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ACCELERATOR DIVISION

ANNUAL REPORTS

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1 July 1972 - 31 December 1974

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FOREWORD

The Accelerator Division was formed as a separate division of the Lawrence Berkeley Laboratory in 1973. Originally called Physics II Division, it acquired its present title when Andrew M. Sessler was designated Director of the Laboratory in November 1973.

Under the leadership of Associate Director Edward J. Lofgren the major activities of the Division comprise operation of the Bevalac, for high-energy and heavy-ion physics, and Advanced Accelerator Research and Development. In addition, there is a small amount of research activity with heavy ions by some members of the Division.

Heavy ions were first accelerated in the Bevatron in 1971. In the period under review here a large effort was devoted to construction of the Bevalac project, in which the SuperHILAC is used as a source of energetic heavy ions that are transported down the intervening hillside by a focusing transfer line, and injected into the Bevatron for final acceleration to an energy of 2.6 GeV/nucleon. This facility is unique in the world as a source of relativistic heavy ions and has opened up a new and rich field of research that has commanded worldwide interest.

Joint studies with the staff of the Stanford Linear Accelerator Center on a positron-electron colliding beam device (PEP) have expanded in scale during this period. PEP will operate with beam energies between 5 GeV and 18 GeV with a peak luminosity of 10^{32} cm^{-2} sec^{-1} at 15 GeV and will be located at SLAC where the present two-mile linear accelerator will be used as an injector. It is hoped that funds for construction of PEP will be available in FY 76.

Research on new methods of particle acceleration by Collective Effects, which had been a strong ongoing program for some years, has contributed significantly to understanding what parameters can be achieved and how they are limited by various instabilities. The production of high accelerating fields by use of electron rings has been demonstrated, and would be useful for heavy-ion accelerators. Work on Collective Effects was phased out early in 1973 as the efforts on PEP and ESCAR were increased.

Detailed design on the world's first superconducting synchrotron was started in July 1973. Named ESCAR, for Experimental Superconducting Accelerating Ring, this is a large-scale experiment in superconducting technology as applied to accelerators and storage rings. Future very-high-energy facilities are projected to rely heavily on superconducting magnets on a large scale with an associated large cryogenic system. Over the years small numbers of superconducting magnets on a laboratory scale have been made with varying degrees of success; ESCAR is intended to address the problem of constructing a large number of reliable magnets with fields of high quality and good reproducibility, and of studying the systems aspects of a multi-component cryogenic device of reasonably large scale. Applications to either a future pulsed synchrotron or a quasi-d.c. storage ring are obvious benefits of this research. A rapid start on this project has been possible because of the large accumulated experience of the LBL superconductivity group, which has developed rapidly-pulsed magnets and operational beam-transfer dipoles and quadrupoles in recent years.

Members of the Accelerator and Engineering Divisions have also participated in a small program (funded by NSF) on the application of intense scanning electron beams for excavation of hard rock. Fundamental studies of the spalling mechanism have been carried on experimentally and a theoretical understanding developed. The conceptual design of a practicable excavator, based on presently available components and materials, has been developed and looks like an attractive possible solution to advancing the rate of hard-rock excavation by a factor of ten or so.

ACCELERATOR DIVISION

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I. BEVATRON/BEVALAC

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The Bevatron/Bevalac facility is operated, maintained, and developed as a research instrument in fundamental physics, chemistry, and biomedical science. Auxiliary facilities, equipment, and services are provided for research groups conducting experiments through the operations and research programs. The study of the principles governing machine operation continues, in parallel with the research program, to provide improvements in performance and reliability. More recently the Bevatron has dramatically expanded its facilities in an effort to diversify and to capitalize on its unique capability. The Bevalac concept linking the SuperHILAC to the Bevatron, produces heavy-ion beams of unprecedented energies, intensities, and mass numbers. The implications of this feat are still to be realized; the immediate benefit is the actualization of a powerful laboratory tool for exploring compound nuclear phenomena as well as providing a potentially superior clinical instrument for diagnosing and treating cancer.

During 1973 and 1974 the multidisciplinary potential of the Bevatron facility has been exploited: The external multibeam system was advantageously used for programs in traditional particle physics, high-energy heavy-ion research, and biomedical experiments. Improvement programs were initiated to increase the proton beam intensity in order to provide new, high-intensity, high-quality secondary particle beams, and to extend the heavy-ion capability to higher intensities and atomic mass numbers. Construction of the Bevalac proceeded, culminating in its successful commissioning in August 1974.

OPERATION AND PROGRAMS

A broad program of fundamental research was carried out at the Bevatron during this period. In 1973 a total of 37 laboratories and universities were involved in Bevatron research programs. Representing these institutions were 48 outside research groups and 36 from LBL. The outside groups accounted for about 55% of the experimental hours: 185 experimenters with Ph.D.'s or M.D.'s, 2 with Master's degrees, and 66 GSRA's participated in these programs.

Sixteen major physics experiments were performed, of which nine were completed. Twenty-five biophysics and biomedical runs were made. In all, a total of 89 experiments were operated, of which 70 were completed.

The performance of the Bevatron was exceptional. The average proton intensity was 4×10^{12} protons per pulse. During a typical month of proton operation, the integrated beam could be expected to be 10^{18}. The heavy-ion intensity was significantly increased as the result of an intensive program to improve the Bevatron vacuum. Cryopumping panels, with a liquid-nitrogen-cooled shield and cooled by 20K helium gas, were installed in the Bevatron vacuum tank. By this means the pressure was reduced from 1.5×10^{-6} Torr to 3×10^{-7} Torr. The intensity and energy of extracted heavy-ion beams are tabulated below:

*Extracted Heavy-Ion Beams in 1973**

	Ion	Particles per pulse on target	Particle energy (GeV/nucleon)
External particle beam	^{2}H	2×10^{11}	0.25 - 2.1
	^{3}He	1×10^{11}	
	^{4}He	2×10^{10}	
	^{12}C	5×10^{7}	
	^{14}N	5×10^{7}	
	^{16}O	1×10^{7}	
	^{20}Ne	1×10^{4}	
Bevalac	^{12}C	5×10^{9}	
	^{20}Ne	10^{8}	
	^{40}Ar	10^{4}	1.9

*In beam line EPB 11

The Bevatron operated almost continuously from July 1973 through February 1974, during which time a total of 36 high-energy physics experiments and 34 biomedical or biophysics experiments were operated. Outside-users groups accounted for approximately 60% of the experimental hours.

During each year the Bevatron has emphasized use of the multichannel external beam system with eight or nine experiments on the floor, and an average of three in operation at any given time. The average multiplicity declined from five in 1969 to three in 1973, and to less than two in 1974 for three reasons: (1) The sophistication and special requirements of recent experiments have reduced the degree of compatibility of experiments; (2) the heavy-ion program typically has required full machine capability for a single experiment; (3) a continued budgetary decline has forced a reduction in personnel, with resultant reduction in simultaneous operations.

The performance of the Bevatron has continued to be excellent. In 1974 the available proton intensity increased to 5×10^{12} protons per pulse, and heavy-ion beams were handled with more versatility and reliability.

The Bevatron operated on a 24-hour-per-day basis with one shift per week devoted to maintenance, until July 1974. This accounted for 5000 hours of accelerator operation during 1973 and approximately 2000 hours through June 1974. Budgetary limitations forced a reduction in the total work week to fifteen shifts beginning in July 1974. Divided into five days at three shifts per day, only thirteen shifts of actual operation could be realized, accounting for 1300 hours of operation for the balance of 1974. Every effort has been extended to provide the maximum utilization of machine operation for the experimental program, consistent with adequate maintenance and support. Substantial reductions in staff and curtailment of the machine development program have been necessary to provide sufficient operation time for scientific research.

The 1973 annual Bevatron Experimenters Meeting was held on January 27 with 99 persons in attendance. The program included a status report on Bevatron operation and development programs, a summary of the current experimental programs, reports of preliminary results from recent Bevatron experiments, and talks concerning advanced accelerator design and related research and development programs.

On 18 January 1974 the first annual Bevatron/Bevalac Experimenters Meeting was held. In addition to status reports, the talks and discussions were concerned with the future of physics research in the momentum range of several GeV/c, which was still felt to be important. The new possibilities presented by the availability of relativistic heavy ions from the Bevalac were examined. The significance of this latter topic was emphasized in a talk by T. D. Lee, who presented theoretical arguments for the production of abnormal states of nuclear matter in collisions of very heavy relativistic ions.

The Bevalac Scheduling Committee held four meetings in 1973. The principal concerns of the Committee were to consider extension requests for experiments in progress and to make recommendations to the Director regarding new proposals. The Committee also reviewed the ongoing operational and experimental programs, and the Bevatron development and improvement programs.

In 1974, the Committee changed its name to the Bevatron/Bevalac Program Advisory Committee. The principal business of the committee in its three meetings was to review the ongoing experimental program, consider extension requests for experiments in progress, and make recommendations regarding new proposals. The Committee was enlarged to include representatives from the fields of Biology and Medicine. This new Committee met for the first time on 18 January 1974, when procedures for the evaluation of the biomedical program were established. During two successive meetings the Committee concerned itself with organizational details relating to the implementation of an experimental program to evaluate heavy ions for diagnostic and therapeutic radiology. Committee members are representative of the fields of radiotherapy, radiobiology, radiation chemistry, and radiological physics.

The Bevalac Users Association, approximately 400 strong, is an organization of active scientists and engineers with a special interest in the Bevalac and its research program. Their combined interests include the areas of biological and medical science, cosmic rays, nuclear chemistry, nuclear physics, and particle physics. The purpose of the Association is essentially twofold: (1) To provide a formal channel for the exchange of information between scientists interested in the Bevalac and between members of the Association and the Bevatron/Bevalac Program Advisory Committee; and (2) to provide a means of offering advice and counsel to the Bevalac management on operating policy and facilities. The Association was officially formed and its charter adopted on 19 January 1974, at the annual meeting of the Bevatron Experimenters held at LBL. At this meeting, the first Executive Committee members were elected. The annual meeting was extremely well attended, reflecting the interest in the Bevatron/Bevalac, and was highlighted by numerous speakers who discussed the research potential of the Bevatron/Bevalac. Undoubtedly among the most exciting prospects were those presented by T. D. Lee's theory on the possibility of new states of nuclear matter.

MACHINE AND FACILITY IMPROVEMENTS

K-Beam Facility

The design of a new high-intensity, stopped K-meson beam was completed in 1973. The components of the beam, while conventional, are nevertheless of advanced design. Large solid-angle of acceptance, short overall beam length, and the inclusion of second-order field corrections of the beam transport elements are essential features of the design. The anticipated yield of stopped K^+ mesons is 0.7×10^5 per 3×10^{12} protons on target. The pion contamination is expected to be less than 10^6 per pulse.

