded by open magnetic field lines. Thus, Tormac consists of a central toroidal plasma on closed magnetic flux tubes surrounded by a sheath of open magnetic field lines where plasma is mirror contained.

A major problem with the Tormac geometry is start-up. Although the geometry has been predicted to be a stable container of plasma, the theory has not been verified experimentally. The difficulty is that the vacuum field, from which a cusp is formed, has all open magnetic field lines. Consequently, if a hot collisionless plasma is injected slowly into the field, particles are all on open magnetic field lines, and, the geometry behaves like a simple mirror. One way to circumvent this problem is to form a high density plasma and apply the cusp magnetic field very quickly after the plasma has been formed. This method of creating a cusp requires turning on a large intensity and large volume magnetic field in microseconds.

The "Puffer" experiment has been developed as a simpler solution to this problem. In this experiment the magnetic field is held virtually constant while it is pulse-filled by a high density plasma from a plasma gun. Fig. 3 shows a schematic representation of the experiment. In Fig. 3 a toroidally symmetric geometry is shown in which a puff of gas is injected into the breech of the plasma gun. The gas is then ionized and accelerated radially outward by a high voltage, high current pulse. A poloidal magnetic field also pervades the region of the gun so that as the plasma is accelerated radially outward a toroidal current is generated within the plasma. The plasma also carries a strong toroidal field.

The plasma gun was designed to meet several special requirements for the "Puffer" experi-
ment. One requirement is that the plasma created in the gun be toroidally symmetric. This is because as the plasma enters into the cusp magnetic field where it is to be stopped, closed toroidal currents will be generated. These currents interact with the cusp field and stop the plasma at its equilibrium position. A second requirement of the plasma is that it consist of \(10^{19}\) particles. This number is a consequence of the need that the plasma be high-energy density and have a small gyroradius compared to the geometric size of the plasma. A third requirement of the plasma is that its directed velocity or particle energy be large enough so that the resulting plasma is collisionless.

To test the operation of the plasma gun and verify that it produces a plasma that meets requirements, a laser interferometer was built and magnetic probes were used. The results of these tests indicate that a toroidally symmetric plasma is indeed formed. A toroidal current up to 6000 amps is measured within the high density toroidal plasma containing up to \(2 \times 10^{19}\) particles; with about a 2 cm minor radius. The radial velocity varies from 15 cm/microsecond to 30 cm/microsecond depending on the fill pressure. However, the plasma energy is 150 joules and is nearly independent of the fill density. These requirements corresponded to a computer program which has been developed to predict the plasma behavior of the gun.

In order to catch the plasma in the Tormac geometry a suitable equilibrium magnetic field has been designed and constructed. The design involved the development of a computer code which can be used to predict the equilibrium plasma configuration for Tormac. To do this toroidal line currents are used to represent the plasma surface. The magnitude of each line current is determined by assuming the plasma is perfectly diamagnetic. These line currents are moved to satisfy pressure balance. With such a code it is possible to arrive at a suitable magnetic field for the "Puffer" experiment. The next phase of the design problem was to predict the behavior of the plasma as it entered this field. For this purpose the time rate of change of magnetic field as seen by the plasma was predicted and a shock model of the plasma behavior was derived.

Experimental measurements of the plasma entering the cusp magnetic field have been carried out using the laser interferometer. These measurements have been able to follow the injection of the plasma into the magnetic field and to observe the catching of the plasma. The resulting time constants and densities are within the range predicted by the theory. Currently additional diagnostics are being installed in the experiment so that with temperature and magnetic field measurements the correspondence of the experimental behavior to the theory can be more completely determined.

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THESIS

OTHER
PUFFER EXPERIMENT

BICUSP FIELD

TOKOMAK-LIKE PLASMA

Fast gas valve

Axial current

Plasma gun

Fig. 3

XBL 781-56
D. ATOMIC PHYSICS STUDIES

INTRODUCTION
Experiments conducted by the MFE Atomic Physics Group provide atomic collision data which is used in the neutral beam development work described above and for the design and interpretation of confinement experiments and reactor concepts by the fusion research community in general.

Activities in 1978 fell into the following broad categories:

A. Production of \( D^- \) ions by electron-capture and -loss collisions of 0.2 to 20 keV \( D^+ \) ions passing through Cs vapor.

B. Production of \( H^- \) and \( D^- \) ions by backscatter of hydrogen projectiles from low-work-function surfaces.

C. Electron-capture and -loss in \( H_2 \), and ionization of the \( H_2 \) target, by 0.1 to 8.5 MeV/amu iron ions

EQUILIBRIUM CHARGE-STATE FRACTIONS OF LOW-ENERGY HYDROGEN BEAMS PASSING THROUGH Cs VAPOR

Charge exchange of deuterium in cesium vapor is a promising way to make intense negative deuterium ion beams for the injection of neutral atoms into tokamaks and mirror machines. Cesium is believed to have the highest negative conversion efficiency of any target medium known, but at low energies there were discrepancies of greater than a factor of two in the previously measured values (the maximum being between 10 and 21%). To resolve these discrepancies a special apparatus for low energy measurements was constructed. The main features are: close spacing between the accelerator, vapor cell, electrostatic analyzer, and detectors to minimize beam loss due to scattering; a recirculating cesium vapor target designed on the same principle as a heat pipe, permitting use of a large-aperture target; detection of the atomic beam with a large acceptance-angle pyroelectric detector; and detection of charged particles with large acceptance-angle, magnetically-shielded Faraday cups. The negative-ion conversion efficiency of deuterium ions in cesium vapor, or the equilibrium \( D^- \) yield, was found to be 35% at a deuterium energy of 300 eV, dropping smoothly to 27% at 1 keV and 2.8% at 10 keV (see Fig.4). These results have now been confirmed for both \( D^- \) and \( D^+ \) as the incident beam (the \( D^- \) beam requires thinner targets, hence experiences less scattering, than the \( D^+ \) beam).

FORMATION OF \( H \) BY BACKSCATTERING FROM CLEAN METALLIC SURFACES

The study of backscattered negative ions from clean metal

STAFF
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K. H. Berkner, W.G. Graham, A. Schlachter, J. Stearns
surfaces bombarded by $H_2^+$, $H_3^+$, $D_2^+$, and $D_3^+$ ions was continued during the year. The main emphasis was on determining the purity of Li, K, Na, Cs, and Rb target surfaces deposited onto a Cu substrate in an ultra-high (5 x $10^{-8}$ Pa, i.e. 4 x $10^{-10}$ Torr) vacuum system. Secondary ion mass spectroscopy of positive ions sputtered from the surface by bombardment of low-energy Ar$^+$ ions was used to determine surface purity. Mass analysis of backscattered negative ions when the surface is bombarded by low-energy $H_2^+$, $H_3^+$, $D_2^+$, or $D_3^+$ ions indicate that most of the negative ions produced at the surface are $H^-$ or $D^-$. The $H^-$ or $D^-$ yield is the product of three probabilities: reflection of the positive ions by the surface, formation of the negative ion, and escape without electron detachment from the surface. These processes are being investigated for the clean alkali surfaces.

**ELECTRON CAPTURE AND LOSS BY HIGHLY STRIPPED IRON IONS IN HYDROGEN TARGETS**

In this series of experiments we are studying atomic collisions of highly-ionized high-Z ions with hydrogen—in particular electron-capture and -loss of energetic ions and ionization of the hydrogen target. A beam of ions from the SuperHILAC in charge state $q$ is momentum analyzed and collimated and passes through a gas-target cell; the slow ions produced in the target are swept out and collected to determine the ionization cross section, whereas electron-capture and -loss are determined by analyzing the charge states of the beam exiting the target.

These processes are of great interest to the fusion program, in which highly-charged high-Z impurity ions in the plasma can alter the deposition profile of energetic hydrogen (deuterium) atoms injected for heating and fueling the plasma. Our measurements also check theoretical models for electron capture and ionization by Olson and Salop and electron loss by Rule and Omidvar$^2,3$.

