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Accelerator and Fusion Research Division Lawrence Berkeley Laboratory

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Conceptual Design Report

NATIONAL CENTER FOR ADVANCED MATERIALS

NCAM

Vol. I
Summary

Lawrence Berkeley Laboratory
University of California
 Berkeley, California 94720

NATIONAL CENTER FOR ADVANCED MATERIALS
CONCEPTUAL DESIGN REPORT

Volume I

March 1983

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94270

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1 Introduction

The National Center for Advanced Materials is designed to provide a national focus for basic research on the synthesis, characterization, and behavior of advanced and strategic materials. This focus will also serve to develop innovative concepts for high technology devices, thereby strengthening the nation's technological base.

American economic health and national security require that we maintain a lead in high technology and establish independence from foreign sources for critical materials. Industrial leadership in high technology is heavily dependent upon rapid exploitation of the results of long-range basic research studies in carefully selected research areas. To meet the challenge of maintaining the U.S. in the technological forefront, it is proposed to establish the National Center for Advanced Materials (NCAM) at the Lawrence Berkeley Laboratory. NCAM will implement U.S. science policy by redirecting the outstanding scientific research capabilities of a national laboratory to address a vital national need, by accelerating basic research in an area that promises medium-term impact on high-technology industries, and by fostering closer ties between industrial and university researchers and their counterparts in the national laboratories.

NCAM will be composed of the Advanced Light Source (ALS) and three complementary laboratories—the Surface Science and Catalysis Laboratory (SSCL), the Advanced Materials Synthesis Laboratory (AMSL), and the Advanced Device Concepts Laboratory (ADCL).

The ALS is the first of a new generation of synchrotron radiation sources. With a nominal electron energy of 1.3 GeV, the ALS is optimized to produce extremely high brilliance photon beams by the use of special magnetic devices called “wigglers” and “undulators”. The electron storage ring is designed to emphasize the capability of these devices. A combination of very low electron beam emittance in the storage ring together with adequate lattice provisions for undulator devices will provide a spectral brilliance that is nearly 10,000 times greater than that of existing light sources.

The nominal ALS electron energy (1.3 GeV) will provide photon beams in the energy range of 0.1 to $\sim 5,000$ eV. The maximum energy (1.9 GeV) extends the capability to 10 keV, while the use of superconducting wigglers will extend the energy range to 40 keV. On the opposite end of the spectra, the ALS also will provide relatively intense beams for experiments in the infrared region. The ALS is also designed to provide beam pulses of very short duration (tens of picoseconds), which will greatly expand the range of experimental capability.

The Surface Science and Catalysis Laboratory (SSCL) will provide facilities to further the fundamental understanding of the physics and chemistry of surfaces. Both basic and applied research projects will be emphasized. Research will focus on understanding catalysis on solid

surfaces and on developing new catalysts in close collaboration with the Advanced Materials Synthesis Laboratory. The initial research program will include studies of atomic rearrangement on surfaces, experiments to determine surface properties under extreme conditions, and studies on zeolite synthesis and characterization.

The Advanced Materials Synthesis Laboratory (AMSL) will be devoted to developing and understanding new kinds of polymers, metals, ceramics, and electronic materials. The AMSL will strengthen the United States' position in the synthesis and analysis of advanced materials by pushing forward knowledge of the structure, composition, and formation of such materials, as well as by pioneering new techniques for synthesizing such materials, and by developing new materials to meet the specifications required for advanced devices or processes. The initial research program will include: electronic materials synthesis and analysis, metal alloy design, zeolite characterization, and studies of crystal structures and phase transitions at high pressure.

The Advanced Device Concepts Laboratory (ADCL) will be a major facility dedicated to fostering the development of novel concepts for devices. Pursuant to NCAM's emphasis on advanced materials, the ADCL will be devoted to research related to high-technology devices utilizing new materials and to innovative approaches to the study of materials. Thus, research at the laboratory will focus especially on developing concepts for devices made possible by new or better understood materials. Initially four projects will be undertaken at the ADCL: developing techniques and devices for x-ray lithographic microscopy, generating concepts for designing reliable, highly stressed components made from advanced brittle materials, improving superconducting devices such as SQUIDs and Josephson junctions, and developing the devices required to exploit the infrared capabilities of the Advanced Light Source.

The NCAM project provides for the upgrading of facilities at the Stanford Synchrotron Radiation Laboratory (SSRL). This includes experimental area improvements, emittance improvements to the SPEAR electron beam, new in-vacuum wigglers, and the development of an x-ray beam from the PEP storage ring. This upgrade will be extremely valuable to researchers during the ALS construction period and the x-ray beam facilities will continue to serve as a valuable complement to the ALS facilities.

Chapter 2 of this volume will provide a more detailed description of the NCAM research potential and a projection of the future programs. It is planned that the NCAM basic research programs and utilization of the Advanced Light Source will be organized to provide maximum benefit to U.S. industry. Industry will participate in the design and use of ALS beam lines and ancillary NCAM laboratories to assure that NCAM basic research addresses America's high-technology needs. An NCAM advisory board composed of scientific leaders from industry, universities, and national laboratories will advise the Laboratory Director on NCAM scientific program directions. The NCAM affiliates, consisting of major research teams from industry and universities, will participate in the design, construction, and use of ALS beam lines. An ALS program advisory committee will review research proposals for the use of ALS beam lines by all qualified experimenters. An NCAM Industrial Fellows program will be established to provide joint LBL-industrial support for participation at NCAM of outstanding industrial scientists in basic research studies of mutual interest to LBL and the scientists' parent company.

NCAM is designed to provide facilities equipped with the most modern tools for synthesizing, probing, and characterizing materials. The ALS will provide a state-of-the-art synchrotron light facility that will meet the needs of the U.S. material science community over the next decade. Strong industry-university collaboration will be developed within the unique facilities of

a national laboratory. With this program, NCAM will be a major force in strengthening the U.S. technological base.

2 NCAM Scientific Research

Introduction

Advances in vital energy-related and high-technology industries depend increasingly on having available new materials with specific properties, as well as new devices to perform special functions. To develop such materials and devices requires a complete scientific understanding of the chemical and physical phenomena that control the properties of materials and the behavior of devices. For example, advances in microcircuitry require fabricating circuits of dimensions so small that surface effects and atomic-scale phenomena control their electronic behavior. Advances in other technologies require for critical components the use of materials with special physical, mechanical, and chemical properties, that are determined by the atomic structure. Major improvements in chemical processing, including petrochemical and fossil-fuel conversion, require an underpinning of detailed knowledge of chemical reactions, kinetics, and catalysis on an atomic and molecular level. To develop the required materials, devices, processes, and techniques demands a coordinated, interdisciplinary attack on a broad range of interrelated problems in synthesis, processing, and fabrication, with complete characterization of the intermediate products and reactions at each step.

The National Center for Advanced Materials is geared to make just such an attack. It will perform contemporary materials research, oriented to meet these needs, and focused especially on understanding the key atomic bases of materials' properties. To study such details, researchers require more sophisticated and more powerful tools for probing their samples. Fortunately, such tools are becoming available, though many techniques for exploiting them remain to be developed.

Synchrotron radiation has become an extremely powerful and versatile tool for probing materials over the past decade. Emitted by relativistic electrons during acceleration, synchrotron radiation has many distinctive features that make it ideal for studying materials. It can be extremely bright and stable at all wavelengths between the far-infrared and x-rays. Moreover, any narrow or broad wavelength band within this range can be selected for a particular experiment. Synchrotron radiation can come in brief, regular flashes, allowing time-dependent processes to be monitored. The light can emanate in a sharply collimated beam from an extremely small source area, so very small samples can be probed. Although the radiation is not fully coherent, it is typically strongly polarized.

The Lynch subcommittee of the Solid State Sciences committee of the National Academy of Sciences argues that the nation needs to strengthen research capability available from synchrotron light sources. It predicts that the available facilities will be oversaturated by the mid-1980's. Since materials science is both one of the nation's top research priorities, and also an interdisciplinary field on which synchrotron radiation will have a huge impact, a materials research facility having a synchrotron source as its centerpiece would be a valuable national resource, and an efficient way to satisfy two national needs.

The National Center for Advanced Materials (NCAM) addresses the scientific need for both advanced materials research and provides for advanced synchrotron radiation facilities. Moreover, it provides laboratories—adjacent to the synchrotron source—that are equipped with the most modern tools for synthesizing, processing and characterizing materials, in a setting supportive of interdisciplinary, industry-oriented, state-of-the-art research. A key component of the center will be the Advanced Light Source (ALS) for generating synchrotron radiation. Three associated laboratories will focus on critical aspects of materials science. These laboratories are the Surface Science and Catalysis Laboratory (SSCL), the Advanced Materials Synthesis Laboratory (AMSL), and the Advanced Device Concepts Laboratory (ADCL). The ALS will be a research facility shared by scientists and engineers from universities and industry throughout the United States. Visiting materials researchers using the ALS will also have access to and support from the three research laboratories comprising NCAM.

Institutional Setting

The National Center for Advanced Materials will be located at Lawrence Berkeley Laboratory (LBL), a national research laboratory funded primarily by the Department of Energy (DOE), and operated for DOE by the University of California. The new center focuses three of the laboratory's strengths—materials research, accelerator physics, and instrument design—onto research addressing the nation's need for advanced materials.

Lawrence Berkeley Laboratory is unique among the national laboratories in being effectively co-located with the Berkeley campus of U.C.—an outstanding research and teaching university. Over 500 students presently work on their advanced degree research at LBL. LBL also has close associations with researchers and departments at the other U.C. campuses. Furthermore, the laboratory has a strong reputation for developing advanced instrumentation and devices.

The National Center for Advanced Materials will be a national facility, open to scientists and engineers from industry, universities, and government. U.S. industry will be involved closely in the design and use of ALS beam lines and the three NCAM laboratories, to assure that NCAM basic research addresses the nation's long-range, high-technology needs. An NCAM advisory board composed of materials science leaders from industry, universities, and federal laboratories will advise the laboratory director on NCAM scientific program directions. NCAM affiliates, consisting of major research teams from industry and universities, will participate in the design, construction, and use of ALS beam lines. An ALS program advisory committee will review research proposals for the construction, modification and use of beam lines by all qualified experimenters. Finally, there will be large, well-supported programs involving guest investigators, industrial fellows, and visiting scientists.

Lawrence Berkeley Laboratory is a singularly appropriate site for a research center devoted to research on advanced materials. Much of the scientific capability needed to start an integrated research program focusing on advanced materials and device concepts is already in

place at LBL and the University of California. The laboratory includes a highly recognized chemical and materials research staff and talent and experience in creating state-of-the-art instruments and apparatus to test new device concepts, new materials, and theories. The ALS design team has participated in designing accelerators, accelerator devices, and particle detectors used at research centers around the world.

The combined resources of LBL and the U.C. Berkeley campus will give the research program at NCAM unparalleled strengths. Already 172 U.C. Berkeley faculty and more than 500 graduate students pursue their research at LBL. Research opportunities at NCAM will attract students from many disciplines, such as computer science, and electrical, mechanical, and civil engineering, that are critical to the high-technology future of the United States. In addition, NCAM work will broaden the range of research opportunities for chemistry, physics, and materials science students, and expose them to the interface between basic science and applications. The training of scientists and engineers will be one of NCAM's significant contributions to the nation.

The industrial fertility of the San Francisco Bay Area in particular, and the West Coast in general, should facilitate productive collaborations between NCAM and industry. Research and development laboratories, high-technology consulting companies, and research facilities operated by the petroleum industry are heavily concentrated on the West Coast. Many of these industrial firms are already leaders in research on materials and devices and their application. Also nearby are several universities and colleges, including Stanford, and the Lawrence Livermore National Laboratory where considerable materials research is done.

Finally, Lawrence Berkeley Laboratory is well versed in establishing and operating national research facilities. The Bevalac, the 88-inch Cyclotron, and the National Center for Electron Microscopy (NCEM) are all national facilities. More than 50 percent of the machine time of the Bevatron/Bevalac/SuperHILAC heavy-ion accelerator is used by guest investigators, visiting scientists, and experimenters affiliated with other universities or laboratories.

Even more relevant to materials science is the National Center for Electron Microscopy. This facility houses two transmission electron microscopes. The Atomic Resolution Microscope (ARM), scheduled to be operating by mid-1983, is the first electron microscope in the world able to resolve individual atoms in materials. The other one, a High Voltage Electron Microscope (HVEM), is already operating. It accelerates electrons to 1.5 MeV, and is therefore the most penetrating electron microscope in the United States. These two microscopes enable physicists, chemists, biologists, and materials scientists to examine unprecedentedly thick samples and achieve unsurpassed clarity and detail in the micrographs. As tools for materials science, these microscopes complement the ALS and should be a valuable asset to NCAM users. NCEM has been operating smoothly and serving the materials science community since 1981.

To summarize, LBL's unique association with an outstanding research university, in combination with its experience operating national facilities and its existing strong programs in accelerators, instrument design, and materials science, make it an excellent site for a national materials research center. Research at NCAM will enhance the already major role LBL plays in graduate education by providing more opportunities for student research and training in key areas of physical sciences and engineering that are vital to the health of U.S. high-technology. Industry involvement in NCAM through programmatic advice, financial cooperation, and research participation will be a prototype for interactions between national laboratories and industry that must flourish, if the nation is to become independent of foreign sources of strategic materials and maintain its leadership position on the international, high-technology front.