By mid 1974 all hardware for the high-intensity K-beam was completed. This included the fabrication and assembly of three specially designed wide-aperture quadrupoles, a modified pole tip for the M5 magnet (first 90° bend), a second 90° bending magnet including its main coil, and a sextupole correction coil. Special magnet-measuring devices have been designed, built, and successfully operated. All magnets have been measured and accepted, with only a few minor corrections. Both electrostatic separators have been built, and existing power supplies have been modified for use with these devices. Separators and power supplies have been successfully tested and all components have been installed and aligned. Tune-up has started and optimization of adjustable parameters has progressed. Initial tests late in 1974 were encouraging. The observed optical properties were in good agreement with calculations. The data suggest that the predicted yields will be realized with the improvements, which were not available for the initial tests.

Bevatron Injector III

In 1972-1973, work on the new high-intensity 50-MeV injection system continued towards its replacement of the 20-MeV proton injector. The basic element of the new system is a 50-MeV linear accelerator that was transferred to LBL from BNL. At the end of 1973 the 750-keV Cockcroft-Walton preinjector was completed and operational. The linear accelerator received final rf tests. The high-energy beam transport line from the linac to the Bevatron and a new inflector were constructed in fall 1973. The full energy beam was produced by the machine on 5 September 1973 on the very first attempt at full operation. Since then, parameters have been optimized and marginal areas improved in reliability. The year 1974 saw the first successful operation of the new 50-MeV linac complex. This new facility increases the intensity of the Bevatron to approximately 2×10^{13} protons per pulse.

The duoplasmatron ion source is being modified to improve emittance and reduce gas flow requirements. Some mechanical modifications have been made to the shell itself to provide better electromagnetic interference shielding for the digital electronics. The selenium rectifiers in the Cockcroft-Walton stack are being replaced by silicon diode strings to provide higher reliability. The operation of the 750-keV beam transport system has been satisfactory from the start.

The 50-MeV linac rf came on with few difficulties, and the tank achieved its design gradient in two days of conditioning. The only significant problem was insulator breakdown at an rf drive loop, which has been corrected by repairing a vacuum leak at that point. The 64-channel monitor for the tank rf amplitude allowed very rapid adjustment of the ball tuners to attain the desired tank tilt. The operation of the rf-manifold* power-distribution system seems satisfactory, and has allowed operation with one rf power amplifier turned off to conserve tube life, since not all amplifiers are needed for low beam-current operation.

The 50-MeV beam transport system has been operated, including the magnetic momentum analysis system. A low-energy tail on the output energy spectrum has been discovered and eliminated by proper tilting of the tank rf field.

Operation of the linac to 30 mA at the exit has been achieved with 85 mA injected. The momentum spread at the exit was small, but has not yet been measured accurately. Improved monitoring of momentum spread and emittance of the 50-MeV beam is being implemented.

A low-intensity beam has been injected into the Bevatron. Development of a high-intensity beam awaits the improved monitoring devices and completion of source modifications that will reduce the gas flow requirements.

Cryopumping the Bevatron Vacuum Tank

In 1972, the basic elements of a cryogenic pumping system for the Bevatron were acquired. Cryopanels were installed in the curved and straight sections of the Bevatron. These panels

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*First full-scale use of this innovation, which allows operation to continue even though a power tube fails.

are cooled with 20 K helium gas and partially shielded with liquid-nitrogen-cooled shields. By the end of 1972 the system was complete with the exception of the installation and testing of the helium refrigeration system. In July and August of 1973 the helium system was commissioned and has operated reliably since that time.

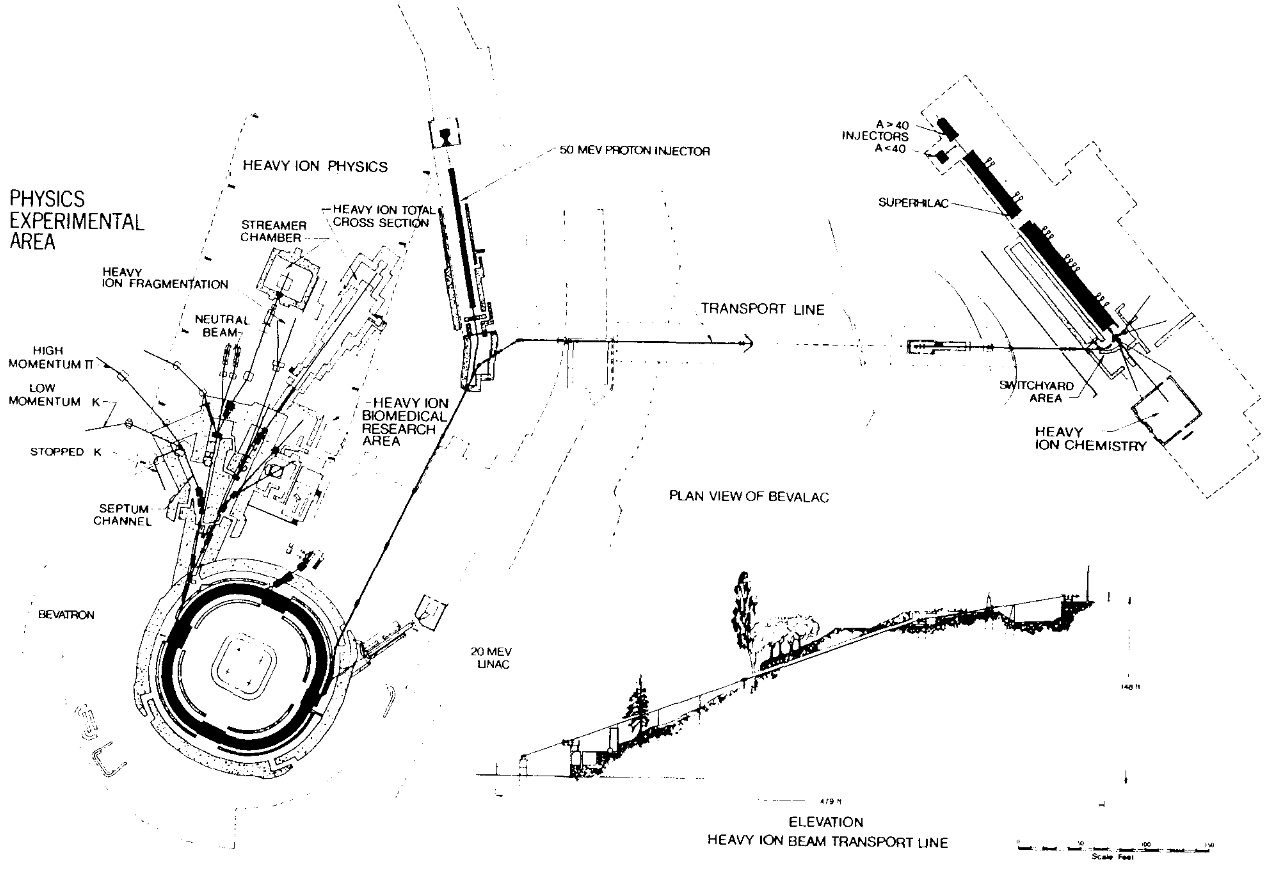
The cryopumping system resulted in an improvement of the Bevatron vacuum from 1.5×10^{-6} Torr to 3×10^{-7} Torr. The improved vacuum has resulted in increased stability of the proton operation and, on the average, a factor of ten increase in the intensity of heavy-ion beams. A secondary but very important benefit for the cryopumping system is the rapid recovery time that can be achieved following maintenance on the Bevatron, which requires the vacuum tank to be open to air.

Heavy Ions

Work continued in 1973 to develop further the Bevatron heavy-ion facility. Beam intensities were increased as mentioned in the section above. In addition, projects were undertaken to provide the software and technological developments by which beams could be efficiently extracted over a broad energy range, and which would permit changes from one operating mode to another with minimal interruption. Developmental work has also progressed toward the goal of providing adequate beam monitoring and particle identification systems.

The Bevalac

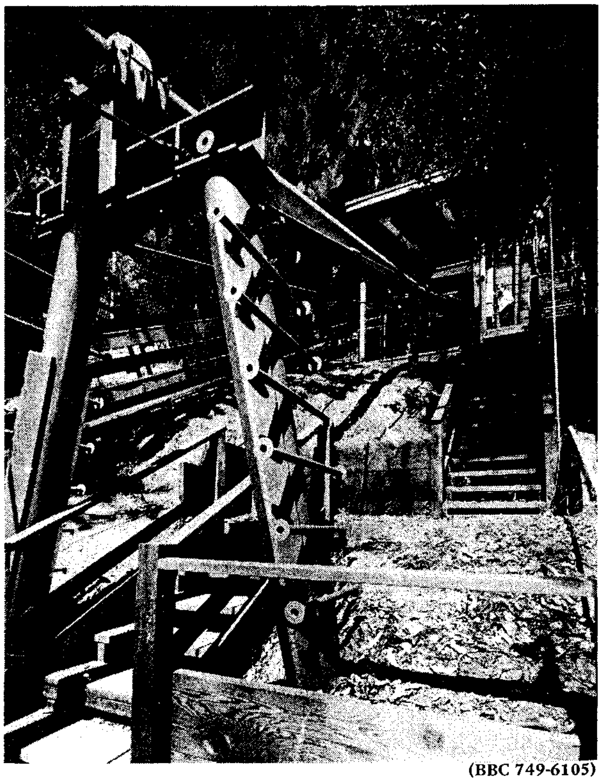
The Bevalac, a construction project linking the LBL SuperHILAC with the Bevatron was conceived in 1971 and funded in 1973 (Fig. 1). By the end of 1973, the hillside tunnel was dug



(XBL 736-749C)

Fig. 1. Bevalac heavy-ion beam transport line from the SuperHILAC to the Bevatron.

and all supports were installed for the transfer line and connecting stairway (Fig. 2). Electrical power was distributed, the magnets were fabricated, and power supplies were procured. However, hillside slippage during the previous winter, even though remote from the Bevalac site, suggested that additional precautions be taken with the Bevalac supports, resulting in increased costs and delays. The transfer line transmits the heavy-ion beams from the Super-HILAC to the Bevatron through a 175-meter-long vacuum pipe which penetrates the intervening hillside. Magnetic elements steer and focus the beam on its way to the Bevatron. The transfer line was completed in the summer of 1974 and began successful operation in August.



(BBC 749-6105)

Fig. 2. A portion of the Bevalac beam transfer line below the hill.

Experiments in biomedical research have indicated the need for a higher degree of machine control, reliability, and stability. The accelerators must be capable of delivering a high-quality beam within the time constraints imposed by biological samples. Improvements in computer control of the accelerator subsystems and the external beam delivery system and in the regulation of magnet power supplies are being implemented to meet the new demands. A clinical environment complete with animal handling and cell culture facilities has been simulated in the new biomedical research area. The first of two experimental caves became operational in May 1974.