To date we have measured cross sections for the processes:

- **Electron capture**
  \[ Fe^{+q} + H_2 \rightarrow Fe^{+q-1} + \ldots \]

- **Electron loss**
  \[ Fe^{+q} + H_2 \rightarrow Fe^{+q+1} + \ldots \]

- **Ionization**
  \[ Fe^{+q} + H_2 \rightarrow Fe^{+q} + [H_2^+, H^+ + H, 2H^+] \]

For $q = 20 - 25$:

- $3.4 \text{ MeV/amu}$

For $q = 11 - 22$:

- $1.1 \text{ MeV/amu}$

For $q = 9 - 14$:

- $0.3 \text{ MeV/amu}$

For $q = 3 - 13$:

- $0.1 \text{ MeV/amu}$

Ron Olson of SRI has calculated cross sections for the following processes:

- **Charge exchange**, $\sigma_{cx}$
  \[ A^{+q} + H \rightarrow A^{+q-1} + H^+ \]

- **Ionization**, $\sigma_i$
  \[ A^{+q} + H \rightarrow A^{+q} + H^+ + e^- \]

where $A^{+q}$ is any heavy ion in charge state $q$. Furthermore, if one defines an electron-loss cross section $\sigma_{loss} = \sigma_{cx} + \sigma_i$, we have found that, for a wide range of energies and charge states, electron-loss cross sections for collisions cross with any ion $A^{+q}$ can be represented by a single curve when plotted with the reduced parameters $\sigma_{loss} \div q$ vs. (energy per amu) $\div q$. (Fig. 5). The curve can be approximated by the analytic expression

\[ q_{loss} = 4.6q \times 10^{-16} \left\{ \frac{32q}{E} \left[ 1 - \exp(-E/32q) \right] \right\}, \]
where $\sigma_{loss}$ is the H-atom electron-loss cross section in cm$^2$, $q$ is the charge state of the ion, and $E$ is the energy in keV/amu. Our results are in good agreement with these calculations, if one corrects for the molecular target in comparing with atomic H calculations.

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FIGURE LEGENDS

Fig. 4.
Equilibrium yield, $F_\infty$, of $D^-$ for $D^+$ in Cs vapor.

Fig. 5.
Solid line: Calculated cross section $\sigma_{loss}$ for electron loss by atomic hydrogen in collision with an ion in charge state $q$; this curve is valid for $1 \leq q \leq 50$ and for energies in the range 50 to 5000 keV/amu. The range of $E/q$ values for which the curve is valid is indicated by the bars drawn in the lower portion of the figure. The uncertainty in the calculated cross sections is 25%.

Dashed line: Plane-wave Born-approximation cross section for ionization only (Ref. 5, 6). Closed symbols: Present experimental results for Fe$^{+q}$ + H$_2$ divided by a number between 1.5 and 2.0 to allow comparison with the calculations (see text). The uncertainty is 30%.

Square, 108 keV/amu, $q = 7$-$11$; triangles, 110 keV/amu, $q = 3$; diamonds, 282 keV/amu, $q = 9$; stars, 290 keV/amu, $q = 10$-$15$; circles, 1140 keV/amu, $q = 11$-$22$.

Open symbols: Published results for H$^+$, He$^{++}$ + H, H$_2$ (representative points only). All results for an H$_2$ target are divided by 2 to allow comparison with the calculations.
Cesium

Fig. 4
Fig. 5
E. ION SOURCE RESEARCH

The most successful method known for heating magnetically confined fusion plasmas is by injecting high power beams of neutral atoms. These atoms penetrate the confining magnetic field, and are trapped after ionizing and charge transferring collisions with the confined plasma. To make the neutral beam, ions are produced in an ion source, accelerated, and converted to neutrals by charge-exchange collisions in a gas cell. The ion source produces not only D\(^+\) ions (we use deuterium as an example), but also D\(_2\)\(^+\) and D\(_3\)\(^+\) molecular ions, which are also accelerated, break up in the neutralizer, and produce undesirable, and sometimes even harmful, components in the neutral beam at 1/2 and 1/3 of the full energy. The most cost-effective way of increasing the full-energy neutral component injected into a fusion experiment is to maximize the D\(^+\) fraction in the original ion beam (as opposed, say, to adding additional beam lines).

Our goal is to develop a computer model of the plasma source, as a tool for predicting the modifications necessary to maximize the D\(^+\) output, and then to compare the model predictions with experimental data. Ideally, the model would have as input only the source geometry, the gas flow, the necessary cross sections, and the arc current and voltage; the output would be the current density of each ionic species at the accelerator.

Our first step was to develop a pulsed digital Langmuir probe\(^4\) as a diagnostic technique, to enable us to measure those plasma properties required for input into the computer model. The probe and accompanying instrumentation is interfaced to a MODCOMP IV computer, to give on-line measurements of the electron distribution function (or the electron density and temperature). The same apparatus can be used to measure fluctuations in the plasma, to try to understand the origins of the ion temperature (about 1 eV), which in many cases limits the beam divergence we can achieve.

Our computational approach was two-pronged. First, we developed a one-dimensional single species model, collisionless, in which we solved the ion equation of motion and Poisson's equation with local ion production and an electron distribution function consisting of a high density, low temperature, component and a low den-
sity component of "primary" electrons. This model reproduced the observed source parameters as far as it was able, and taught us that the plasma remained basically symmetric in spite of obvious asymmetries in the source (one wall partially transparent, for instance, simulating the ion accelerator). Since this first model had only a single-component (D, D^+), it was obviously unable to predict the beam composition.

The second step was to develop a zero-dimensional (ignoring variations in plasma properties with position), multi-species model. In this model we solve all the pertinent coupled rate equations for the production and destruction of all ionic species. Confinement times are calculated from results of the one-dimensional model. The input for this model is the source geometry (volume and areas for loss of particles), the gas flow, measured electron density and temperature, and fraction of primary electrons. For two cases for which sufficient experimental data existed, the model was able to calculate accurately the current densities at the wall of all three ionic species (D^+, D_2^+, D_3^+). The next step, now in progress, is to add inelastic collision processes for electrons. Detailed knowledge of the electron energy distribution can then be replaced with the easily measurable parameters of arc current and voltage, making the model useful for predictive purposes.

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F. NEUTRAL BEAM DEVELOPMENT

INTRODUCTION

The LBL Neutral-Beam Development Program, part of a joint LBL/LLL effort, has as its goal the development of multi-megawatt beams of energetic (presently 120 keV) hydrogen or deuterium atoms for injection into magnetically confined plasmas. Hydrogen ions are accelerated and electrostatically focused in a multiple slot accelerator array, then neutralized by charge exchange with hydrogen gas. Most of the work centers on the development of large-area, uniform plasma sources, accelerator structures, and beam diagnostic techniques. Highlights of 1978 were successful operation of both a 120 keV, 65 A deuterium system for the TFTR tokamak at the Princeton Plasma Physics Laboratory and a one-fifth scale source for the Doublet III tokamak at General Atomic Company (80 keV, 80 A hydrogen, 0.5 sec). The full size source for the latter was also fabricated.

TFTR SOURCE

The development of a deuterium source suitable for the TFTR tokamak (120 keV, 65 A, 0.5 sec) proceeded along the following lines:

1. Development of a suitable long-pulse plasma source.
2. Design, with the aid of a computer code, of an accelerator slot configuration for 120 keV beams.
3. Construction and test of a 15-A prototype system.
4. Design and construction of the full-size source (10 cm by 40 cm grid array).

A cross-section of the TFTR source is shown in Fig. 6. This source was operated at 120 kV on Test Stand IIIB for 15-msec pulses (limited by power supplies). Tests up to the 0.5-sec design pulse-length await completion of the High Voltage Test Stand at LLL. Sample operating characteristics for 120-kV deuterium and hydrogen beams are given in Table I.

<table>
<thead>
<tr>
<th>Gas, Beam Type</th>
<th>Gas Flow</th>
<th>I_{accel}</th>
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<tr>
<td>D_2</td>
<td>15 T-ℓ/sec</td>
<td>67A</td>
<td>98 kV</td>
<td>200 mA</td>
<td>-2 kV</td>
<td>11A</td>
<td>53V</td>
<td>2300A</td>
</tr>
<tr>
<td>H_2</td>
<td>28 T-ℓ/sec</td>
<td>94A</td>
<td>96 kV</td>
<td>220 mA</td>
<td>-2 kV</td>
<td>12.5A</td>
<td>59V</td>
<td>2200A</td>
</tr>
</tbody>
</table>

Table I: Sample Operating Characteristics of the TFTR Module for 120-kV deuterium and hydrogen beams.
The suppressor- and gradient-grid currents increase with increasing gas flow, indicating they arise from ionization of gas in the grid region. Only preliminary results on species and beam divergence are available at this time. For deuterium operation the accelerated ions are approximately 70% $D^+$, 20% $D_2^+$, and 10% $D_3^+$. The beam can be characterized by a bigaussian source uniformly distributed over a 10cmx40cm area at the source with 1/e halfwidths of approximately 1.1' x 0.4'. This is better than the 1.3 x 0.4' observed for the smaller source. At this time it is not clear whether this apparent improvement is real or whether it is instrumental.

