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Accelerator & Fusion Research Division

1983

Summary of Activities

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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August 1984

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MASTER

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FOREWORD

The activities described in this summary of the Accelerator and Fusion Research Division are diverse, yet united by a common theme: It is our purpose to explore technologically advanced techniques for the production, acceleration, or transport of high-energy beams. These beams may be the heavy ions of interest in nuclear science, medical research, and heavy-ion inertial-confinement fusion; they may be beams of deuterium and hydrogen atoms, used to heat and confine plasmas in magnetic fusion experiments; they may be ultrahigh-energy protons for the next high-energy hadron collider; or they may be high-brilliance, highly coherent, picosecond pulses of synchrotron radiation.

At the Bevalac — the nation's only relativistic heavy-ion synchrotron — ions as heavy as uranium, stripped of some or all of their electrons, are used for studies in nuclear physics, nuclear chemistry, atomic physics, and astrophysics, as well as radiotherapy and biophysics. In 1983 one of the most exciting successes was the production of extremely dense nuclear matter, a step toward the eventual study of the postulated quark-gluon plasma. We are now studying the next steps to be taken in the search for this yet-unobserved state of matter: How can it be created? How will we detect it?

Heavy ions are also of interest to our Heavy-Ion Fusion Group, whose focus is on an induction linear accelerator as the "driver" in a conceptually simple inertial-confinement fusion scheme. In this scheme, intense heavy-ion beams would be accelerated, then directed at a small pellet of deuterium and tritium fuel, which would be compressed and heated to the point where a thermonuclear burn occurs.

The high-energy physics community is now looking toward a proton-proton collider having an energy of 20 TeV in each beam. Accordingly, our high-energy physics program was highlighted in 1983 by the development of magnet designs for this Superconducting Super Collider and by wide-ranging theoretical studies of pertinent accelerator physics issues. In the first half of 1984, LBL hosted the SSC Reference Designs Study, and AFRD physicists played pivotal roles in this preliminary design phase — roles we expect to continue during the ongoing national R&D effort.

LBL is also the leader in developing neutral-beam systems for the magnetic fusion energy program. In support of the programs at the Princeton Plasma Physics Laboratory, Lawrence Livermore National Laboratory, and GA Technologies in San Diego, our work concentrates on both positive- and negative-ion-based neutral beams as means for heating, refueling, and confining reactor plasmas. In the spring of 1984, our positive-ion source was chosen as the common source module for all program needs starting in the mid-1980s.

Interest in synchrotron radiation in the x-ray and ultraviolet regions of the spectrum led in 1982 to our concept for a major new research facility — the Advanced Light Source. In 1983 this same interest produced the Center for X-Ray Optics, whose broad charter is to develop techniques for the transport, analysis, and detection of x-ray and vacuum ultraviolet radiation for basic and applied research. At the same time, work has continued on how best to produce intense, tunable coherent radiation across the electromagnetic spectrum, from microwaves to x-rays.

In the microwave region, we are investigating the free-electron laser as a source of rf power for the next generation of linear accelerators. One exciting development in early 1984 was the use of such a device to amplify an 8-mm signal more than a thousandfold (to an estimated 100 MW). At much shorter wavelengths, the free-electron laser may also allow us to take a significant step beyond magnetic wigglers and undulators in producing brilliant ultraviolet radiation and x-rays. Exploration of this possibility is well under way in 1984.

The summary of activities that follows takes these major programs through the end of 1983. During the entire period covered here, the Division Head was Hermann A. Gruner, now the Laboratory's Deputy Director for General Sciences. Our aim in 1984 is to maintain and extend the lively programs he has directed for the past five years.

Klaus H. Berkner
Acting Division Head

ACCELERATOR AND FUSION RESEARCH

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8.0 RECOMMENDATIONS FOR FUTURE STUDY

The present study was limited in scope to a room-scale approach, and employed a number of idealizations and approximations commensurate with existing knowledge about the site and available modeling capabilities. This section identifies issues which warrant further study to improve the reliability of predictions for the thermohydrological performance of a high-level waste repository in basalt.

8.1 Flow Geometry

The present study employed a two-dimensional axisymmetric model, whereas the actual repository system is three-dimensional. The important system features were preserved and the error introduced by these approximations are not expected to influence the general conclusions developed from the study. However, it is not possible to formally quantify the accuracy of the 2-D model without comparing the results to a fully three-dimensional calculation. Three-dimensional models require a rather large computational effort, but, to validate the 2-D approach, it would be sufficient to study a small number of representative cases.

8.2 Fractured Porous Medium

The rock mass was approximated as a porous medium. However, the Hanford basalts are fractured and the fractures control fluid flow. Thermodynamic conditions within the fractures may deviate significantly from volumetric averages for larger rock volumes which were considered in the present study. For instance, pore pressures in the fracture system may be lower than in the rock matrix, so that boiling in the fracture system may occur throughout a more extensive volume. Due to the small volume of the fractures this

During fiscal 1983, the Bevalac and SuperHILAC provided 5302 hours of beam time for nuclear science and biomedical experiments. One hundred seventy-five scientists participated in the research programs. As national facilities, the Bevalac and SuperHILAC are used by qualified researchers from around the world; about half of the available research time is used by scientists not affiliated with LBL. Beam time is apportioned by Program Advisory Committees, which review submitted proposals twice each year. In addition, the users have formed users' associations for the purpose of exchanging information and recommending operational and procedural improvements.

Successful completion of the Bevalac High Intensity Uranium Beams Project in 1982 and subsequent Bevalac operations have brought rich rewards to the nuclear physics world. To enhance these rewards, our priorities during the past year have been to operate for as many hours as possible, consistent with power costs and our level of funding. Table 1 summarizes the operations during FY 1983 and compares them with our projections for the next three years.

Operations Summary

	Fiscal year			
	1983	1984	1985	1986
Bevalac operation (hours)				
Research	3083	3900	3500	3900
Tuning	1261	1750	1690	1750
Machine studies	444	384	375	384
Unscheduled maintenance	735	960	1000	960
Scheduled shutdowns	3237	1790	2195	1766
Total	8760	8784	8760	8760
Beam utilization for research (hours)				
Bevalac nuclear science	1863	2600	2800	3200
Bevalac biology/medicine	1220	1300	1400	1600
SuperHILAC	2220	2200	2220	2220
Total	5303	6100	6420	7020
Number of Bevalac and SuperHILAC experiments receiving beam	48	54	54	60
Number of participating scientists	175	185	185	210
Institutions represented				
Universities	20	20	22	24
National laboratories	4	4	4	4
Other	10	11	12	15
Total	34	35	38	43
Users of beam time (%)				
LBL	50	50	50	50
Universities	35	35	35	35
Other national labs	5	5	5	5
Other institutions	10	10	10	10

Table 1. Operating summary for the Bevalac facility, including projections for fiscal 1984 through 1986. The Bevalac "beam utilization" hours for 1985 and 1986 exceed the total "research" hours, because the nuclear science and biomedical programs will, at times, have effectively simultaneous use of the beam.

About half of the Bevalac beam time is devoted to users not affiliated with LBL. The focus of support for this user community is the Accelerator Research Coordination (ARC) Office, which supports the researchers at all stages, from proposal submission through the actual running of experiments. In addition, researchers at the Bevalac and SuperHILAC have formed users' associations that meet periodically to exchange scientific information and to convey their views to LBL management. The current executive committees of the two users' associations are listed in Table 2.

Proposals for research time are submitted twice a year to Program Advisory Committees (PACs), one each for the Bevalac nuclear science program, the Bevalac biomedical program, and the SuperHILAC program. These expert panels (see Table 2) recommend recommended allocations to the Laboratory Director. In addition, the LBL scientific director of each program may allocate about 10% of the available research time on a discretionary basis. Because of the special needs of the patient therapy program at the Bevalac, day shifts during the week are reserved for this purpose. Parasitic beam time between patients, off-hour shifts during the week, and weekends are shared between the nuclear science programs and the other biomedical programs.

Table 2. Membership lists for the Users' Association Executive Committees and the three Program Advisory Committees (PACs). The lists include members selected in early 1984.

Bevalac Physical Sciences Users' Association Executive Committee

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

SuperHILAC Users' Association Executive Committee

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

Bevalac Nuclear Science PAC

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

Bevalac Biomedical PAC

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

SuperHILAC PAC

D. Fossan, State University of New York at Stony Brook (chairman)
S. Datz, Oak Ridge National Laboratory
K. Gelbke, Michigan State University
J. Hardy, Chalk River National Laboratory
J. Randrup, LBL

Nuclear physics at the Bevalac centers around the use of relativistic heavy-ion beams unavailable at any other facility in the world: Fully stripped uranium nuclei, for example, can now be produced at energies of 960 MeV/amu. Several experiments in 1983 focused on processes within nuclei compressed to nearly four times normal density and heated to more than 100 MeV (roughly 10^{12} degrees Celsius). The resulting observations nourish the hope of reaching higher energy densities in expectation of seeing a plasma of elemental quarks and gluons. Other experiments have illuminated the process of particle production within the nuclear volume, the mechanism of ion energy loss in matter, and the hydrodynamical behavior of nuclei during nuclear collisions. Still other results have suggested the existence of nuclear fragments (so-called anomalous) that interact in nuclear emulsions much more strongly than current theory would allow. Researchers at the SuperHILAC have continued to study heavy-ion reaction mechanisms and atomic physics. The use of SuperHILAC beams to ionize a gas, thus producing highly charged heavy ions with low kinetic energy, has, in fact, been a major contributor to the recent renaissance of atomic spectroscopy. At the same time, the biology and medicine program has used the unique features of heavy-ion beams in very different ways, conducting clinical studies of their value for local tumor control and for radiosurgery.

Research by Accelerator Users: Highlights

Broadly, nuclear physics research at the Bevalac focuses on: the behavior of nuclei undergoing collisions that greatly increase the density and pressure of the nuclear matter. Very clean beams for such collisions have now been produced by use of thin defining slits that change the charge state of unwanted ions, thus causing them to be subsequently rejected. To increase the efficiency of ion production, we have also studied charge states for uranium and other elements as functions of energy, stripper material, and foil thickness. Mathematical models have now been developed to predict these functional relationships. At the SuperHILAC, research at lower energies focuses on heavy-ion reaction mechanisms, atomic physics, nuclear structure, and exotic nuclei.

Nuclear Physics

Equilibration, Hydrodynamics, and Compressed Nuclei. Studies of central niobium-niobium collisions have shown us that secondary particles are emitted nearly isotropically in the center of mass system. Thus, to a good approximation, the two nuclei must stop each other prior to disintegration. This implies that most or all of the energy available at the Bevalac can be deposited in the nuclear volume — a finding that supports the hope that the *quark-gluon plasma* might be produced by such collisions at only slightly higher energies. In similar experiments, observations confirmed two phenomena predicted by hydrodynamical theories of nuclear behavior: "bounce-off," in which spectator nuclear fragments get a sideways push, and "side-splash," in which participant fragments are ejected at large angles with respect to the beam direction. Figure 1 illustrates the results from one such experiment.

We have studied the dense nuclear states produced in relativistic heavy-ion collisions by examining the suppression of pion production — a result of energy loss into compressional modes of excitation. As a result, a nuclear equation of state has been derived for densities up to 3.5 times normal. More recently, a density 3.8 times normal has been produced in lanthanum-lanthanum collisions (see Fig. 2).

Anomalous. From June 28 to July 1, the Second Workshop on Anomalous was held in conjunction with the 6th High Energy Heavy Ion Study. The amount of data supporting the existence of short-lived nuclear fragments — first postulated on the basis of emulsion results — led to a consensus that they are real. However, two experiments later in the year, using stacked Cerenkov detectors, failed to turn up anomalous behavior in over a million secondary reactions. These experiments should have revealed fragments with mean free paths substantially

Fig. 1. Computed density and temperature contours and velocity vectors following a noncentral Me-U collision. The angular deflection of the projectile residue (top left) and the motion of the target residue (bottom) are illustrations of bounce-off. Recent experimental evidence supports hydrodynamic calculations such as these. [From H. Stöcker, J. A. Maruhn, and W. Greiner, *Phys. Rev. Lett.* 44, 725 (1980).]

shorter than 1 cm, assuming exponential absorption. The anomalous question remains unresolved, however, since anomalous may violate the assumption of exponential absorption and since the Cerenkov and emulsion experiments may record very different types of interactions.

Search for Fractional Charges. A "quark search" was conducted in 1983, using a composite target and a 1.9-GeV/amu ^{56}Fe beam. The multicomponent target consisted of copper, to be analyzed subsequently by electrostatic Van de Graaff techniques; tiny iron balls for magnetic levitation experiments; mercury, allowing subsequent analysis of mercury droplets; and lead, to enhance the probability of quark production. The target was surrounded by about two tons of carbon

Fig. 2. Streamer chamber tracks of the secondary particles produced by a $^{139}\text{La} + ^{139}\text{La}$ collision. The beam energy was 1.0 MeV/amu.

Accelerator Operations

tetrachloride to capture light particles that might escape the target itself. Only the mercury from the target and samples recovered from the carbon tetrachloride have been analyzed, leading to an upper limit of one fractionally charged particle per 2×10^6 interactions. The remaining target materials are still being analyzed.