Computer-controlled dosimetry and beam-quality measuring devices have been installed and operated in the first experimental cave. Radiobiology experiments aimed at evaluating the diagnostic and therapeutic potential of heavy ions have begun utilizing the Bevalac-produced beams.

Nuclear science studies of heavy-ion processes begun in 1971 have continued in the large spectrometer area of the external beam facility. In addition, calibrations of instruments destined for orbital and suborbital cosmic-ray studies were routinely carried out in the same experimental area.

Polarized Proton and Deuteron Beams

A study program was carried out in 1973 to determine the feasibility of accelerating polarized protons and deuterons to high energy in the Bevatron. The depolarization calculations were very encouraging, and there is every reason to believe that a polarized beam capability for the Bevatron is feasible. Such a capability would also yield a polarized neutron beam by stripping high-energy deuterons. Future plans, however, do not include the implementation of such a facility at this time.

The LBL-UCLA Streamer Chamber Facility

The LBL-UCLA streamer chamber development was completed in 1972. However, technical problems encountered in operating a 30-cm-long liquid hydrogen and deuterium target within the streamer chamber remained. This technology, which employs a helium refrigeration system to liquify the hydrogen or deuterium, was perfected early in 1973. The streamer chamber facility has proved to be a dependable and flexible experimental tool, and is in great demand for pion physics in the few GeV/c range. More recently the heavy-ion physics program has used the streamer chamber to produce dramatic pictures of heavy-ion fragmentation processes.

Improvements in Operational Systems

The year 1973 saw a continuing program to improve the control, monitoring, stability, and flexibility of Bevatron operational functions. The focus of this effort was a digital control system, which employs PDP-8 computers to fulfill individual tasks. Attention was given to the areas of magnet power supply, the Bevatron acceleration system, the beam extraction system, the new 50-MeV proton injection system, and beam monitoring and particle identification.

Superconducting Beam Line Test

In January 1973, three superconducting magnets were set up in a Bevatron beam line to determine their operational behavior under actual experimental running conditions. After preliminary running for extended periods (40 days), unmanned except for periodic checks, the performance was sufficiently proven to start operation on the experiment. This experiment, a negative π beam into a xenon chamber, commenced in July 1973 and operated for 17 weeks (some 2800 hours) into November 1973, finally terminating during a building-wide power interruption. The magnets during this time were more stable than comparable conventional magnets. The operation was as routine and trouble-free as other conventional beam-line components -- a very successful introduction. Compressor maintenance would have been required at about 3500 hours of service. With a reserve compressor and dual on-line purification, continuous runs of 6000 hours should be achievable.

Digital Control Master Oscillator

Historically the tracking of the Bevatron rf with the magnetic guide field has been controlled by ferrite cores saturated by the guide field. This system gives at best a 95% approximation of the required conditions. With the advent of accelerated particles other than protons, a more versatile and stable device was required. This was accomplished by replacing the old master oscillator with a voltage-controlled oscillator (VCO). The control voltage is developed and provided by a 16-bit digital-to-analogue converter (DAC). A new digital word is sent to the DAC at each 1-gauss increment of the guide field. Feedback of the radial position of the particle beam is also incorporated. In addition, a memory unit, storing information from modest-intensity heavy-ion beams, can be used to program the rf for very low-intensity heavy ions of the same charge-to-mass ratio. The new rf control has proven to be a very powerful tool in accepting and accelerating the wide range of particles the Bevalac will utilize over the next few years.

High-Voltage Clearing Electrodes

High-voltage clearing electrodes have been installed in the Bevatron gap to increase particle acceptance at injection and to aid during beam extraction. These electrodes will suppress vertical transverse coherent instabilities due to ion-electron interactions. The unbunched particle beam forms a potential well in which are trapped free electrons created by ionization of residual gas. The electrons oscillating in this potential well interact collectively with the unbunched particle beam, causing instabilities. Electric fields from the clearing electrodes suppress this behavior and allow proton beam intensities greater than 10^{13} particles per pulse to be realized. Voltage switching allows proper gradients to be supplied for both injection and extraction conditions.

Photomultiplier Feedback Resonant Beam Extraction

The spill behavior of the external beam is measured with scintillators or water Cerenkov cells and photomultiplier tubes. Correction signals are fed back to the spiller magnet. The system has been found to work over a range of 10^{10} in beam intensity, is useful for both proton and heavy-ion operation in reducing magnet ripple structure, and provides more beam uniformity. In addition, the use of the feedback makes many operating adjustments less critical.

Bevatron/Bevalac Multiwire-Chamber Monitoring System

The fabrication and testing of a system of sixteen multiwire proportional chambers for proton and heavy-ion beam monitoring has been completed. All sixteen chambers and associated 64-channel multiplexers have been fabricated, eight of which have been operated in experiments performed during 1974.

The sixteen chambers will be strategically positioned throughout the Bevatron/Bevalac external beam facility to provide spatial and beam intensity monitoring with a higher degree of precision than was previously available. Operating as beam current detectors in either the ionization or proportional region and spanning the range of available intensities, each chamber will display 64 separate channels of updated, high-resolution x- and y-spatial information at a maximum rate of 16 times per Bevatron spill. A central multiplexer and analog-to-digital converter will store and display the information from all chambers. Computer access to the stored digital information is provided for future use.

The multiwire chamber system has been operating continuously since autumn of 1974. An additional chamber located on the plunged extraction magnet M1 has been installed and operated in the main ring vacuum. This chamber provides the much-needed information on radial growth at resonant extraction for low-intensity heavy-ion operation.

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II. ADVANCED ACCELERATOR RESEARCH AND DEVELOPMENT

Group Leaders: *T. Elioff and D. Keefe*

POSITRON-ELECTRON PROJECT

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PEP is an acronym for Positron-Electron-Project (previously Proton-Electron-Positron system), and it refers to a high-energy physics facility which has been proposed jointly for construction by the University of California's Lawrence Berkeley Laboratory and by the Stanford Linear Accelerator Center (SLAC) at Stanford University. PEP is a colliding-beam storage-ring facility that would enable scientists to observe electron-positron collisions of very much greater reaction energy than is possible by means of conventional accelerators, and is a significant step in energy beyond existing electron-positron colliding-beam systems.

In the summer of 1971, a group of physicists at LBL and SLAC, including visitors from CERN and Frascati, studied the feasibility of a facility that would consist of an electron storage ring and a proton storage ring. They concluded that no known physical limitation of the behavior of stored beams would prevent the achievement of luminosities sufficient to yield useful reaction rates for many important high-energy interactions. This conclusion initiated an informal SLAC-LBL joint study.

The next step was to clarify the physics objectives and the feasibility of experiments to obtain these objectives. A large number of SLAC and LBL physicists participated, and the physics study was completed in mid 1972. As a result of the overwhelmingly encouraging findings, SLAC and LBL accelerator physicists and engineers began working toward the conceptual design of the PEP storage-ring system.

A lattice system was developed for both rings, which had the advantage of equal cell lengths for both electron and proton magnet systems. Lengths of the straight-section insertions were shortened in the interest of economy, and the configuration of magnetic elements for providing the interaction region was greatly simplified in the first year of the development. Magnet apertures were reduced considerably from the first design considerations. Optimization of the interaction-point β functions and beam emittances, together with introduction of dispersion in the beams at the interaction point also improved the luminosity of the system. An acceptable design was accomplished on which further improvements could be made.

Other efforts in 1973 involved consideration for the design of the electron rf system (closely connected with the SPEAR improvement program) and the proton rf system. Models of possible proton systems were studied. The possible effects of rf noise were investigated with experiments at the Bevatron, where coasting beams up to 10-minutes duration were achieved. These tests helped to establish the threshold for noise levels at various frequencies in the proton rf system that affect the survival of a bunched coasting beam.

Fabrication of a second superconducting magnet identical with the latest LBL pulsed-magnet design was initiated with the cooperation of the superconducting group. Tests provided information on design and construction problems that may be encountered in the art of achieving consistent field quality in a large system of superconducting magnets such as required by the PEP proton system.

Theoretical work continued with studies of bunch lengthening, noise effects on stored beams, and schemes to simulate the beam-beam interaction. Computer programs for orbit dynamics were developed to a more comprehensive state and improved for greater efficiency and flexibility.

By the summer of 1973, the PEP design evolved into a dual ring configuration, with the proton ring located directly above the electron ring in a single tunnel. The proton ring design consisted of superconducting magnets capable of containing protons up to 200-GeV, and the electron ring was designed for up to 15-GeV electrons. Accelerator physicists from throughout the world were invited to participate in the one-month 1973 Summer Study during which improvements were incorporated into the design. In general, the overall feasibility of the PEP system was supported.

Following the 1973 PEP Summer Study, physicists at LBL and SLAC concluded that a single electron-positron storage ring, operated at beam energies up to 15 to 20 GeV and capable of yielding high luminosity in electron-positron collisions, was a straightforward extension of existing techniques and that such a ring could be designed and built immediately with confidence.

With these facts in mind, the laboratory managements at LBL and SLAC jointly decided to propose the immediate design and construction of the 15-GeV electron-positron storage ring, PEP. They also agreed to locate PEP at SLAC and to design the electron-positron ring and its housing to be compatible with the future addition of a 200-GeV proton ring. The Regents of the University of California and the Trustees of Stanford University signed an agreement in February 1974, outlining joint financial and management arrangements for the project.

The main component of the proposed facility is an electron-positron storage ring having six bending arcs and six long straight sections. The facility is shown in Fig. 3. The electrons and positrons are produced in the SLAC linac and introduced into the storage ring via two beam transport paths emanating from the end of the two-mile-long accelerator and joining the storage ring in the northwest and southwest straight sections. Beams of energies up to 15-GeV can be injected and stored, and, at a future date, components could be added to permit stored-beam energies as high as 20 GeV. Also, provisions are made in the design of the ring housing so that a synchrotron-radiation research facility could be added in the future.

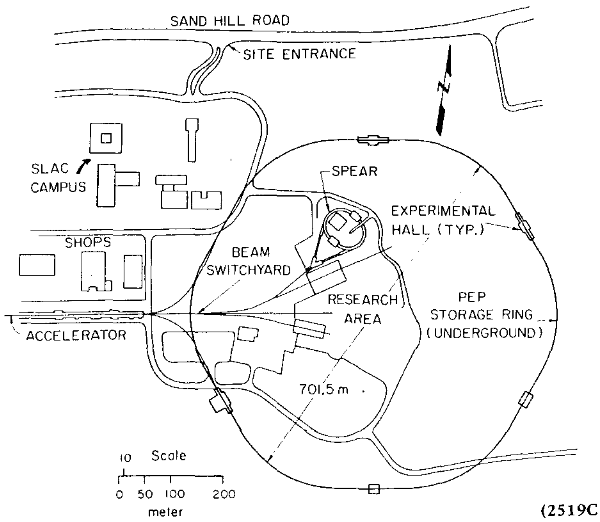

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Fig. 3. Layout of the PEP ring superimposed on an aerial schematic of the SLAC site.