**DOUBLET III**

The Doublet III tokamak at General Atomic Company will require 80-kV, 80-A, 0.5-sec injector systems. Because of the small apertures available for access into the tokamak, the accelerator grids have to be curved to focus the beam at approximately 5 meters. A 80-kV, 15-A, 0.5-sec source was used to demonstrate that the design parameters can be achieved. The 80-A source was designed and fabricated, and testing was begun in 1978.

**DIAGNOSTICS**

The test facilities are used not only for the development of injectors, but also for the development of diagnostic techniques, controls, and power supply components.

The standard diagnostic tool for determining the beam profile is a thermistor array embedded in our thermal-inertia beam dumps: 2-cm thick copper plates in a V-shape configuration to limit the peak power density (Fig. 7). The thermistor readings are recorded by a computer prior to the beam pulse and after the beam pulse to determine the thermal imprint of the beam. The plates are cooled between beam pulses, during which time the computer is used to fit the thermal pattern to a bi-gaussian distribution which characterizes the beam. The power deposited to the calorimeter is determined either from the thermistor temperatures or by water-flow calorimetry. We have recently found that the epoxy used to bond the thermistors to the copper plates deteriorates after repeated thermal cycling in vacuum, resulting in a poor thermal joint. We are investigating other bonding techniques.

Another diagnostic technique that has proven extremely useful is Doppler-shift spectroscopy of the light emitted by the atoms in the beam. An optical spectrometer equipped with a 500-channel vidicon is used to analyze the beam divergence of all energy components in the neutral beam, the relative population of full-, half-, and third-energy components, and the aiming direction of the beams.

**MAGNETIC BUCKET SOURCE**

In order to try to improve the fraction of the beam that is in atomic ions ($D^+$), as opposed to that in molecular ions ($D_2^+$, $D_3^+$), we have produced and are testing a series of "bucket" sources, following similar work at UCLA, ORNL, and Culham Laboratories in the U.K. These sources are characterized by rows of permanent magnets around the outer walls, which improve the ion and electron...
LBL "65-AMP" NEUTRAL BEAM SOURCE MODULE

(65-Amp, 120-keV, 0.5-sec)
confinement times. We have measured the fraction of atomic ions in beams produced from plasma sources of varying axial lengths (along the beam direction), and have observed that for a fixed ion current density, the fraction of atomic ions increases with increasing source depth. It appears, then, that the magnets do not directly affect the atomic ion fraction, but permit the source to be made deeper and still maintain tolerable ion and electron losses to the walls. An example of one of these bucket sources is shown in Fig. 8.

LIAISON

The Engineering and Technical Services Division is designing and fabricating prototype neutral-beam lines for TFTR and DIII. Close liaison is maintained between these groups and the Neutral-Beam Development Group to assure that the beam lines will be compatible with the sources.

Neutral Beam source development was judged sufficiently mature by the U. S. Department of Energy that industrial participation was invited, in the form of two contracts to industrial firms to fabricate one each complete neutral beam source for TFTR, with all hard seals and able to be remotely maintained. From the experience we have had so far, it appears that industry will be able to contribute to solving our difficult fabrication problems. However, continued contact, both at the management and at the technical level, is required to ensure that the end product will be useful.

FIGURE LEGENDS

Fig. 6. Cross section of the 120-kV, 65-A, 0.5-sec TFTR injector module.

Fig. 7. Thermal-inertia beam dump.

Fig. 8. Photograph of a "bucket" plasma source for a 10 cm by 10 cm accelerator.

PUBLICATIONS IN PROCEEDINGS OF CONFERENCES


TALKS AT CONFERENCES


K.H. Berkner, C.F. Burrell,


UNPUBLISHED INTERNAL REPORTS


III. ADVANCED ACCELERATOR DEVELOPMENT

A. PEP

INTRODUCTION

The last Division Report described the start of construction for the PEP project. The period of this report is one of peak activity in all facets of the development and construction of PEP. Major construction contracts were underway for the tunnels and buildings that house the PEP storage ring and its associated experimental detectors. Procurements, fabrication of parts, and assembly of the various technical components were in full swing at LBL and SLAC. The first round of PEP experiments was selected and many experimental groups across the country, as well as at LBL, began fabricating the complex devices that will explore electron-positron collisions at PEP energies. Contracts were awarded for the installation of the varied PEP storage ring components. These activities, briefly described below, are geared for the first beam turn-on near October 1979.

OVERVIEW

PEP (the Positron-Electron Project), 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 (Fig. 9). Basically, the project will provide a storage ring (beams circulate continuously for several hours) in which counter-rotating beams of electrons and positrons will 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.

The ring tunnel scribes a circumference of approximately 1.4
Fig. 9 An overall site view of PEP and its relationship to the SLAC linear accelerator and existing research facilities. PEP roads, above-ground structures, and landscaping plans are indicated.
miles and varies in depth between 20 and 80 feet below ground. The curved sections will contain the bending magnets, which constrain the beams to their closed orbits. The straight sections contain 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.

Two injection tunnels will contain the magnets for directing beams from the existing linear accelerator (PEP's injector) into the PEP main ring system. The vacuum tube within which the beams must circulate is visible at the center of the bend magnet. The tunnel is approximately 3 meters wide and the vacuum tube dimensions are approximately 5 cm vertically and 12 cm horizontally.

In a typical interaction hall, half of the building is above ground and half is below ground level where the PEP beams traverse the structure. The remainder of the building protrudes into a lower yard area for level access of heavy equipment required by experiments. The above-ground building structure to the right, which is positioned directly above the PEP tunnel, contains klystrons for the radiofrequency power system, magnet power supplies, and instrumentation and control systems. At Region 8 this structure also contains the central computers and main control center.

The hall has two sections: the below-ground portion constructed of heavy concrete walls and an outer metal frame building (Fig. 10). 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 assembly and repair of experimental devices while the beam is in operation.

**PROGRESS OF CONVENTIONAL FACILITIES**

**Summary**

The conventional facilities consist of the various buildings, tunnels, roads and utilities for the project. Five phased construction contracts (valued at $23 million) were developed in order to realize the planned schedule for installation of technical components and beam turn-on.

During FY78, four of the five conventional facilities construction subcontracts were active. The Linac Junction work, Subcontract No. 321, was completed; this consisted of building the first segment of the PEP North and South Injection Tunnels (NIT and SIT) onto the existing LINAC structure. The Initial Site work, Subcontract No. 322, was also fulfilled; it consisted of massive excavation for 2 of the 5 interaction areas along with installing the main utility feeder lines around the PEP site and constructing most of the PEP Ring Road.

The Beam Housing Subcontract No. 323 was begun and advanced to near completion. Being the largest of the five construction subcontracts, it consisted of the concrete construction of the 2.2 kilometers of PEP's beam housing and the interaction halls at four locations around the ring. The Support Facilities, Subcontract No. 324, begun late in FY78, deals with construction of the steel-framed assembly portion of the interaction halls, the seven support buildings and installation of all local utilities.

**Details:** In early FY78, mass excavation of the five interaction areas was completed along with the construction of approximately 3/4 of the PEP Ring Road which traverses the site. (The remaining road segment presently awaits backfilling of the final portion of beam housing in Region 11 over which the road passes.) The
Fig. 10 A cutaway version of the interaction hall of Region 2, showing the above and below ground sections.
The initial earthwork subcontract also included laying the mechanical and electrical trunk lines which traverse the site. The mechanical trench consists of piping for cooling water supply and return, domestic water, low conductivity water and compressed nitrogen. The electrical trench contains a duct bank to house the power distribution cables. Approximately 4000 feet of the mechanical trunk line and 5400 feet of electrical duct banks were completed early in the fiscal year. The remaining branches to each of the interaction regions will be completed in FY79.

During FY78 most of the 2.2 kilometers of PEP's main beam housing was constructed and backfilled along with the North and South Injection Tunnels (NIT and SIT) which are each about 135 meters long. About 65% of the beam housing consists of a reinforced concrete box section which was formed and poured in an excavated trench which was then backfilled. All but a 22-foot section of the "cut and cover" housing was completed. The remainder of the beam passageway consists of mined tunnel utilizing steel I-beams and sprayed-up shotcrete for support. The first area to be mined was Region 3, which resulted in a firm, dry tunnel with the 800 feet of mining completed in 31 days. The other portion of mined tunnel was comprised of Regions 11 through 9 and the North Injection Tunnel. This area had considerable ground water which was expected; nevertheless, the mining operation was completed near the end of FY78.

At the same time the beam housing was under construction, the concrete interaction halls were being built sequentially starting at Region 8 followed by Regions 12, 4 and 2. The halls typically consist of a 14 meter-high by 20 meter-wide by 17 meter-deep reinforced concrete structure. On either side of the halls is a system of retaining walls which hold back the earth shielding covering the beam housing. During FY78, the concrete portion of Interaction Halls 4, 8 and 12 were essentially completed while Region 2 was about 30% finished. Region 6 was left undeveloped and currently a special experimental hall is being designed. The Region 10 interaction area occurs underground in the mined area and will be finished along with the adjacent tunnel.