Research at the SuperHILAC. Study of nuclear reaction mechanisms remains the backbone of research at the SuperHILAC. In 1983 one important study looked at the energy and angular distribution of protons and alpha particles emitted from heavy-ion fragments, in an effort to characterize the emitter: Is it the combined dinuclear system or is it post-breakup fragments? The answer is not conclusive, but the source appears to be fragments. Atomic physics is a second field of concentrated study. Indeed, the use of heavy-ion beams (usually Au^{53+} or U^{58+}) to ionize gases, thus producing highly charged heavy ions with low kinetic energy, has contributed significantly to the rekindling of interest in atomic spectroscopy. Fine-structure splittings in hydrogenlike and heliumlike ions up to argon have provided stringent tests of the theory of quantum electrodynamics in a strong Coulomb field.

During 1983 other investigators continued their research on nuclear structure, using high-Z projectiles (xenon and lead) available at the SuperHILAC. Discrete and continuum gamma ray spectra were used to study the properties of nuclei at very high spin. Finally, LBL and GSI began a collaboration to search for superheavy elements by irradiating a ^{248}Cm target with ^{48}Ca , but no events ascribable to superheavy element decay were found. On the other hand, the on-line isotope separator (OASIS) was in full operation, and it aided in the discovery of nearly a dozen new proton-rich isotopes.

The Bevalac biomedical program has two primary objectives: (a) to provide fundamental new information on the biological effects of heavy charged particles and to understand the mechanism of these effects in terms of track structure, and (b) to apply this knowledge in a rational approach to medical applications of heavy ions, including malignant tumor radiotherapy and treatment of inoperable blood vessel malformations in the brain.

Explorations of the biological effects of charged particles began in the 1950s when accelerator development provided fluxes and dose rates suitable for biological experimentation with microorganisms. Classic early experiments were conducted at LBL using the predecessor of the SuperHILAC. When the Bevalac became available in 1975, the door was opened for animal experimentation, as well as exploration of medical applications for heavy ions. Today, the Bevalac remains the only accelerator in the world capable of producing heavy-ion beams at energies and intensities sufficient to deliver useful doses to deep-seated tumors.

Three medical programs were in progress at the end of 1983. Approximately 70% of the available biomedical beam time is devoted to one of these — the radiotherapy program.

Radiotherapy Trials. Our largest effort is devoted to clinical studies that will lead to randomized radiotherapy trials for assessing the extent of local tumor control that can be achieved with heavy ions. One hundred thirty-five patients received irradiation during fiscal 1983, bringing to 642 the total number of patients who have participated in the studies since 1975. The planned randomized trials will extend these studies by comparing heavy ions, helium ions, and photons. The expected advantages of heavy charged particles for radiotherapy are related to the ease with which the dose can be localized (as suggested by Fig. 3), thus sparing critical normal tissue, and the ability of the particles to kill hypoxic tumor cells that are resistant to other forms of radiation.

Using the helium beam at the 184-Inch Cyclotron, we continue to achieve excellent local control of uveal melanomas. More than 150 patients have now

Biology and Medicine

Fig. 3. A highly schematic depiction of dose localization with heavy ions. The prominence of the Bragg peak allows the effective dose to be concentrated in deep-seated tumors, even those near sensitive organs.

been treated, and the control rate after a median two-year follow-up is 95%. Vision has been preserved in approximately two-thirds of the patients. In patients receiving precision high-dose helium radiotherapy for tumors near the base of the skull, the spinal cord, or the paranasal sinuses, a continued local control rate of approximately 80% has been achieved. Median follow-up in this group of patients is about 12 months.

Radiosurgery Program. The heavy-ion radiosurgery program provides radiosurgical research support for applications of stereotactically directed heavy-ion beams for the study and treatment of patients with intracranial vascular disorders. Exploratory research is directed at the application of charged-particle beams as neuroscience probes, at the study of brain tissue tolerances and the nature of neurological disease states, and at the development of an effective radiosurgical technique using the Bevalac's carbon beam. In addition, at the 184-Inch Cyclotron, we have developed a stereotactic radiosurgery beam line for the 230-MeV/amu helium-ion beam, and a safe, reliable, and effective method of radiosurgery has been developed to treat inoperable, life-threatening intracranial disorders.

Biophysics. The third of the biomedical programs is a broad biophysics program, ranging from chemical characterization of breaks in DNA to lifespan studies and studies of radiation carcinogenesis in mice. The fundamental question addressed by many studies concerns the dependence of biological response on linear

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energy transfer (LET). Current studies emphasize the use of the plateau portion of the Bragg ionization curve, where the variation in LET is small. Relationships between relative biological effectiveness and LET have been explored in several model systems. We have looked at the ratio of single-strand to double-strand DNA breaks, the killing of several different normal and tumorous human cell lines, and damage to various animal organs and tissue types. Other results indicate that the LET dependence of deleterious late effects of radiation may be different from that of cell killing. Carcinogenic effects remain high at a level of LET where cell killing in either cultured cells or normal tissues is diminished.

When the maximum Bevalac energy is not required, we are now able to produce substantial intensities of very heavy ions (10^7 per pulse for gold, for example). We do this by not stripping at the exit of the SuperHILAC and thus accelerating a low-charge-state ion in the Bevalac. By this technique, we not only avoid dilution of the beam into many charge states, but also present a much cleaner beam to the transfer line, making tuning much easier. These partially stripped ions are deliverable to any of our nuclear science experimental areas. If stripping is desired, it can be done at the Bevalac exit. In addition, the high magnetic rigidity of these partially stripped, low-energy beams allows the Bevatron to operate in an efficient mode.

Reexamination of the optics of the SuperHILAC exit and the transfer line led us to reposition the final injector stripping foil so that charge-state separation for heavy ions is now easier. Improvement, however, is still possible. Unambiguous charge-state identification continues to be the sought-after goal.

In collaboration with GSI and CERN, design work began in late 1983 on a new heavy-ion preinjector for the CERN PS complex. It will provide oxygen beams for heavy-ion studies at PS and SPS energies (up to 200 GeV/amu). A research team from LBL's Nuclear Science Division will participate in these experiments, now scheduled for fiscal 1986. The preinjector package consists of an electron-cyclotron-resonance ion source, a heavy-ion radio-frequency quadrupole (RFQ) linac, and beam-matching elements. The physics design of an RFQ linac to accelerate O^{6+} is complete. Engineering, now under way at LBL, is being based on experience gained with the RFQ built for the Bevatron local injector upgrade.

Accelerator developments are aimed at more efficient use of operating time, higher beam intensities, and more effective charge stripping. Completion of the "fast switching" program will be a major step toward the first of these goals. The objective is to allow the nuclear science and biomedical programs to share beam time on a very short time scale. This requires flexible and stable systems (permitting reproducible tunes), and an ability to change ion species, energy, and beam line in minutes. Improvements to the detectors and amplifiers at the SuperHILAC are also under way.

Rapid beam-line and beam-energy switching for a single ion type has progressed at the Bevalac to the point of being routine. Still to come, however, is the ability to switch rapidly between different ion species — an ability that will allow the nuclear physicists to use the beam between closely spaced patient irradiations. Currently, the biomedical program has exclusive use of beam time during weekday working hours, even though the beam is actively used only a few minutes each hour. The goal is to make the radiotherapy operation essentially "invisible" to the nuclear science program. The necessary improvements, involving the addition of the RFQ linac and the rebuilding of the front end of the Bevatron local injector (see Figs. 4 and 5), were in their final stages at the end of 1983.

When complete, the local injector upgrade will permit the Bevatron local injector to inject ions as heavy as silicon in quantities sufficient for therapy and

Accelerator Research

Accelerator Development Activities

Fast Switching and the Local injector Upgrade

Fig. 4. The upgraded Bevatron local injector. The duoplasmatron source, the RFQ linac, the first Alvarez linac, and the first stripper are new components of the injector, due to be fully operational in 1984.

Fig. 5. View down the beam line of the local injector's RFQ linac.

other light-ion uses. The RFQ linac has been built and tested, and the new ion source system is nearly finished. The 20-MeV Alvarez tank is being modified, and the high-power rf system is nearly in place. We expect routine operation to begin in 1984.

One problem that arose when we undertook the local injector upgrade project was delivering protons to Bevalac experimenters. We solved it by gen-

Accelerator Operations

erating high intensities of singly charged molecular hydrogen ions in the SuperHILAC's FVE injector, giving them an initial 600-kV acceleration through its column, then injecting them into the Bevatron without stripping. Protons are created by stripping the relativistic molecular hydrogen ions at the exit of the Bevatron, yielding a maximum energy of 2.1 GeV. Generating protons with "full energy" (4.9 GeV) must await studies to determine the magnetic field characteristics of the Bevatron at the 200-gauss level, so that protons, rather than ionized hydrogen molecules, can be injected at the 5-MeV maximum energy of the upgraded local injector.

As part of a new program for intensity improvement, we have begun to develop a new ion source known as MEVVA (metal-vapor vacuum arc, see Fig. 6). Early results indicate that this device will substantially increase available currents of very heavy ions at reasonable charge states (+5 or +6, for example). A prototype source has already produced uranium beam intensities on a test stand in excess of 100 electrical mA of U^{+5} , and we now plan to incorporate a MEVVA source in the SuperHILAC ABEL injector.

Also under way at the end of 1983 were studies of ways to solidify the ten-fold intensity increases we see when the heaviest beams are not stripped at the SuperHILAC exit and to provide substantial improvements in beam utilization efficiency. To achieve these objectives, we will concentrate on upgrading components of the transfer line between the SuperHILAC and the Bevatron.

Another continuing improvement project is the development of more efficient charge strippers. Ion beams emerge from sources at low charge; higher-charge states are required for efficient acceleration and beam transport. Additional electrons are usually stripped from the ions by passing the beams through thin foils. Now, however, our beams are so intense that thin foils are rendered ineffective after a very short time (a few minutes to a few hours) in the beam. One alternative is a vapor stripper, which, for our applications, consists of a stream of oil vapor of sufficient density to strip the ion beam passing through it. The vapor molecules are in motion at all times, so there is no question of burnout or failure. The vapor stripper is currently in use in the ABEL injector, but the available charge states are lower than those from a foil stripper.

A second alternative, under development during 1983, is a thin-film liquid stripper. By throwing oil from a rapidly rotating wheel, this device creates a film sufficiently thin to serve as a good stripper. Once again, the oil is always in motion, so problems of burnout are not present. Preliminary results with this design are very encouraging.

Intensity Upgrade

Other Improvements

Fig. 6. The MEVVA ion source, showing a uranium plasma plume streaming through a hole in the anode (left) and expanding along the magnetic field en route to the extractor (right).

As part of our efforts to support outside users, a new data reduction building was built in 1983 to house two VAX 11/780 computers and their associated peripheral hardware. Computer delivery is scheduled for 1984. Also, engineering and ion-optics studies are well-advanced for a new combination low-energy beam line and secondary kaon beam line.

Improvements in user facilities at the SuperHILAC have centered on gas-filled heavy-ion detectors that provide large acceptance angles for high-efficiency coincidence experiments (see Fig. 7). In addition, 1983 saw significant progress on the High Resolution Ball, an array of 21 Compton-suppressed, high-purity germanium detectors. This apparatus will permit a new class of nuclear structure experiments to be undertaken at the SuperHILAC in late 1984 or 1985. Also at the SuperHILAC, development of new rf power amplifiers, which began in 1980, culminated in 1983 with the fabrication of two prototype units having two significant improvements over the old units. First, the new design uses a power amplifier tube readily available on the market, in contrast to our original tubes, which are no longer even repairable. And second, a redesign of the rf system with the new amplifiers throughout will effect substantial energy savings by eliminating many components necessary for operation of the original system.

Fig. 7. View of the detection system inside the 60-inch scattering chamber at the SuperHILAC.

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2.

HIGH-ENERGY PHYSICS

DURING 1983 LBL'S SUPPORT of the nation's high-energy physics program focused on the design and development of high-field superconducting magnets, on theoretical accelerator physics issues, and on the design of stochastic beam-cooling systems. In all of our efforts, we placed increasing emphasis on the anticipated needs of the proposed Superconducting Super Collider (SSC). A program to build this multi-TeV, high-luminosity proton collider was the unanimous recommendation of the new facilities subpanel of the High Energy Physics Advisory Panel, which issued its findings in July 1983. Current plans are for a proton-proton machine with beam energies of 20 TeV and luminosities as high as $10^{33} \text{ cm}^{-2}\text{sec}^{-1}$. The envisioned energies entail a ring with a 90- to 164-km circumference, depending on the magnet design adopted.

In support of this major undertaking, we prepared to serve as the host institution for the preliminary SSC design effort, scheduled to commence in January 1984. This first phase of the SSC program — the Reference Designs Study — precedes an actual decision to proceed with design R&D. During this initial step toward an SSC, the study group is slated (a) to study the feasibility of designs based on three types of magnets (3, 5, and 6.5 T), (b) to perform a credible cost estimate for each design, and (c) to produce a thorough design and cost estimate for at least one self-consistent SSC facility.