Description of the National Center for Advanced Materials

The purpose of NCAM is threefold. It will provide a national focus that integrates interdisciplinary and long-range research on the synthesis, characterization, and behavior of advanced materials, with a parallel effort to develop innovative concepts for energy-related and high-technology devices. Secondly, it will provide, in the Advanced Light Source, a next-generation synchrotron light source, operated as a national facility for United States science and engineering research. Finally, the NCAM program will address the national need for highly trained scientific and engineering manpower by expanding participation at LBL of UC-Berkeley faculty and graduate students into vital areas of physical sciences and engineering.

The National Center for Advanced Materials will have four components in three buildings. The Advanced Light Source (ALS), as the centerpiece of NCAM, is the first accelerator designed explicitly to use insertion devices—wigglers and undulators—to produce intense beams of synchrotron radiation for probing the structure and composition of materials. Researchers at the Surface Science and Catalysis Laboratory will use the ALS and other state-of-the-art instruments and techniques to study surfaces and the process of catalysis. The thrust at the Advanced Materials Synthesis Laboratory will be to synthesize and characterize energy-related, high-technology, and strategic materials, using the ALS and other means. This laboratory will share a building adjacent to the ALS with the Advanced Device Concepts Laboratory, a facility devoted to research on the design of high-technology devices utilizing new materials and on innovative devices for exploring and characterizing the relationships between materials and their properties.

Advanced Light Source (ALS)

The Advanced Light Source is the first of a new generation of electron storage rings dedicated to producing synchrotron radiation. It will complement existing U.S. facilities by providing increased brilliance in a spectral range spanning from the infrared to x-rays.

Most synchrotron radiation generated by the ALS will be produced using insertion devices—wigglers and undulators—that enhance the production of photons. The ALS includes twelve long straight sections to accommodate these devices. Undulators will increase photon brilliance by 10,000 times over what is possible using conventional bend magnets. Existing synchrotron light sources currently are being retrofitted with insertion devices, to the extent allowed by their design. Figure 3-4 compares ALS brilliance with that of other Synchrotron radiation sources, with and without the insertion devices they have or plan to install.

The ALS design is optimized to produce from wigglers and undulators intense fluxes of photons in the energy range between 0.1 and 5000 eV. A combination of very low electron beam emittance and optimized undulator design will provide an extremely high spectral brilliance. Up to 10^{18} photons per second per mm^2 per milliradian² per 0.1% bandwidth will be emitted in the peak energy range (see Figure 2-1). High-field, superconducting wigglers will be developed and installed in the ALS to supply some beam lines with high-energy photons up to 40 keV.

The unique time structure of the ALS is characterized by very short pulses—about 35 picoseconds long. This pulse length makes possible studies of transient phenomena, such as chemical reactions and relaxation processes, and adds greatly to the power of the ALS as a tool

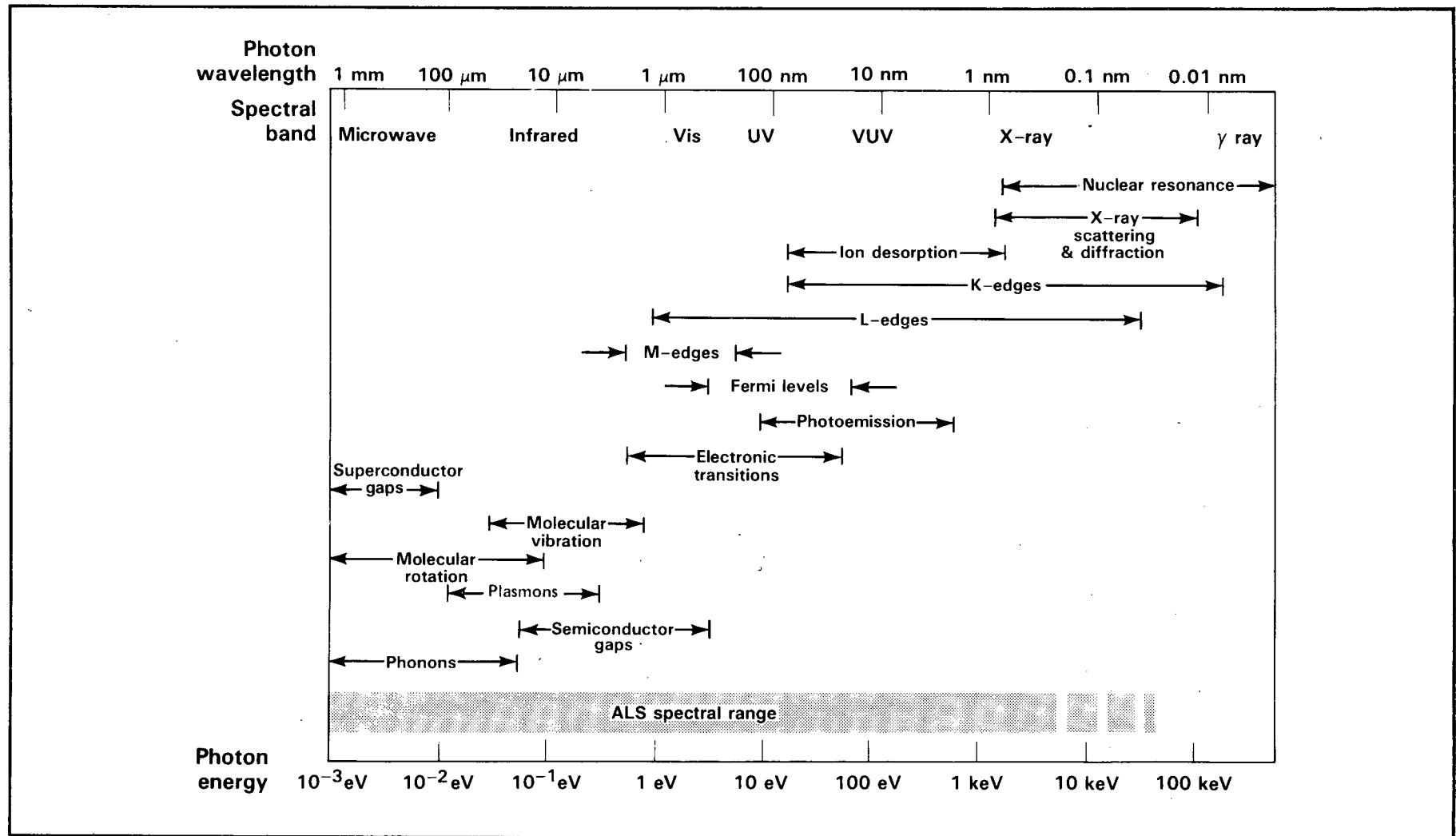


Figure 2-1a. Spectral ranges of materials process.

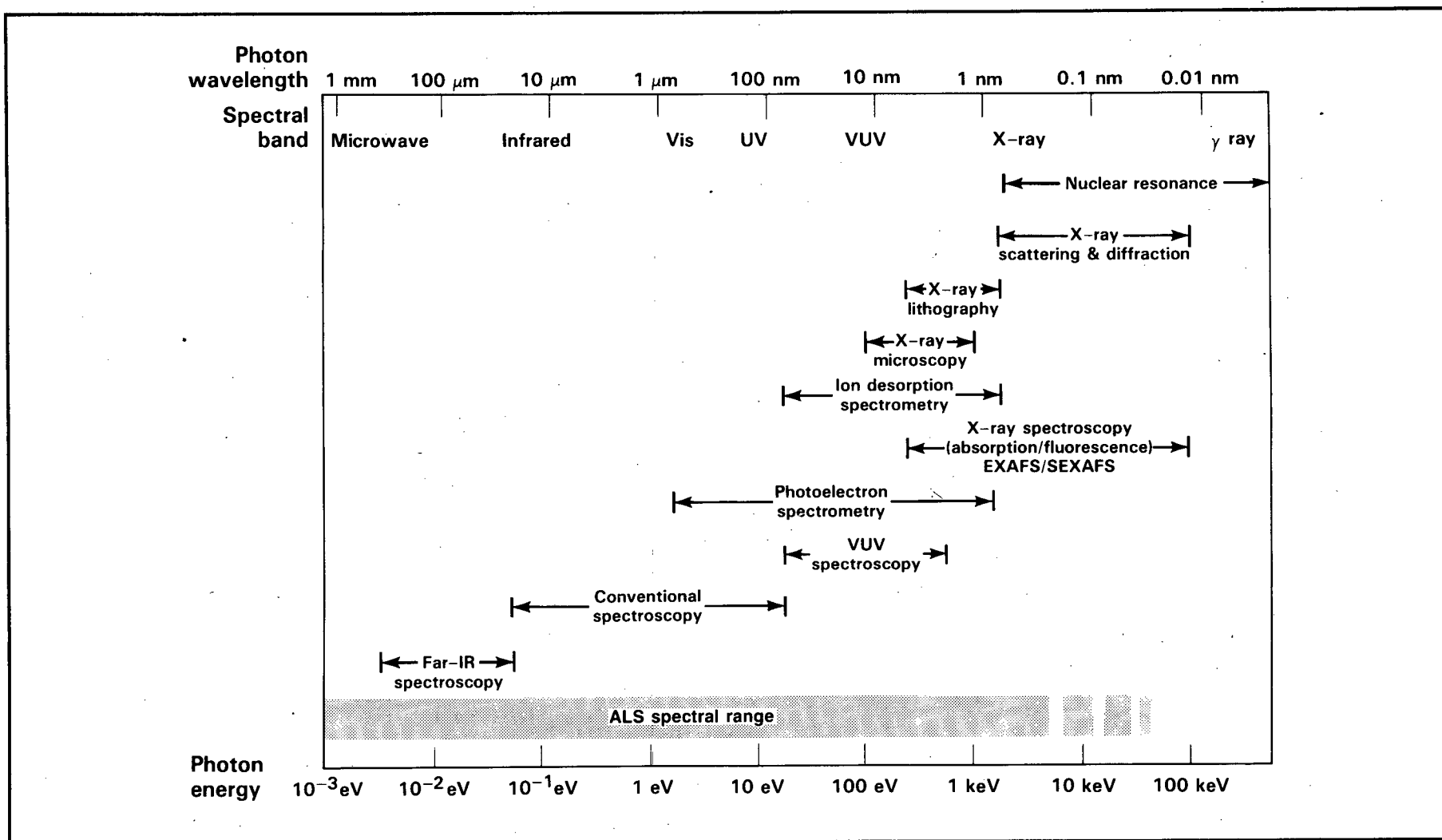


Figure 2-1b. Materials science using SR light.

for materials science. Both the pulse length and the interval between pulses can be adjusted to suit the needs of experimenters. Possible values for the pulse separation range between 2 and 500 nanoseconds.

The ALS is described in detail in Chapter 3. Briefly, it will consist of a 50-MeV linear accelerator, a nominal 1.3-GeV "booster" synchrotron, a nominal 1.3-GeV electron storage ring, and many associated photon beam lines. The booster will cycle at a 1-Hz repetition rate, and it will inject electrons into the storage ring until the desired current is reached. The storage ring will have a circumference of 182.4 meters, and it will contain 12 straight sections, each 6 meters long, for wigglers and undulators. The storage ring has been designed for an electron beam with a very low emittance of $6.8 \times 10^{-9} \pi$ meterradians. This feature ensures that the synchrotron radiation comes from a very small source area to produce photon beams of high brilliance.

The ALS will be operated by Lawrence Berkeley Laboratory as a national facility. An advisory panel of potential users will be assembled to clarify user needs and to plan appropriate beam lines and user-support facilities. This group will be consulted as construction proceeds, and will provide the nucleus of a Program Advisory Committee to review experimenters' request and allocate beam lines and operating hours once the facility is completed. NCAM affiliates, major research teams from industry, universities, and government supported laboratories will participate in the design and use of ALS beam lines.

Construction of the ALS will be completed by FY89. At that time, it will begin operating full time for experiments. Initially only the first complement of beam lines will be installed. This approach allows for considerable flexibility in implementing novel beam-line technology and new techniques for probing materials that have not been envisioned yet. A permanent staff of approximately 80 scientists, engineers, operators, and technicians will operate the ALS on a three-shift basis. In addition the staff will work with the scientific community to design and construct additional sophisticated photon beam lines and to upgrade the ALS continuously.

Surface Science and Catalysis Laboratory (SSCL)

The Surface Science and Catalysis Laboratory will be devoted to studying surfaces and processes on surfaces. Basic understanding of surfaces, interfaces, and of reactions on them is critically necessary to guide materials development in a variety of major industrial areas. For example, the effectiveness of industrial catalysts depends on reactions at active sites on the surfaces of particles. Advances in microcircuitry require working in dimensions so small that surface-specific effects significantly influence electrical and other properties. In addition, the properties of surfaces control the way a material reacts to extreme conditions, such as irradiation, heat, exposure to acid or caustic substances, or corrosion. Moreover some very useful devices are based on the properties of interfaces between two different types of materials. Examples include Schottky barriers (interfaces between semiconductors and metals) and heterojunctions (boundaries between two semiconductors).

The research program at SSCL will build on the strong existing base of materials, surface-science, and catalysis studies at Lawrence Berkeley Laboratory. The SSCL building will be located adjacent to the Materials and Molecular Research building, where similar work is presently done, and near the National Center for Electron Microscopy (NCEM). Roughly 110 scientists, students, and staff will be housed in the new laboratory.

Research at SSCL will include both theoretical efforts and experiments using the ALS, the microscopes at NCEM, and other modern tools of surface science. Special effort will focus on

resolving ambiguities in the understanding of key aspects of surfaces and catalysis.