The proposed storage ring is designed to generate a luminosity of 10^{32} cm^{-2}s^{-1} per interaction region at a beam energy of 15 GeV. This luminosity appears adequate to support a vigorous experimental program. The overall circumference of the ring (Fig. 3) is about 2.2 kilometers. The general parameters of the system are shown in Table I.

In May 1974 a formal proposal with the design parameters outlined above was submitted to the AEC and work continued toward improvements of the conceptual design. In the meantime electron-positron rings operating in Europe and the U.S. revealed that a wealth of new and previously unexpected high-energy physics information concerning the structure of elementary

TABLE I. General Parameters

Beam energy, E	15 GeV
Nominal maximum	15 GeV
Minimum	5 GeV
Design luminosity per interaction region, L_{max}	
At 15 GeV	10^{32} cm^{-2} s^{-1}
Below 15 GeV	$10^{32}(E/15)^2$ cm^{-2} s^{-1}
Nominal crossing angle, 2δ	0 radians
Number of interaction regions	6
Number of stored bunches, N_b	3
Available length at each interaction region	20 m
Straight section length	130.416 m
Gross radius of arcs	220.337 m
Magnetic bending radius	169.916 m
Maximum diameter of ring	701.505 m
Circumference of ring	2166.912 m
Effective length of bending magnets	5.561 m
Number of bending magnets	192
Effective length of cell quadrupoles	0.780 m
Number of cell quadrupoles	96
Number of insertion quadrupoles	24
Bending field at 15 GeV	2.9447 kG
Maximum quadrupole field at bore radius	<7.5 kG

particles, both leptons and hadrons, was forthcoming from electron-positron collisions. These experiments suggest that it is urgent to move on to energies higher than those available from existing machines. The recently discovered long-lived ψ particles created in electron-positron collisions at SPEAR serve to confirm the urgency.

In August 1974 a second PEP Summer Study was held chiefly for particle physicists. Their purpose was to evaluate critically the criteria for the PEP experimental areas and to help ensure that the PEP conceptual design would meet the requirements of a wide range of future experiments. Following the study, detailed layouts and perspectives were prepared for practical arrangements of interaction areas showing alternate structure designs, access features, locations of electrical and mechanical equipment, roads, electronics housing, etc. A cost analysis of the variations was performed. In general, the recommendations of the Summer Study Group are consistent with the PEP Proposal of April 1974. Figures 4 and 5 show a cut-away and a perspective view of an experimental area, which is located at one of the six straight

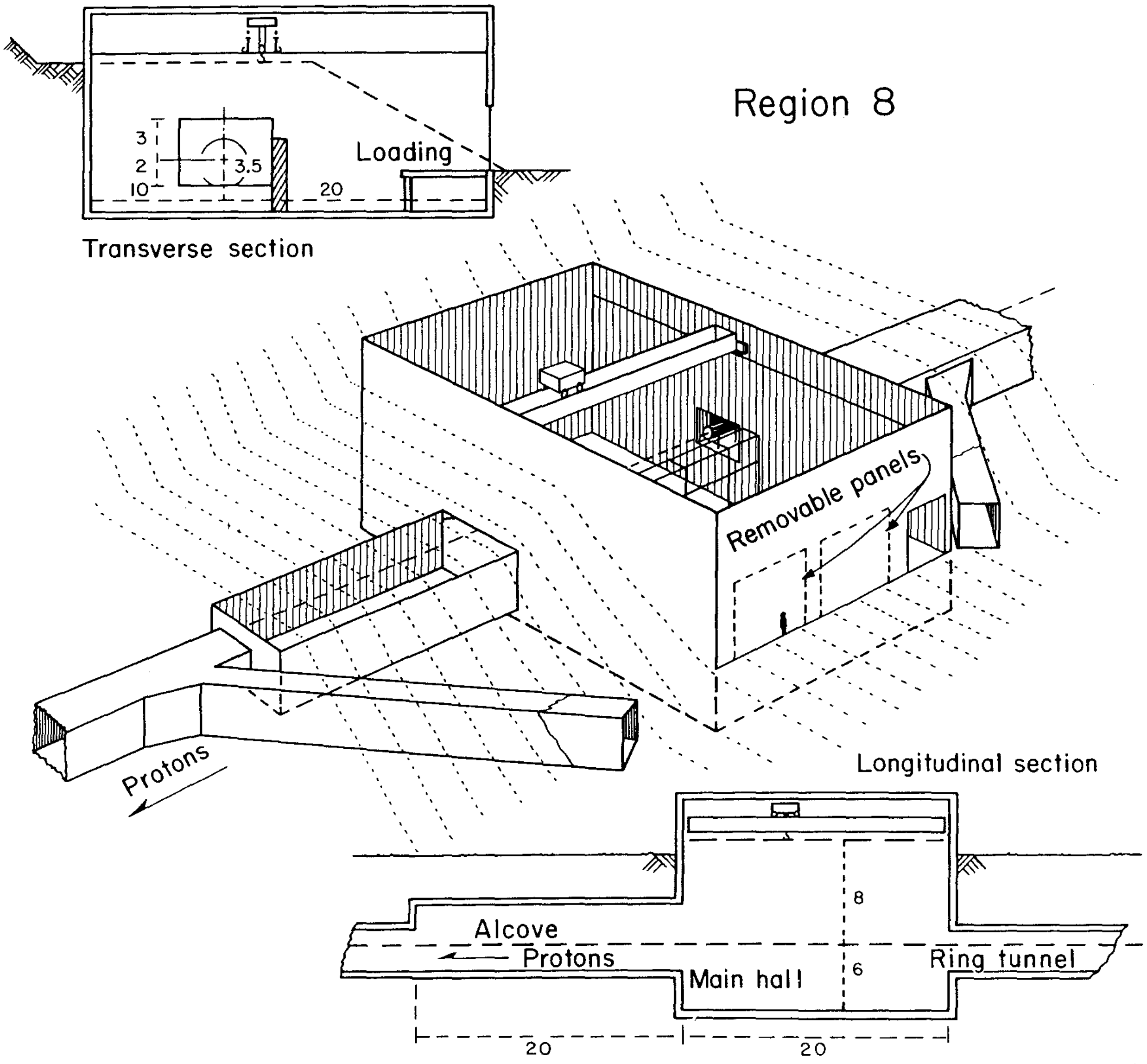
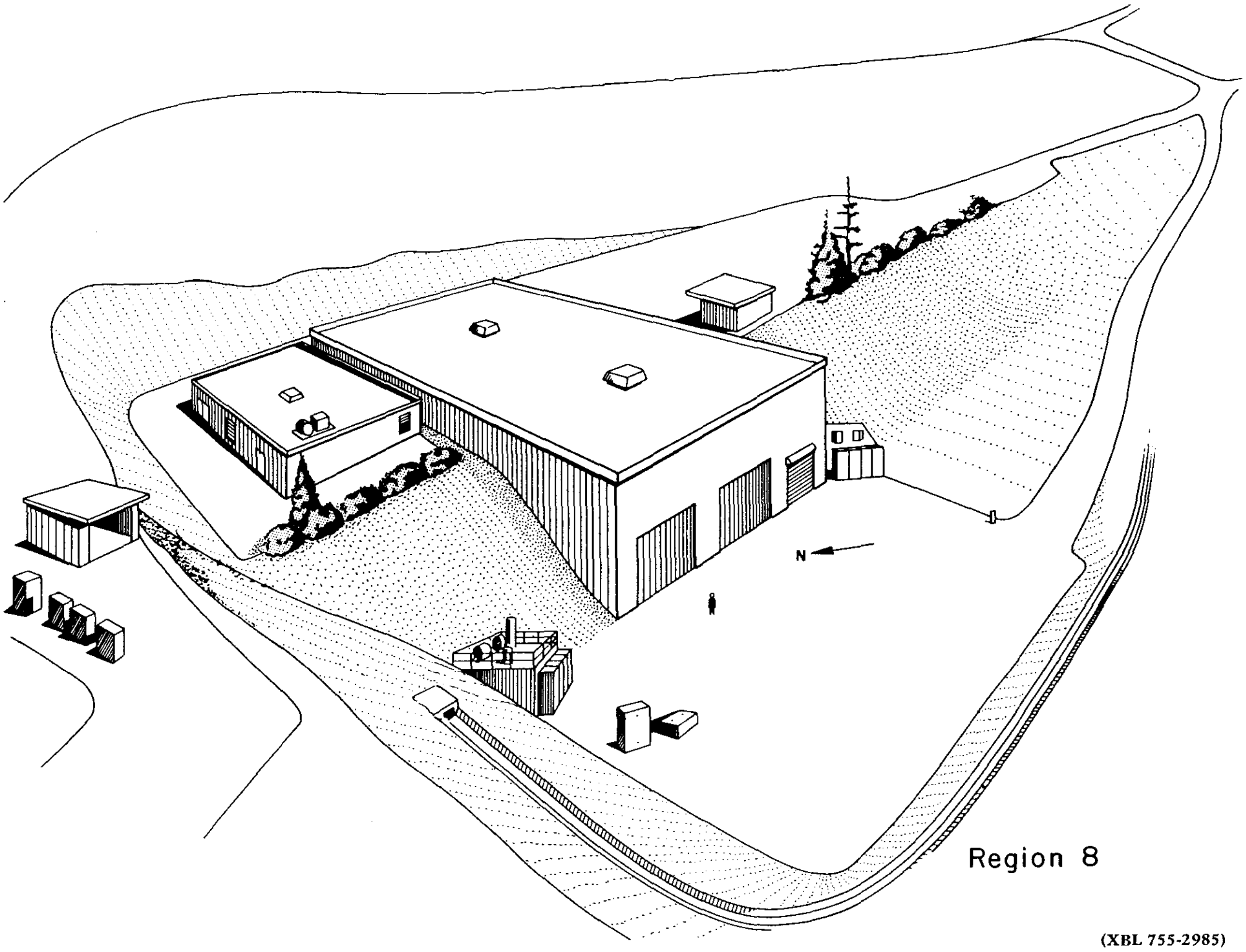


Fig. 4. Cutaway drawing of the experimental area at PEP.

(XBL 755-2986)



(XBL 755-2985)

Fig. 5. Perspective drawing of the experimental area.

sections of the ring shown in Fig. 3.