During 1983 — even before the Reference Designs Study began — our most visible supporting role in the SSC program was as designer of the 6.5-T magnet proposed for the main ring. However, we devoted substantial attention to wider accelerator design issues as well. In addition, we continued our cooperative efforts with Fermilab in developing a stochastic beam-cooling system for the largest superconducting accelerator already in operation — the 1-TeV Tevatron.

Superconducting Magnets

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Superconducting Magnets

Several 1-meter prototype magnets were tested in 1983, each embodying different design concepts. Some of the developments being pursued in the quest for higher field strengths are windings of Nb₃Sn conductor, smaller bore diameters, smaller copper-to-conductor ratios, optimized coil configurations, and operation of Nb-Ti-wound magnets at 1.8 K. Among our achievements during the year was an accelerator-type magnet producing a record field of 8.8 T. With an eye to reliability, economy, and field uniformity, we proposed at year's end a two-in-one SSC magnet design based on the well-characterized Nb-Ti conductor that would produce a central field strength of 6.5 T at 4.5 K.

Prototype Magnet Development

Our efforts to develop magnet designs suitable for a large, multi-TeV accelerator have produced a series of four model dipole magnets. Their specifications are summarized in Table 3, and one of the models is shown in Fig. 8. The bore diameter of these models is relatively small, an economy allowed by the small spatial cross section of the beam in a multi-TeV hadron machine. Using these magnets, we have evaluated winding techniques, cable designs, and the effects of different copper-to-superconductor ratios. More dramatically, we have reached the highest fields ever achieved with accelerator-type dipole magnets.

Model D9-A was successfully tested in 1982, and the first tests of D9-B and D10-C were conducted in the first months of 1983. The results demonstrated that high fields could be achieved with the well-characterized Nb-Ti alloy at 1.8 K (the temperature of superfluid helium). In addition, the successful test of D10-B showed for the first time that a copper-to-superconductor ratio below unity was feasible. We successfully tested D10-A, the first high-field Nb₃Sn dipole model, in November 1983. This design used the first "internal-tin" Nb₃Sn cable made in the U.S. The cable was wrapped with fiberglass and wound in the unreacted state. After reaction at 700°C (the final metallurgical step taken to produce the Nb₃Sn), the windings were vacuum impregnated with epoxy. This wind-and-react construction method — an alternative to winding prereacted cable — offers the advantage of winding with ductile cable and using

Table 3. Specifications for four prototype dipole magnets tested in 1982–1983 and for the 6.5-T design proposed for the SSC.

	D9-A	D9-B	D10-B	D10-A	SSC
Bore diameter (mm)	58	58	58	58	40
Length (m)	1	1	1	1	17.5
Configuration	4 layer	4 layer	4 block	4 block	2 layer, 2-in-1
Conductor	Nb-Ti	Nb-Ti	Nb-Ti	Nb ₃ Sn	Nb-Ti
Cu-to-conductor ratio ^a	1.5	1.0/1.3	0.86	1.0	1.3/1.8
Cable					
Configuration	Rect	Keystone	Rect	Rect	Keystone
Strand diameter (mm) ^a	0.69	0.76/0.69	0.81	1.73	0.81/0.65
No. of strands ^a	23	21/23	27	11	23/30
Field strength (T)					
At 4.5 K	5.9	6.9	7.0	8.0	6.5
At 1.8 K	8.0	8.6	8.8	—	—

^aWhere two numbers appear, they refer to cable specifications for inner- and outer-layer windings.

Fig. 8. Two 1-meter experimental model magnets. The upper photograph shows Model D70-A, a Nb₃Sn-wound magnet, which has achieved a field of 8.8 T at 4.5 K. The lower photograph shows a model built to test the 4-mm-bore SSC magnet design. It uses a ring-and-collet design and Nb-Ti superconductor.

small bend radii, but it requires further development of an epoxy-impregnation system. If the cable is reacted before it is wound, more conventional insulation can be used, but the reacted cable is very brittle and thus requires special handling.

Based on our experience with the design and fabrication of high-field magnets, we are developing in collaboration with Brookhaven National Laboratory (BNL) a 6.5-T, two-in-one dipole magnet system for the SSC. The preliminary design is based on highly homogeneous Nb-Ti operating at 4.5 K, but we are keeping open the possibility of operating at higher fields (8-9 T), which would mean using the same winding at 1.8 K or a Nb₃Sn winding at 4.5 K. Our experimental models will be about 1 meter long, with a 40-mm bore diameter and two layers of Nb-Ti cable. At the end of the year, the first model was nearing readiness for a January 1984 test (see Fig. 8). Brookhaven will then build and test 4.8- and 17.5-meter models of our design, using our cable. Still later, we plan to design and test quadrupoles and other special-purpose magnets.

Our SSC magnet design reflects concerns about both economy and reliability. Among the parameters we sought to optimize were the magnet configuration, magnetic field strength, physical aperture, operating temperature, and assumed current-carrying capacity of the superconductor. Some of the important magnet specifications are summarized in Tables 3 and 4, and Fig. 9 shows a cutaway perspective of the design.

The two-in-one design shown in Fig. 9 offers several advantages, including (a) the need for only one cryostat, (b) mechanical rigidity, (c) a reduction in the amount of iron that would be needed in a double-yoke design, and (d) a reduction in the amount of superconductor that would be needed in the absence of

SSC Magnet Design

Table 4. Additional specifications for the 6.5-T, two-in-one magnet design for the SSC.

General	
Overall length (m)	17.5
Magnetic length (m)	16.6
Iron yoke outer diameter (cm)	33.0
Bore tube inner diameter (cm)	3.34
Mass of conductor, per aperture (kg)	220
Mass of iron, total (kg)	8649
Central field (T)	6.5
Current (A)	5400
Inductance (mH)	65
Stored energy, each aperture (MJ)	0.95
Winding (per aperture)	
Inner layer	
Number of turns	17
Inner diameter (cm)	4.0
Outer diameter (cm)	5.88
Cable length (m)	1152
Cable mass (kg)	104
Maximum field (T)	6.82
Outer layer	
Number of turns	22
Inner diameter (cm)	5.94
Outer diameter (cm)	7.88
Cable length (m)	1492
Cable mass (kg)	116
Maximum field (T)	5.43
Conductor	
Inner layer	
Cable twist pitch (per cm)	0.2
Number of superconducting filaments	525
Filament diameter (μm)	23
Strand twist pitch (per cm)	0.8
Outer layer	
Cable twist pitch (per cm)	0.2
Number of superconducting filaments	400
Filament diameter (μm)	19.4
Strand twist pitch (per cm)	0.8

the close-fitting iron yoke. The magnetic strength (6.5 T) is close to the maximum that can be economically produced at 4.5 K using a two-layer coil similar to the successful Tevatron and CBA designs. Higher fields economize on circumference-related costs but use significantly more of the costly superconductor. The small physical aperture of our design (3.3 cm) will adequately accommodate the beam of a high-energy collider. The operating temperature is a conservative 4.5 K. Operation at 1.8 K would produce a central field strength of about 8 T, but further study is needed to determine any cost benefits of lower-temperature operation.

The conductor we chose for our design is the same niobium-titanium alloy used in the Tevatron magnets, but we are working with the manufacturer of the conductor to improve its current-carrying ability. This ability is reflected in the conductor's critical current density J_c , which is a function of both temperature and magnetic field. A high value of J_c implies that higher fields are available with a given cabling configuration, or, for a given field, that less superconductor

is required. In principle, Nb_3Sn has a higher J_c under most conditions, but this material is still under development, and its cost and performance cannot be reliably specified. The cable itself, shown in Fig. 10, has the cross-sectional shape of a truncated wedge (or "keystone") so that it can be "stacked" tightly around the bore tube. The winding configuration is shown in Fig. 11.

As part of our magnet development activities, we are also developing a self-energized local correction winding that can compensate for major field errors. In addition, we expect that continuing work in the coming months will produce a mechanically improved cable with our "internal flat" design and with up to 30 strands. This should result in a more rigid winding and a more uniform magnetic field. To test longer models, we also plan to build a 15-foot test cryostat capable of 1.8 K operation.

Looking to the future, we plan to construct a Nb_3Sn model, based on our SSC design, using the same process we pioneered with Model D10-A. The cable sizes will be nearly identical to those of the Nb-Ti cables used in the two-layer SSC design.

Fig. 9. A cutaway perspective of the 6.5-T dipole magnet designed for the SSC.

Related Research

In anticipation of a major effort over the next several years to prepare for the SSC, LBL has begun to look at three major accelerator design issues, each related to our magnet design efforts: (a) basic design and parametric studies, (b) accelerator physics and beam dynamics studies, and (c) subsystem and component technology.

Other Aspects of SSC Design

Basic Design and Parametric Studies

We are examining the basic accelerator design parameters and their interrelationships with a view to understanding the tradeoffs among performance, risk, and cost. As part of the Reference Designs Study, we will develop a matched lattice and an optimized set of parameters for the 6.5-T magnet option. The aim is a luminosity of $10^{33} \text{ cm}^{-2}\text{sec}^{-1}$, a beam stable for at least 24 hours, and an acceptably low level of synchrotron radiation. Parameters of interest include number of interactions per bunch crossing, number of particles per bunch, number of bunches, bunch separation, beam emittances, amplitude function at crossing, crossing angle, and rf voltage and frequency.

In the coming year, we will investigate the sensitivity of the lattice to magnetic field imperfections. This study, which will relate the optics to the stability of the beam, is an element in any performance-cost tradeoff study. We also plan to examine the interaction region layouts from the point of view of machine performance and user requirements.

Accelerator Physics and Beam Dynamics Studies

We are also looking at the stability of the beam and analyzing performance-limiting phenomena. A major part of this effort is related to the magnet designs. We are investigating the effect of the expected field errors on the long-term stability of the beam, as well as studying the impact of a small superconducting coil radius on the nonlinear resonances. The result of this work will be proposals of ways to correct for the effects of the inevitable field errors.

In addition, we are applying tracking and theoretical studies to the problem of the nonlinear fields driven by persistent currents in the superconductor. This effect is well-known to magnet designers, but it is only when studied in the context of a global machine design that its full impact can be understood and

Fig. 19. (a) Cross-sectional view of "keystoned" 23-strand cable, proposed for use in the inner windings of the SSC dipole magnets. (b) Illustration of a single strand of superconductor, showing 525 constituent filaments of Nb-Ti.

Fig. 11. (a) A simplified perspective of the proposed SSC dipole. The superconductor cable lies in many elongated loops along the length of the magnet, as suggested by the arrows showing the direction of current flow in the coils. The orientation of the induced magnetic fields and the direction of the beams in the bore tube are also shown. The holes in the iron reduce field variations and serve as channels for coolant flow. (b) A winding for a short SSC prototype magnet. The flared, "dog-bone" ends are necessary because the wide cable and narrow bore tube do not allow a tighter geometry. Each single-bore model magnet requires four such windings, two for the inner layer, two for the outer.

corrective action suggested. A likely solution, mentioned earlier, is the use of local corrective windings in each magnet. A test of this technique is planned for early 1984.

An important part of stability assurance is related to collective effects. At the beam intensity required by the performance objectives for the SSC, we expect collective phenomena, such as interactions between the beam and the walls of the vacuum chamber and between the beam and the accelerating cavities, to become important. Feedback systems and auxiliary corrective magnets will be needed to damp these instabilities. We are working toward an understanding of how these requirements relate to the vacuum chamber radius — thus to the aperture of the magnets — and to the design of other components.

We have just begun to study the essential specifications of the basic accelerator components needed for the SSC. These will include, for example, the rf system and the number, rating, and tolerances of the power supplies. Important goals of this work are to identify critical areas of research and to verify that the parameters implied by the design performance are in the realm of present or near-future technology.

Subsystem and Component Technology

The technique of stochastic cooling is applicable to particles such as antiprotons circulating in a ring. Sensitive electrodes are needed to pick up from each passing particle the tiny signal indicating its deviation from the mean transverse

Beam Cooling

position and velocity of the beam. That signal is then amplified and transmitted downstream by fast electronics to a kicker electrode, where it is applied as a corrective impulse to the same particle (Fig. 12). The development, production, and testing of components for stochastic cooling of antiprotons is being carried out in support of the Tevatron proton-antiproton collider project at Fermilab. In addition, we are beginning to pursue improvements in this technology and its more general application to feedback systems in the SSC.

Fig. 12. A simple illustration of the principle of beam cooling.

During 1983 prototype beam-cooling arrays operating between 2 and 4 GHz were constructed for the Tevatron, and beam tests with these and with the previously fabricated 1- to 2-GHz units were completed. Production is under way. Primary and secondary combiners for all arrays have been developed, and we expect to settle on production design details in early 1984. A special four-array electrode structure for core pickup has been modeled, and a unit will be made for the TEV-I accumulator at Fermilab. Probes and rf antennas for testing the production electrodes will be designed shortly.

Input circuits, through the preamplifiers, are being designed at LBL. These operate at 80 K and will use low-noise preamplifiers developed for this purpose. We expect these preamplifiers and their bias regulators to be produced in the LBL shops. Absorbers to suppress traveling waves and resonances in the beam aperture will be specified, based on tests with available ferrite materials. Also, ways of avoiding coupling from kickers to pickups through the vacuum aperture will be addressed.

In the coming months, we will use the results of our work at 2-4 GHz to project the benefits and problems of extending the cooling-system frequencies to the 4- to 8-GHz range.