The following topics are examples of research to be pursued at SSCL: kinetics of surface diffusion and of sintering of particles with cross-sections less than 0.1 square micrometer; research on novel catalysts, for example dual particle catalysts, remote-source catalysts, and non-metallic catalysts, such as zeolites; research on homogeneous, liquid-phase catalysis; research on atomic and electronic structure of interfaces; and research on the response of surfaces to extreme conditions.

Plans call for initiating research at SSCL during FY84 with three projects. These projects will focus, respectively, on elucidating the atomic structure of surfaces, interfaces, and within solids, on investigating the relationship between the synthesis and structure of zeolites, and on studying surface properties under extreme conditions. These projects are discussed in more detail in the FY84 research program of this chapter.

Advanced Materials Synthesis Laboratory (AMSL)

The Advanced Materials Synthesis Laboratory will be a facility devoted to developing and understanding new kinds of metals, ceramics, polymers, and electronic materials. The AMSL will strengthen the United States' position in the synthesis and analysis of advanced material on three fronts. It will push forward knowledge of the structure, composition, and formation of such materials, it will pioneer new techniques for synthesizing materials, and it will develop new materials to meet the specifications required for advanced devices or processes.

The research program at AMSL will expand on the existing ceramics, metallurgy, and electronic materials work already underway at LBL. In addition it will open new research fields, of particular interest to industry. Although not included in NCAM's FY84 scientific program, research on polymers and composites will be performed at NCAM, after being initiated in the FY85 to FY86 timeframe. Laboratories, facilities, and offices for AMSL scientists will be based in an L-shaped building to be built adjacent to the ALS. This building will be shared with the Advanced Device Concepts Laboratory. It will provide space for about 180 people.

The Advanced Materials Synthesis Laboratory will increase the effort devoted to basic studies of the physics and chemistry of electronic materials, and couple this work closely with electrical engineering research on microelectronics, circuit design, and circuit fabrication. An electronic materials synthesis facility will provide pure and doped bulk semiconductors and epitaxial films. An advanced ceramic processing facility will enable ceramic compositions, particle sizes, and product forming to be studied, controlled, and optimized at every stage of processing. A similar facility will be set up for metallurgy. Theoretical research to model the atomic and electronic structure of materials will unite with experimental research to confirm the structures, validate the theories, and thereby solidify the understanding of the relationship between microstructure and material properties. This theoretical effort will be a key part of research on materials produced via high pressure phase transitions. Such materials may, if metastable like diamond, have unique mechanical and other properties. Tiny samples of such materials, made in a diamond anvil can be probed using the ALS. As part of AMSL, new programs will be initiated in polymer science, in aqueous and salt corrosion, in the physical and mechanical properties of composites, and in solid-state chemical reactions.

During FY84 four research projects will be started at the AMSL: electronic materials synthesis and analysis, metal alloy design, zeolite synthesis and characterization, and studies of phase transitions at high pressure. These four projects are described in detail later in this chapter.

Advanced Device Concepts Laboratory (ADCL)

The Advanced Device Concepts Laboratory will be a leading facility to foster the development of novel concepts for devices. Pursuant to NCAM's emphasis on advanced materials, work at ADCL will be devoted to high-technology devices utilizing the new materials and to innovative approaches to the study of materials. Thus, research at the laboratory will focus especially on developing concepts for devices made possible by new or better understood materials, and for devices that will enable materials to be characterized and understood better. These basic studies will be directed toward fundamental understanding and toward new concepts for devices and systems that may take 5 to 15 years or longer to develop fully. Thus device research at ADCL will emphasize the long-range studies that will benefit U.S. industry. The ADCL will share with AMSL the L-shaped building adjacent to the ALS. The proximity of the two laboratories should facilitate the flow of ideas between the groups, thereby enhancing and stimulating both research efforts.

The Advanced Device Concepts Laboratory will integrate broadly interdisciplinary basic research. Specialists in computer-aided design, robotics, systems, and all fields of engineering will work with materials scientists to develop and test concepts for tomorrow's devices. A committee formed of research scientists from high-technology industry will be invited to advise the ADCL staff and suggest important device and systems problems to be tackled.

The program will start in FY84 with four projects: developing x-ray lithographic microscopy, generating concepts for designing reliable, highly stressed components made from advanced brittle materials, improving superconducting electronic devices, such as SQUIDs and Josephson junctions, and developing high-speed, sensitive detectors and devices required to exploit the infrared capabilities of the ALS.

NCAM FY84 Research Program

As construction starts on NCAM facilities, the research program will also get underway. This core program builds directly on expertise already available in the LBL-U.C. Berkeley science community. As NCAM grows from a proposal to a full-fledged national research center, there will be increasing participation by scientists and engineers from universities, industry, and government laboratories throughout the United States.

The initial research programs have been selected carefully to insure that NCAM evolves smoothly to a productive national research center. The core projects sample fundamental problems in most of the research areas to be pursued at NCAM, while expanding on the existing base of expertise, interests, and programs already in place at LBL. Moreover, some of the charter projects anticipate needs for new devices and materials to optimize the performance of the ALS, or they may require a long lead time to develop the high-technology facilities required for their research. In the following descriptions, the projects are grouped according to the designated NCAM laboratory

Surface Science and Catalysis Laboratory (SSCL)

The purpose of the SSCL is to further the fundamental understanding of the physics and chemistry of surfaces. Both basic and applied and both experimental and theoretical studies will

be performed. In FY84 there will be studies—primarily theoretical at first—of the atomic structure of solids and their surfaces, experiments to determine the response of surfaces to extreme conditions, and research to characterize new zeolites and other industrially promising catalysts.

Zeolite Synthesis and Characterization Program. Zeolites are the largest single class of catalysts used in industry. They are used commercially in many processes, for example to catalyze hydrocarbon cracking to produce high-octane gasoline, to prepare a precursor of dacron, and as a water softener in many detergents. In petroleum processing alone, zeolites save an estimated \$3 billion per year by increasing the yield of high-octane gasolines by 7 to 8 percent.

Zeolites are crystalline aluminosilicates. Their usefulness as catalysts derives from their intricate and elegant crystalline architecture. Pore openings within any particular zeolite have a well-defined shape and size that allow molecules with a compatible shape and size to enter. Thus, zeolites are shape-specific catalysts facilitating chemical reactions involving the favored molecules.

Whereas some zeolites are naturally occurring minerals, those used as industrial catalysts are primarily synthetic. The possible compositions and structures for synthetic zeolites are almost infinite. But the synthesis of new zeolites is largely a black art. The 50 to 60 synthetic zeolites made to date have been synthesized empirically—with no knowledge of how to achieve desired properties or structure. The common way to make zeolites is from aqueous solutions of sodium silicate and sodium aluminate, under controlled conditions of temperature, pressure, and pH.

One goal of zeolite research at NCAM is to develop a firmer scientific basis for the synthesis of zeolites, by obtaining a better understanding of the relationship between their structure and the way they are made. Armed with a basic understanding, researchers may be able to design zeolites to perform particular chemical tasks, and then synthesize the designed crystal. The approach will be to grow several types of zeolite crystals that differ in composition or synthesis technique, and to study in detail the development of structure, pore size, and chemical properties through the nucleation stage. Another approach to be explored is to try to construct them unit by unit, in a controllable way. One possibility is to synthesize them in organic solvents, to avoid the undesirable hydrogen-bonding and ionic-bonding that typically dominate reactions in aqueous solutions.

Atomic Structure of Solids: Surface and Bulk. Since almost all properties of surfaces depend on their atomic and electronic structure, determining this structure is perhaps the most basic problem in surface physics. The combined theoretical and experimental attack on this problem at SSCL should produce a deeper understanding of the atomic, electronic, and vibrational structure of surfaces. With this understanding, it may be possible to use the theory to suggest methods for developing surfaces with desirable properties.

The theoretical part of this research will focus on predicting bulk and surface crystal structures using quantum mechanical calculations. The method involves calculating the total energy for several candidate configurations of atoms, and selecting the minimum-energy geometry as the one preferred by nature. One approach is to calculate separately the energies from the two dominant types of interactions in solids: interactions between ions and electrons, and among the electrons. The ion-electron interaction is calculated using pseudopotentials, and the electron-electron interaction is the sum of Coulomb interactions and exchange-correlation interactions. Another approach—pioneered at U.C. Berkeley and LBL—determines the total energy of a solid by modelling it as a system of electrons and ions using a Fourier combination of atomic-like

orbitals. This method saves significantly on computer time and memory when complicated atomic structures are being considered.

Initially work will concentrate on determining the atomic and electronic configuration of exposed surfaces of silicon, germanium, and carbon, and of interfaces, such as heterojunctions and Schottky barriers, between two different solids. The electronic and atomic structure of these surfaces control their properties. Subsequently, techniques will be perfected to calculate where and how adsorbates attach themselves to a semiconductor surface, and to gain an atomic-scale understanding of the catalytic properties of the surfaces of transition metals.

In parallel with these theoretical activities, experiments to check and confirm the structure of the modelled surfaces will be performed using advanced Low Energy Electron Diffraction (LEED), Surface Extended X-ray Absorption Fine Structure (SEXAFS), photoelectron diffraction, and atomic-resolution electron microscopy.

Surface Properties Under Extreme Conditions. Extreme conditions of pressure, radiation, and chemical attack alter the structure and composition of the surfaces of materials. The changes induced may be beneficial when they improve the mechanical or chemical integrity of the surface by forming a protective coating. Alternatively, the extreme conditions may destroy the surface. Research at SSCL on surface properties under extreme conditions will obtain insight useful for minimizing surface damage and for designing new coatings and materials that are especially resistant to attack.

Three major projects will be initiated eventually under the umbrella of this proposal. Most likely only one program will start in FY84. The other efforts will be added as NCAM's research program expands.

The FY84 research will concentrate on plasma deposition as a technique for applying surface coatings. Protective layers can be deposited from low-energy plasmas onto any material. The correlation between the coating structure and the energy states of molecules and molecular ions in the plasma will be determined in order to understand the mechanism of plasma deposition. With this knowledge, it should be possible to control the process of plasma deposition to tailor the properties of the coating for the intended use.

A later project will use the ALS to probe surfaces modified by intense radiation, inflicted for instance by laser light. With an understanding of the way radiation affects surfaces, techniques for protecting the surfaces can be developed, and techniques exploiting the mechanism of radiation damage can be harnessed to produce beneficial changes in the surfaces. One aspect of this study will strive to develop new techniques for studying radiation-damaged surfaces.

The third study will seek to understand at a molecular scale the interface between two different solids, such as metals and oxides or polymers and inorganic materials. The behavior of such interfaces controls the phenomena of lubrication and adhesion—two industrially important processes.

The ALS will be an excellent tool for studying the structure of surfaces and for monitoring the way they change under extreme conditions. It may be possible to use the ALS to see into the solid and probe the transition region between the altered surface and the undisturbed interior. The time structure of the ALS should allow the process of surface change to be monitored with unprecedented clarity.

Advanced Materials Synthesis Laboratory (AMSL)

Initially four research projects will be developed in the Advanced Materials Synthesis Laboratory: electronic materials synthesis and analysis, metal alloy design, studies of crystal structures and phase transitions at high pressure, and zeolite synthesis. The zeolite research program will be a joint effort with the SSCL, and is described under that laboratory.

Metal Alloy Design. Both product-oriented and technique-oriented research related to processing metallic materials will be performed at AMSL. Initially the product-oriented research will focus on "near net-shape processing" to minimize waste and costly intermediate processing performed primarily by foreign industry. The technique-oriented studies will emphasize on-line metals characterization and process control. These efforts could help boost the competitive position of the domestic metals industry, if it adopts the new technology.

Research to establish weld spinning as a viable technique for manufacturing large metal structures will be a top priority. In weld spinning, metal structures can be produced in their final shape by spinning them continuously out of molten weld metal. This process naturally assures uniform properties and grain sizes throughout the metal structure, and thereby obviates the need for forging. Moreover, by varying and controlling the composition of each added layer of metal, it may be possible to overlay liners of special composition—corrosion-resistant, for example—that are difficult to add using conventional casting and forging techniques.

Improving on-line analysis and control of metals production will be a second major thrust of this research. The ALS should be an invaluable tool for this task. It will be a powerful and versatile test device for exploring and demonstrating the capabilities of intense light sources to reveal the structural and chemical properties of metal while it is being formed. In addition, the ALS can be used to probe in detail processes that can be monitored superficially by less sensitive techniques—using compact and affordable magnetic, electric, or acoustic sensors—and thereby calibrate those sensors so that they can be used with confidence, on-line in metals production.

The third effort in metal alloy design at AMSL will develop innovative techniques for metals processing. This research will expand on existing work to use high-powered lasers for treating metal surfaces. Lasers have been able to create on metals amorphous coatings that simultaneously resist wear and corrosion. The ALS should be an outstanding facility for creating such coatings, monitoring the formation of the coatings, and analysing their structure and properties.

Electronic Materials Synthesis. Research on electronic materials will have two major thrusts. While one emphasis will be to synthesize novel and useful electronic materials, a parallel effort will be to gain a comprehensive understanding of the formation, structure, composition, and interaction of both native and extrinsic defects in electronic materials. This latter work is especially crucial, because practically all electronic properties of the materials used in sensors and devices stem from impurities and defects.

The AMSL program on electronic materials will build on the expertise gained at LBL during the recent, highly successful effort to obtain bulk crystals of ultrapure germanium. This material, unmatched in purity and crystalline perfection, has become a new base for radiation detectors, as well as an incomparable material for studying the key role impurities and defects play in determining the electronic properties of a semiconductor.