In addition to the continuing study of the experimental areas, the PEP research and development activities at LBL and SLAC during the past year are summarized briefly below:

Theory

Theoretical studies have been concerned with the following areas:

- Magnet tolerances and alignment requirements
- Detailed specifications for magnetic field quality
- Sextupole systems for chromaticity requirements
- Aperture requirements for a complex of tune requirements and varying injection considerations
- Higher order modes in rf cavities
- Beam-beam interaction simulation programs
- Bunch lengthening phenomenon

In general a greater understanding of these phenomena has been achieved in support of the PEP conceptual design proposal.

Injection System

The initial concept for injecting electron and positron beams from the SLAC accelerator into the PEP ring was reviewed. Subsequent efforts addressed the SLAC beam properties, the modifications necessary at the linac exit, and the required diagnostics and controls necessary to deliver a specified beam to the PEP ring.

The ring injection scheme has been simplified by injecting the beam in the vertical plane via a Lambertson septum magnet to the inflection kickers. The effect upon the injection system of the distribution of the rf system in six locations around the ring was considered (see below), and it was determined that up to a 12-m length of rf cavities can be accommodated adequately between the injection kicker magnets.

The optics and layout of the beam transport lines from the accelerator to the storage-ring straight sections were redesigned for optimization. The goals were to achieve flexible emittance matching, to define and establish limits for emittance, to obtain "near" achromaticity of the beam at the injection point, and to achieve energy definition with a resolution of 0.3%.

A tentative specification was made that the injection system should be able to inject into any one of the several possible PEP lattice configurations in which it might operate. The required range of tuning of the transport system was then defined in terms of eleven typical lattice configurations presently being studied, and their cost and aperture consequences evaluated.

RF System

The installation of the SPEAR II rf system (which is considered a prototype for the PEP system) was remarkably trouble-free. Further thought has gone into the question of the distribution of rf around the PEP ring. In order to ensure that the collisions of the counter-rotating bunches will be concentric at each of the six interaction points, the rf cavities must be distributed around the ring with at least threefold symmetry.

At maximum stored current and maximum beam energy, each circulating beam in PEP will consist of three short (∿ 10 cm) bunches. The large electric charge carried by such a bunch (∿ 2.5×10^{-7} coulomb) will, because of its short duration, give rise in the accelerating cavities to the transient excitation of many parasitic modes, i.e., modes other than the intended accelerating mode. The energy loss of the stored beam from this process has been estimated by several methods, and measurements on SPEAR have been made. AT LBL a number of simple rf cavities were constructed for the purpose of estimating losses due to higher-order modes. The results are in agreement with calculations and with measurements on SPEAR cavities. As a consequence, the rf system for PEP has been redesigned with a smaller number of cavities and with klystrons of higher power to supply the energy loss to the higher-order modes.

Main-Ring Bend Magnets

Models of the principal magnets are being fabricated to verify and to optimize design criteria and fabrication techiques. The die for punching laminations for the main-ring bend magnet was received in July 1974, and the laminations have been punched. Design of the bend-magnet stacking fixture has proceeded. The model bending-magnet coils have been designed and the coil winding fixture is complete. Completion of test models of both dipoles and quadrupoles is expected early in 1975.

Developments toward the specifications of the high-field-quality insertion quadrupoles (used in high-β regions) have continued. An optimized pole contour has been developed and fabrication of a full-scale model is in progress. This model will test field quality requirements, fabrication techniques, and proposed control flexibility via auxiliary coils.

Magnet Power Supplies and Controls

In order to reduce costs, alternate schemes by which to achieve the requisite power supply regulations without transistor regulator banks have been studied. The possibility of using correction windings on each of the magnets as a means of coupling transistor corrections into the system is being studied.

Development has begun on a new magnet-current monitoring transductor. A power supply test facility has been set up to model and test new regulation schemes. All instrumentation and control functions have been reviewed and their requirements more accurately defined in order to provide for the most efficient methods for integrating all control functions and ensuring their compatibility with the overall computer-control systems.

Alignment

Studies have indicated that an inertial guidance system might be usable for survey and alignment of the PEP tunnels and components. If the system is accurate enough, its use could drastically reduce the time required for survey and alignment of the ring. More "conventional" survey alignment techniques are being pursued concurrently. There are, of course, both technical and economic balances between the degree of alignment precision needed and the number of correction elements available.

A metal shell representing the full-size PEP tunnel has been fabricated at LBL and erected at SLAC. Mock-ups of magnets, also fabricated at Berkeley, have been installed along with associated wave guides and cable trays, etc. A full half-cell mock-up now exists. The tunnel mock-up will be useful for checking out alignment techniques, as well as for other purposes such as component layout, equipment handling, etc. A schematic of the tunnel cross section is shown in Fig. 6.

Radiation and Shielding

Shielding calculations have been made to ensure that, at the elevation at which PEP is to be constructed, the earth overburden provides adequate radiation shielding. The thickness of earth shielding is adequate so that site boundary radiation levels are maintained under 5 mrem/year with a 200-GeV proton storage ring operating at stored intensities of $\approx 5\times10^{13}$ protons. Some additional shielding would be added to interaction areas as required, in order to ensure negligible radiological impact. Radiation levels resulting from the 15-GeV positron and electron rings will be negligible.

Vacuum System

The vacuum chamber system for PEP is similar to that of SPEAR II in many respects. Ten bend chambers, made with the SPEAR II die, were received in 1974. Three 12-m bend chambers were fabricated with very good results. The preliminary design for the quadrupole vacuum chamber is proceeding well, and three chambers have been fabricated, using a cross section that closely approximates the final PEP version.

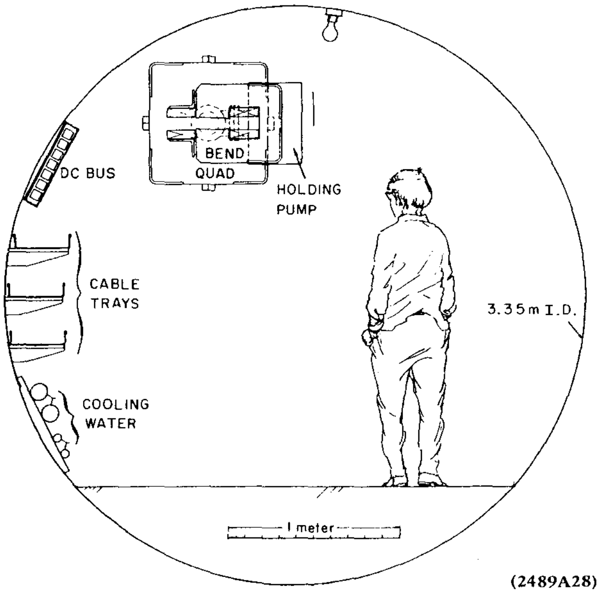


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Fig. 6. Cross section of the PEP housing.

Conventional Facilities

During the summer of 1973, following a moderate exploratory program of test drilling, a brief seismic refraction survey of the PEP site was performed. Correlations with pertinent parts of SLAC's original site investigation program were made and will continue in 1975.

Distribution layouts for utilities were made for further evaluation. Detailed layouts and perspectives were prepared for locations of electrical and mechanical equipment, roads, electronic rooms, etc. Cost analyses of variations in utility components and distribution systems are currently under way.

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COLLECTIVE EFFECTS RESEARCH: ELECTRON RINGS

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R. T. Avery, W. W. Chupp, L. Drager, A. Faltens, A. A. Garren, D. George, E. C. Hartwig, W. Herrmann, G. R. Lambertson, L. J. Laslett, C. Macdonald, D. Mohl, R. Nemetz, W. A. Perkins, J. M. Peterson, C. Pike, J. Rechen, V. Romano, A. Salop, W. Salsig, U. Schumacher, A. M. Sessler, L. Smith, and *D. Vanecek*

Experimental and theoretical work has continued on the development of suitably intense electron rings as a vehicle for collective acceleration of ions (see Figs. 7 and 8). Very large collective accelerating fields can be achieved if electron rings can be formed reliably that are of compact dimensions and contain large numbers of electrons. It was felt not to be worthwhile to proceed to experiments on extraction and acceleration of the ion-loaded ring unless one could be confident of reliably creating stable rings with holding fields of a few megavolts per meter. The main difficulties encountered early on in the program, and which demanded the major experimental and theoretical attention during the period under review, were concerned with the limitations of ring quality imposed by destructive collective instabilities. The most important concerns are the longitudinal instability, the transverse resistive-wall instability, and the ion-electron instability associated with the names of Koshkarev and Zenkevich.

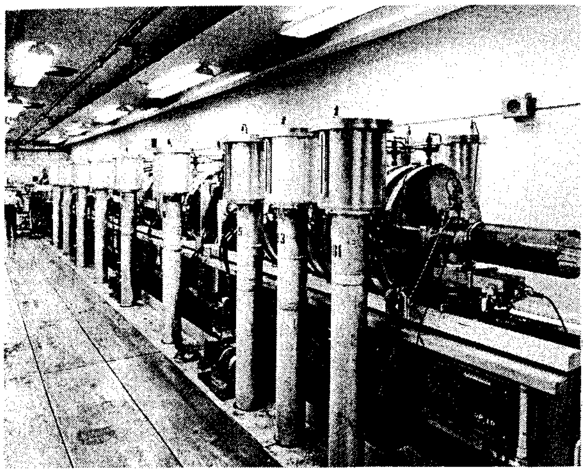
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Fig. 7. View of the 4-MeV electron linear induction accelerator.

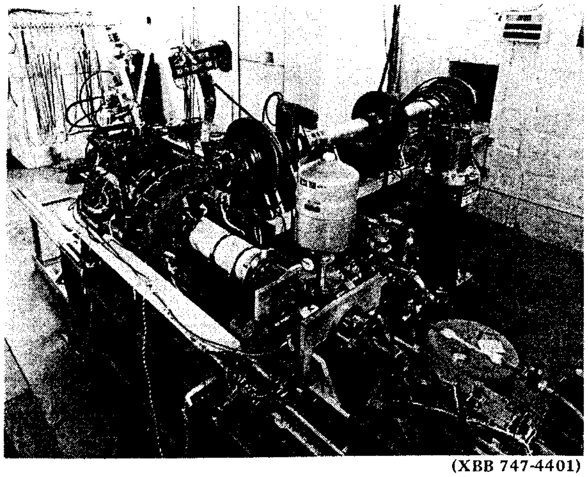
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Fig. 8. View of the compressor with magnetic accelerating solenoid on the left.