During 1983 we also began to look ahead to the use of feedback systems on the SSC. Accelerator physics studies have shown that, more than any preceding accelerator, the SSC must utilize feedback to achieve both economy and performance. In fact, we must be able to project the capabilities of systems for suppressing instabilities and counteracting noise if we are to specify important parameters such as momentum spread, emittance, peak current, rf cavity impedance, and bore tube construction. For this reason, we must establish the conceptual feasibility of feedback systems being invoked in current SSC designs. Later work will develop and test critical components such as beam sensors, signal-processing circuits, and transmitters. Some systems must have a broad bandwidth for addressing singly the thousands of beam bunches. Interactions between otherwise separate systems will be discovered and evaluated. Available electrodes and circuits will be tested, and new components will be developed.

High-Field Superconducting Magnets

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3.

MAGNETIC FUSION

LBL'S PRINCIPAL CONTRIBUTION to the development of magnetic-confinement fusion in the U.S. centers around neutral beams as a means for heating, refueling, and confining reactor plasmas. These neutral beams comprise hydrogen or deuterium atoms, produced by neutralizing beams of either positive or negative ions. Our work on both positive- and negative-ion-based beams is coupled with the research efforts at the Tokamak Fusion Test Reactor (TFTR) at Princeton, the Magnetic Fusion Test Facility (MFTF) at Livermore, and Doublet III at GA Technologies, Inc., in San Diego.

We have developed sources of positively charged hydrogen and deuterium for all of these facilities, where positive-ion-based beams provide the auxiliary heating required to operate the experimental reactors. (Figure 13 shows the neutral-beam system at Princeton's TFTR.) Increasingly, however, attention is turning to negative-ion-based systems, since positive ions are difficult to neutralize at high energies (see Fig. 14). Energetic neutral beams based on negative ions, then, are now seen as a possible means for generating and maintaining potential barriers in tandem mirror fusion systems and as an alternative to rf heating for heating the plasmas in next-generation tokamak reactors. The challenge is to produce a high-current (5–10 A), steady-state beam with an energy of at least 400 keV.

As currently conceived, the necessary neutral-beam injector will comprise a source of D^- ions, an accelerator and beam transport system, and a neutralization region. We are working actively on two ion sources and have already achieved currents thought to be within a factor of two of those needed for a 400-keV injector. Several strong-focusing concepts are candidates for the accelerator section, including transverse field focusing and electrostatic or rf quadrupole focusing. Attention at LBL has concentrated on the former. Among neutralization methods, laser photodetachment is the most attractive option — a scheme in which the beam traverses a continuous-laser resonance cavity.

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Fig. 13. Cutaway view of Princeton's Tokamak Fusion Test Reactor, showing the positive-ion-based neutral-beam injector.

Neutral-Beam Development

Negative-ion-based systems are now viewed as having fewer limitations than positive-ion systems, largely because they can be more efficiently neutralized at high energies. Nonetheless, much important preliminary work on neutral beams involved positive ions. Short-pulse (0.5 second) positive-ion sources and beam lines were developed at LBL for TFTR and Doublet III, and a prototype long-pulse source has been designed and tested. Further testing and technology transfer to industry will continue into 1986. The current shift of emphasis to negative ions reflects the need for high beam energies, whether to confine plasmas in mirror reactors or to penetrate the sizable plasmas of advanced tokamaks for heating or refueling. Our work on negative-ion systems has included work on two kinds of sources — one that generates ions at a biased cesiated surface and one that produces ions in a hot plasma — and on a promising acceleration and transport system, the transverse field focusing accelerator. For neutral-beam development, we rely on several test facilities, each in effect a neutral-beam injection system. The largest of these facilities, the 120-kV, 50-A Neutral Beam Engineering Test Facility, is used for positive-ion

Fig. 14. Plot of neutralization efficiency for positive and negative hydrogen and deuterium ions, as functions of energy. The efficiency of negative-ion neutralization depends on the neutralization scheme chosen.

source development but is slated for conversion to a negative-ion facility beginning in 1986.

Effort in 1983 was concentrated on development of the long-pulse Advanced Positive-Ion Source prototype (Mk-I APIS). This source, shown in Fig. 15 on the Neutral Beam Engineering Test Facility (NBETF), provides design data for the MFTF-B tandem mirror and for the proposed long-pulse upgrades of the TFTR and GA tokamaks. The source produces a beam of 10×40 cm cross section, and by the end of 1983, we had obtained several hundred full-power (80 kV, 40 A for deuterium), 30-second shots. In addition, the source was operated with gas from an oxygen-contaminated deuterium bottle in preparation for the so-called pure-beam tests for Livermore's MFTF-B. In these tests, magnetic momentum selection will be used to separate contaminants from deuterium. Finally, a set of 5-second-long pulses of 80-kV hydrogen ions was run for GA Technologies to demonstrate the capability of changing ion mass.

The APIS R&D program has been funded at LBL and Oak Ridge National Laboratory for several years as a competition to develop the best generic positive-ion source module for confinement program needs starting in the mid-1980s. Both laboratories have pursued research, design, and fabrication programs, and qualification tests on both candidate sources began in late 1983 at LBL's NBETF. A decision on which source is to be used by confinement research laboratories is expected in early 1984.

Our aim in the negative-ion-based program is to develop negative-ion sources and accelerator/transport systems that will ultimately lead to neutral-beam systems suitable for full-scale reactor applications. Tandem mirror reactors require these intense beams to create and maintain electrostatic potential barriers in the end plugs, and such beams can also be used to heat and drive current in tokamak reactors. In the mirror machines, the beam energies must be high enough to create a plasma-confining potential, and in the tokamaks, the beam must be energetic enough to reach the interior of reactor-size plasmas. For both applications, the beam systems must operate continuously at several hun-

Positive-Ion-Based Systems

Negative-Ion-Based Systems

Fig. 15. The Advanced Positive-Ion Source prototype, mounted on the Neutral Beam Engineering Test Facility. The accelerator is behind the clear plastic shroud, with the plasma source at its left.

ded keV — energies so high that the beams cannot be produced efficiently from positive ions.

Our approach has been to concentrate on two significant steps toward practical applications of negative-ion-based neutral beams: first, the generation of steady-state negative-ion beams at about 1 A and, second, the acceleration and transport of negative ions, initially at 80 keV, finally at 200–500 keV. The time scale for development is paced by anticipated applications in the mid 1990s.

The first source to be brought to a high level of development was the surface-conversion source, in which a cesiated, negatively biased molybdenum or tungsten electrode is embedded in a plasma (Fig. 16). During 1983 we produced a steady-state 0.9-A current of H^- from such a source and were able to operate at 2 A for short periods. A shortage of adsorbed cesium on the converter surface limits ion production; therefore, we are working to improve the cesium feed to the converter surfaces. During 1983 we also experimented with different crystalline forms of molybdenum and tungsten, but found that monocrystalline converters are no better than the polycrystalline ones used initially.

The presence of cesium in the surface-conversion source is a nuisance, since it carries with it the danger of contamination and electrical breakdown problems. An alternative source, which operates without cesium, is the volume-production source, in which negative hydrogen ions are produced in a plasma rather than on a converter surface. A plasma with a low electron temperature (about 1 eV) and an ion density of 10^{11} cm^{-3} can contain a surprisingly large fraction of negative ions, but the process by which they are created is not yet understood. One hypothetical mechanism is dissociative attachment of vibrationally excited hydrogen molecules (Fig. 17). In a joint effort with the Los Alamos National Laboratory, we recently obtained 38 mA/cm^2 of H^- from such a source, with a transverse ion energy spread (or "temperature") of about 0.5 eV. This temperature is much lower than can be obtained with surface-conversion sources (usually a few eV), which reduces problems of beam divergence. With this same volume-production source, we also demonstrated that the output increases linearly with power into the discharge, as shown in Fig. 18, and that negative-ion production can be obtained at source pressures down to 3 mTorr. Furthermore, we found that high-mass impurity ions are no more abundant than in positive-ion sources.

The most promising acceleration and transport system for negative ions is the *transverse field focusing (TFF)* accelerator. In such an accelerator, a field is set up between pairs of curved deflecting plates, which both deflect and focus the beam of charged particles. Average straight-line motion can be obtained by

Fig. 16. A surface-conversion source, opened to show the curved converter electrode and the eight tungsten filaments.

Fig. 17. Schematic depiction of the mechanism of dissociative attachment, proposed to explain the generation of negative ions in volume-production sources. Vibrationally excited H_2^- is briefly converted to unstable H_2^- , which then dissociates to yield a negative hydrogen ion.

having successive pairs of plates curve in opposite directions; acceleration is achieved by adjusting the mean voltage in each succeeding pair of plates (see Fig. 19). Computer simulations of the TFF concept have been promising, and a cryogenically pumped 80-keV transport and matching section is slated for testing in the coming year.

Test stands are required for developing and testing neutral-beam injection modules and system components. Our test facilities thus serve as prototypes for neutral-beam injection systems for confinement experiments.

During 1983 Test Stand IIIA was converted from a positive-ion facility to the principal test site for the negative-ion-based program. As such, it is being developed as a 160-keV, 2-A, seconds-to-dc test facility for research on sources, accelerators, transport systems, neutralizers, controls, and diagnostics. Currently, operation is being limited to short pulses (about 1 second) to allow us to determine the electrical characteristics of accelerators and transport systems, while monitoring x-ray production. Later, operation will be extended to 30-second pulses and finally to dc.

Test Stand I is also used in the negative-ion program, primarily for developing sources in the 1- to 2-A range, but also for beam acceleration to 40 keV. Neither of these test stands has neutron shielding for deuterium operation, so only hydrogen operation is normally possible.

For development of higher-energy neutral beams, a new facility or an upgrade of an existing facility will be required. To cover next-generation mirror and tokamak needs, the facility should be capable of accelerating 5–10 A of

Test Facilities

Fig. 18. Plot of ion current and current density vs discharge current for a volume-production H^- source.

Fig. 19. Conceptual design for a 400-keV negative-ion-based beam line using transverse field focusing systems for acceleration and beam transport. A schematic illustration of the TFF concept is shown in the inset.

negative deuterium ions to 500 keV, with a pulse length of many hours. As a first step, we plan to upgrade the Neutral Beam Engineering Test Facility (NBETF) at LBL to provide 200-keV testing capability. This work is scheduled to begin in 1986. An additional upgrade or a new facility will be required for 500-keV development to serve advanced tokamak and mirror machines.

Currently, the NBETF (shown schematically in Fig. 20) is a 120-kV, 50-A (or 80-kV, 65-A) test facility capable of 30-second pulse lengths and with a 10% duty cycle. It is used for general neutral-beam development of LBL and Oak Ridge positive-ion sources. It is an operational facility with an experienced operating crew; fully operational cryogenic, electronic, and mechanical systems; and a sophisticated diagnostic and data archival system. Recently, it has been used successfully to test 80-kV, 30-second neutral-beam modules and to carry out preliminary pure-beam tests for MFTF-B.

Atomic Physics and Theoretical Studies

Concurrent with the design and testing of neutral-beam systems, work continued in 1983 on developing diagnostic techniques for measuring beam impurities, atomic and molecular species distributions, and source and beam characteristics. Basic and applied theoretical work was also pursued with the aim of better understanding the processes and interactions that occur in plasmas.

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

Diagnostic techniques must measure impurity content in intense deuterium-atom beams, atomic- and molecular-ion species distributions, and ion-source and atom-beam characteristics. To achieve these ends, we have developed an on-line laser-fluorescence diagnostic method to measure the composition of neutral beams (including impurities) during injection into a plasma-confinement experiment. A simple schematic representation of this technique is shown in Fig. 21. In the near future, we expect to extend this technique to allow remote measurements of the energy distribution in beams of fast hydrogen atoms, as well as the beam emittance. This requires the generation of vacuum ultraviolet (Lyman) radiation to excite ground-state hydrogen atoms and/or visible (Balmer) radiation to detect metastable excited hydrogen atoms. For this work, we have available

Atomic Physics

Fig. 21. Schematic illustration of a laser fluorescence diagnostic technique. The excitation wavelength is chosen to excite fluorescence only from the contaminant species being measured.

Fig. 20. Schematic view of LBL's Neutral Beam Engineering Test facility. The ion source shown in Fig. 15 is at the far right.

at LBL an intense tunable laser light source, consisting of a 0.5-joule pulsed excimer (Xe-Cl) laser and two high-power pulsed dye lasers. This source covers the wavelength range from vacuum ultraviolet to infrared. Several frequency-multiplication techniques are being developed to generate the vacuum uv radiation: Raman shifting, third harmonic generation (frequency tripling) in a gas jet, and sum-frequency (four-wave) mixing.

Our ion-source research covers both the surface-conversion and volume-production mechanisms. Study of volume-production sources is especially closely tied to our diagnostics work, since the same vacuum uv light source can be used to measure the distribution of vibrationally excited ground-state hydrogen molecules in (or emerging from) an H^+ source discharge. One- or two-photon excitation to an electronically excited state, followed by fluorescent decay or ionization by another photon, can be used to determine the population of vibrationally excited H_2 . Our calculations for dissociative attachment of electrons to vibrationally excited hydrogen molecules support the argument that this mechanism is at least partially responsible for the H^- production in volume sources (see Fig. 17). Future measurements will correlate the distribution of H_2 vibrational states with extracted H^- .