Initially, research on synthesizing electronic materials will concentrate on growing crystals of ultrapure silicon and of gallium arsenide. High-purity materials are needed to study the interactions between intrinsic defects and impurities that control electronic behavior. Impurity concentrations as low as 1 part in 10^9 —the purity of the best commercially available samples—

overshadow some of these key effects. At NCAM, crystal pullers for silicon will be able to grow large crystals with only 1 electrically active impurity per 10^{11} atoms of the material. Bulk gallium arsenide crystal—the substrate material for molecular beam epitaxy (MBE)—will be grown with improved structural perfection and without the chromium doping which is presently used to make them semi-insulating.

In parallel with the effort to grow crystals, the existing molecular beam epitaxy (MBE) facility will be expanded to allow some problems associated with that technique for making layered semiconductors to be addressed. Specifically, it is hard to control the quality and reproducibility of the crystal layers. Research at NCAM will address the following aspects of this problem: control of purity and doping concentrations, investigation of possible ways to improve the sticking coefficient of arsenic and phosphorus, and establishment of optimal growth conditions and an automatic growth program. As a long-term goal, NCAM electronic materials research will seek to adapt the MBE process for fabricating layered dielectric and magnetic materials, and explore its potential for fabricating microcircuitry.

At AMSL, analysis of the ultrapure and new materials will focus on understanding their electronic behavior. The ALS and other advanced instruments should make it possible to image defects in semiconductor crystals and to study the electronic structure of shallow and deep centers with very high energy resolution.

High Pressure Crystal Structures and Phase Transitions. High-pressure forms of crystalline substances offer an almost untapped source of new materials. These materials, if metastable under normal pressures, may have unusual properties that can be put to good use. Research at AMSL will concentrate on determining the structure of high-pressure phases of crystals as well as on studying the process of phase transformation. The work will combine ongoing theoretical studies of crystalline structures with a new experimental effort using the ALS to probe the structure and to obtain time-lapse snapshots of the atomic rearrangements occurring within a crystal during a phase change.

Initially this research will focus on predicting from first principles the conditions under which several pure crystalline elements change their structures. In addition this work will indicate what the properties of the high-pressure forms will be, and whether they should be stable under ordinary conditions. Calculations will be made for tetrahedrally coordinated semiconductors, simple metals, and Group V semimetals. Already, successful computations have been made for two semiconductors, germanium and silicon, and for a simple metal, aluminum. Similar calculations are planned for carbon and for other simple metals, including beryllium, magnesium, zinc, cadmium, thallium, indium, gallium, and lead. The Group V semimetals are highly isotropic, and require, therefore larger computational facilities than cubic or hexagonal elements. They present, however, a fascinating series of phase transitions, which, although understood quantitatively, still require enormous amounts of theoretical effort. In particular, bismuth is known to make transitions from its ordinary-pressure rhombohedral semimetallic phase to a rhombohedral semiconductor, and subsequently to a simple cubic metal. Calculations of its properties are planned for FY84.

With the occupation of localized f-levels, transition metals present one extra degree of freedom in their structure, and therefore an added computational challenge. These metals have valence transitions at high pressure. For example, at high pressure, cerium changes from its gamma phase, in which the f-level is occupied by one electron to an alpha phase, in which the f-level occupancy is nominally zero. The interesting phenomenon, however is caused by

fluctuations between the two occupancies, which gives rise to intermediate valence states. New methods based on functional density formalisms are being developed now at LBL. If successful, these methods may make it possible to calculate such phase transitions and to understand more thoroughly the physics of valence instabilities and their phase transitions.

As the theoretical and computational capabilities improve, this research will be expanded to include studies of superconductivity under pressure. A variety of solids, including organic TMTSF (tetramethyl-tetraselena-fulvalene) salts and magnetic semiconductors become superconducting under pressure.

An experimental program using the ALS to monitor atomic rearrangements during phase transitions will be set up. Preliminary studies will be performed to make sure that experimental stations at the ALS can be equipped with diamond anvil cells for obtaining high hydrostatic pressures, and that the proper equipment is developed to measure the optical properties of solids undergoing phase transformations.

Advanced Device Concepts Laboratory (ADCL)

The Advanced Device Concepts Laboratory will be a leading facility to foster the development of novel concepts for devices. Initially four projects will be undertaken at the ADCL: developing techniques and devices for x-ray lithographic microscopy, generating concepts for designing reliable components made from brittle materials, improving superconducting devices such as SQUIDS and Josephson junctions, and developing the devices required to exploit the infrared capabilities of the ALS.

Structural Design with Brittle Materials. The hardness, strength, chemical resistance, and electrical and thermal properties of brittle materials, such as ceramics and glasses, make them outstanding candidates for many uses. But their tendency to break prematurely eliminates them from many considerations. Research at the ADCL will provide a sound scientific basis for designing reliable components made from advanced brittle materials. The thrust of the work will be threefold. It will develop a method for testing brittle materials nondestructively, using intense infrared light to image and characterize flaws. It will devise and validate a computer-aided procedure for evaluating the probability that a component with a certain flaw distribution will fail in its intended use. Finally, it will develop innovative designs for devices that use brittle materials in ways that do not stress them to their breaking point.

Initially, work will concentrate on developing a finite-element computer program that incorporates weakest-link statistics. The program will calculate the survival probability of individual, small volume elements of the component on the basis of the stresses they experience and their flaw population. Then weakest-link concepts will be applied to determine the probability that the entire component will survive. The results of controlled experiments performed in parallel with the numerical work will be used to validate the computer algorithms.

Research to devise novel methods for evaluating individual brittle components before they are built into devices will also start immediately. Such methods would improve the reliability of devices by allowing manufacturers to reject defective components. One promising, nondestructive probe uses intense, well-focused infrared light from a source, such as the ALS, to image and characterize small flaws and incipient cracks in and on the brittle components. In FY84, the technique will be tested at the National Synchrotron Light Source, using samples of Si_3N_4 , Al_2O_3 , and Si with well-controlled surface flaws. Subsequent studies will examine the flaws beneath machined surfaces, and attempt to relate the flaw measurements to the probability the

specimen will fail.

In FY86 and beyond, this project will develop innovative design concepts for making high-technology devices from brittle materials. These computer-aided designs would get around the fragileness of the brittle components by using them in ways that did not stress them to their breaking point. Used in compression, ceramic components of turbine engines, for instance, would not be likely to break. However, turbine engines and other devices to be built with brittle components must be significantly redesigned to insure that the components experience only compressive stresses.

The advanced design work will rely strongly on the understanding obtained through experimentation and finite-element modelling, of the flaws within brittle materials, and how these flaws control a brittle component's mode of fracture. Proposed designs will be evaluated using the finite-element program, and the most reliable design will be selected.

Infrared Capabilities of the Advanced Light Source. The purpose of this project is to prepare for the ALS to be a source of infrared radiation, especially for spectroscopy. As an infrared source, the ALS should be about 100 times brighter than standard laboratory sources. Furthermore, its radiation will span a broader spectral range—into the far infrared—than is available conventionally, and the rapid, pulsed nature of light from the ALS will make possible spectroscopic studies of fast chemical processes. To exploit both the brilliance and the time structure of the ALS fully, however, requires developing special spectroscopic systems and beam-line components.

A bend magnet on the ALS will provide a beam of infrared radiation which is diffraction limited in the vertical direction and which fans out into the full bend angle of 10° in the horizontal plane. The time-averaged brilliance of this source is equal to that of a black body with a temperature of $3 \times 10^5 \text{K}$. During a 35 picosecond pulse, however, the brilliance is equivalent to that of a black body at about 10^7K . By comparison, standard laboratory infrared sources are black bodies at 1000K to 3000K—a factor of 100 to 10,000 dimmer. Wigglers and undulators will not increase the infrared spectral brilliance obtainable from the ALS.

Initially the work will concentrate on designing and building a beam line to extract the infrared signal from a bend magnet on the ALS and convey it to an experiment area. Provisions will be made to switch the beam to any of several types of infrared spectrometers. For example, to permit conventional spectroscopy in the far infrared, and to evaluate the infrared output of the ALS, a Fourier transform spectrometer will be used, equipped with special detectors designed to span the far infrared. To perform time-resolved experiments, however, a diffraction-grating monochromator capable of a spectral resolution on the order of 1 cm^{-1} will be required. In addition, high-speed infrared detectors and fast electronic systems must be developed to make the measurements in time-resolved experiments.

An experimental program will be initiated to evaluate the properties of the ALS as an infrared source and to explore its novel features. These studies should provide important new scientific data as well as testing the capabilities of the ALS. For instance, the fast time structure of the ALS will be tested by using it to make detailed measurements of the relaxation processes which determine the speed of response of photoconductive infrared detectors, and which play a role in the operation of other fast semiconductor devices. For experiments of this type, the sample can be excited using light from a laser, using electrical pulses, or with light from the ALS. The subsequent relaxation will be probed using repetitive pulses from the ALS.

Finally, new infrared spectroscopic techniques may be possible with the ALS. The narrow, bright, fan-shaped beam may make it possible to measure infrared optical properties in a

scattering geometry. This novel technique could enable small samples, such as quasi-one-dimensional conductors, to be probed. These conductors are currently the subject of active research in solid-state physics because they harbor many fascinating phenomena. Some of these phenomena, such as plasma frequencies, phonon modes, and energy gaps due to superconductivity, charge-density waves, and spin-density waves, lie at far-infrared frequencies. The brilliance of the ALS may also make possible grazing-incidence infrared spectroscopy—a technique that could reveal the vibrational spectral of molecules chemisorbed on surfaces. The eventual goal is to observe chemical reactions, as they take place on surfaces.

High Temperature SQUIDS. Research at the ADCL will seek to improve superconducting electronic devices. Initially, the effort will focus on SQUIDS—Superconducting QUantum Interference Devices. Later, the developed technology may be applied to other superconducting devices, such as computer elements, analog-to-digital converters, and far-infrared detectors.

Exceedingly sensitive detectors of voltages and magnetic fields, SQUIDS are at the heart of sophisticated tools used now in geophysical prospecting, biomedicine, and laboratory instrumentation. They would be more sensitive, however, if they were smaller, and more useful if they could operate at higher temperatures, in the range 10 to 12K, now achievable in commercially available cryocoolers. Most SQUIDS now operate at 4.2K and must be kept cold using liquid helium.

The main thrust of work on SQUIDS at the ADCL will be to make the devices and their key superconducting components smaller, more reliable, and able to operate at temperatures around 10 to 20K. Josephson junctions, consisting of two layers of superconductor separated by an ultrathin, electrically insulating oxide layer, are the main components of SQUIDS. A SQUID includes two Josephson junctions connected in parallel on a superconducting loop.

Critical to this effort will be research to understand and minimize low-frequency flicker noise ($1/f$ noise) that arises both within the superconducting material and within the Josephson junctions. This noise limits the capabilities of SQUIDS. Recent research at Cornell indicates that the $1/f$ noise in the junctions comes from localized states or defects in the insulating layer. Ionization of these states modifies the energy barrier provided by the oxide layer, thereby making it easier or harder for electrons to tunnel through the barrier. Since electrons tunneling through the barrier produce the desirable signal from the SQUID, defects in the barrier cause fluctuations—noise—in the signal. The fewer defects there are, the quieter the junction. Therefore one goal is to fabricate Josephson junctions with characteristics as near to ideal as possible. To develop or select the best method for fabricating low-noise junctions, ADCL scientists will use many different controlled methods for making Josephson junctions out of niobium. Then they will analyze and compare the density of localized states in the insulating barrier using synchrotron radiation and other techniques.

Noise in the superconducting material itself probably comes from the motion of trapped flux lines. To understand it in the hopes of minimizing it, the researchers will study the $1/f$ noise in several different superconductors.

In parallel with the work on niobium—a metal that becomes superconducting at 9.5K—other research will focus on making “high-temperature” Josephson junctions and SQUIDS. Such devices might be based on niobium nitride or niobium tin, which have critical temperatures around 16K and 18K, respectively. High-quality SQUIDS made from these materials could be incorporated in almost any instrument, because they could be kept superconducting by commercially available cryocoolers. Special effort will concentrate on optimizing the reliability and

sensitivity of these devices, while minimizing their $1/f$ noise. One approach is to make them smaller, since smaller SQUIDs and Josephson junctions are inherently more sensitive and less noisy than larger ones. X-ray lithography using the ALS will be explored as a promising method for miniaturizing Josephson junctions, SQUIDs, and other electronic devices.

After they are perfected, very reliable, high-temperature Josephson junctions could become the heart of next-generation supercomputers. In turn, very reliable SQUIDs could be used in instruments to detect gravity waves. The SQUIDs could increase the sensitivity of gravity-wave detectors phenomenally. Whereas current detectors can sense at best one gravity wave in several months, SQUID-based instruments should detect several gravity waves per week, if current theories about gravity waves are correct.

X-ray Lithographic Microscopy. A new technique for probing the structure of living cells will be developed and tested at the ADCL. The technique will use x-rays from the ALS to reveal the details of the cell lithographically. The lithographic record, itself very fragile, will be copied onto a sturdy and durable ultrathin replica that can be examined using a high-resolution transmission electron microscope. The National Center for Electron Microscopy at LBL has ideal electron microscopes for these purposes.