The longitudinal (negative mass) instability proved to be the most intractable problem. (The transverse coherent instability is amenable to more degrees of control, e.g., by manipulation of the magnetic guide field.) As a result of extensive experimental and computational work, we arrived at a design of metallic liner which we believed would provide an electrical environment of adequate conductivity to allow reasonably large electron numbers to be stable and still would not interfere unduly with penetration of the pulsed magnetic field. The resistivity of the etched stainless-steel foil averaged 45 milliohms per square (Fig. 9). By injecting a two-turn beam with 2% energy spread (full width), rings with electron number 6×10^{12} after injection were regularly achieved, without significant degradation by instabilities.

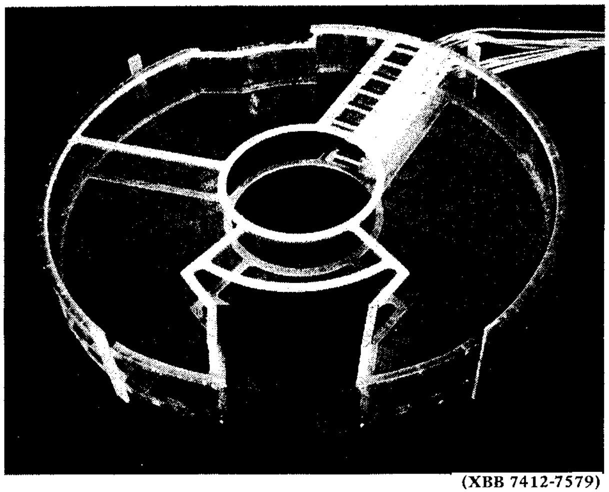
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Fig. 9. Metal liner for compressor interior.

Several lengthy experiments were next made on how to achieve optimum ring quality. The diagnostics used included: current pickup loops to monitor the ring current near injection and near the end of compression; fast-response loops to detect any high-frequency rf signals if instabilities should arise; optical observation of the minor cross section of the compressed ring both in the visible and infrared; an asymmetric pulsed magnetic field to kick the ring axially into the side wall -- the timing of the x-ray pulse giving a measure of the axial ring size; and an obstacle probe that could destroy the beam as it was compressed -- the duration of the x-ray pulse giving a measure of the radial size.

The result of these observations was that in the latest model of compressor we could regularly form compressed rings with a holding field of 5 MV/m and more, without any problems from *collective* instabilities; the typical ring parameters being: $N_e \approx 2 \times 10^{12}$, $R = 3.9$ cm, $2a = 3$ to 4 mm (FWHM radial), and $2b = 5$ to 6 mm (FWHM axial). A disappointing feature, however, was the observation of serious broadening of the ring in the axial dimension, which led to loss of more than half the electrons during compression as a result of passage through single-particle resonances at $n = 0.36$, 0.25 and 0.2. Both these actions have the result of reducing the holding field.

The main conclusion is that the design of the electrical environment used allows control of collective instabilities up to electron number $N_e = 6 \times 10^{12}$. With proper trimming of the magnetic field to reduce the perturbations that drive *single-particle* resonances, this apparatus should be able to produce rings with holding fields some six times larger than the observed 5 MV/m, viz., 30 MV/m.

The experiment at Berkeley on the use of electron rings to accelerate ions was suspended in June 1974 because of lack of research funds. There was no time available to perform experiments on the extraction and acceleration of the ring.

A number of interesting studies on the potential uses of electron rings was carried out before this time, however. For example, if it can be demonstrated that electron rings can be used to accelerate heavy ions stably over long distances (tens of meters), then they could have an attractive application in medical therapy and diagnosis since the ion energy needed could be achieved by magnetic acceleration alone. The feasibility of this application was examined in detail by L. J. Laslett, and sets of possible ring parameters were derived by extensive computational work subject to the following input conditions:

a. The number of ions was adequately large to ensure positive axial focusing of the electrons.
b. The momentum spread and the number of electrons in the ring were suitably chosen to remain below the threshold for the negative mass instability.

c. The numbers of ions and electrons were such as to ensure stability for ion-electron oscillations of the type studied by Koshkarev and Zenkevich. Specifically, the numbers were chosen to avoid the lowest quadrupole resonance; whether this is limiting, is not known yet.

Briefly, Laslett's results are as follows:

a. The electron number, N_e, was typically (1 to 1.5) × 10^{13}.

b. The ion number, N_i, was typically $10^{11}/C$, where C is the charge state of the ion.

c. The length of the solenoid required to accelerate ions to a certain energy depends on the selected charge state, C.

d. Alternatively, the final ion energy achievable with a solenoid of given length depends on the selected charge state, C. For example, a 35-meter solenoid would produce neon ions with 300 MeV/u for $C = 5$ and 100 MeV/u for $C = 2$.

e. To produce neon ions mainly with $C = 5$ or more, would require holding the ring for 3 to 4 milliseconds before release into the accelerating column. To produce ions mainly with $C = 10$ would probably demand very stringent control of background gas contaminants unless additional hardware features could be devised to shake loose periodically the undesired ions created from the background gas.

Thus, if the feasibility of ion acceleration over long distances can be established, these results show there are several choices of operating parameters which could reach useful energies without resorting to electric acceleration of the electron ring.

Another study was made of the possible use of the electron ring as a spectroscopic source of highly-stripped ions. A characteristic feature of the electron ring is that once an atom of neutral gas has suffered an ionizing collision, the ion remains trapped in the potential well of the ring and becomes the target for successive ionizing collisions so that it acquires a progressively higher charge state. In the process, the cold atomic electrons released are expelled by the potential of the ring and are not available for recombination. There is essentially no experimental information about the cross sections for collisional ionization of ions that are multiply charged or the reverse process of electron pickup from neighboring neutral gas atoms. There have been extensive calculations at Berkeley using theoretical models to determine how the mean charge and charge distribution of the ions contained in a ring progress in time, and how the velocity distribution of the ion evolves.

There is considerable interest at Berkeley in constructing a special compressor for the specific purpose of creating intense compressed rings to be used for stripping and containing ions, so that the spectroscopy of such ions can be studied, as well as the cross sections for ionization and electron capture. Present studies in this field of physics rely on the techniques of beam-foil spectroscopy in which ions travel at high speed through a stationary stripping foil. By contrast, the relativistic ring of electrons acts like a moving stripper and leaves the stripped ions virtually at rest. Such measurements are of great fundamental interest not only in atomic physics but also are of great importance to solar physics and more recently to fusion research for the determination of the role of very heavy ions that can cool the plasma in a reactor.

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SUPERCONDUCTING ACCELERATOR: ESCAR

G. R. Lambertson in charge

R. T. Avery, R. C. Acker, P. C. Bean, F. H. Bierlein, V. O. Brady, R. A. Byrns, J. G. Carrieri, R. J. Caylor, W. W. Chupp, E. R. Close, J. S. Colonias, W. F. Eaton, T. Elioff, A. Faltens, A. A. Garren, W. S. Gilbert, M. A. Green, H. A. Grunder, E. C. Hartwig, E. H. Hoyer, E. L. Knight, L. J. Laslett, J. W. Lax, B. S. Levine, E. J. Lofgren, K. H. Lou, M. MacAshian, R. M. Main, J. R. Meneghetti, R. B. Meuser, V. More, R. Peters, J. M. Peterson, C. D. Pike, W. L. Pope, J. B. Rechen, L. Smith, J. W. Staples, J. T. Tanabe, R. H. Thomas, F. L. Toby, F. Voelker, H. W. Vogel, E. R. Wellington, and *R. C. Wolgast*

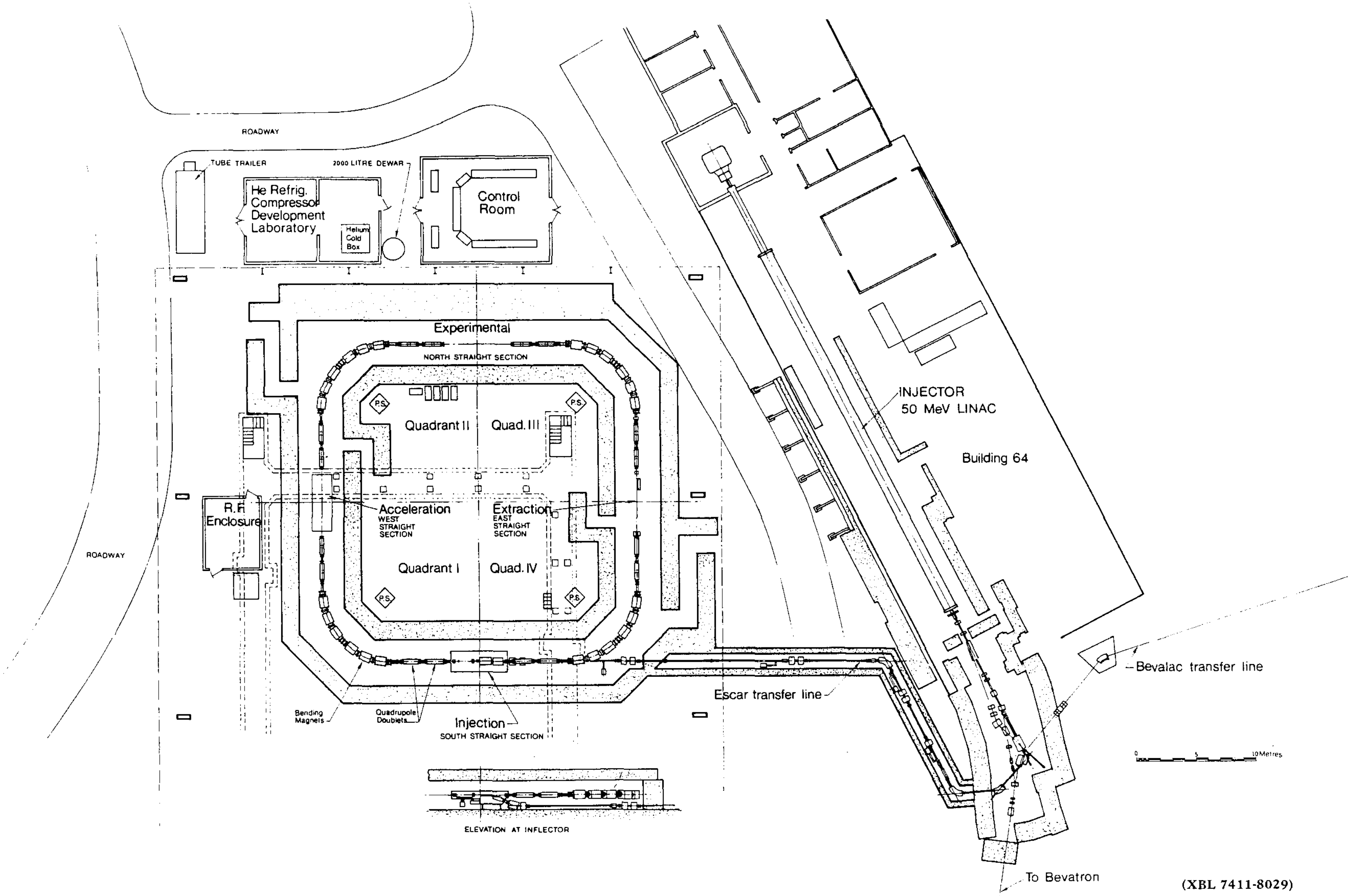
Design work started in July 1974 for the project named ESCAR, the Experimental Superconducting Accelerating Ring. The object of this program is to design, construct and operate a small proton synchrotron and storage ring employing superconducting magnets. From this project, data and experience will be obtained that will be needed for knowledgeable and responsible planning of future large superconducting synchrotrons or storage rings. The concept and preliminary specifications were established in 1973; these call for the following values of major parameters:

Guide field ———— 46 kilogauss
Pulse rate ———— 6 per minute
Maximum proton energy — 4.2 GeV
Injection energy ——— 50 MeV
Intensity ———— 4×10^{12} protons/pulse
Pressure ———— 10^{-11} Torr

A plan view of the ESCAR ring and injection line is shown in Fig. 10. As shown, it will be located at the end of the Bevalac experimental hall. The accelerator will make use of the present 50-MeV linac injector for the Bevatron.