As construction of portions of the beam housing were completed, installation of utility runs began therein. At fiscal year's end, installation of LCW piping, 480 and 208 volt wireways, cable trays and lighting were completed in the South Injection Tunnel and begun in Regions 6 through 8.

The above activities are displayed in the construction photos (Figs. 11 through 15).

TECHNICAL COMPONENT ACTIVITIES
The PEP technical components include a variety of magnets for the main ring, the injection and beam transport elements, power supplies, radiofrequency system, vacuum components, the survey and alignment system, and a broad category covering the overall instrumentation and control for the storage ring. The past year (FY77) was geared to development, design and testing of engineering models of various components. FY78 can be characterized by all systems moving into full scale production.
Fig. 11  September 1977, Looking West: The first segments of the North and South Injection Tunnels were built onto the existing linear accelerator.
Fig. 12  April 1978, Looking East: Cut and Cover beam housing construction was completed and backfilled during the fiscal year.
Fig. 13 June 1978, Looking South: Box section type beam housing approaching Region 4 Interaction Hall in foreground.
Fig. 15 September 1978, Looking East: Region 8 Interaction Hall with backfilled retaining walls on either side, awaits construction of the steel-framed Assembly Hall.
Magnets: Nearly 700 magnets of different types are in the process of fabrication. The principal elements within the main ring lattice are ~200 dipole and ~200 quadrupole magnets. The 20 foot-long dipoles each weigh 10 tons.

During the year the design of the support stands for the main ring magnets were changed from metal framed structure to concrete support rafts with metal inserts in order to effect economies. These rafts were rapidly produced near the end of FY78 in preparation for magnet installation scheduled for January 1979. While some initial difficulty was experienced by an outside vendor in achieving the specified tolerances for the laminations of the main ring, full scale production was finally achieved during the year in time to meet the assembly schedule at SLAC. Production of the ring dipole magnet coils has proceeded satisfactorily.

The vendor for the main ring quadrupole coils was unable to epoxy impregnate the coils in a satisfactory manner. These coils are now being produced in both LBL and SLAC shops in order to meet the PEP schedule. Sextupole magnets were developed and designed during the year and production started near the year's end.

The special insertion quadrupole magnets which must focus the beams to small size at the interaction point require high quality fields over a large aperture. The design goal of field errors less than 1 part in $10^4$ over full aperture was achieved and production proceeded ahead of schedule.

Injection System: The PEP Beam-Transport and Injection Group has the responsibility of designing, building, and testing the apparatus for bringing the electron and positron beams from the Stanford two-mile linear accelerator down to the PEP tunnel and injecting them properly into the PEP storage ring.

Two beam-transport lines are being built, one for the electron beams on the north side and the other for positron beams on the south. Each line is about 225 meters long and contains 45 magnets and 32 other devices for beam monitoring or control. In addition, 72 support structures and a vacuum system having about 168 components are integral parts of each line. A common vacuum pumping station is another essential element in the beam-transport system.

Each of the two injection systems also has an array of magnet structures that are part of the storage ring itself. The array consists of 3 pulsed "kicker" magnets and 4 d.c. magnets which serve to steer the injected beams onto suitable orbits in the PEP ring while creating no net disturbance to the beams already stored there.

During FY78 some 60 of the beam-transport magnets were fabricated and checked by magnetic measurements. Also about 52 beam devices, 72 support structures, and 300 vacuum components were fabricated. The vacuum pumping station was first assembled and checked out at LBL, then taken to SLAC where it was reassembled and put into successful operation. All of the components of both transport lines were installed in the two injection tunnels from the junction with the SLAC linac to the temporary 20-foot sand-bag barriers 40 meters downstream. All of the magnets were powered to check the electrical systems and the magnet polarities. Similarly, checks were made on each of the beam devices installed. The vacuum lines were connected to the new pumping station and successfully leak-hunted. All of the critical components were surveyed.
and aligned to the theoretical beam line.

The pulsed kicker magnet design was changed radically in March. The previous design used a ferrite magnetic yoke outside a ceramic vacuum chamber because it involved the least electrical power to energize, had ideal magnetic-field uniformity, and produced negligible higher-mode beam losses. However, high cost and long delivery time encountered in the procurement of the ceramic assemblies, induced us to revert to an "air-core" design involving no ceramic and no ferrous material. As a result, an essentially new magnet configuration had to be calculated and engineered, both mechanically and electrically. The design was largely completed and procurement of parts began by the end of FY78.

Survey and Alignment: The PEP Survey and Alignment Group is responsible for the precision alignment of all beam elements in the PEP storage ring. Because this is a difficult task requiring a large survey crew, a Laser Surveying System (LSS) has been developed in order to achieve increased speed and improved accuracy. PEP beam elements are aligned relative to a precisely aligned laser beam, and offsets and elevations are measured using specially developed instruments. Centering laser targets on the laser beam is done using electronic instruments, and the difficulties of surveying with optical telescopes are avoided. The manual handling of survey data is nearly eliminated by the use of digital distance encoders and on-line computers, because survey data is automatically acquired and analyzed by computers. Alignment instructions are provided by computer printouts.

Reference elevations will be provided by an extremely accurate Liquid Level System developed for PEP. This system consists of a water-filled pipe installed around the PEP ring, with read-outs installed every 25 meters for sensing the surface level of the water.

During FY78 most of the LSS was fabricated and tested, including all the equipment associated with the lasers and with the measuring instruments. Figures 16, 17, and 18 show the laser system, transporter vehicles, and automatic read-out micrometer.

Radiofrequency System: Twenty-four r.f. cavities are required for the PEP ring. Eight units are located symmetrically at each of the Regions 8, 12 and 4. The r.f. system maintains the energy of the circulating beams by resupplying the energy that is lost continuously to synchrotron radiation and other high frequency cavity losses of the vacuum chamber system.

The r.f. system operates at 353 MHz. New 500-kilowatt klystrons (12 are required) have been developed at SLAC to meet PEP requirements. Tests of the first klystron were underway at the beginning of FY78 and fabrication of production units began in February 1978. Eight klystrons were completed and tested by the end of the year.

The first 5-cell r.f. cavity was welded in September 1977. By the end of the year all units had been assembled and welded and eleven were tested to full power.

Other activities included the procurement of wave-guide and klystron power supplies and the detailed design of the low-level r.f. system and the overall system instrumentation and control.

Vacuum System: The vacuum system is more complex than it appears. It basically consists of nearly 1.5 miles of specially extruded aluminum piping with associated bellows and flanges and special provisions for beam monitors, collimators, slits and
Fig. 16 A close-up view of the laser and of a laser target mounted on an optical plummet. The precision translation stages are used in aligning the laser beam over survey monuments.
Fig. 17 An electric vehicle and its trailer, used for transporting the PEP Laser Surveying System.
Fig. 18 The Automatic Readout Micrometer (ARM) is used to measure offset distances from magnets to the laser beam. The telescoping tube is adjusted so that the laser target is centered on the laser beam, and a simple push of a button encodes the length of the ARM and transmits the data to an on-line computer.
instrumentation. The vacuum chambers in the curved sections of the ring are water-cooled in order to dissipate up to 3 megawatts of power from synchrotron radiation. Within the field of the bending magnets, the chambers have special sections for sputter-ion pumps.

There are nearly one hundred 14.5 meter-long sections (approximately 5 cm x 12 cm cross section) for the curved sections of the PEP ring. Each of these sections is surrounded by two bending magnets and two quadrupole magnets. Nearly all of these units have been fabricated and are ready for installation. The major work remaining is for the straight section chambers particularly the complex sections that are tailored for experimental requirements near the interaction points.

Instrumentation and Control (I&C): The I&C area has many components too numerous to detail. Major systems included are the communications system, master oscillation and tuning systems, synchrotron light monitor and other beam control and diagnostic instrumentation, vacuum system instrumentation, safety-machine-protection, and personnel protection systems, r.f. and magnet controls, and all cabling associated with these systems. Of course the computers that monitor and/or control most of the above systems are of major importance. Seven peripheral computers are stationed around the ring at each interaction region support building and at Sector 30 of the linac. These units funnel information and control signals from the two larger central computers in the main control room at Region 8.

Both interfacing hardware and software systems have been in design and production stages during the year. Instrumentation components such as the synchrotron light monitor, wall current monitors, tune measurement system are well into production. All computers (Fig. 19) have been delivered and are being tested. The computer operating system software is partially complete at this time.