X-ray lithographic microscopy using synchrotron radiation can be a very powerful tool for looking at biological specimens. The ALS will be such a bright source in the energy range of interest (100 eV to 1 keV or wavelengths between 1 and 10 nm), that exposure times on the order of seconds to minutes may be adequate to reveal the structural details in the specimen. Short exposures tend to inflict less damage on the sample and can capture the specimen's structure during dynamic processing without the blurring associated with long exposure times. Moreover, the intensity of the beam allows thick, uncut cells and micro organisms to be examined, even in an aqueous environment. Thus the topological features of the living organism should remain intact. This aspect of x-ray lithographic microscopy is a clear advantage over transmission electron microscopy, which requires that samples be cut into a thin enough slice that electrons can pass through to the recording photographic film or to the detector. The spatial resolution attained with x-ray lithographic microscopy has yet to reach the ultrahigh-resolution standard set by TEM. Unique information should be available, however, at considerably higher resolution than that of conventional, light microscopy.

Initial research will perfect the techniques for replicating the lithographic record of the x-ray image. The replicas will be made of a very thin carbon-platinum layer, and will be quite durable even under the viewing conditions of an electron microscope. Solvents must be found to insure that residual resist is removed from the replica. In addition, the extent to which the replication process distorts the image will be measured and minimized.

Parallel studies will focus on the original lithographic record—a photoresist. Available resist materials are very susceptible to damage by the electron beam while they are being viewed under the electron microscope. Collaboration with a polymer research program to be set up soon at NCAM will aim at developing durable x-ray resists that can be viewed directly without damage, using transmission electron microscopy. Currently damage to the resist can be the factor limiting the accuracy and spatial resolution of x-ray lithographic microscopy if a replica is not made.

The researchers plan to use the new technique to study important types of cells and fundamental biological processes. These uses will also test the capabilities of the technique. Two cell systems that are currently under investigation by the structural biophysics group at LBL will be

the first to be probed with the new technique. Considerable information on the microstructure of these systems is already at hand. Therefore, the capabilities of x-ray lithographic microscopy can be checked by comparing the images with the known structural features of these systems. At the same time, each of the systems has questions associated with its structure that have not been answered by applying present techniques, yet that could very likely be answered with the data to be obtained from x-ray lithography.

The two cell systems to be studied are pulmonary macrophage cells and the helical sperm cell of the octopus, *Eledone cirrhosa*. Pulmonary macrophages consume minute, foreign particles and bacteria, thereby keeping lung tissue clean. This process, termed phagocytosis, remains an area where much is still to be learned. Images made using x-ray lithographic microscopy of whole-cell macrophages could help to reveal the structural changes occurring during phagocytosis.

Although the helical sperm cell of the octopus has been studied by a variety of biophysical techniques, the internal structure has been difficult to reconstruct. X-ray lithographic microscopy, since it can view whole cells, could provide clues for uncovering the structural secrets that help the cell maintain its unusual, large, helical form. In addition, the cell should be an excellent sample for testing the fidelity and resolution of x-ray lithographic microscopy.

An added dimension for x-ray microscopy using the ALS exploits the distinctly different signatures of the low-Z elements in the spectral range between 50 eV and 1 keV. The differences are due to k-edge absorptions in these elements. By selecting carefully the wavelength of the synchrotron light used to etch the resist, it should be possible to make an image that highlights the distribution of a particular low-Z element. Then one could identify on the x-ray image or its replica areas of a specimen that are particularly rich or poor in the selected element, and thereby gain added insight into elemental distribution and the association between small-volume microchemistry and important biological processes.

3 Advanced Light Source

Introduction to Synchrotron-Radiation Sources

The Advanced Light Source (ALS) is a synchrotron radiation source consisting of a 50-MeV linear accelerator, a 1.3-GeV "booster" synchrotron, a 1.3-GeV electron storage ring, and a number of photon beam lines, as shown in Figure 3-1.

As an introduction to a detailed description of the Advanced Light Source, this section provides brief discussions on the characteristics of synchrotron radiation and on the theory of storage rings.

Characteristics of Synchrotron Radiation

Over the past several decades, the construction of particle accelerators and storage rings dedicated to high-energy physics research has led to the capability to store electron beams at high energy (up to many GeV) for periods up to many hours. When a circulating electron beam is deflected by the bending magnets in a storage ring, an intense flux of electromagnetic radiation, called synchrotron radiation, is produced. Relativistic effects cause this synchrotron radiation to be emitted in a narrow cone centered about the electron-beam direction. For electron energies on the order of 1 GeV, the half-angle of this cone is typically a fraction of a milliradian. Originally, synchrotron radiation was viewed primarily as an annoyance, because of the need to compensate for the electron-beam energy loss by using a powerful radiofrequency accelerating system. However, it was soon recognized that synchrotron radiation is useful for a wide range of physical, chemical, and biological experiments, quite unrelated to the original purpose of electron storage rings. More recently, electron storage rings specifically dedicated to producing synchrotron radiation have been designed and constructed. Most storage rings in this second generation of synchrotron-radiation sources are just becoming operational.

Two measures of photon beam intensity will be defined here, to permit comparisons of photon beams. First, we consider the quantity called "spectral brilliance," which is measured in the following units:

$$\text{Spectral Brilliance} = \frac{\text{number of photons}}{\text{s} \cdot (\text{mm})^2 \cdot (\text{mr})^2 \cdot (0.1\% \text{ bandwidth})}$$

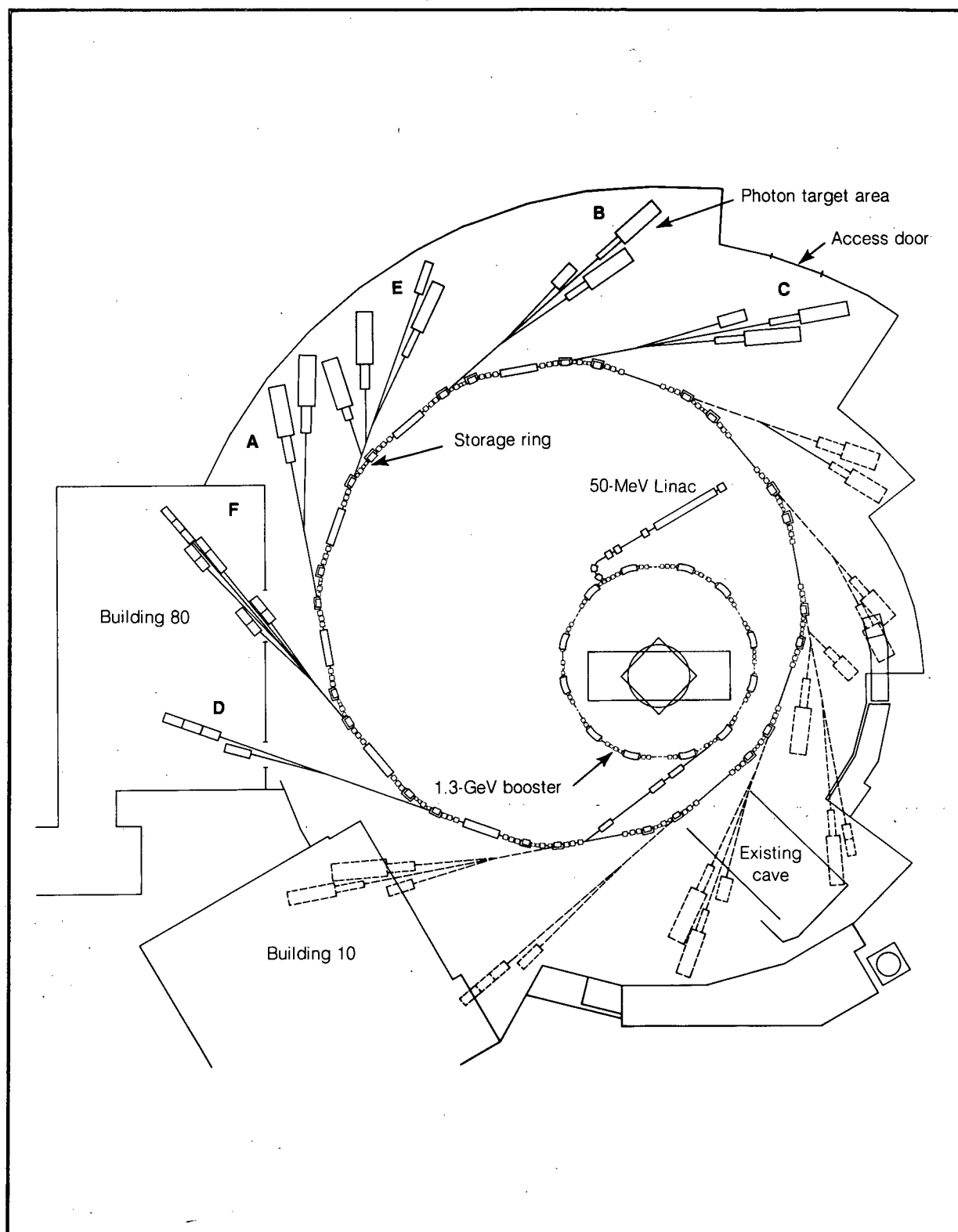


Figure 3-1. General plan for Advanced Light Source

XBL 833-8926

This quantity is the spectral intensity of the radiation divided by the phase-space volume into which the radiation is emitted. (The phase-space volume is the product of the cross-sectional area of the electron beam, measured in mm^2 , and the solid angle of the cone of radiation, measured in mr^2 .) A second useful measure of photon intensity is usually called "photon flux," defined as

$$\text{Photon Flux} = \frac{\text{number of photons}}{s \cdot \text{mr}(\theta) \cdot (0.1\% \text{ bandwidth})}, \text{ for all } \psi.$$

This quantity is the spectral brilliance integrated over the following three variables: the electron-beam width, the electron-beam height, and the vertical angle ψ . Note that the photon flux is still a differential quantity with respect to the horizontal angle θ . For experiments that require the synchrotron radiation to originate from a small volume in phase space, spectral brilliance is a figure of merit for photon intensity. For experiments that can use photons from a large volume of phase space, the integrated quantity of photon flux is a better measure of intensity.

Storage-ring dipole bending magnets, which keep the electron beam in its approximately circular orbit, can produce useful beams of synchrotron radiation. However, special magnetic devices inserted in storage-ring straight sections can produce far more intense photon beams with greater flexibility in terms of photon beam characteristics. These magnetic devices, called "wigglers" and "undulators," are characterized by static transverse magnetic fields that alternate in direction periodically as the electrons traverse the length of the device. The distinction between wigglers and undulators is given by the dimensionless parameter

$$K = 0.934 B \lambda_w$$

where B is the magnetic field (in Tesla) and λ_w is the spatial period (in cm) of the alternations of the field. for $K \gtrsim 10$, the magnetic device is called a "wiggler," and the spectral distribution of the synchrotron radiation is smooth and wide, as it is for a bending magnet. That is, in a wiggler the interference effects of the radiation are small, and the wiggler acts like a series of bending magnets whose synchrotron radiation combines to provide an intense beam. Wigglers particularly enhance photon flux. For values of $K \lesssim 1$, however, interference effects are important, and the device is called an "undulator." The synchrotron radiation from an undulator is spectrally compressed into a series of narrow peaks (see Figure 3-2), so undulators can provide unparalleled spectral brilliance. More detailed discussions of the radiation from wigglers and undulators are available in the literature [1].

It should be noted that the effect of a wiggler or an undulator on the operation of a storage ring is much less than that of a bending magnet of comparable strength, because of the cancellations produced by the spatially alternating fields. Therefore, one has far greater flexibility in selecting undulator and wiggler parameters than in selecting bending-magnet parameters. This flexibility is particularly useful because the energy of the synchrotron-radiation photons can be controlled by selecting the strength of the magnetic field without changing the electron energy.

Theory of Storage Rings

This subsection will present a brief discussion of the theory of electron storage rings. Some basic concepts concerning transverse and longitudinal particle dynamics will be introduced, and some important beam-loss mechanisms will be discussed.

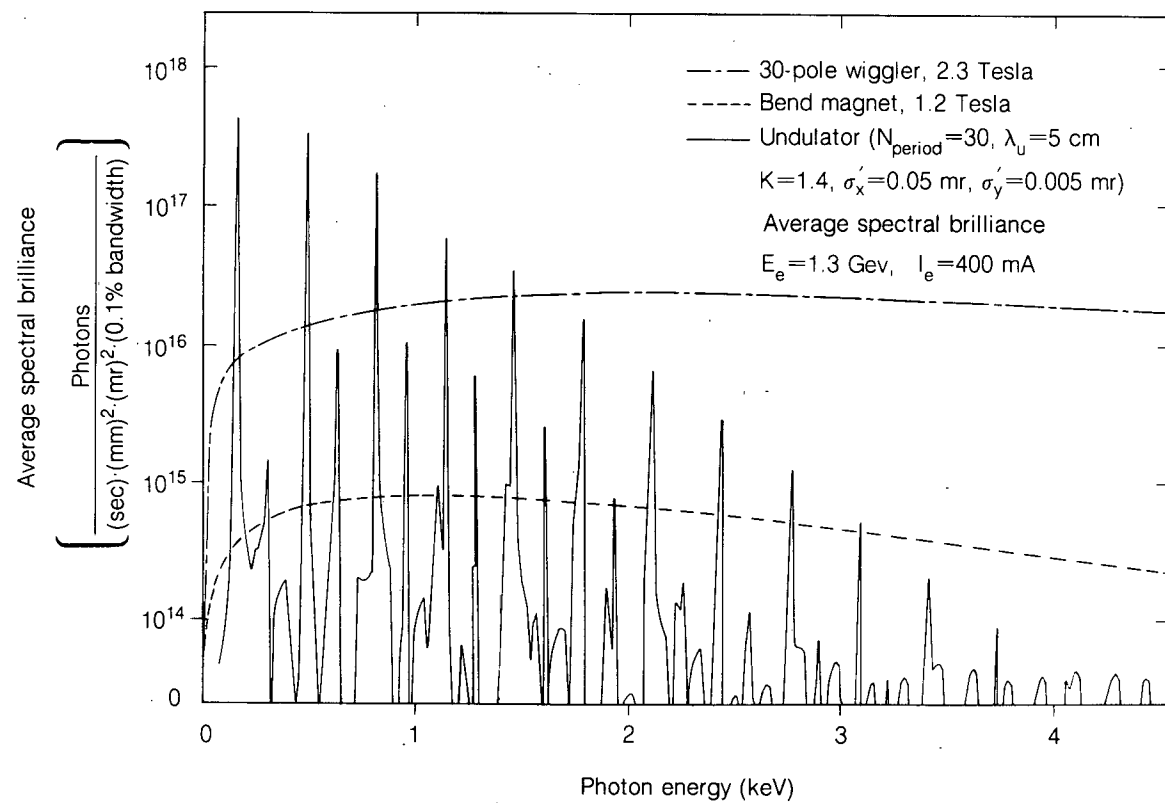


Figure 3-2. Spectral brilliance of bend magnet, wiggler, and undulator.