Beyond work in direct support of neutral-beam development, several achievements are worth note. We have, for example, proposed a new technique (which we call collisional pumping, by analogy to optical pumping) that uses multiple charge-changing collisions in a polarized target gas to produce an intense nuclear-spin-polarized beam of hydrogen, deuterium, or tritium ions or atoms. We calculate that a polarized beam of very high intensity could be made and perhaps used to heat and fuel a fusion plasma with polarized reactants. We have also found an empirical scaling rule for electron-capture cross sections for a variety of fast, highly charged ions in gas targets. This rule allows us to predict yet-unmeasured cross sections for many projectile-target combinations.

Finally, using the SuperHILAC, we have found conclusive evidence for resonant electron transfer and excitation in measurements with fast, highly charged vanadium ions colliding with helium atoms. This process is analogous to dielectronic recombination, an important energy-loss mechanism in high-temperature plasmas.

Theoretical Plasma Physics

Nonlinear Dynamics. Our study of nonlinear dynamics, especially in continuous media such as plasmas, has had three major components, conceptually unified by the use of modern differential geometric methods:

- The use of phase-space and complex-manifold techniques for studying multidimensional wave propagation in inhomogeneous and anisotropic media. The Maslov approach to eikonal theory has been extended to allow for more general coordinate transformations in ray phase space, and the Weyl symbol calculus has been used in analyzing these transformations. This will allow for considerably more flexibility in dealing with singularities in wave propagation.
- The unification of averaging methods in diverse physical contexts using the mathematical theory of reduction. One of the important achievements has been our Hamiltonization of Whitham averaging and of perturbation expansions. This accomplishment leads to a more systematic treatment of reduction techniques, which up to now have been more an art than a science.
- The analysis of continuous Hamiltonian dissipative systems with a view to studying equilibrium, stability, and transport. In the course of this analysis, a new formulation of dissipative systems has been invented, which yields an extremely concise derivation of standard kinetic equations. We plan to use this formulation to discover new evolution equations and to investigate the stability of such systems.

Finally, in a realm common to the study of nonlinear dynamics and plasma heat-

ing, we are investigating a new approach to wave-plasma interaction. Beginning with an exact phase-space Lagrangian for a plasma interacting with an electromagnetic field, a Lie transform is introduced to yield an action principle for waves and oscillation-center distributions. Self-consistency of nonlinear interactions is assured. We plan to apply this method to turbulent transport.

Plasma Heating. Our investigations of plasma heating embrace the fields of basic theoretical study outlined above and several areas of applied plasma theory as well. Among these latter, we are studying

- The spatial structure of drift-cyclotron loss-cone modes and drift waves in inhomogeneous plasmas. One of the major results of the previous year's work in this area was the completion of a substantial computer code for solving the integral equation that describes electrostatic modes in a cylindrical plasma column. This code makes no approximations concerning the relative magnitudes of density scale length, wavelength, and gyroradius; thus, it complements the usual studies based on the WKB approximation or a small-gyroradius expansion scheme. In addition, it is explicitly designed to deal with cylindrical geometry.
- The interaction of drift Alfvén wave turbulence and ballooning modes in tokamak geometries. Understanding this interaction is important for several reasons, all having to do with plasma stability. Starting from the electron drift kinetic equation, the gyrokinetic ion equation, and quasi-neutrality, we have derived a reduced set of nonlinear equations to describe drift Alfvén waves, ballooning modes, and microtearing modes, as well as their nonlinear interactions.
- Relativistic effects in gyrokinetic theory and ponderomotive phenomena. Our attention to these effects has been prompted by the important role relativistic electrons play in the stability of many fusion devices. These electrons have a thermal gyroradius comparable to that of the much colder ions, so that finite-gyroradius effects are quite important for them. We have derived a relativistic gyrokinetic equation suitable for plasma stability studies in arbitrary magnetic geometries. An important feature of this derivation is the use of Hamiltonian perturbation techniques.
- Radio-frequency stabilization of interchange modes in axisymmetric tandem mirrors. By using a cold-plasma action principle, we have obtained self-consistent equations for the low-frequency plasma motion and for the wave amplitudes. The singular behavior at gyroresonance, found by other workers, disappears in our self-consistent treatment. Hamiltonization of the system allows the use of Arnold's method to obtain nonlinear stability criteria.

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4.

HEAVY-ION FUSION

DURING 1983 THE AFRD Heavy-Ion Fusion group continued its work toward a better understanding of high-current heavy-ion accelerators that eventually could be used to generate electrical power by means of inertial-confinement fusion (ICF). LBL's program centers around the induction linac as the basis for a conceptually simple ICF scheme in which heavy-ion beams are accelerated to high current, then focused onto a small pellet of deuterium and tritium fuel. The beams heat the pellet surface, creating a rocketlike ejection of the surface material that, in turn, compresses and heats the fuel to the point where a thermonuclear burn occurs. Though related approaches are being pursued at Lawrence Livermore National Laboratory and Los Alamos National Laboratory (using lasers) and at Sandia Albuquerque (using light ions), heavy-ion accelerators have much to offer, especially in terms of efficiency and high repetition rates.

In October 1983, a major portion of the heavy-ion fusion program was transferred from the DOE Office of Defense Programs to the Office of Energy Research, where it is managed by the Office of High Energy and Nuclear Physics. In connection with the proposal to make this transfer, this latter office requested a reappraisal of the U.S. program in heavy-ion fusion research. The result was the *Heavy-Ion Fusion Accelerator Research Program Plan for FY84-FY89*, which DOE has acknowledged as a reasonable basis for program planning. The principal objective is "to develop heavy-ion accelerator technology and perform appropriate ion-beam experiments to the point where adequate data exist for evaluation . . . of heavy-ion accelerators as inertial confinement drivers."

As part of the program plan, the linear induction accelerator was chosen for development, largely for three reasons: (a) the induction linac is conceptually simpler, and probably cheaper, than alternative acceleration methods; (b) considerable experience has already been accrued in its use; and (c) the most serious technical issues confronting development of the linac can be resolved with a small or medium-size accelerator. As an illustration of the first of these points, Fig. 22 compares conceptual designs for ICF drivers based on an induction linac and an rf linac.

Exploration of linac technology as applied to heavy-ion fusion is highlighted by three milestones. First, the single-beam transport experiment (SBTE), already under way, examines the stability of a high-current cesium beam through 4) focusing-defocusing (FD) lens pairs. Second, the multiple-beam experiment

Experiment	M. Firth	M. Lampert	M. Titefback	J. Bisognano	Administrative	J. Zelter
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C. Chavis	W. Greenway	R.G. Nemetz	A. Warwick	C. Celata		
W.W. Chupp	E.C. Hartwig	C.D. Pike		D. Judd		
E.R. Edwards	R.R. Hippie	T.J. Purcell	Theory	G. Kraft		
A. Fakens	C. Houston	S.S. Rosenblum	L. Smith	L.J. Laslett	J. Kono	*SLAC
	C.H. Kim	C.L. Stoker	(group leader)	E. Lee	A. Lundblad	
	A. Kruger	G.L. Tabler		W.B. Hermanns/dt	S. Mesetz	
					A. Williams	
					G. Wong	

Fig. 22. Conceptual designs for inertial-fusion drivers based on rf and induction linac accelerators.

(MBE) will transport 16 independent beams through a single accelerating structure. Finally, the program culminates in the High-Temperature Experiment (HTE), which, as currently conceived, will focus and overlap multiple high-current beams on a 2-mm-diameter spot.

Single-Beam Transport Experiment

The SBTE is the first step on the path to the HTE. Its principal goal is to study the stability of a high-current beam of heavy ions (Cs^+) as it is transported through an array of quadrupole magnets. The destabilizing effect of mutual electrostatic repulsion has been the main uncertainty, but initial results have allowed us to revise upward our estimates of the maximum transportable currents. As part of the SBTE, we have also developed long-lived ion sources, more accurate means of diagnosing transported current, and efficient ways of varying beam current and emittance — two parameters that affect the stability limits of the beam.

The SBTE was designed to investigate the long-term stability of space-charge-dominated heavy-ion beams in an alternating-gradient (AG) lattice. Our goal is to characterize stability thresholds and instability modes. The threshold information is of immediate interest as we seek an optimum accelerator design for the proposed HTE.

The apparatus for the SBTE, shown in Figs. 23 and 24, consists of an ion source, injector, matching section (quadrupoles M1-M5), transport section (quadrupoles Q1-Q82), and a diagnostics chamber. The lattice half-period is 15.24 cm, and the bore diameter is 5.08 cm. The total length of the transport section is about 13 meters. The parameter ranges of the Cs^+ beam are (a)

Background and Experimental Results

Fig. 24. The apparatus for the single-beam transport experiment, with the ion source in the foreground.

Fig. 23. Cutaway view of the experimental apparatus for the single-beam transport experiment. The matching section comprises matching quadrupoles M1-M5, and the transport section includes focusing and defocusing quadrupoles Q1-Q12. The total transport length is about 13 meters.

kinetic energy, 80–160 keV; (b) current, 0.7–23 mA; and (c) emittance (ϵ_N), 0.8×10^{-7} to $6 \times 10^{-7} \pi$ rad-m.

It is useful to view such an AG focusing lattice in a "smoothed" sense, that is, as providing an average restoring force to the axis of the system. The motion of a single particle (or each particle in a low-current beam) is then sinusoidal and is characterized by an angular phase advance σ_0 per cell of the lattice. Thus, if σ_0 is arranged to be 60° , a particle will execute one complete transverse oscillation (betatron oscillation) in passing through $360^\circ/60^\circ = 6$ lattice periods. In a high-current beam, however, the mutual electrostatic repulsion of the particles provides a defocusing force that acts to cancel part of the lattice restoring force. (The allowable extent of this canceling effect has been the object of intensive theoretical studies for the past seven years.) In the presence of the combined lattice focusing and space-charge defocusing, a single particle executes a much slower betatron oscillation, described by a depressed phase advance σ , which is always smaller than σ_0 . Figure 25 illustrates these concepts schematically.

The larger the beam current we seek to transport, the smaller σ becomes. (In our experiment, current and σ are approximately inversely related.) Since a crucial feature of the induction linac approach is the need to transport as much current as possible, it is vitally important that we establish the lowest attainable value of σ . For a transport lattice set to give $\sigma_0 = 60^\circ$, the initial speculation was that $\sigma \approx 40^\circ$ might be the limit. Careful computations first lowered this estimate to 24° , then gave rise to hopes that we could do even better. Our results this year with the SBTE have established that $\sigma = 8^\circ$ can be reached without compromising beam stability. Because of these encouraging results, we will continue our pursuit of still lower values to see whether, in fact, there exists any limit beyond which damaging effects occur.

Hardware Improvements

Source Development. During 1983 we developed techniques for making cesium-loaded zeolite and for coating our sources with it. We characterized the output of our second in-house source and found that it can sustain more than 30 mA of Cs⁺ emission at temperatures of 980–1000°C, with a uniformity of $\pm 10\%$. This second source is equal in quality to our first one, which has shown no degradation in performance after a year of operation — four times the useful life of the longest-lived commercially prepared source.

Fig. 25. Schematic depiction of the concepts of phase advance and depressed phase advance. Both express, in units of degrees, the fraction of a full (360°) betatron oscillation executed per lattice period.

Faraday Cup Standards. To measure ion current, we previously relied on shallow charge collectors (gridded Faraday cups) that were required to fit in the 2-inch gaps between the electrostatic quadrupoles of our lattice. Unfortunately, the biased grids intercept some 2% of the beam, and some electrons produced at the grids can travel to the collector. We thus faced current measurement uncertainties of about 10%. We have now constructed and installed a deep Faraday cup, without a grid but with a biased ring, at the exit of our channel and have found that the current saturates ideally in either polarity (electron retention or expulsion). This cup provides a good absolute standard. (This deep cup does, indeed, indicate about 10% more current than we have measured with the shallow ones.)

Beam Attenuation and Emittance Control. As discussed above, one of the major objectives of the SBTE is to explore the beam current limits in a long quadrupole-focused channel — limits imposed largely by the beam space charge. The value of σ , which we use to measure the transport limit, can be varied by varying the beam current and/or the emittance. Control of these parameters is therefore critical.

Current attenuators made of fine-wire grids of various transparencies (0.035, 0.095, 0.12, 0.33, 0.39, 0.58, 0.89, 0.95, and 1.00) have been mounted on an off-center wheel in front of the source, so that the degree of attenuation can be changed without opening the vacuum system. The wheel also has several small apertures to generate pencil beams, which are useful for checking the uniformity of the source, for checking the alignment of the beam line, and for studying the coherent betatron oscillations.

The improved emittance control grids are composed of three Hexcel grids ($1/8 \times 1/8 \times 1/16$ inch each, and 0.2 inch thick all together). The normalized beam emittance can be varied from 1.2×10^{-7} to 6×10^{-7} π rad-m by varying the bias voltage on the center grid from zero to 17 kV. Even with no bias voltage, the presence of the grids raises the emittance from 0.8×10^{-7} to 1.2×10^{-7} π rad-m.