Power Supplies

The variety of PEP magnets and circuits requires a variety of power supply systems. The ring magnet system is an ideal application for choppers, as the power is predominately supplied at one location, thus bulk conversion of AC to DC can be accomplished in large common DC supplies from which many choppers are fed. (There are 19 different circuits of dipole, quadrupoles, and sextupoles).

Even though the chopper is a time-quantized controller, (but one that must be artificially rather than naturally commutated as in the AC-fed circuit), it can decrease both the average delay time and small-signal loop time-constant in direct proportion to its increased repetition rate over the 6 pulse system. If a system is close to meeting its performance requirements with a 6 pulse thyristor system, going over to a 4 or 5 times faster chopper system is more desirable than adding the transistor bank. The choppers do not produce subharmonic frequencies in the output current, a common problem with AC commutated controlled rectifiers.

The injection beam transport system is also divided into a number of families of Bends and Quadrupoles. Except for the magnets that are common to both transport lines, the circuits are identical in the North and South Injection Tunnels (NIT and SIT). The power supplies for the Injection and Transport System are located at the end of the existing building over the linear accelerator at Sector 30. The Injection components are designed for a maximum of 15 GeV operation with 800 amps in the quads. There are
Fig. 19 Initial tests of peripheral and central PEP computers. (From left) Bob Belshe, Vic Elischer, Chet Pike, Don Rondeau and Roger Swinelle.
both families and individual magnets to be separately controlled. The level of performance required here is ±0.1% rather than ±0.01% needed on the main ring circuits. The injection supplies are standard 6-pulse SCR supplies.

There are trim and steering actuators located at each of the six support buildings around the ring and at Sector 30. They supply a variety of loads for both machine and experimenter requirements. All of these 174 actuators are identical and rated at 35 volts and 60 amps, in either bipolar or unipolar operation. The actuators at each location are supplied from a common 40 volt, 1000 amp DC supply. Sixteen of the actuators are also used as current bypasses around individual dipoles connected in series strings for fine adjustment of the Injection Transport System.

The power supplies for the north and south injection beam transport systems have been installed and tested. Twenty-four 400A chopper modules have been completed. The two large 1400A chopper modules and the DC power supplies are in production. The trim and steering actuators and associated DC supplies have been designed and will soon be in production.

TECHNICAL INSTALLATION
The technical installation begins as portions of the Support Facilities Contract work above are completed. Included here are the magnet DC power distribution system, instrumentation and control cabling systems and their distribution, installation and connection of magnets, r.f. system components, vacuum systems, installation of electronic racks, and all instrumentation. Six contracts totaling nearly $3M are involved in this effort. The major part of this work for the injection system took place during the summer shutdown of the linac.

The two major contracts for installation of main ring components and all associated electrical work were planned and developed and awarded near the end of the year in preparation for first main ring magnet installation in January '79.

Other related work accomplished included the determination of all electrical cable requirements and the advanced procurement thereof. Equipment racks for power supplies, radiofrequency systems and instrumentation and control systems were fabricated and wired so as to be available for installation in a prefabricated condition.

Plans were also developed for the installation of power systems and power supplies for experimental detectors. Buildings ("counting houses") were designed for the electronics and data control centers for the experiments at each experimental region. The experimental electronics also necessitates chiller plants for the cooling of the equipment of each experiment. Three contracts were developed for experimental power, counting houses, and chiller plants for which the aggregate value approximated one million dollars. This work is planned for early 1979.

OTHER ACTIVITIES
Radiation Studies
LBL and SLAC Radiation Physics Groups working as members of the PEP Shielding Group reviewed those parts of the shielding design which were required for completion and approval of Title I drawing, for construction of beam housing structures. The PEP Shielding Group was subsequently dissolved and an informal Radiation Safety Working Group was formed to address any remaining safety problems. Safety aspects of the following items were discussed and approved for PEP I:
Main ring shield design
Ducts and penetrations
Interaction hall shielding
Beam containment
Ring access.

Preliminary studies on shielding for PEP II were begun. Muon calculations are in progress for the straight ahead approximation, with scattering, and with trapping in magnetic fields. The Radiation Physics Group has combined the MORSE and HETC neutron and proton transport codes and it is expected that they will be extensively used, particularly in studies of IR hall shielding effectiveness.

**Computer Program Development**

The beam alignment program (ALIGN) after extensive development was converted to run on the SLAC IBM triplex system. The program was used to determine monitor positions and correction field strengths for closed orbit corrections in the PEP main ring. The program was also modified to include the capability of calculating the 'eta' function in the vertical plane.

Survey coordinates were calculated for both PEP injection lines. Output was used from the SLAC and LBL versions of the program (TRANSPORT) as input to the program (INJECT) which generates survey coordinates in the appropriate surveyor's notation.

In order to maximize graphics capability for PEP, the program INLIN has been modified to use the LBL graphics package (IDDS) to produce Cal Comp. plots. This provides a flexible way of producing scaled plots of the INLIN output.

The IBM version of the SYNCH program has been brought nearly up to the current capability of the CDC version. In particular, the beam-matching facilities now function properly in both versions.

**Theoretical**

Work has continued on problems of coupling and emittance growth in PEP due to various types of misalignments. Improved formulas have been derived for chromaticity calculations. These improvements are being incorporated in the SYNCH computer program.

Various studies were directed toward chromaticity correction problems. Sextupole configurations were developed over a wide range of operating parameters. Control programs were developed for operational control of the PEP sextupoles.

The theory of non-linear chromatic effects was developed with the emphasis on obtaining efficient computational algorithms for calculating and controlling non-linear chromaticity.

Experiments were conducted at SPEAR to investigate the flip-flop beam-beam effect to ascertain the potential limitation which this effect would have on PEP beam intensities. The understanding of the instability of one beam due to the presence of the other is a continuing investigation.

With regard to future additions to PEP, a new conceptual design for a possible PEP proton-electron system has been developed. It includes a 300 GeV superconducting proton ring in the present PEP tunnel, situated above and below the present electron ring, which it crosses in four of the six straight sections. The beams cross at a small angle, and are separated beyond the interaction region by a septum-magnet system acting on the proton beam. Crossing of the electron ring by the proton ring, rather than the reverse, is chosen in order to avoid synchrotron radiation in the experimental areas, which would result if the electrons were bent away from the protons. A preliminary set of general parameters and lattices have been determined.
A lattice system for a small electron storage ring to cool protons in the Fermilab accelerator was designed (Garren and Herr). The ring includes wiggler magnets to shorten the synchrotron-radiation damping times, and thus better cool the protons. This type of research has potential application to a proton-electron facility in PEP, where cooling protons by an electron storage ring could help make the protons better able to tolerate the beam-beam effect that occurs at the collision points between the proton and main electron storage ring, and thus lead to higher luminosity.

PEP EXPERIMENTS

In April of 1977, the PEP Experimental Program Committee (EPC) considered the first experimental proposals. These proposals involved nearly 200 physicists from over 25 different laboratories and universities. Four of the first ten proposals were approved. At the second round in January 1978, three of ten proposals were approved by the EPC, thereby bringing the approval total to seven. In September of 1978 an eighth experiment (PEP-20) was approved following recommendations of the EPC. LBL physicists are involved in five of the eight approved experiments which are listed below.

SUMMARY

PEP-4: Time Projection Chamber Facility ("TPC"); LBL
UCLA, Yale, Univ., UC-Riverside, John Hopkins.

PEP-5: General Survey of Particle Production ("Mark II"); LBL, SLAC.

PEP-6: Lepton/Total-Energy Detector ("MAC"); Univ. of Colorado, Northwestern Univ.

PEP-9: PEP Forward Detector Facility ("Two Gamma"); UC-Davis, UC-San Diego, UC-Santa Barbara.

PEP-2: A Proposal to Search for High Ionizing Particles; UC-Berkeley, LBL, SLAC.

PEP-10: Proposal for a High-Resolution Spectrometer at PEP; ANL, Univ. of Michigan, Indiana Univ., Purdue, SLAC, and LBL.

PEP-14: A Search for Free Quarks at PEP; LBL, Northwestern Univ., Stanford, Univ. of Hawaii.

PEP-20: DELCO Detector Facility; CalTech, Stanford, and SLAC.

PEP-2 and PEP-14 have very specific objectives: PEP-2 will search for the long-sought-after magnetic monopole, and PEP-14 will look for the speculated fundamental constituents of matter.

The PEP-5 detector will be a tried-and-true general purpose system - the Mark II apparatus, which will move from SPEAR to PEP; it will be the only large scale facility that can be guaranteed to be ready for PEP turn-on. This detector, which possesses good particle tracking, muon identification and excellent shower calorimetry, is an advanced design of the Mark I that revealed the psi particles and the new charm physics.