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The periodic arrangement of bending and focusing magnets, separated by field-free drift regions, is called the “*lattice*” of a storage ring. From the viewpoint of particle dynamics, this lattice and the radiofrequency (rf) accelerating structure are the fundamental components of a ring [2,3].

The *transverse motion* of particles may best be described in terms of deviations from the “equilibrium orbit.” This equilibrium orbit is the unique periodic solution of the equations of motion for a particle with the nominal momentum, p_0 . It has the property of being closed on itself and is characterized by a local curvature $\Omega(s) = 1/\rho(s)$, where s is the distance measured along the orbit. A general particle trajectory may be described by $x(s)$ and $y(s)$, the horizontal and vertical distances from the equilibrium orbit. For a particle with momentum $p = p_0 + \Delta p$, the equations of motion, to first order, are as follows:

$$\frac{d^2x}{ds^2} + K_x(s) \cdot x = \frac{1}{\rho(s)} \frac{\Delta p}{p_0}$$

$$\frac{d^2y}{ds^2} + K_y(s) \cdot y = 0$$

The right-hand side of the second equation is zero for accelerator designs in which the beam bending magnets deflect the beam only in the horizontal plane. The functions K_x and K_y are determined by the lattice elements, and they are usually piecewise constant.

The “pseudo-harmonic” solutions to these equations of motion are given in terms of the “betatron oscillations” of the particle trajectories. For a particle with nominal momentum p_0 , a trajectory in either plane may be described in terms of oscillations whose amplitude depends on the initial conditions and is proportional to $\beta^{1/2}$, where $\beta(s)$, the Courant-Snyder “beta function,” is a positive function that depends on the lattice configuration and has the same periodicity as the lattice. This beta function has units of length and is readily calculated using computer codes. The phase of the betatron oscillations is given by

$$\psi(s) = \int_0^s \frac{ds}{\beta(s)}$$

The trajectories of off-momentum particles exhibit an additional deviation from the equilibrium orbit in the horizontal plane, and this offset is given by

$$x_p = \eta(s) \frac{\Delta p}{p_0}$$

where the dispersion function $\eta(s)$ depends on the lattice configuration and is periodic in s .

The “tune” of an accelerator, i.e., the number of betatron periods corresponding to the accelerator circumference C , is given by

$$\nu = \frac{1}{2\pi} \int_0^C \frac{ds}{\beta(s)}$$

The electron beam in a storage ring is normally characterized by a Gaussian density distribution in both transverse directions, so the density distribution may be conveniently described by a standard-deviation width σ . In terms of the lattice functions β_x and β_y , the beam emittances are defined as

$$\epsilon_x = \frac{\sigma_x^2(s)}{\beta_x(s)} \quad \text{and} \quad \epsilon_y = \frac{\sigma_y^2(s)}{\beta_y(s)}$$

The *longitudinal motion* of an electron is dominated by a balance between the energy loss from synchrotron radiation and the compensating energy gain from the radiofrequency accelerating system. The time-averaged synchrotron-radiation power loss per electron is given by

$$P_\gamma = \frac{2}{3} \frac{r_0 c}{(m_0 c^2)^3} \frac{E^4}{\rho^2}$$

where E is the electron energy and r_0 is the classical electron radius. The energy loss in one turn is then

$$U_0 = P_\gamma T$$

where T is the transit time for one turn. This energy loss is compensated by the rf acceleration voltage

$$V(t) = V_0 \sin(h\omega_0 t)$$

where h is an integer (the "harmonic number") and ω_0 is the revolution frequency in radians per second of a particle with $p = p_0$. If $eV_0 > U_0$, the electron beam can be captured in h stable bunches around the circumference of the storage ring.

Synchrotron radiation is emitted in a forward cone centered about the electron direction of motion, so the electrons lose both longitudinal and transverse momentum. Since the rf system restores only the longitudinal component of momentum, the transverse electron motion is *damped*. Energy damping also occurs, because particles with different momenta follow different trajectories and experience different energy losses.

The above results are obtained by assuming a continuous energy loss from radiation. However, synchrotron radiation is actually a statistical process involving the loss of energy in discrete quanta, and there is a *quantum excitation* of the beam in the horizontal plane in regions with non-zero dispersion. This excitation leads to a random-walk diffusion superimposed on the damping process. The competition between damping and quantum excitation leads to equilibrium values for the energy spread and horizontal emittance of the electron beam. Emittances are larger at higher electron energies.

In a perfectly constructed and perfectly aligned electron storage ring having no coupling between the horizontal and vertical planes, the vertical emittance of the electron beam would

become negligibly small. However, in any actual machine, the unavoidable construction and alignment errors produce closed-orbit errors, horizontal-vertical coupling, and vertical dispersion. In turn, these effects can produce a vertical emittance with a magnitude approaching that of the horizontal emittance.

To store the beam for long periods in an electron storage ring, it is necessary to avoid various types of *beam loss mechanisms*. These mechanisms may be categorized as single-particle effects (which do not depend on the number of circulating electrons) and collective effects (which depend on the magnitude of the circulating beam current).

The most important *single-particle loss mechanisms* are the linear and non-linear *resonances* of the storage ring. These resonances can lead to transverse beam growth and resultant beam loss; thus, they must be avoided through the careful selection of storage-ring parameters and the accurate construction of storage-ring elements. A related problem is the correction of the natural chromaticities of the storage ring (defined as $p \, d\nu/dp$) through the use of carefully placed sextupoles. *Gas scattering* also leads to particle losses and is controlled by maintaining an extremely good vacuum throughout the storage-ring vacuum chamber.

Collective effects may be subdivided into incoherent and coherent mechanisms. An example of an incoherent effect is the space-charge defocusing of the electron beam, including image effects. This defocusing is normally unimportant for tightly bunched beams, because of the cancellation of electric and magnetic forces at relativistic energies. However, if *ions* become trapped by the potential well of the beam, these forces do not cancel completely, and the electron beam can be focused. Since compensation for this effect may be difficult, the ions must be cleared from the vacuum chamber. Another important incoherent effect is the Coulomb scattering of particles within the beam. In the *Touschek effect*, the transverse momentum of particles within a dense bunch is transformed by hard collisions into longitudinal momentum, and particles are lost from the longitudinal potential well of the bunch. The severity of this problem depends on the charge density within each bunch, so it is exacerbated by a storage-ring design that has a very small electron-beam emittance. Designing for an acceptably long Touschek lifetime for the electron beam requires a careful selection of storage-ring parameters. *Multiple collisions* within a bunch are another manifestation of Coulomb scattering, and they can lead to an increase in the electron-beam emittance. This effect is small as long as the growth time resulting from multiple collisions is long compared to the radiation damping time.

Transverse and longitudinal *coherent instabilities*, which are due to interactions between the beam and its environment, are encountered in electron storage rings, and they must be controlled to achieve a large circulating current of electrons. These instabilities can be roughly divided into coupled-bunch oscillations and single-bunch (or internal) oscillations.

The source of *coupled-bunch instabilities* is easy to understand. Since each beam bunch oscillates in a three-dimensional potential well with three characteristic frequencies, the many bunches represent many similar oscillators that are coupled through the beam environment and that can drive each other on-resonance. The primary method for reducing coherent effects is to provide a spread in the oscillator frequencies. Longitudinally, this may be accomplished by adding a "Landau Cavity" to make the potential well more non-linear. Transversely, an rf quadrupole can be used to split the frequencies of the bunches. Alternatively, these instabilities may be controlled by altering the beam environment to decrease the coupling between bunches (reducing the impedance of the storage ring and rf cavities) or by adding active feedback to stabilize the bunches.

Internal-bunch modes are more difficult to correct. To control the transverse modes, the natural negative chromaticity of the storage ring must be corrected to zero by using sextupoles. For internal-bunch modes as well as coupled-bunch modes, the primary method of alleviating coherent instabilities is to reduce the impedance of the storage ring at high frequencies by providing a smooth vacuum chamber.

Storage Ring

The electron storage ring for the ALS has a nominal operating energy of 1.3 GeV, which has been chosen to provide intense photon beams of the desired energies.

Design Considerations

The design of the Advanced Light Source has been optimized to achieve two major goals. This facility is designed to provide intense photon beams (especially in terms of spectral brilliance) in the nominal energy range 0.1 eV to 5000 eV, and the ALS is designed to provide very short pulses of synchrotron light (tens of picoseconds) for the many experiments with timing requirements in this range. In order to achieve these goals, the storage ring incorporates twelve long straight sections in which special magnetic devices, wiggler and undulators, will provide intense beams of synchrotron light. Wiggler and undulator magnets have become increasingly important and successful as high-intensity synchrotron-radiation sources, and the capability to design and construct such devices has improved greatly. Therefore, the ALS will take advantage of the photon-beam intensity and the flexibility of such devices, and most or all of its photon beams will originate from wigglers and undulators rather than from bending magnets. Since wigglers can each service several photon beam lines, over 30 beam lines can eventually be constructed at the ALS from these sources as well as additional beam lines from bending magnets.

Aside from providing high photon-beam intensity, the use of wigglers and undulators has another important advantage. If the wiggler or undulator fields are higher than the bending-magnet field, the photons emitted will have higher energies than those from bending magnets. That is, a relatively low-energy electron beam can provide high-energy photons from a high-field wiggler or undulator. An electron energy of 1.3 GeV appears optimal for the ALS, since it will provide intense photon beams with energies from 0.1 to 5000 eV, the major region of interest. This electron energy is high enough for a long beam lifetime, yet low enough to permit a very low electron-beam emittance.

For the benefit of synchrotron-radiation experiments requiring high-energy photons, the ALS will be operated at electron energies up to 1.9 GeV. Photons with energies up to 10 keV will then be available from undulators, and photons with energies up to 40 keV will be available from a superconducting wiggler. However, at higher electron-beam energies the ALS will have an increased electron beam emittance and, therefore, reduced spectral brilliance in some photon beams. Also, the electron bunch lengths will be increased.

The low electron-beam horizontal emittance is very desirable for a synchrotron-radiation source, because a low emittance means a small cross-sectional area for the electron beam. In turn, a small cross-sectional area implies a high photon-beam spectral brilliance, as is evident from the definition of spectral brilliance given earlier. Furthermore, a small emittance for the electron beam permits the construction of very-high-performance undulators.

Several considerations are important in the choice of a frequency for the radiofrequency accelerating system. Foremost is the desire to provide a very short bunch length for the benefit of experiments with critical timing requirements. A fairly high frequency (around 500 MHz) has been selected to provide photon pulses approximately 35 ps long. For those experiments requiring long dead times between successive pulses, the storage ring will be operated with a few electron bunches, at lower average electron currents.

Major Parameters

The major parameters of the ALS can best be understood by making a comparison (see Table 3-1) with existing electron storage rings dedicated to synchrotron radiation. The most prominent feature of the ALS design is the large number of straight sections for wigglers and undulators. These special synchrotron-radiation sources will provide greatly enhanced photon-beam performance, as compared with bending magnets, and the required straight sections account for the relatively large circumference of the ALS. The second noteworthy feature of the ALS is the very small design value of the horizontal emittance of the electron beam. This emittance has been carefully minimized in the ALS design in order to maximize the intensities of the photon beams, in general, and to increase greatly the spectral brilliance of the undulator photon beams, in particular. The excellent performance of wigglers and undulators permits the selection of modest values for the electron energy and electron current, while maintaining outstanding photon-beam performance. In the table, comparisons are given for Aladdin, the storage ring located near Madison, Wisconsin, and for the National Synchrotron Light Source (NSLS), which operates two storage rings located at the Brookhaven National Laboratory in New York. The Stanford Synchrotron Radiation Laboratory (SSRL) uses the SPEAR storage ring at Stanford, California.