The superconducting magnet system is made up of separate dipoles and quadrupoles with a total of 56 elements. They are arranged to permit acceleration to full energy without encountering rf phase transition, a simplification that removes one cause of beam loss at high intensity. In the spirit of ESCAR being an experiment in accelerator physics, however, there is provision to readjust the magnets so that transition may be brought into the accelerating range and allow the study of this same unwelcome effect that is present in many synchrotrons. Power supplies for the magnets will be phase-controlled rectifiers. The dipoles will be connected in series; quadrupoles will be in four separate circuits to permit adjustment of focusing conditions. By November 1974, the optical focusing effects of the end fields of the circular-bore magnets had been analyzed and refined estimates of the expected beam sizes and tunes are in progress.

Magnet developmental work has been largely directed toward the detailed design of the dipole units. In these, the superconductor will be a 17-wire flattened cable; each wire contains 3000 filaments of NbTi, 6 microns in diameter. Samples of cable have been received from manufacturers, and contracts have been let for amounts sufficient for winding the first magnets. The cabled conductor has low losses in the pulsed field, and its flexibility aids in winding it into the shapes needed to give the desired field quality. The restriction of using practicable winding geometries will lead to field deviations which have been computed to be about one part in a thousand; in addition, random errors in placement of conductors will cause deviations of the same order. Full-size



(XBL 7411-8029)

Fig. 10. Schematic layout of the Experimental Superconducting Accelerator Ring.

model coil windings are being made to develop the techniques of winding and positioning coil segments in a way suitable for later production runs.

The role of iron in dipole design was analyzed with emphasis on whether it should be inside the cyrostat close to the coils (cold) or outside the cryostat (warm). The result of calculations of iron saturation effects and structural aspects indicates that the developmental work required on the cold-iron option would be much greater than for the warm-iron case. The greater assurance of field quality and shorter schedule of the warm-iron design thus led to its adoption for ESCAR.

Early in the study, extensive studies were made of the alternative systems for the circulation of liquid helium coolant through the magnets. Parallel-flow and counter-current-flow schemes have been rejected in favor of a simple series connection of the 56 cryostats with unidirectional flow of two-phase helium. A single controller at the refrigerator can regulate this entire ring. Proposals have been received from vendors for the fabrication of a 1500-watt cold box for the 4.2 K temperature of the magnets. Cryopumping will be utilized throughout the vacuum system; this choice is made for ESCAR as an experiment to learn whether the reduced cost and attractive simplicity of this approach is suitable in practice for future larger accelerators or storage rings. A ventilated clean room has been constructed for vacuum developmental work and assembly. A test chamber with a 4.2 K cryopanel suitable for ESCAR straight sections is now being assembled. Cryosorption pumps are under design.

An rf system for accelerating the beam in a single bunch has been planned. After acceleration, excitation at the 11th harmonic and possibly later at the 44th harmonic will produce a short bunch for the study of stabilizing intense short bunches.

The beam for injection will be brought from the Bevatron 50-MeV linac by means of a transfer line using normal-conductor magnets that are now being fabricated. Care has been taken to preserve beam brightness in the transfer line so that vertical stacking in the ESCAR aperture may be used to achieve full intensity when required.

Sixteen girders from the now-defunct Cambridge Electron Accelerator synchrotron will be used to support the ring magnets. These are on hand, and a three-point positioning system has been designed for them. Eight monuments, now being constructed, will be used in a survey grid, and alignment will use taping and optical tooling techniques with the monuments as references.

An advisory group with members from throughout the United States has been set up to provide technical guidance for ESCAR and communication with other laboratories. This group met with the laboratory staff in May and in November 1974.

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SUPERCONDUCTIVITY PROGRAM

W. S. Gilbert in charge

R. C. Acker, A. R. Borden, W. W. Chupp, W. F. Eaton, R. A. Kilpatrick, E. L. Knight, E. F. McLaughlin, R. B. Meuser, F. L. Toby, F. Voelker, and *E. Wellington*

Pulsed Dipoles

Pulsed dipoles of small aperture (7 - 10 cm in diameter), such as would be used in a future superconducting synchrotron, have been under development for several years. Many different techniques have been explored over the years for making satisfactory magnets.

Our latest magnets use compacted rectangular cable and B-stage epoxy-coated insulation that is cured after the magnet winding is completed. Pulse dipole no. 8, with a close-fitting, cold-iron return yoke reached material short-sample performance of 39 kG central dipole field with cyclic loss as expected from the 10-μ diameter NbTi filaments. There was no measurable degradation of performance on pulsing to the rate of one cycle per second. A short-life test of 4600 cycles (from zero field to 35 kG and back to zero) was run, and the transition current and measured losses were the same at the end as they were before the pulse series. Magnetic field measurements have been made at various levels of excitation with a set of multipole coils in the cold bore of the magnet.

A more advanced pair of pulse magnets (9A - 9B) was built simultaneously to test the reproducibility of magnet construction. The degree of similarity of the two magnets was measured by their integrated magnetic fields. Field measurements on these latest pulsed dipole model magnets indicate that the quality required in synchrotron systems is achieved. Results showed that construction techniques were satisfactory and the fields reproducible to an accuracy of 10^{-3}.

Conductor Evaluation

The program for testing and evaluating new conductors has continued, including new multifilament (6 - 10μ) cables requested by LBL, and also conductors used by NAL in the energy doubler program. A cooperative superconducting procurement, development, and testing program is being carried on with Oak Ridge, LASL, LLL, and NAL. The superconductor, NbTi, is common to all these programs.

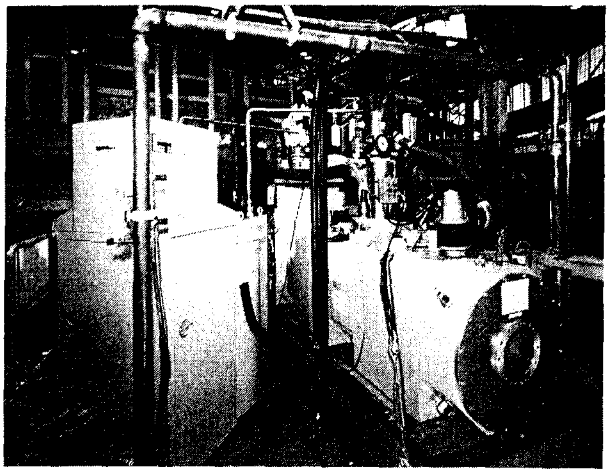
In addition to the above, more conventional superconductor, we are testing a variety of high-field, high-temperature superconductors that use multifilament Nb_3Sn and that are under development by the Inorganic Materials Research Division at LBL.

Transport Magnets - Bevatron Beam Line

A superconducting beam-transport line was installed at the Bevatron. The dipole with a 20-cm clear bore has a maximum dipole field of 40 kG. The quadrupole doublet, also having a 20-cm warm bore, has a maximum gradient of 2.4 kG/cm. Both magnets are cooled by a CTI model 1400 helium refrigerator liquifier (see Fig. 11).

Operational testing of these beam-transport magnets in a Bevatron beam line was largely completed in 1974 with successful operation over a period of approximately nine months. The final run was approximately 3000 hours long, continuously operating in closed refrigeration mode.

These high-strength beam elements have been lent to FNAL for use at their internal target facility and are scheduled to resume operation in spring 1975.



(XBL 734-2407)

Fig. 11. Bevatron beam line showing superconducting transport magnets.

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III. HARD ROCK TUNNELING USING PULSED ELECTRON BEAMS *

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It has been demonstrated that intense submicrosecond bursts of energetic electrons cause significant pulverization and surface spalling of a variety of rock types. The spall debris generally consists of sand, dust, and small flakes. If carried out at rapid repetition rate this can lead to a promising technique for increasing the speed and reducing the cost of underground excavation of tunnels, mines, and storage spaces. The conceptual design features of a Pulsed Electron Tunnel Excavator capable of tunneling approximately ten times faster than conventional drill/blast methods have been a major part of these studies.

Rock Spalling by Pulsed Electron Beams

Successful spalling of granite, basalt, greenstone, and other rocks using single high-current, high-voltage (1 to 4 MV) electron pulses of less than 1 μs duration has been established in these experiments. More recently, spalling also has been successfully demonstrated in experiments using the ∿ 9-MV Hermes II accelerator at Sandia-Albuquerque, which delivered 64 kJ per shot to each rock sample. The resulting spall and debris for some single-pulse shots are shown in Fig. 12. The spalls were 7- to 15-mm deep by 120- to 130-mm diameter with volume removed (neglecting any corners knocked off) of 51 to 82 cm^3. This corresponds to specific energies (energy deposited/volume removed) of 0.78 to 1.25 kJ/cm^3.

Generally, the depth of the spall is found to vary roughly as the voltage of the electrons, and the volume of the spall roughly as the energy content (joules) of the beam pulse.