The PEP-4 facility, the TPC, is being built at LBL. With a powerful superconducting magnet and a detection chamber, the TPC can identify particles more completely than any other. This device will inaugurate a new generation of refined colliding-beam experiments. Coupled with the TPC will be PEP-9, the Two-Gamma Facility, whose special magnets and detectors will study the important, but difficult class of events in which the beams interact by photons instead of neatly annihilating. The 2- \lambda detector covers the solid angle from the beam direction up to 180 mrad in the forward and backward direction; it has charged particle
tracking, superb electron and photon detection and muon identification.

The MAC facility (PEP-6) will surround its interaction region with 500 tons of iron and counters. MAC is the only detector with hadron calorimetry in either the PEP or PETRA programs; thus it is sensitive to events in which a large fraction of the energy is carried away by neutrinos. By tagging such events as having missing neutrinos, a selection is made on events related to weak interactions. MAC also offers superb muon identification since the hadron calorimeter can be used as a finely segmented muon filter. MAC's detection system is extremely uniform across the entire solid angle, making it especially attractive for the study of asymmetries due to the interference of the weak and electromagnetic forces. This will provide a picture that is complementary to that of the general detectors of PEP-4 and PEP-5.

The High Resolution Spectrometer (PEP-12) brings to PEP an added dimension. By using the very large superconducting magnet from the 12 foot bubble chamber at Argonne, the charged particle momentum resolution is increased by approximately a factor of 5 over all other existing detectors. At the same time the magnet is so large that a variety of detectors can be placed inside of it while still maintaining very high momentum resolution. Thus in the long term this detector offers a great deal of flexibility as a general facility.

In PEP-20 the existing DELCO detector will be upgraded for operation at the higher PEP energies. The detector is well suited for the role of an early survey of PEP phenomena, particularly in recognizing events with low energy electrons. These events are a good signature for the study of new states at PEP due to the presence of additional quarks. This detector also offers the possibility of K/m separation at high energies; it will be the only detector with this separation until the start of operation of the Time Projection Chamber in mid-1980. The physics goal is to measure inclusive single and multi-electron production and to investigate quark fragmentation.

The current plan would place PEP-20 (DELCO) in Region 8, PEP-5 (Mark II) in Region 12, PEP-4 (TPC) and PEP-9 (Two-Gamma) together in Region 2, PEP-6 (MAC) in Region 4, and PEP-14 (Quark Search) followed by PEP-12 (HRS) in Region 6.

Delivery of the halls to experimenters is scheduled for spring 1979, with the start of beam collisions by October 1979. Many support systems have been developed for these varied detectors during 1978.

Shielding: The designs for earthquake resistant yet quick access shielding walls and curtains necessary to isolate the operating detector from nearby experimenters and nearby electronics have been developed, and construction started.

Computer: Six on-line computers have been acquired for the PEP program. The system is based on the 32-bit VAX 11-780 computers. These computers and their peripherals will be available in each of the interaction regions. The local computers will also be tied to the TRIPLEX at SLAC and to the CDC 7600 at LBL with high rate data links.

Counting Houses: All the plans for the counting houses were developed in 1978, and construction will start in the spring 1979. The air conditioning plant for each one of the interaction regions was also developed and is now being procured.

Motion of Detectors: All the systems for moving the detectors
from the assembly area to the beam area have been developed. These systems must move the detectors while fully cabled so as to prevent larger interferences with the operation of the machine. All detectors can be removed from the beam area in approximately 48 hours; they can be installed from the assembly area into the beam area in a period of approximately one week.

Installation Plans: Detailed installation plans for each one of the detectors have been prepared since the available period is extremely short considering the complexity of the detectors.

Other Support Systems: All other support systems, such as alignment, cooling of the detectors, safety and earthquake restraints, have been developed and are ready to be implemented for all of the various detectors.

A comprehensive agreement exists between each detector laboratory, SLAC and LBL to itemize the responsibilities of the groups involved, the R&D milestones and the proposed distribution of funds to the participating institutions.

Due to limited finances and limited time, the start of operations for each detector has been phased so that some of the detectors will go on beam at the beginning of PEP operations, while more complex detectors will do so only about 6 months after the start of beam operations. Thus, we expect to have MKII, MAC, DELCO, the Free Quark Search and the Monopole Search ready by beam turn-on time while the TPC and associated 24 detectors and the High Resolution Spectrometer will move on beam sometime in April of 1980. With the eight PEP detectors and the five PETRA detectors, we expect highly competitive programs which will result in very fast exploitation of these machines and hopefully, the production of new and important data on a relatively short time scale.

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B. ESCAR

INTRODUCTION

ESCAR (Experimental Superconducting Accelerator Ring) was conceived as a project in accelerator technology development which would provide data and experience to insure that planning for larger superconducting synchrotrons would proceed in a knowledge-able and responsible manner. It was to consist of the fabrication and operation of a relatively small proton synchrotron and storage ring with superconducting magnet elements for all of the main ring. The project was funded and design work began in July 1974. During the next two years it became increasingly apparent that the funding rate was directly limiting the rate of completion of ESCAR and that an intermediate goal, a test of the unconventional aspects of the project, was desirable. To that end, twelve dipole bending magnets, one-half of those required for the total ring, were installed at the site along with the 1500 watt helium refrigerator-cryogenic distribution system, electrical power supplies, vacuum systems, and necessary instrumentation. This truncated system was put through an extended series of tests which were completed in June 1978 at which time the ESCAR Project was terminated. Highlights of the test results are reported below.

Magnet Characteristics.

Of the three types of magnets planned for ESCAR, (multipole trim coils, quadrupole focusing magnets and dipole bending magnets), the dipoles were seen to involve the greatest effort. The requirements were for 4.6 T central field, 0.95 meter integrated-field length in an overall length of 1.2 meters, capable of being pulsed at 0.1 Hz. The field was to be of storage ring quality, i.e., no field multipoles greater than $10^{-3}$ of the dipole field in twenty-four dipoles, with a series-current field inequality of less than 0.1%. These requirements were all near the state-of-the-art, but were considered attainable. Fig. 20 is a production dipole cross section.

Magnet Production

Twelve dipole magnets of suitable quality were produced from August 1976 to June 1977. Each of these had been operated to

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Fig. 20. Production dipole cross section.
determine magnetic field quality and cryogenic soundness. The dipole field was aligned to a vertical reference to within 0.1 milliradian, and the coil had been centered within the iron shield. Each magnet was trained to between 3.5 and 4.3 T; the remainder of the training would take place as part of the operations at the accelerator site.

Site Installation

Twelve completed dipoles were aligned on support girders and joined to form ESCAR ring quadrants IV and I at the site. All magnets formed one series cryogenic helium circuit. Electrically, each group of six dipoles was connected in series, on one power supply with three current leads, the center-tap connection permitting energy extraction from whichever three-magnet group contained the normal-going magnet. The assembly of magnets is seen in Fig. 21.

Test Objectives

The planned test sequence was to conduct cryogenic experiments on one quadrant, then on both together, followed by electrical tests in the same sequence. Test objectives were these:

a. Test the two-phase helium distribution concept, which involved gravity separation of liquid in magnet cryostats with weir-controlled levels.

b. Observe the 1500-watt refrigerator under variable loads and transient (magnet quench) conditions.

c. Measure the cryogenic heat loads of the various components.

d. Observe the thermal insulating and beam tube vacuum systems at room temperature and with cryo-pumping taking place on helium-cooled surfaces.

e. Test magnet power, quench protection and energy extraction concepts on multiple-magnet assemblies.

f. Train magnets in place in groups to test for quench contagion and to see if such training is effective and feasible.

g. Evaluate the instrumentation, the controls, and the quality of diagnostic information.

Two-Quadrant Cryogenic Tests

When all twelve magnets, in two groups of six each, were connected cryogenically, they were cooled and filled with liquid helium, attaining fill rates of over 400 liters per hour. Heaters in the transfer line ahead of the second quadrant were used to alter the two-phase helium quality so that the behavior of helium liquid levels in a downstream quadrant could be observed. The system remained stable and predictable while the major refrigeration heat load was transferred between the transfer line heaters and the refrigerator internal heater.