Table 3-1
Electron Storage-Ring Design Parameters

	ALS (Proposed)	Aladdin	NSLS (VUV)	NSLS (X-ray)	SSRL (SPEAR)
Electron Energy (GeV)	1.3 (1.9 max)	1	0.7	2.5	4
Electron Current (mA)	400	500	1000	500	100
Circumference (m)	182.4	88	51	170	234
Horiz. Emittance (10^{-8} π m-rad)	0.68	6	8	8	40
Bunch Length (ps)	35 (nominal)	80	400	400	100

Table 3-2 presents a more detailed list of parameters for the ALS electron storage ring. It should be emphasized that the selection of parameters is a process of compromising among competing, and often conflicting, design considerations. For example, a low electron-beam emittance requires very strong focusing in the storage ring, but this focusing leads to large values of

natural chromaticity, which can be difficult to correct. A more complex compromise arises from a consideration of the electron-beam lifetime, as limited by the intra-beam scattering (Touschek effect) and gas scattering. Since the Touschek effect depends on the electron energy, the electron current, the horizontal beam emittance, and the rf frequency and voltage, the choice of a set of these parameters is constrained by the necessity to design for an acceptable beam lifetime of more than 6 hours. Chromaticity is defined as $p \, d\nu/dp$.

Table 3-2
Advanced Light Source Design Parameters
(Electron Storage Ring)

Electron Energy (GeV)	1.3 (1.9 max)
Electron Current (mA)	400
Circumference (m)	182.4
Horiz. Emittance (π m-rad)	6.8×10^{-9}
No. of Superperiods	12
No. of Long Straight Sections	12
Length of Long Straight Sections (m)	6
Max. Horiz. Beta (m)	13.3
Max. Vert. Beta (m)	13.3
Horiz. Tune	13.8
Vert. Tune	7.8
Horiz. Chromaticity	-32.0
Vert. Chromaticity	-17.5
Energy Loss per Turn—Dipoles Only (keV)	64
Radiofrequency (MHz)	499.65
Harmonic Number	304

1.9-GeV Operation:

Dipole Field (T)	1.60
Max. Quad. Gradient (T/m)	22.9
Energy Loss per Turn—Dipoles Only (keV)	291

Figures 3-3 and 3-4 show the spectral brilliance of the ALS photon beams for an electron current of 400 mA. The spectral output of undulators consists of a number of sharp peaks, as shown in Figure 3-2. Figure 3-3 shows smooth curves drawn through the maxima of the spectral peaks for each undulator. The top curve in Figure 3-4, however, is the envelope of the curves in the preceding graph. For all ALS and NSLS curves in Figure 3-4, the electron beam vertical emittance was assumed to be one-tenth the horizontal emittance. Since the undulator spectra consist of peaks, it is necessary to vary the undulator fields to scan over all desired photon energies. For undulators constructed with permanent-magnet technology, the field strengths are varied by changing the magnet gaps. The label "average spectral brilliance" means that the spectral brilliance has been averaged over time, i.e., the small duty factor of the electron beam has been ignored. While an electron bunch traverses an undulator, for example, the instantaneous spectral brilliance is much higher than is shown in these figures. The instantaneous electron

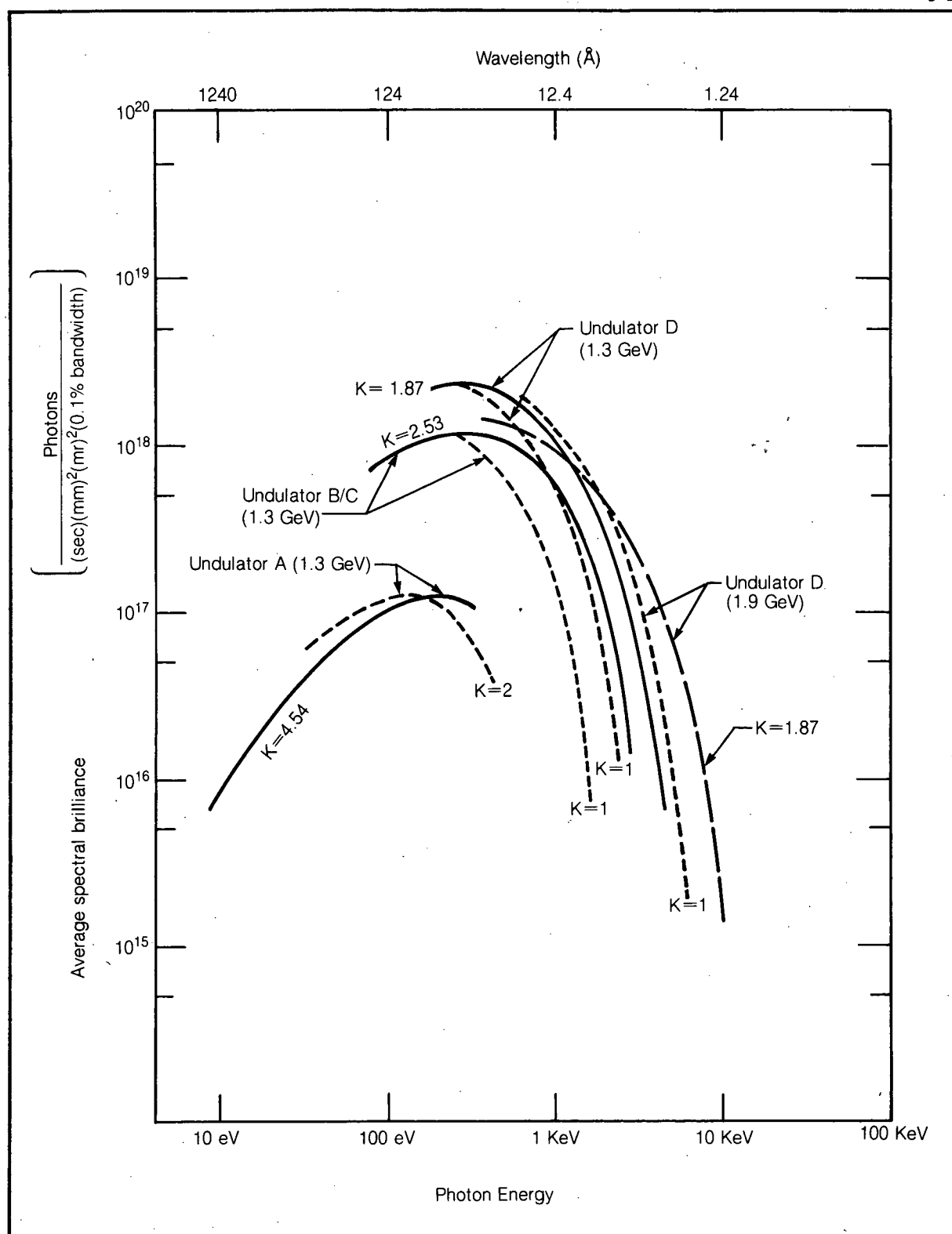


Figure 3-3. Spectral brilliance of ALS undulators.

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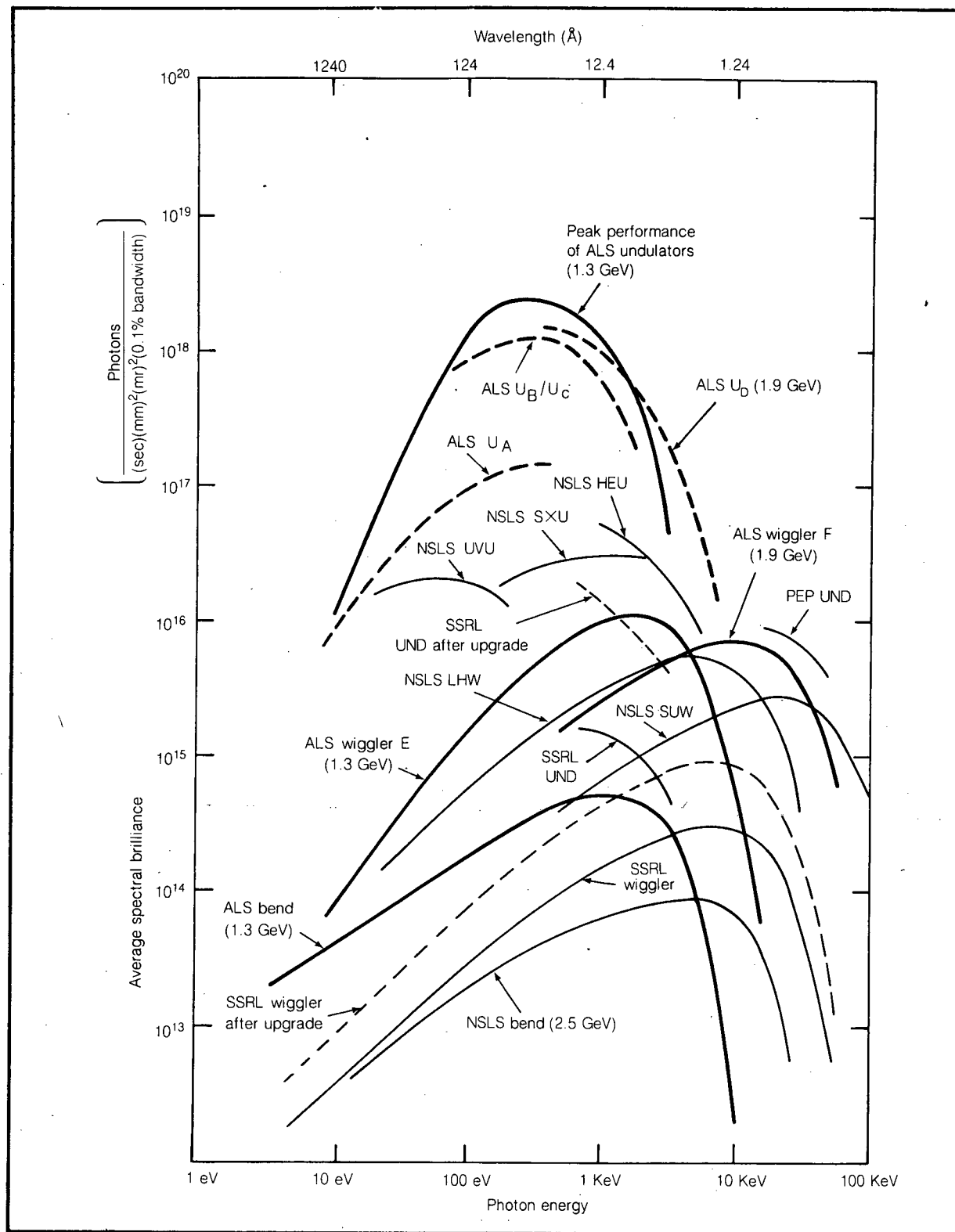


Figure 3-4. Spectral brilliance comparisons.

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current is tabulated for several operating modes later in this section.

To compute the spectral brilliance introduced in the above, one starts from the following quantity

$$\text{spectral brightness} = \frac{\text{number of photons}}{(s)(\text{mr})^2(0.1\% \text{ bandwidth})}$$

This quantity is unambiguously determined from electromagnetic theory. The spectral brilliance is then obtained by dividing the spectral brightness by an effective source area S , which is given by

$$S = 2\pi\Sigma_x\Sigma_y, \quad \Sigma_{x,y} = \sqrt{\sigma_{x,y}^2 + (\lambda L + \sigma_{x,y}'^2 L^2)/4}$$

in the case of a wiggler or an undulator of length L . Here, $\sigma_{x,y}$ and $\sigma_{x,y}'$ are the one-standard-deviation sizes and angular divergences of the electron beam, and λ is the wave length of the observed photon. S is a measure of the effective source area including the effects of diffraction and the extended nature of the source (i.e., depth of field effects). However, it should be mentioned that the definition of S is somewhat arbitrary and different authors may use different numerical factors. For a bending magnet source, both the diffraction effect and the depth of the field effect can be neglected (except in the far infrared region), so that

$$S = 2\pi\sigma_x\sigma_y.$$

Figure 3-5 shows the photon flux from the bending magnets at the ALS and the much higher photon fluxes from the ALS wigglers. Note that a superconducting wiggler magnet can provide photons with energies up to about 40 keV. These curves are calculated for a current of 400 mA.

The theory of electron storage rings has not been developed to the point where we can predict with complete certainty the peak operating parameters that can be achieved with a storage ring. Nevertheless, in this section we shall present the approximate parameters for a few ALS standard operating modes and also discuss the limitations on these parameters. The "initial performance goals" which are given in Table 3-3 represent the state-of-the-art performance as scaled from existing storage rings, and these figures may be used as a general guide by prospective users of the ALS. The peak currents in this table can be used to calculate instantaneous spectral brilliances and photon fluxes from Figures 3-4 and 3-5, which show curves for 400 mA average current. The "ultimate performance goals" represent some extrapolation from current experience, and they should not be used to plan synchrotron radiation experiments at this time. However, these ultimate goals are consistent with presently understood limits on storage ring performance, and it is our intent to design the ALS so that it can be operated at these conditions.