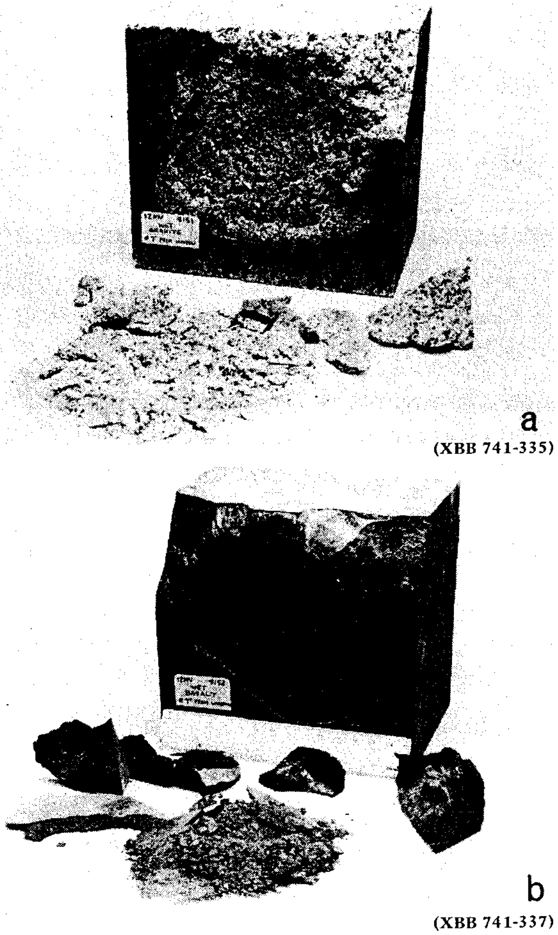

Fig. 12. Rocks each bombarded with single 64 kJ pulse, including spall debris:
a) granite, s_c = 26 ksi;
b) basalt, s_c = 46 ksi.

Hard rocks spall almost as readily as soft rocks. Generally, wet rocks spalled somewhat more than dry rocks. The fracture mechanisms occurring on this very short time-scale are becoming better understood and are primarily due to tension induced by stress waves caused by thermomechanical expansion pressures, supplemented in the case of wet rocks by thermally-induced pressure within the interstitial water. Experimental results have been related successfully to the brief times required for initiation and propagation of cracks in rocks.

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Specific Energy for a Useful Excavating Accelerator

The foregoing experiments were carried out at existing available accelerators under a limited range of operating conditions. In particular, the radial distribution of beam intensity typically was sharply peaked in the center with relatively large tails; also all experiments were carried out on a single-shot basis. A more uniform current distribution could require as little as one-third as much specific energy. Further, if rapid-fire operation were used, there is reason to believe that larger volume of spalls would result because of heating and/or incipient cracking produced by preceding pulses. Thus, for a rapid repetition-rate accelerator designed specially for excavation, it is reasonable to expect lower specific energies (perhaps 100 to 400 J/cm^3 or less) than the $\sim$ 1.0 kJ/cm^3 reported above. For design purposes, a value of 250 J/cm^3 is assumed. In arriving at the required accelerator output, a 25% allowance is added to the foregoing value to compensate for losses in windows and in the air, and for albedo, x-ray production, etc.

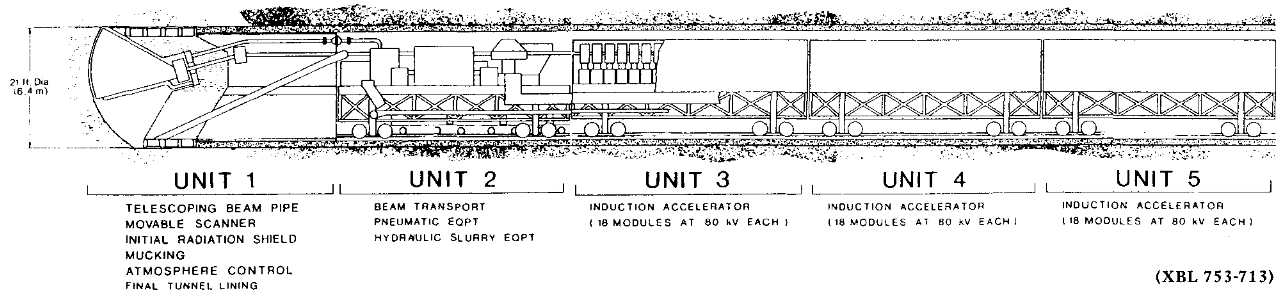
Example Pulsed Electron Tunnel Excavator

Studies have concentrated on an example accelerator with 9-MW average beam power, which would thus be capable of removing 104 m^3 (136 yd^3) of rock per hour, or in other words, advance a 6.4-m (21-ft.) diameter tunnel at a rate of 3.2 m (10.6 ft.) per hour. This is about an order-of-magnitude greater advance rate than by present-day drill/blast techniques.

In order to assess the possibilities of this technique for rapid tunneling, the conceptual design of a Pulsed Electron Tunnel Excavator has been prepared. Several features of this excavator are shown in Figs. 13 - 15. Note that the accelerator proper is just one element -- though a large one -- in the overall design, which also integrates provisions for major construction functions such as tunnel lining, muck removal, and ventilation on a continuous basis. Access is available to handle unusual circumstances which might be encountered.

A linear induction accelerator producing electron pulses (5 MV, 5 kA, 1.0 μs = 25 kJ) at a 360-Hz rate has been selected for this example, thus providing the required average electron beam power output of 9 MW. All of the beam parameters proposed have been met or exceeded in existing electron-beam machines, but not simultaneously. Extension of accelerator performance to these parameters would require development of some components but appears to be well within the state-of-the-art.

The accelerator will consist of 64 accelerating modules each producing 80-kV pulsed voltage. A module may be thought of as a pulse transformer in which the transformer cores are driven by a pulse-forming network connected to the primary windings and in which the electron beam constitutes the secondary circuit.



(XBL 753-713)

Fig. 13. Conceptual example of a pulsed electron tunnel excavator.

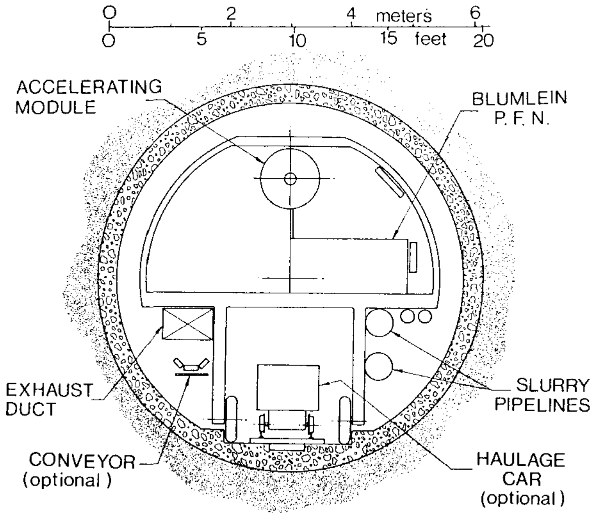


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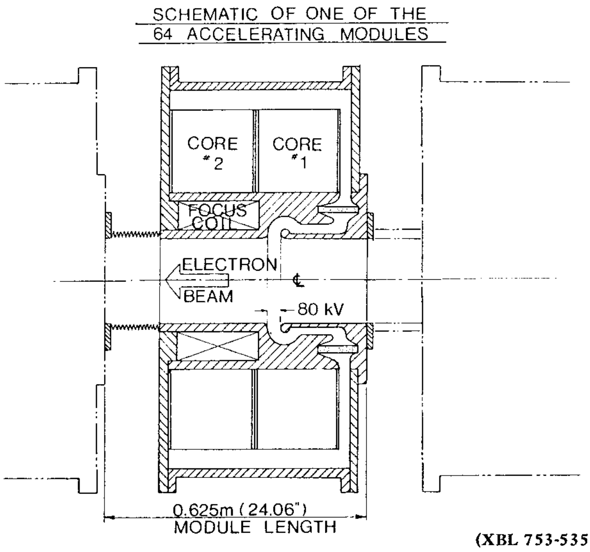
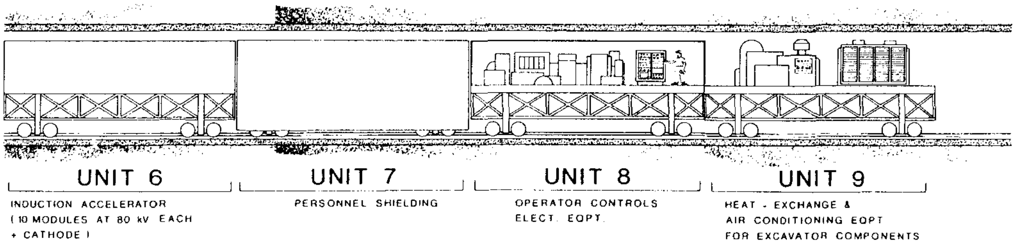
Fig. 14. Cross section through accelerating unit of pulsed electron tunnel excavator.



(XBL 753-535)

Fig. 15. Schematic of one of the 64 accelerating modules.

The electron beam pulses will be scanned by a combination of (slow) mechanical and (fast) magnetic means across the rock at the tunnel face in a prescribed pattern. The requirements for the scanning system are severe as it must transmit 9 MW of electron beam from high vacuum to air, must scan in a reasonably precise manner, and must survive for long time-periods in the hostile tunnel environment without being damaged by either the spall debris or the electron beam. Several promising approaches are under consideration. One consists of passing the electrons through a directly water-cooled foil window for high-vacuum isolation followed by a modestly-evacuated mechanically-moved snout at the end of which is a moveable foil window (located about 10 cm from the rock face). Other possibilities include such schemes as 1) A series of beam apertures which provide vacuum grading, 2) Rotating beam apertures which are open only momentarily when the beam is pulsed, 3) A hundred or so individual windows with electromagnetic scanning, or 4) A water film flowing on the outside of a window. Further study of the scanning system is needed, but it appears that some one or combination of methods will prove suitable.



(XBL 753-713A)

Fig. 13. (Continued)

The spall debris is mostly sand, dust, and small flakes, but larger pieces may be produced also. The bulk of the debris will be picked up pneumatically at the face and then placed in an hydraulic slurry pipeline for transport to the tunnel entrance. Slurry transport is a fast, continuous and economical technique for transporting large volumes of muck. Large pieces will be coped with by a conveyor at the face and then crushed and slurry-transported. A belt conveyor and muck cars are shown also, but they may not be needed.

Tunnel support and lining will be provided by partial tunnel shield (surrounding the scanner) followed immediately by casting of the final concrete lining using either slipform or extrusion means. Concrete supplies will be transported to the face by pipe or conveyor. Alternatively, precast concrete segments or structural steel sets could be placed instead, but they would require interruption of accelerator operation during their installation.

The accelerator will produce intense x-rays during operation. The operating crew will be fully protected by a shielding system of concrete, water, and safety doors built into one unit of the excavator. The several meters of rock cover which is (by definition) over the tunnel protects the general public. Recent irradiations of rock samples at Berkeley show that there is no induced radioactivity; thus when the machine is turned off, the crew can approach the tunnel face immediately.

Ozone will be produced when the electron beam passes through the air to reach the rock face. Pneumatic suction at the face followed by the negative-pressure exhaust ventilation duct will transport the ozone to the tunnel entrance where it will be diluted with air or chemically treated.

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