Quadrant I Electrical Tests

Guided by experience from the first quadrant test, the voltage holdoff capability of the second 6-magnet string was improved and the voltage generated by the energy extraction was reduced. These voltage tests were conducted with all interanal connections at their operating temperatures and in helium, as the dielectric strength of helium is considerably less than air or most other gases. The power supply responded properly in all second-quadrant tests. Three magnets, in series were powered as a group, and, upon detection of a transition, the energy extracted from all three as a group. The voltage limit of 700 V resulted in only 60% of the total magnet energy being deposited in the dump resistor, and the magnet current also decayed more slowly. As much as 275 kilojoules was deposited in the normal-going magnet, more than the energy stored in any one magnet.
Fig. 21. Two-quadrant ESCAR magnet assembly
The training process with this arrangement was slow, probably due to the excessive energy being dissipated in one magnet on each quench. One magnet eventually developed a resistive character during this training although it had undergone more than 100 quenches during its previous individual training. This experience stresses the importance of having this initial testing and training cover the highest voltage and energy deposition to be expected under installed operating conditions.

Vacuum Observations

Concurrent with the tests above, the behavior of the various vacuum systems was observed, and, as necessary, leak-hunting procedures were developed. Leaks ranged from annoying to crippling. Several involved helium, which is not cryopumped to any great extent or pumped well by conventional pumps.

Generally, the insulating vacuum systems performed as expected. Initial pumping to the $10^{-5}$ torr range was sufficient to determine leak-tightness. When liquid helium was present, the pressures dropped to the $10^{-7}$ torr range, and pumps could be valved off.

One of ESCAR's principal features and a major departure from conventional accelerator vacuum practice is the use of the beam bore tube as a distributed cryopump. The 14 cm diameter stainless steel bore tube is bathed, on the outside, with the magnet's liquid helium at about 4.2°K. With proper rough pumping and operational procedures, ultimate pressures in the $10^{-12}$ torr region are expected.

These bore tubes, while initially cleaned before assembly and carefully handled throughout, did not undergo any special cleaning, bombardment, baking or outgassing treatment. Each six-magnet string was provided with special end closures and was pumped by a liquid nitrogen trapped 4-inch diffusion pump. Nude Alpert-type ion gauges in room-temperature bore extensions were used to monitor pressures at each end of each magnet group, and also directly over the pump trap. A gold-seal high vacuum valve could isolate the pump from the bore tube. The pressures recorded by these gauges were typically in the $10^{-7}$ torr range when the system was warm, and below $10^{-9}$ torr when liquid helium was present in the magnets.

One of the more interesting vacuum experiments involved a nude ion gauge mounted on a bracket within the cryogenically cooled bore tube itself. Even though this gauge radiated 7 to 10 watts to the bore tube, the pressure indicated as low as $10^{-11}$ torr, the lower limit for this gauge.

CONCLUSIONS

The ESCAR Project was an appropriate means to address the total systems problems involved in a realistic combination of superconductivity, cryogenics and existing accelerator science.

In comparison with other superconducting accelerator projects being pursued, the combined requirements of rapid pulsing, storage-ring magnet field quality, and compactness were quite demanding. Reducing the task was the license to take greater risks because of the relatively small size and the experimental nature of the project. A program of complete tests and measurements on each magnet prior to installation in the ring was essential to the interpretation of the systems test. An omission was our failure to anticipate the voltage stresses in the full system; even then, only electrical connections peculiar to the full quadrant structure, not the test setup, were vulnerable to breakdown. Behavior of the magnets in the
systems test was encouraging in that no quench contagion, or other exotic problems appeared.

A significant outcome of the two-quadrant tests was the successful performance of the cryogenic system. That performance included a demonstration that a simple two-phase circulation scheme was not only free of flow instabilities that some persons had considered likely, but that the heat removal was adequate to serve a synchrotron pulsing at 1 tesla sec. The success does not remove the still-existing need to adapt and modify the commercial refrigerator for greater operational convenience.

The ESCAR experiment did not proceed sufficiently far to capitalize on the opportunity to evaluate its cold-wall vacuum system, but the straightforward achievement of low pressure without surface conditioning and the freedom from helium leaks in the bore-tube system were encouraging results. Techniques for locating leaks in the various insulating-vacuum and helium systems were devised as needed, but these were barely adequate and this aspect of a new accelerator should be given proper consideration to insure against excessive waste of operational time.

The electrical systems could be regarded as straightforward, and in most respects that has been the case, but the important area of magnet safety and quench protection introduced demands on the design of both magnets and cryogenic system. It should therefore be considered early in the component development stage. The best method for disposing of the stored magnetic energy is still without general agreement and depends on the details of a particular application.

While there was not the opportunity to achieve all the goals, successes during the development and tests completed did advance the art in the following areas:
- utilization of cable superconductor
- repeatability in coil production
- high field quality
- magnet testing and alignment techniques
- cryostat design
- screw compressors and modern refrigerators
- high-capacity cryo-distribution (two-phase)
- operation safety in vacuum and helium systems.

We also were able to stimulate the serious consideration of cold-wall vacuum for accelerators. We advise that designers provide adequate excess capacity in parameters such as current density and refrigeration and incorporate the total system requirements early in the design process. With such precautions, the benefits of the technologies should be available along with reliable operation, free of unexpected limitations.

ACKNOWLEDGEMENTS
Many people have made significant contributions to ESCAR over the years of the project’s existence. Although it is not practical to list all their names here, we do extend our thanks.

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C. ACCELERATOR THEORY

Heavy Ion Fusion

Theoretical work in connection with the Heavy Ion Fusion program covered three major areas: stability of transport of intense beams, final transport and focusing of beams onto a target and parametric studies of accelerator systems.

On the stability question, the parameter ranges of stable and unstable motion have been mapped out as thoroughly as seems justified by the necessary mathematical assumption that the particle distribution function in the four-dimensional transverse phase space is micro-canonical (K-V distribution). In one particularly fortunate case of an isolated instability, an excellent agreement was found with a simulation calculation performed at the Naval Research Laboratory. With the backing of further simulation work, a practical parameter region has been found which should be free of instability and associated emittance growth. This work has come to an end; the agreement of theory and computer experiment inspires confidence in using the simulation approach for specific questions that might arise in the future.

Final focusing requires delivery of a beam onto a spot a few millimeters in radius at a distance of several meters from the last focusing element. In this situation, chromatic aberrations and third order aberrations due primarily to the fringing fields of the last focusing doublet or triplet are important considerations. The consequences of these aberrations have been investigated and requirements established for delivering most of the beam to the target. Since these requirements are sufficiently restrictive, some preliminary work was done on correcting schemes involving octupoles near the final lenses and combinations of bending magnets and sextupoles in the upstream transport lines. This effort continues, in collaboration with ANL.

A systematic parameterization of the six-dimensional phase space constraints from source to target was formulated and used to examine various proposed scenarios generated here and at other laboratories. As others have also found, schemes involving synchrotrons as the major accelerating elements appear unattractive and have been abandoned, at least for the present. A computer program has been developed to optimize induction linear accelerator design; this as a joint effort of the theory group and the engineering group.

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Stochastic Cooling

During FY78, it was decided to undertake development of this technique for producing brighter beams. The experiments are to be carried out on the newly constructed electron cooling ring at FNAL, with the immediate purpose of contributing to the design of a $\bar{p}p$ colliding beam facility at FNAL. The role of the theory group has been to assist in the design of the experiment, participate in the development of design of the facility in collaboration with FNAL and other laboratories and to develop a theoretical framework, including a computational program, which will help to interpret results of the experiments.
IV. HEAVY ION FUSION

INTRODUCTION
The year began with the Second Heavy Ion Fusion Workshop held at Brookhaven National Laboratory, Oct. 17-21, 1977, while the end of the year almost coincided in time with the Third Heavy Ion Workshop (Sept. 19-26, 1978) held at Argonne National Laboratory. In the preparation of this report we have therefore drawn heavily on some of the material and reports that were presented by the LBL HIF Staff at the latter workshop.

During the year a number of intensive work sessions of short duration took place on specific topics:

Parameters for HIDE (Heavy Ion Demonstrated Experiment): Roger Bangerter, Edward Lee and Simon Yu, all from Lawrence Livermore Laboratory, helped greatly in defining the goals and parameters for a minimum HIDE. It was felt that with a beam energy of 30 kJ and a beam power of 3 TW, three goals could be met in the following order of importance: demonstration of accelerator performance, scaled beam-propagation experiments in low-pressure gases, and a target coupling experiment in slab geometry at a specific energy of 20 MJ/gm.

A Synchrotron-based HIDE design: The scientific staffs of the SuperHILAC and Bevalac collaborated with us on an intensive two-week design effort to explore the possibility of a low-cost HIDE design based on a synchrotron and external induction linac buncher. A 5 TW, 50 kJ example using Bi+1 injected at 500 MeV and accelerated to 3.5 GeV was the focus of most of the study. The plan was to extract the team in a single bunch—to be further bunched externally by induction modules—and thus avoid a multiplicity of final transport lines to the target. It is recognized that the lower the energy the less attractive the synchrotron approach becomes, and at an energy of only 3.5 GeV it was apparent that no convincing solution could be found unless unduly optimistic assumptions were made about the ability to do bunching and debunching operations without dilution.