The single-beam transport experiment is one of the benchmarks in a wide-ranging research program that can also point to many significant individual achievements. Among these in 1983 were the development of an electronic "harp" for diagnosing beam profiles, tests of a collective-field focusing theory, and improvements of linac components. All of these efforts, together with the SBTE itself, have a direct bearing on definition of hardware for the anticipated MBE (and ultimately the HTE).

Other Experimental and Developmental Activities

Beam Diagnostics Development

Electron Beam Probe. The electron beam probe (EBP) was developed as a non-destructive diagnostic of ion-beam space charge. The last half of 1983 saw two major developments in the analysis of EBP data. The first was the refinement of the model distribution by replacing the uniform ion-beam model with a Gaussian beam model, more nearly reflecting independent small Faraday cup measurements. The second was a new understanding of the electron halo, a result of the fact that the contracting ion beam does work on the trapped secondaries, thereby raising the electron temperature.

Multiple-Wire Beam Profile Measurements. We have constructed a multiwire beam scanner (a so-called harp), in which each wire is equipped with a sample-and-hold circuit coupled to a multiplexer output and a storage oscilloscope. Thus, a profile of the beam may be taken with a single pulse. Several more harps, designed to allow rotation in a plane, are under construction. By applying reconstruction techniques used in biomedicine (tomography) to the signals from such devices, complicated beam distributions may be reconstructed. The same technique can also be used to reconstruct the profiles of all the beams of a multiple-beam array.

Neutralized-Beam Focusing Experiment

The goal of the neutralized-beam focusing experiment is to demonstrate focusing of a charge- and current-neutralized Cs^+ beam by a solenoid magnet. The major idea, due to Robertson [*Phys. Rev. Lett.* **48**, 149 (1982)] is that focusing depends on the beam-generated collective field, in contrast to the normal situation, which involves the magnetic force on the individual ions. In the absence of space-charge forces, an electron beam passing through a solenoid would be focused relatively strongly because of its large charge-to-mass ratio. Correspondingly, an ion beam would be focused relatively weakly. If one had a two-component beam in which the two species were strongly coupled through space-charge forces, the combined beam would come to a common focus somewhere between these two extremes (see Fig. 26).

To generate the collective field needed to achieve a common focus, the ion beam must have sufficient current to exceed a threshold value. The large Cs^+ contact-ionization source at LBL provides enough current density to allow a test of this idea. In addition, the beam must be current- and charge-neutralized by comoving electrons. A grid placed in the beam to intercept a small fraction of the ions produces enough secondary electrons to neutralize the beam. A solenoid wound on the outside of the vacuum tank of the accelerator generates the focusing magnetic field.

To date we have propagated an intense, well-neutralized beam over a distance of approximately 10 meters. We have developed a capacitive probe to measure the beam space-charge potential, but the measured value and its dependence on magnetic field strength do not agree with theoretical expectations. A more definitive test of the theory, however, requires a cleaner experiment. In particular, the grid-neutralization scheme fails to provide a sufficiently cold source of electrons for a proper test of the lens idea. The residual poten-

Fig. 26. The effect of collective-field focusing. According to one theory, a charge- and current-neutralized beam of electrons and ions should be brought to a common focus, rather than to two foci that depend on individual charge-to-mass ratios.

tial of the neutralized beam may be large enough to wash out, at least to some extent, the potential of the lens.

To get colder electrons and better neutralization, work on an annular filament cage has begun. Relatively cold electrons will be produced by thermionic emission from hot filaments. As the beam passes through the cage, hot electrons will be replaced by cold ones. In case the filaments do not produce enough cold electrons, we are also considering an option in which plasma would be formed in the cage. Simulations by others indicate that a beam passing through such a cloud of electrons (or plasma) should be neutralized with residual potentials of about 1 volt. This is cold enough to allow the collective field of the lens to dominate the electron dynamics, an assumption of all theoretical analyses to date.

Long-Pulse Induction Unit. In March 1983, we first accelerated heavy ions with the long-pulse induction unit installed on our Cs⁺ beam line. This unit permits energy gains up to 250 keV for 1.5- μ sec pulses. During recent months, we have sought to decrease time delays and variations in the low-level triggering system of the induction unit. The initial system used silicon-controlled rectifiers (SCRs) or thyristors for pulse repetition and amplification within the triggering chassis and in the external timing chain. Consequently, the cumulative delays and jitters of three SCRs in series were added to the total delay. The variation in time delays ranged up to 1 μ sec. Better SCRs and junction transistors were tried before settling on field effect transistors (FETs) for the trigger amplifiers. The FETs have negligible jitter and delay, and faster rise times than the SCRs. In a life test, one long-pulse module with the new triggering circuit survived 5×10^6 pulses.

Insulator Development. Our development of large, inexpensive insulators for accelerator applications has focused on three areas: (a) continuing measurements of vacuum outgassing of filled and unfilled polymers, (b) production of Polysil test insulators for the Naval Research Laboratory, and (c) design and specification of five large Polysil insulating columns manufactured by Polytch, Inc., of Redwood City, California.

The MBE will test as many of the physics and engineering features of the HTE as possible on a relatively small scale. By employing multiple ion beams, accelerated through a statistically interesting number of independently pulsed accelerating modules (see Fig. 27), it will serve as a test setup for integrating into a practical engineering design the concepts developed for transport and accelerating components, vacuum system components, and alignment and support structures.

Most of our activities in 1983 had a direct bearing on the definition of the MBE hardware. These activities included the SBTE, the diagnostics and accelerator developments just described, and the continuing conceptual design efforts on the HTE.

After discussions with colleagues at Los Alamos National Laboratory (LANL), we settled on 2 MeV as a suitable design goal for the pulsed MBE injector. The injector design is proceeding at LANL. The MBE parameters will be fixed in early 1984 to allow for prompt design and construction of the various accelerating modules.

Fig. 27. Cutaway perspective of a single MBE induction/focusing unit. The inset shows the arrangement of the quadrupole electrodes.

Induction Accelerator Development

Multiple-Beam Experiment

Theory

Theoretical work focuses on the HTE. Preliminary conceptual designs use electric quadrupoles in the first sections, followed by a magnetic-focusing regime in which the ion bunch length decreases approximately linearly with length. In the final transport section, beyond the linac exit, tenfold longitudinal compression and a corresponding current increase are expected. One-tesla magnets

will be needed to prevent excessive radial beam expansion. The final lens system must focus the beam to a radius of 1 mm at a standoff distance of 1–2 meters. Theoretical consideration has also been given to beam-target interaction at temperatures of 50–100 eV and to instability thresholds for heavy-ion beams.

Induction Linac. In earlier years, design and cost estimates for induction linac systems in the power-plant class (kinetic energy about 10 GeV) were based on studies of the major portion of the linac; special regions — linac entrance and exit regions, drift compression lines, and final lenses, thought to constitute less than about 20% of the cost — were not studied in detail. For the planned HTE system (kinetic energy about 100 MeV), the linac entrance and exit regions nearly merge, and the drift line length is about 20–40% of the total linac length. During 1983 the problems of these regions have been addressed. We have developed conceptual designs and are now considering detailed design options.

We have developed a new computational framework for linac design, in which both the acceleration $\dot{z}$ of a reference particle at the center of the bunch and the bunch length l are prescribed as functions of time. Many properties of the system can then be calculated simply. Additional assumptions, including a value of the low-current phase advance σ_0 , allow us to compute the space-charge-depressed phase advance σ at head and tail, cell half-length L , and maximum beam radius a . Adopting a rule for the minimum allowable σ (at the tail) leads to a determination of maximum transportable charge per beam by either magnetic or electric quadrupole as a function of z . The procedure then consists of altering the originally assumed functions $\dot{z}(t)$ and $l(t)$ with the goals of (a) reducing total length, (b) attaining specified final bunch length and velocity difference between the head and tail of the bunch, (c) transporting the given charge per beam, and (d) avoiding excessive velocity difference at intermediate positions, all without requiring impractical accelerating field strengths.

By repeating this process iteratively, we have obtained acceptable (but not fully optimized) designs sharing the following properties:

- Initial acceleration is very small until the bunch has moved a distance several times its length. Allowable maximum acceleration is attained only at or near the linac exit.
- Electric quadrupoles are used until they become too weak (assuming 2-MeV injection); they allow a shorter injected bunch and are less costly than magnetic quadrupoles.
- Bunch compression is not practical in the electric focusing regime; in the magnetic regime that follows, bunch length decreases roughly linearly with distance.
- The head-to-tail velocity difference at the linac exit may be adjusted over a reasonable range by making changes in the last 20–40% of the linac. Such changes have little effect elsewhere.
- The velocity difference has a rather large maximum value at an intermediate distance along the linac. Imposing a prudent upper limit (about 20%) on this parameter constrains the rate of acceleration in this region and prevents further shortening of the linac.

Many of these results are summarized in the acceleration schedule shown in Fig. 28.

Final Transport. The transport lines that carry the beams from the linac exit to the final lenses are extensions of the linac magnetic quadrupole arrays. Because of head-to-tail velocity spread produced in the linac, a drifting bunch collapses on itself longitudinally, the compression being stopped primarily by longitudinal space-charge forces as the bunch arrives at the target. Tenfold length compression and current increase are contemplated. As the current increases, σ is

HTE Design

Fig. 28. A possible acceleration schedule for a High-Temperature Experiment accelerator. Bunch length, energy, and current are shown as functions of position z along the accelerator length. The bunch initial length l_0 (25 meters) is indicated on the abscissa. This schedule assumes Na^+ ions injected at 2 MeV.

further depressed to very low values (on the order of 1° per period) at the end, and beam radius increases. To avoid excessive radial expansion, higher pole-tip fields than those in the linac are required near the end (about 1 T as compared with 0.4 T).

Final Focus. The final lens system for an HTE must focus high ion currents to a radius of about 1.0 mm at a standoff distance of 1–2 meter. It is essential that the system accommodate the predicted momentum variation of about $\pm 1\%$ and current variations that could be as large as $\pm 50\%$. In addition, the design should permit adjustments of spot position and should accommodate a broad range of pulse energy, current, and radius. We have prepared a rough layout that achieves these aims. It consists of four closely spaced, high-field quadrupole lenses in a FDFD configuration. The strength of each lens is independently adjustable.

Other Theoretical Studies

Spot Heating Calculations for HTE. The HTE will study the interaction of a high-current ion beam with a material target, as well as test the accelerator system that produces the beam. Target temperatures in the range 50–100 eV are considered sufficiently high to examine relevant material interaction features, for example, depositional anomalies, hot electron generation (if any), stability of the beam in a plasma plume, target charge-up, etc. Previously, the predictions for the beam-target interaction were made with the code LASNEX (at Livermore and Los Alamos). However, this is a time-consuming and not generally available tool, which is thus ill-suited to the rapid survey needed to guide HTE design. A simple model of the beam-target interaction has therefore been devised, which allows us to make rapid approximate calculations and which contains the principal physical processes simulated by LASNEX. In cases we have examined so far, the temperature calculated from this simple model lies above the LASNEX-computed surface temperature and below the computed peak interior temperature.

Longitudinal Stability. Theoretical understanding of the high-current beam dynamics typical of induction linac drivers has progressed considerably during the past year. Longitudinal bunch stability, bunch compression and its impact on final focusing systems, and transverse space-charge limits on beam transport have been addressed both analytically and through particle-simulation codes. In particular, this work has provided input for design studies of the HTE.

Any accelerator beam is subject to longitudinal instability driven by resistive

machine impedance. This resistive wall instability has been a significant factor in limiting current for a variety of accelerators. For an infinitely long, uniformly dense beam with no thermal velocity spread, this machine impedance leads to backward-moving growing waves and forward-moving decaying waves. For bunched induction linac beams, it has been suggested that reflection coupling of growing and decaying waves could be stabilizing. Results from a particle-simulation code have confirmed this conjecture. From this study, we have found a threshold condition for instability, which defines a maximum tolerable module impedance of a few hundred ohms per meter. With this limit, there appears to be sufficient flexibility in machine parameters to permit both good linac efficiency and long-term longitudinal stability. Work is under way to define similar criteria for multiple beams.

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5.

CENTER FOR X-RAY OPTICS AND SOURCES OF XUV RADIATION

THE LAST FEW YEARS have seen rapid progress in the development of intense sources of radiation in the vacuum ultraviolet and soft x-ray regions of the spectrum — collectively, xuv radiation. These sources include laser-produced plasmas, other transient plasmas, and most importantly, storage rings and other devices generating synchrotron radiation. To keep pace with this rapid development, LBL has begun research on two fronts. First, we recently established the Center for X-Ray Optics, whose broad charter is to extend the use of xuv radiation (whatever its source) for basic and applied research. Second, we are conducting the research necessary to make practical the next generation of synchrotron light sources. The archetype for these sources is the Advanced Light Source (ALS), a 1.3-GeV storage ring proposed in 1982. The first six beam lines slated for development would cover the energy spectrum from a few eV to tens of keV.

The Center for X-Ray Optics was created in response to the growing need for new optical components and techniques applicable to the xuv region of the electromagnetic spectrum. It has already organized collaborations to develop and use a broad range of new technologies, and experimental and theoretical work has begun on mirrors, gratings, and detectors; on multilayer optical coatings; and on freestanding microstructures to be used as diffractive elements for x-ray focusing and imaging. An especially exciting prospect for the future is the demonstration of x-ray microholography using tunable coherent radiation.