A two-day Topic Workshop on The Optics of the Final Focus was held on August 7 and 8, 1978, and there was outside attendance from ANL, BNL, and SLAC. The attendees, topics discussed and summary notes are given at the end of this section.

During the year a computer link was established between the CDC7600 system at LBL and the TI-ASC system at the Naval Research Laboratory. This allows us to have direct access to the numerical simulation data of
I. Haber and thus has added an important dimension to our collaboration with NRL. There is also a continuing fruitful collaboration with S. Penner at NBS; he uses a simulation code of a different type.

We have benefited by the one-year visit (ending July 1978) by Ingo Hofmann from the Max-Planck Institute for Plasma Physics, Garching, Germany, the continuing half-time collaboration of W. B. Herrmannsfeldt of SLAC, and the frequent interaction with R. O. Bangerter and his colleagues at LLL.

THE EXPERIMENTAL PROGRAM

The experimental efforts at LBL have been focused on both the development of a large aperture 2 MeV, 1A Cs+1 ion beam1) using contact ionization and pulsed drift tube techniques as an injector for an induction linac and, also, a 750 kV, 60 mA Xe+1 ion beam2) using multi-aperture accel-decel extraction and a Cockcroft-Walton accelerator high gradient column for an R.F. linac source.

The One-Ampere Cesium Source

A schematic diagram of the Cs+1 beam experiment is shown in Fig. 22. Neutral Cs atoms, generated either by heating metallic Cs or a (CsCl + Ca) mixture, are sprayed onto a hot iridium plate (anode) of 30cm dia. which is at a temperature of 1200-1400°K. The ionization potential of Cs (3.9V) is less than the work function of iridium so that most of the Cs atoms are adsorbed on the anode surface as ions. The supply rate of Cs atoms is determined by the oven temperature and is designed in such a way that there is ~ 1% of a monolayer (1mC) of Cs accumulated on the anode when the extraction voltage pulse is applied to it. The Cs+1 ion emission rate is determined by the temperature and coverage of the iridium hot plate and is designed to be about 5 times the space charge limited current. In this space-charge limited operation the beam emission is uniform over the surface, independent of the non-uniformities of the temperature of the anode and the neutral Cs flux.

The space-charge limited current is 1A for the extraction voltage of 500 kV which was applied to the anode. Emission-limited operation occurred when the anode temperature was below 1100°K, in which case the Cs+1 current was independent of the applied voltage pulse and depended only upon the anode temperature.

Cs depletion was observed when the anode temperature was high and the neutral Cs supply was low. In this case all the available Cs ions were used up during the earlier part of the voltage pulse. The space-charge-limited condition was recovered when the oven temperature was increased in this case.

Beam neutralization could increase the current above the classical space charge limit. Our current measurement is not yet accurate enough to establish this because of the undetermined secondary electron correction. Although the secondary electron effect was measured to be small in our earlier Cs test stand experiment, we are building improved diagnostics to delineate the phenomenon.

Time-of-flight measurements proved that virtually all of the beam was composed of Cs+1 ions. The beam also had orders of magnitude lower intrinsic neutral background pressure compared to any electron-bombardment ionization source. This is as expected since the Saha-Langmuir equation shows that more than 99% of the incident Cs atoms are ionized. The ion beam has a very low thermal velocity equal to the temperature of the anode (0.1 eV). It is thus very bright. Normalized emittance based on the thermal spread is calculated to be $\frac{e\Delta \lambda}{\pi} = 0.006$.
Fig. 22. Diagram of Cesium Source.
the 750 kilovolt Walton accelerator. The 39 MeV Xe+1 beam was transported from the Walton accelerator.

...
Fig. 24. Typical beam current pulse.

100 µsec/cm

XBB 780-14192

20 m A/cm
system, there are many possible
design configurations of the in-
duction accelerator.

If a specified beam charge
\((I \tau)\) is to be delivered to the
target and the injected ions will
be necessarily delivered at non-
relativistic energies, the in-
duction accelerator must differ
considerably from the well known
electron linear accelerator which
functions in a constant velocity
mode and, therefore, utilizes a
system of iterated standard
accelerator modules.

In the case of the linear
induction accelerator for heavy
ions, non-relativistic ions
\((\beta > 0.5)\) must be accelerated to
relativistic velocities \((\beta \rightarrow 1)\); as
a consequence there is no fixed
accelerator module and, in fact,
many configurations are possible
as design options. An additional
important consideration in the
design of the accelerator system
is the capital cost investment.

In order to attack this
problem in the conceptual design
stage we have developed a computer
program (LIACEP) which is capable of
sorting through a variety of
possible engineering input options
at each eV point along the machine
and delivering cost and design
information output.

Differential cost information
is also generated. Cost minima
are thus presented as well as the
variation in the regions near
minimum options which can there-
fore be utilized effectively by
designers in the design of the
actual accelerator system.

THEORETICAL ACTIVITIES

Progress this year has been
achieved in three major areas:
beam transport, final focusing,
and parameter studies.

1. Beam Transport: Further
work on instabilities of the
Kapchinskij-Vladimirskij (K.V.)
distribution has led to revision
of the recommended choice of
maximum transportable power for
design purposes. A significant
achievement has been the success-
ful comparison between our theore-
tical results and the simulation
computations by Irving Haber for a
particular unstable mode; this
comparison gives credence to both
the theoretical and simulation
work and suggests that the simula-
tion approach can be trusted when
applied to more realistic dis-
tributions, which cannot be treat-
ed analytically.

2. Final Focusing: The work
of A. Garren\(^2\) on the parameteri-
zation of a final focusing doubles
has been extended to triplets,
which are more suitable in certain
parameter regimes. The effect of
third order geometric and fringing
field aberrations in the final
lens system has been explored,
leading to constraints on the
emittance of the individual beams
approaching the target. The
effect of chromatic aberrations
has been studied quantitatively
and appears to be somewhat more
serious than indicated by the
previously used rule of thumb;
work has begun on the correction
of these aberrations by the use of
bending magnets and sextupoles
upstream from the final lens
system.

3. Parameter Studies: In
light of the constraints imposed
by the final focusing system, the
six-dimensional phase space re-
quirements have been reformulated
and used to develop a number of
R.F. linac and synchrotron scen-
arios. As others have found, the
synchrotron schemes do not look
very attractive, particularly
since the trend this year has been
toward lower kinetic energy and
higher current, whereas the virtue
of a synchrotron is rather to
provide high kinetic energy at low
current.

ACKNOWLEDGEMENTS

For assistance in the work
summarized in the present note we
express our thanks to our col-
leagues J. Bisognano, V. O. Brady,
and S. Chattopadhyay.
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TOPICAL WORKSHOP
Focusing of Beams onto the Target of a Heavy Ion Fusion Reactor: Summary of a meeting held at Lawrence Berkeley Laboratory, August 7-8, 1978.

An informal meeting was held to exchange information on work that has been done and to identify the areas most in need of investigation.

The main participants were the following: R. Arnold, S. Fenster, E. Colton, (ANL); A. Maschke (BNL); M. Donald, K. Halbach, A. Garren, L. Smith, D. Neuffer, D. Judd, G. Lambertson (LBL); K. Brown, W. Herrmannsfeldt (SLAC).

Relevant work has been done on the following topics: beam line design for Hearthfire III - E. Colton, S. Fenster; beam line design from an induction linac - A. Garren, D. Neuffer; preliminary study of the magnitude of aberrations from the final lenses - D. Neuffer; procedures to correct chromatic aberrations without producing large geometric aberrations, using sextupoles - K. Brown; ways to produce achromatic beam spots with quadrupoles only - K. Halbach; dimensionless scaling of parameters for the final doublet - A. Garren.

Summarizing the work to date, beam lines for final focusing with beam and target parameters currently under consideration are probably feasible from the standpoint of linear optics, but non-linear and space charge effects require more study.

Therefore, further or new work is especially needed on: a) correction of second order aberrations in currently designed beam lines with sextupoles, b) evaluation of third and higher order aberrations in these lines, c) calculations on quadrupole and sextupole settings of the beam-line, taking account of space charge, d) allowance for the fact that space charge will vary with position along the bunch and with path length, if the bunch is imploding longitudinally, e) estimates of tolerances, and f) extension of scaling curves to take account of aberration.

As information of the above topics is developed, it should be possible to determine if the presently proposed target-beam parameters are realistic from the standpoint of the final focusing, and, if not, in what ways they should be adjusted.

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