Center for X-Ray Optics

The Center for X-Ray Optics was created in 1983 to take the lead in developing new x-ray optical components and techniques for both science and industry. In the few months of its existence, the Center has begun to organize laboratories and collaborations whose ultimate aim will be to develop and use new technologies for the efficient transport, focusing, dispersion, and detection of radiation with photon energies extending from 20 eV to many keV. Our aim is ultimately to provide a national resource for all scientists working in the xuv spectral region, including those at the various synchrotron radiation facilities. Low-cost

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facilities will be developed for all aspects of the program except fabrication, which will be done elsewhere. During fabrication, assistance in element characterization, together with guidance and feedback, will be provided through the Center.

Among the Center's first efforts have been experiments aimed at producing well-blazed gratings in crystalline silicon by orientation-dependent etching. By this method it appears possible to make xuv echelles — gratings that operate in a high-order mode, thus achieving high spectral resolution with a relatively coarse spacing. Experiments are also under way to evaluate and address the effects of power loading on synchrotron radiation optics. Concepts to be pursued include active control of the surface figure using interferometric monitoring and reduction of the flux at the mirror by prefiltering with broad-band multilayer reflectors.

Future efforts will address surface characterization for both figure (which affects image quality) and surface roughness (which affects scattering). Plans also include work on multilayer coatings for extending x-ray interference experiments, new reflective capabilities, and modest spectral selection methods (such as mode selection for undulator radiation). We also plan more extensive efforts at photon energies below 100 eV — where little work has been done to date — in hopes of extending the working range of soon-to-be-built free-electron lasers. This will require capabilities for coating with low-Z materials such as boron and beryllium. The safest and least expensive route for producing coatings with highly toxic materials (such as beryllium) has not yet been determined, but it will likely involve cooperative efforts with facilities well-trained in these procedures.

Scientific collaborations have already been established to focus on microfabrication techniques, mirror technology, and pulsed sources. A collaborative effort with IBM's Watson Research Center, for example, is seeking to improve the yield and quality of diffractive x-ray zone plates and transmission gratings having feature sizes in the 50- to 200-nm range (see Fig. 29). This collaboration will soon include an LBL employee in residence at Yorktown Heights, New York; later we expect to concentrate the LBL/IBM effort in Berkeley and to extend feature sizes to 10 nm. Such components, when combined with appropriate

Fig. 29. An electron micrograph of an etched "resist" for use in fabricating a freestanding diffraction structure. The pattern of concentric circles was created by electron-beam writing, followed by chemical etching. The structure will next be electroplated with gold, then dissolved to leave a gold Fresnel zone plate. (Photo courtesy of Dieter Kern, IBM.)

radiation sources, will provide an order of magnitude advance in high-resolution x-ray microprobing. Early demonstration experiments will likely be conducted both at Brookhaven's National Synchrotron Light Source and at the Stanford Synchrotron Radiation Laboratory.

These advances in microfabrication will be tied to the development of a large-field-of-view (about 1 cm) high-resolution electron beam scanner, which will operate at low voltages for compatibility with new resist materials. This new writing capability will be integrated into the existing microfabrication laboratories of the Electrical Engineering and Computer Sciences Department on the UC Berkeley campus, where significant interaction with industry already takes place. There it will also be available to students and industrialists who use these laboratories to advance their own research projects. The new electron beam scanner will be a substantial addition to the microlithography capabilities available to general scientific and industrial researchers.

In the coming months, additional collaborative efforts with xuv users will focus on the design, fabrication, testing, and characterization of reflective optics. One of the difficulties confronting designers of reflective systems for short-wavelength radiation is an extremely small glancing angle, as shown in Fig. 30.

Finally, one of the most exciting prospects for the future — x-ray microholography — is the kind of development we can expect by combining advances that should be within our reach during the next few years. These advances include intense quasi-coherent synchrotron radiation sources, complex microfabricated diffractive structures, multilayer reflective optics, and fast x-ray detectors.

Synchrotron radiation is being increasingly viewed as an optical probe with enormous potential in many fields of research. Exploiting this potential will mean constructing an advanced facility as a source of intense coherent light. Such a source will require an electron beam of low emittance, together with insertion devices (wigglers and undulators) that cause small-amplitude oscillations in the beam. The result is tunable coherent xuv radiation of great spectral brilliance — radiation that will be an invaluable research tool in the biological sciences, in atomic and molecular physics, in studies of chemical reactivity,

Research on Future Light Sources

Fig. 30. Glancing incidence reflection of visible radiation and x-rays. The size of the critical glancing angle depends on the relative refractive indices of the two media, which depend in turn on the wavelength of the radiation. The case illustrated for visible light is the familiar "total internal reflection." Because of the small critical angle for x-rays, however, early attempts to reflect x-rays from solid surfaces were unsuccessful, and even today, the design of reflective optics is complex.

and in the materials and surface sciences. The ALS, proposed in 1982, would be a source of such light over a wide energy spectrum. Additional work has already produced advanced beam-line components, preliminary evaluations of vacuum component material and fabrication techniques, and undulator designs that yield light of variable polarization.

Advanced Light Source

Until synchrotron radiation became available as a by-product of high-energy physics research, sources of ultraviolet light and x-radiation lacked the virtues of intensity, coherence, and tunability — virtues available to users of lasers in the visible and infrared regions of the spectrum. Bending-magnet synchrotron radiation has for two decades provided the sought-after intensity, and permanent-magnet insertion devices (Fig. 31) that cause small-amplitude oscillations in an electron beam now promise tunable, coherent radiation as well. The prospect is for a new class of research machines dedicated to fields requiring brilliant, variably polarized picosecond pulses of vacuum ultraviolet and soft x-ray radiation.

In 1982 the Laboratory proposed building such a machine — the Advanced Light Source (ALS) — based on a 1.3-GeV storage ring comprising 12 long insertion devices with different spectral characteristics (Fig. 32). The first six beam lines for general users were slated to cover the energy spectrum from 5 eV to 40 keV. Such a facility would provide a research tool of unparalleled power and would offer a unique opportunity for collaborative research ventures among workers from national laboratories, universities, and industry. The impact would be felt in biology and biochemistry, where, for example, new imaging and scattering techniques would become feasible; in atomic and molecular physics, where the resolution limits of several spectroscopic techniques would be extended; in studies of chemical reactivity; in materials science, where bulk and surface states of matter could be explored with improved methods based on x-ray absorption, diffraction, small-angle scattering, and fluorescence excitation; and in industrial applications such as microfabrication techniques.

In support of efforts to realize these benefits, work continued throughout 1983 on means for generating and stabilizing the necessary low-emittance, high-intensity electron beams and on the design and fabrication of advanced insertion devices.

Fig. 31. Schematic illustration of an insertion device (a wiggler). Radiation is emitted into a narrow angle as the electron beam accelerates in response to the applied magnetic force. The induced oscillations lie in the horizontal plane. If electromagnetic radiation is co-propagated with the electron beam, and if the radiation wavelength and magnet period are properly chosen, a wiggler can operate as an amplifier of the radiation (see p. 61).

Perhaps the central requirement for generating radiation with significantly improved characteristics is an electron beam of low horizontal emittance. Low emittance means a small cross-sectional area and a small solid angle for the electron beam, which imply, in turn, emitted radiation with high spectral brilliance. Furthermore, a small emittance permits the construction of high-performance undulators, which are the key to coherence. Obtaining high-intensity, low-emittance electron beams requires control of instabilities and development of ultrahigh vacuums, advanced beam-position sensors and control systems, pulsed magnet systems, and rf systems.

Efforts to understand and control coherent instabilities were well along in 1983. They will ultimately yield guidance in the design of accelerator hardware (especially rf and vacuum components) that will minimize the impedance of the storage ring at high frequencies. Future studies will be directed toward determining the need to develop rf quadrupoles to produce a tune spread to stabilize coupled-bunch modes, a higher-harmonic cavity to provide Landau damping by introducing a synchrotron frequency spread, and a broad-band feedback system to suppress coherent beam growth phenomena.

Achieving Low Emittance

Fig. 32. Layout for the proposed Advanced Light Source, showing the six beam lines to be developed initially (A-F) and the six available for future use.

Also crucial in minimizing beam emittance is an ultrahigh vacuum of the order of 10^{-9} Torr. The conventional approach to achieving this objective is to use ultraclean surfaces and to incorporate extensive ion pumping, then to wait for the synchrotron radiation to desorb the residual tightly bound carbon monoxide molecules from the surfaces of the vacuum chamber. In the past year, we have begun to explore and test faster and more economical means of achieving the same ends. Pretreatment at $800\text{--}1000^\circ\text{C}$ in a vacuum furnace and ion glow discharge are among the approaches we are investigating. In addition, criteria will be established for overall design and fabrication practices used for storage ring vacuum system components. For example, we are now evaluating wall materials for vacuum chambers exposed to synchrotron radiation.

An alternative approach currently under study for the storage ring is a dual vacuum chamber in which the electrons circulate in one chamber and the synchrotron radiation passes through a narrow slit into an antechamber that incorporates extensive vacuum pumping. Most of the desorbed molecules would be pumped in the antechamber, so significantly lower pressures could be achieved in the beam circulation chamber.

Fast kicker magnets and their power supplies are critical subsystems of the injector for an advanced storage ring. The rise time, fall time, and field flatness requirements are near the current state of the art for these types of devices. The most difficult design will be that of the fast extraction kicker of the booster ring. We therefore plan to develop a power supply for this magnet and to study the effects of various types of energy storage and switching schemes. The magnet and its pulser must be integrated into a single unit with minimum critical transmission paths if the required switching times are to be obtained.

The final requirement for obtaining and maintaining low beam emittances is the rf system. The resonant cavity for the main ring rf system is a vital element in the rf system design. The optimum cavity shunt impedance is important in minimizing the power required for acceleration while still maintaining good beam stability. In the course of our research, the effects of fundamental-mode shunt impedance on the higher-order modes will be studied, together with ways of reducing the high-order-mode shunt impedance while maintaining a reasonable impedance at the fundamental frequency.

Insertion Devices and Beam-Line Components

In addition to efforts directed at ensuring low emittance, more efficient and more economical insertion devices (which will not perturb the low-emittance electron beams) must be developed. The three generations of radiation sources shown in Fig. 33 suggest the direction of our efforts. To date the magnetic structures for insertion devices have been of either a pure rare-earth-cobalt or hybrid design. The associated vacuum chambers have generally been of a rigid

Fig. 33. A highly schematic depiction of three generations of synchrotron radiation sources, showing the angular distributions of the light emitted by each. Undulator radiation is emitted in an intense laserlike beam, whereas radiation from a bending magnet is akin to a sweeping searchlight.

or flexible configuration, respectively, with the magnetic structure outside the chamber. With the magnets out of the vacuum, peak magnet performance is compromised: The vacuum chamber wall thickness dictates a loss of aperture. New designs for in-vacuum devices are now being explored to achieve both cost effectiveness and improved performance. These configurations will be examined for their effects on the electron beam.

Work has also begun on ideas for multiundulator systems that can produce elliptically polarized light and that allow rapid (10^{-3} sec) variations in the direction of polarization. A design developed in 1983 is shown in Fig. 34.

Finally, the high radiation intensities that will be produced by future photon systems will require development of masks and collimators that can dissipate large heat fluxes. Accordingly, we have designed high-heat-flux collimators and attenuators for one of the beam lines at the Stanford Synchrotron Radiation Laboratory, and we are working on preliminary designs for other beam-line components for the same facility. In concert with developing designs for these components, we expect to refine our computer program for calculating radiation source power distributions, which will then be used for thermal design evaluations of the beam-line components. With this routine, we will be able to evaluate temperature distributions and resultant stresses and strains in optical components illuminated by intense synchrotron light.

Fig. 34. An arrangement of undulators that could be used to generate variably polarized radiation.

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6.

OTHER PROGRAMS

TWO OTHER PROJECTS IN AFRD are outgrowths of larger established programs, but their importance in establishing new directions for the Division warrants a separate section. Experiments at the free-electron laser at Livermore were first undertaken to study one source of the hot electrons needed in some magnetic-confinement fusion schemes. This study continues, but even more excitement is being generated by the possible use of an FEL to power a high-gradient linear accelerator. The second project, the design of a dedicated heavy-ion accelerator for biophysical research and radiotherapy, was spurred, at least in part, by the success of the biomedical program at the Bevalac (see pages 6-8).

Free-Electron Laser

A free-electron laser converts the kinetic energy of a relativistic beam of electrons into coherent radiation, usually by means of a periodic array of magnets called a wiggler. Together with workers at Lawrence Livermore National Laboratory, we have constructed an electron laser facility and used it to amplify 34.6-GHz microwave radiation. Ultimately, this technique might be used as an alternative to the gyatron as the basis for electron-cyclotron resonance heating — the likely source of the "hot electrons" required in some approaches to magnetic-confinement fusion. The free-electron laser also allows us to study the feasibility of a linear collider of, say, 300 GeV X 300 GeV. The practical possibility of such a collider depends on establishing a high accelerating gradient and effecting economies of power consumption. We can do both by operating at high frequencies, and the FEL offers just this possibility.

When a properly designed electromagnetic field is imposed on a beam of electrons, the electrons will be accelerated in such a way as to emit coherent radiation. The result is a *free-electron laser (FEL)*. The wavelength of the emitted radiation depends on the "wavelength" of the periodic field and the energy of the electrons. We have long known that this conversion of kinetic to electromagnetic energy is possible, but only in recent years, with the experimental realization of the FEL, has much attention been given to it. The principles of the FEL are illustrated in Fig. 31, which shows a wiggler designed for a source of coherent soft x-rays.

Free-Electron Laser

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The experimental FEL at the Lawrence Livermore National Laboratory's electron laser facility (ELF) is designed to produce coherent radiation in the millimeter-wavelength regime. It was built to explore the practical possibility of using an FEL as a source of microwave power. In particular, we are interested in applications to magnetic-confinement fusion. At least two of the approaches to magnetic fusion, namely the tandem mirror with thermal barriers and the Elmo bumpy torus, require "hot electrons" for their successful operation. The means for heating the electrons is likely to be electron-cyclotron resonance heating; indeed, some experience has been obtained with this approach using gyrotrons as a source of the rf power. Future devices, however, will require several megawatts at higher frequencies (100 GHz or even 160 GHz). The FEL is a possible alternative to the gyrotron.

The ELF uses the beam generated by Livermore's Experimental Test Accelerator (ETA) and is attached to the end of the ETA's beam propagation section. The ELF itself can be broken up into three sections (Fig. 35) — a beam-conditioning region, the interaction region, and the microwave diagnostics section. The first section reduces the current in the 4.5-MeV beam from 8 kA to 1 kA and reduces emittance from about 100π mrad-cm to 30π mrad-cm. The beam-conditioning section also has an electron energy filter that allows an energy band of a few percent to pass into the wiggler section. The interaction region is the actual FEL. Here, the beam propagates through a rectangular wave-guide and is subjected to a periodic wiggler field transverse to the beam direction. This wiggler field has a period of 9.8 cm and provides the pump wave for the FEL. Each two-period section of the wiggler has its own pulse power supply, so that the wiggler field can be varied, or tapered, along the interaction region. A tapered field is expected to maximize the output energy of the laser radiation.

An input signal of the desired laser frequency is injected at the beam entrance to the interaction region. This signal is then amplified in the FEL

FEL Experiments at the ELF

Fig. 35. Diagram of the electron laser facility at Lawrence Livermore National Laboratory. S1 through S3 and Q1 through Q3 indicate steering magnets and quadrupole doublets, respectively.

wiggler. At the exit of the interaction region, the electron beam is swept out of the rectangular wave-guide by a transverse magnetic field. The microwave radiation propagates down the wave-guide, where pulse shape, total energy, and frequency spectrum are measured.

Experiments have now been conducted at 34.6 GHz ($\lambda = 8.6$ mm). We have studied beam conditioning and transport and have found beam matching to the wiggler (with respect to beam size, entry angle, and transverse beam displacement) to be of critical importance. Diagnostics at the wiggler entrance are being improved to allow better matching. Spontaneous emission from the beam passing through the wiggler ($\gamma = 7.4$), measured between 24.6 and 40 GHz, yielded 2–4 W of radiation. When a magnetron-generated 34.6-GHz signal was co-propagated with the electron beam and the resonance condition was satisfied, the signal was amplified by a factor of 2.3.

Two-Beam Accelerator

The FEL also presents an opportunity to study the feasibility of a high-gradient linear collider of, say, 300 GeV $\times$ 300 GeV. If such a collider were to operate at the gradient of the Stanford Linear Collider (17 MeV/m), it would be 35 km long. Furthermore, such a device would consume prodigious amounts of power. Thus, one would very much like to obtain larger accelerating gradients and reduce the power consumption of such a collider. As it turns out, we can do both by going to high frequencies. The FEL offers just this possibility, for it is a high-peak-power device that can be operated over a wide range of frequencies.

It is probably adequate to increase the frequency over that of the Stanford collider by about a factor of ten to 30 GHz. At this frequency, one can probably attain gradients as high as 250 MeV/m, reduce the power requirements to 150 MW, and still have a structure that can be manufactured and aligned.

The use of an FEL as the power source for such a high-gradient structure opens up the very interesting possibility of a two-beam accelerator (TBA), three conceptual designs for which are shown in Fig. 36. In such a machine, one of the beams is an intense (about 1 kA), low-energy (about 3 MeV), and long-pulse (about 30 meters) beam. The other beam — comprising the particles we are really interested in — consists of a few particles (about 10^{11}) in a short bunch (about 1 mm), which is taken to very high energies (about 375 GeV) in about 1.5 km. Operation at a repetition rate of 1 kHz, which would be quite feasible for the FEL, yields a luminosity of $4 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$.

To explore the concept of a TBA, we plan a balanced program of theoretical studies, experimental table-top investigations, and FEL experiments at the ELF in Livermore. At the end of three years, we should know enough about the elements of a TBA to make a knowledgeable judgment as to whether it is attractive for further development.

Physics of the TBA. As we conceive it, the TBA is really a power-transforming device: It takes power from the power lines to an induction accelerator, to a low-energy beam, then to radiation (via a wiggler), which powers a high-gradient accelerating structure, and finally, to the few high-energy particles one is interested in studying. Thus, a number of components of a TBA need to be studied.

One of these crucial components is, of course, the FEL. We have devoted considerable effort to designing and building the FEL, which is very similar to the one that would be needed in a TBA. Nonetheless, one critical question remains: Can we operate a single-pass FEL in a "steady-state" mode, that is, for many kilometers? For this to be possible, there must be no increase in the electron-beam energy spread or in the electron-beam transverse emittance in a steady-state FEL.

In regard to transverse emittance, an FEL can be designed like any transport system, and we know that beams can be transported for kilometers. And in regard to energy spread, since an FEL is a coherent device and hence is signifi-

Fig. 36. Three conceptual designs for coupling the low- and high-energy beams of a two-beam accelerator: (a) dual structure, (b) single structure, and (c) composite structure. In all of the designs, an induction unit replenishes the energy of the low-energy beam, which thus becomes essentially a power transformer.

cantly coupled to only one mode of the radiation field, there will be neither damping nor undamping of the electrons. We are thus confident that both requirements for steady-state operation can be met. Indeed, during the past two years, we have been studying the steady-state FEL precisely for this application.

Recently, we have used computer simulations to study a steady-state FEL. We have mated high-gain amplifiers with a 125-meter-long steady-state FEL. The steady-state section consisted of simultaneous acceleration by a dc potential, deceleration by a microwave field, and microwave "leakage" that would power the TBA. After the first 20 meters, about 15% of the electrons were not trapped and were therefore accelerated (to $\gamma = 130$). (In a TBA, they would be extracted immediately.) The remaining electrons remained trapped at the equilibrium γ of 6.2. After 125 meters, only 0.5% of the trapped particles escaped (possibly due to integration inaccuracies). These results, though preliminary, indicate the potential of the TBA.

Theoretical Studies. Theoretical work must ultimately underlie any practical plans for a TBA. In particular, we must understand how best to feed power into high-frequency structures, what frequencies yield optimal operation, and how structure scaling laws will affect the design of the TBA structure. We will also extend our computer modeling of steady-state operation before considering the design of a steady-state FEL. Finally, TBA system studies must be undertaken to put all the pieces together.

Table-Top Experiments. Many aspects of the TBA can be studied without resorting to the ELF. For example, we plan to fabricate a 1-cm structure, a tenfold scaling of the SLC 10-cm structure. We already know that such a structure is

probably not acceptable for a TBA, but many things can be learned from its study. In particular, we need to explore various fabrication techniques, taking into account tolerance requirements. Using this 1-cm structure, coupling can be studied at low power, and we shall make extensive studies of reflection, standing wave ratios, gradients, mode structure, etc.

The next step will be fabrication of 1/2- and 2-cm structures. We propose to do this later in our studies so that we can profit from preceding theoretical work and from the coupling studies on the 1-cm structure. Coupling studies on the 1/2- and 2-cm structures will then follow.

ELF Experiments. Studies at the ELF will be of two sorts. First, we plan high-power excitation studies. Initially, we will work at 8.6 mm, then at 4.2 mm and 1.72 cm. We shall use a structure that is long enough to obviate end effects and yet short enough to ensure that with the radiant energy available from the ELF we can achieve significant gradients (near 250 MeV/m).

Second, we shall be carrying out extensive studies of FEL physics. Very little is known about high-efficiency FEL operation in the millimeter range. Accordingly, we plan (a) to study peak-power dependence (at various frequencies) on electron energy spread, electron beam emittance, and electron current; (b) to study the mode structure of the FEL and to look at how this depends upon wave-guide size; (c) to investigate the FEL's sensitivity to energy mismatch, the alignment of the wiggler, imperfections in the wiggler field, and the amplitude of the initial microwave field; and (d) to study the stability and spectrum of output radiation as functions of all the FEL parameters, including input electron beam current, electron energy spread, etc.

Medical Accelerator

The failure of conventional radiotherapy to control cancers at their sites of origin, before they spread more widely, accounts for about 100,000 deaths in the U.S. each year. A possibility for reducing this number is the therapeutic use of heavy ions in place of x-rays. Heavy charged particles are more effective than x-rays in killing oxygen-starved tumor cells, and, unlike neutrons, they allow the dose to be localized with great precision. Studies of charged-particle radiotherapy are currently conducted by LBL's Biology and Medicine Division at the Bevalac and the 184-Inch Cyclotron, but more conclusive trials, together with a more extensive program of basic biophysics research, require a hospital-based facility. As now conceived such a facility would be based on a synchrotron about 30 meters in diameter, which would accelerate ion species from protons to argon to energies up to 800 MeV/amu. Beams could be delivered sequentially to different treatment rooms, thus permitting treatment of about 100 patients per day.

Lawrence Berkeley Laboratory has conducted a strong and comprehensive program in basic radiation biophysics for many years. (The ongoing program at the Bevalac is described on pages 6-8.) This activity notwithstanding, however, many facets of the program, from heavy-ion radiotherapy trials to basic research on radiation-damage mechanisms at the molecular level, would benefit from a dedicated hospital-based heavy-ion accelerator. During 1983 a preliminary reference design for such an accelerator was produced as part of a joint initiative of the Biology and Medicine Division and AFRD, with support from the National Institutes of Health.

One of the principal purposes of a hospital-based medical accelerator would be to conduct randomized radiotherapy trials with heavy charged particles. This aim imposes certain restrictions on the specifications of the accelerator and further demands a design of utmost simplicity and reliability. Values for a few of the accelerator parameters are summarized in Table 5, and Fig. 37 shows a plan view of a complete medical accelerator facility. The range of available ion

Particle species	^4He to ^{28}Si , ^{40}Ar and ^{56}Fe
Beam energy (MeV/amu)	
At injection	8
On target, minimum	70 (4-cm range with ^4He)
On target, maximum	800 (30-cm range with ^{28}Si)
Intensity (ions/sec)	$\geq 3 \times 10^7$ Si
Duty factor	20–60%
Repetition rate	2–4 Hz
Synchrotron circumference (m)	91.8
Number of magnets	
Dipoles	12
Quadrupoles	18
Magnet lengths (m)	
Dipoles	3.2
Quadrupoles	0.4
Dipole magnetic field (T)	1.593

Table 5. Performance specifications and basic synchrotron lattice specifications for a preliminary medical accelerator reference design.

Fig. 37. Plan view of a possible layout for a medical accelerator facility. The injector, comprising several ion sources, an RFQ linac, and two Alvarez linacs, is located above the plane of the synchrotron. The final beam energies for each of the injection elements is shown.

species and beam energies provides flexibility in the choice of ion at tissue penetration ranges from 4 to 30 cm. The minimum required intensity (3×10^7 ^{28}Si ions/sec) corresponds to about 100 rad/min, allowing treatment times of about 1 minute.

The envisioned injector system includes redundant ion sources similar to those in use at the SuperHILAC, a radio-frequency quadrupole (RFQ) linac identical to that developed for the Bevalac local injector upgrade (see Fig. 5), and two Alvarez linacs, each followed by a stripper. The synchrotron itself comprises 12 bending magnets, 18 quadrupoles, 6 sextupoles, 18 steering magnets, and additional magnets for beam abort. The bending magnets will be of an H-shaped cross section, with pancake windings encircling the poles. They will be curved because of the large bend angle and the relatively short bending radius.

Specialized beam delivery techniques are also required in a medical accelerator. Most importantly, the beam must produce a uniform field ($\pm 2\%$) over a 30-cm diameter. A scattering foil-occluding ring method developed for proton radiotherapy is effective for light ions, but an advanced magnetic system like the one shown in Fig. 38 may be needed for the heavier species. The delivery system will also require focusing, bending, and steering magnets similar to those in the synchrotron ring.

A final important component of the medical accelerator facility is a computer system to control the accelerator itself and to monitor and control dose delivery.

Fig. 38. Schematic of an advanced beam delivery system, showing in idealized form the principles of a "wobbler" magnet. This delivery system provides a uniform dose throughout the treatment volume.

Free-Electron Laser

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