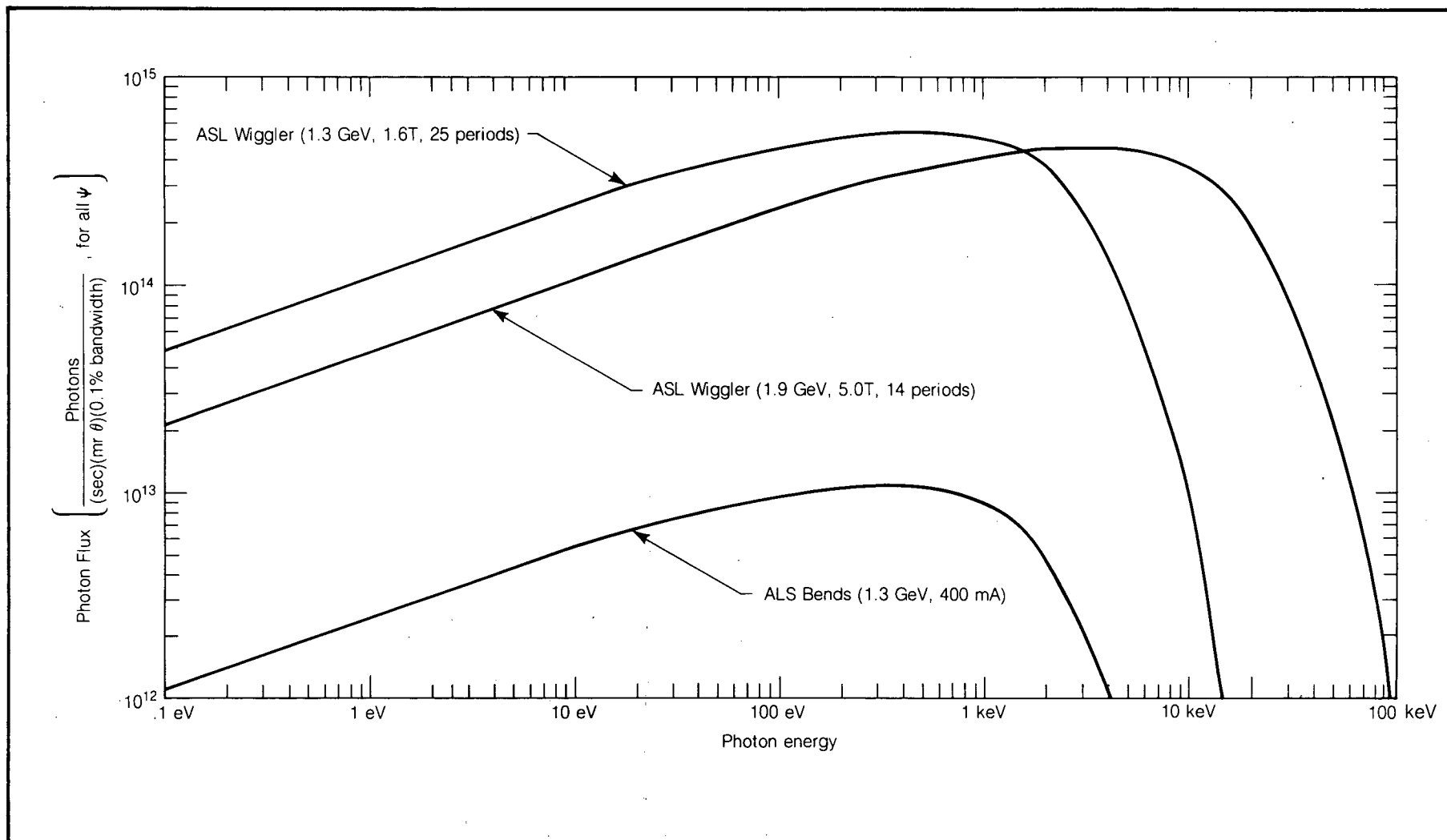


Figure 3-5. Photon flux.

Table 3-3
Approximate Parameters for
ALS Standard Operating Modes

Energy (GeV)	0.9	1.3	1.3	1.3	1.9
No. of Bunches	250	250	20	4	250
<i>Initial Performance Goals</i>					
Average Current (mA)	400	400	200	30	400
Bunch Length (ps)	23	23	38	35	27
Peak Current (A)	34	34	128	104	29
<i>Ultimate Performance Goals</i>					
Average Current (mA)	400	400	400	200	400
Bunch Length (ps)	23	23	50	90	27
Peak Current (A)	34	34	194	270	29

In estimating the peak operating parameters presented in Table 3-3, a number of possible limitations to storage ring performance must be considered.

The threshold current for the longitudinal microwave instability [4] is given by the relation

$$I_{th} = \frac{F \nu_s^2 (E/e)}{\sqrt{2\pi} \alpha \left| \frac{Z}{n} \right|} \left(\frac{\sigma_s}{R} \right)^3$$

where ν_s is the synchrotron tune, σ_s the rms bunch length, F a form factor, and Z the broadband component of the longitudinal impedance for mode n . When the current stored exceeds this value, the bunch lengthens to satisfy the condition. The maximum of $|Z/n|$ has been estimated to be 8Ω for SPEAR and less than 1Ω (excluding rf cavities) for the large rings PEP and PETRA, located respectively at Stanford in California and at DESY in Hamburg, Germany. For the ALS with smooth vacuum chamber construction, 2Ω or less should be realizable. At frequencies above cutoff, $|Z/n|$ decreases to the free-space impedance, which for the ALS beam pipe will introduce a few tenths ohm. The bunch lengths for various operating conditions are summarized in Table 3-3, where the rolloff of $|Z/n|$ for short bunches is scaled from SPEAR until the free-space value above cutoff is attained.

Transverse single-bunch instabilities can be driven by the broadband transverse impedance. The slow-growth "head-tail" instability will be stabilized in the ALS by sextupole correction of the machine chromaticity. The fast-growth transverse instability sets an upper limit on the maximum bunch current that can be stored. For the ALS, the threshold current is over 75 mA/bunch and should not interfere with the planned modes of operation, as indicated in Table 3-3.

Narrowband impedances from, for example, parasitic modes of the rf cavities, can produce long wake fields that couple succeeding bunches and cause longitudinal instability. Care in the design of the rf system (to reduce the Q of higher modes of the cavity) is fundamental in eliminating this coherent effect. The rise time τ for the dipole mode is given by [5]

$$\frac{1}{\tau} = \frac{\omega_0 e I \alpha}{4 \pi \nu_s E} \left[n Z_n e^{-\frac{1}{2} n^2 \sigma_d^2} \right]$$

and should be the most severe coupled-bunch stability. From past experience in damping cavities at the Photon Factory (KEK, Japan) and at the Synchrotron Radiation Source (Daresbury, England), it is estimated that at approximately 75 mA, the growth rate for the fastest growing mode will equal the synchrotron radiation damping rate. It has been the experience at both the NSLS VUV ring and the KEK Photon Factory that higher currents do not lead to catastrophic beam loss, but rather to finite longitudinal bunch oscillations. For the KEK Photon Factory, which has a comparable instability threshold, the longitudinal coupled-bunch instability has not been a limiting factor in attaining more than 200 mA of stored beam. A small second rf system, which would provide either a bunch-to-bunch shift or an internal-bunch spread in synchrotron frequency, will provide sufficient damping to achieve the design current of 400 mA without any residual oscillation. It has also been found at SPEAR that certain configurations of filled buckets are more stable than others. The ALS injection scheme provides flexibility in selecting configurations of bunches, so that the most stable operating mode can be found. Transverse coupled-bunch modes will be less severe and can be stabilized by natural radiation damping or, if necessary, by a modest bunch-to-bunch tune spread from rf quadrupoles.

In addition to the single-particle synchrotron radiation, energy loss can occur through higher-order-mode excitation [6] and coherent synchrotron radiation [7] in the bending magnets. Conservative estimates indicate that higher-order-mode losses will dominate over coherent synchrotron radiation even for the shortest bunches in the ALS. For the 4-bunch, 30-mA mode, higher-order-mode losses of 80 kV/turn can be expected. For the 20-bunch, 200-mA mode the losses will be 95 kV/turn. Great care must be taken in the construction of storage ring components to avoid vacuum chamber components which can behave as high-frequency resonant cavities. The passage of dense bunches of electrons can excite intense standing waves in such cavities and produce component failure through overheating.

A primary goal in the design of the ALS is to provide electron bunches of extremely short duration with many milliamperes of current per bunch. A variety of effects which are sensitive to the planned high peak currents has led to the choice of an rf system which can provide 3 MeV peak electron energy gain per turn. With this choice, Touschek lifetimes are longer than 25 hours for the standard operating modes (the initial performance goals given in Table 3-3). There is also the potential of achieving tens of milliamperes per bunch (the ultimate performance goals) with Touschek lifetimes of 10 hours or longer. For fixed bunch length, the permissible current scales linearly with rf voltage. Furthermore, providing 3 MeV energy gain per turn results in a zero-current bunch length of 20 ps at 1.3 GeV; thus we have a safety margin in achieving a 35-ps bunch length, even if the storage ring impedance for smooth rings turns out to be inductive at high frequencies as is suggested by experience at PETRA. Finally, both the fast-growth transverse-instability threshold and the coupled-bunch longitudinal-instability threshold are eased by operation at higher synchrotron frequencies. These considerations have led to the selection of a powerful radiofrequency system for the ALS.

Scattering from residual gas and intrabeam scattering can reduce stored-beam lifetime. At a pressure of 10^{-9} torr, the gas scattering lifetime with a 400-mA beam current is estimated to be 13 hours, if the minimum vertical gap at an undulator is 9 mm. Intrabeam scattering can also lead to both longitudinal and transverse emittance growth. For the ALS, the synchrotron

damping rate exceeds the rates of growth by at least an order of magnitude, and thus there should be no significant impact.

Even at a vacuum of 10^{-9} torr, the electron beam can become neutralized in a few seconds, if positive ions become trapped in the potential well formed by the beam. These ions can produce a focusing force that is nonlinear with respect to displacement from the central orbit, so they can cause both tune shifts and tune spreads in the electron beam. Even worse, the electron-beam emittance can grow substantially (possibly through encountering resonances because of the tune shift), and the beam lifetime can be substantially reduced.

Although the presence of ions has been seen to improve beam behavior in some cases, it seems clear that ion trapping should be avoided in the ALS if necessary. There are three standard methods of avoiding ion trapping. First, the storage ring can be run with fewer bunches of electrons, so that a fraction of the circumference is empty. The rest of this section will discuss this strategy in some detail. Second, clearing electrodes may be used to remove the ions. However, the addition of clearing electrodes may be awkward in some locations and is likely to produce an unattractive increase in the impedance of the storage ring. Third, the electron beam can be replaced with a positron beam, at a substantially increased cost. This last option is discussed in some detail at the end of the Section titled "Injection System."

Ion trapping by bunched electron beams can be simulated using an analytic model in which the space-charge force of an electron bunch is represented by a thin focusing lens [8,9]. The electron bunch has a Gaussian density distribution, so the focusing force is not linear with displacement from the central orbit. However, for simplicity we assume a linear lens whose strength is taken to be the actual focusing force near the electron beam axis. Therefore, the electron beam is represented as a lattice of converging lenses in which ions execute transverse oscillations. For ion motion to be stable in such a lattice, the ion mass must exceed a critical value given by

$$A_c(\text{a.m.u.}) = 2 \left(\frac{\pi R}{n} \right)^2 \frac{m_e}{m_p} \frac{I}{I_o} \frac{1}{\sigma_y(\sigma_x + \sigma_y)}$$

where R = mean radius of storage ring
 n = number of equally-spaced electron bunches
 I = total electron beam current
 I_o = Alfven current
 σ_x, σ_y = transverse beam dimensions.

Ions with masses lower than A_c will be overfocused vertically and therefore not be trapped.

The above expression can usefully be re-written as

$$A_c(\text{a.m.u.}) = K \frac{I}{n^2}$$

where the constant K is a figure of merit that depends solely on the parameters of the storage ring. A large value of K is preferred, since it indicates a relative immunity from ion trapping.

Table 3-4 shows how various storage rings compare, in terms of ion trapping. First of all, it is evident that the ALS has unusually large values of K , meaning that the ALS is relatively immune to ion trapping because of its large radius and small beam size (which in turn is due to

a low emittance). Second, the operating modes of the ALS, other than the 250-bunch case, all have A_c larger than 10. Since the NSLS VUV ring does not exhibit ion trapping with a value of A_c equal to 10.45 (for single-bunch operation), it seems that ion trapping is not likely at the ALS when the number of bunches is no more than about 20.

It is believed that carbon monoxide is a major component of the gas which is found within operating electron storage rings. Therefore, it is reasonable to assume that singly-charged, molecular carbon monoxide ions (mass 28) might present a serious problem in terms of ion trapping. Since the above model predicts that ions above mass 10 could be trapped at the VUV ring during single-bunch operation, and since ion trapping was not observed, it appears that this model is somewhat pessimistic.

Table 3-4
Ion Trapping in Storage Rings

Name	E(GeV)	σ_x, σ_y (mm)	K	n	I(A)	A_c	Ions trapped
ADONE	1.5	3.5,2.0	14.42	3	0.6	.96	yes
DORIS	3.0	6.0,0.3	644	480	0.9	.0025	yes
NSLS VUV	0.7	0.66,0.21	209	9	0.10	0.26	yes
	0.7	0.66,0.21	209	1	0.05	10.45	no
SPEAR	2.5	3.0,0.55	411	4	0.1	2.57	probably
ALS	0.9	0.114,0.036	90,400	20	0.2	45.2	
	0.9	0.114,0.036	90,400	250	0.4	0.58	
	1.3	0.165,0.052	43,200	20	0.2	21.6	
	1.3	0.165,0.052	43,200	250	0.4	0.28	
	1.3	0.165,0.052	43,200	4	0.03	81.0	
	1.3	0.165,0.052	43,200	4	0.2	540	
	1.9	0.241,0.076	20,300	20	0.2	10.2	
	1.9	0.241,0.076	20,300	250	0.4	0.13	

A series of numerical simulations was carried out to check the analytic model. Ions were tracked through a series of lenses either with linear forces or with non-linear forces (Gaussian electron bunches). The simulation results confirm the analytic calculations. In particular, these simulations do not reveal any ion trapping which is not predicted by the analytic calculation, and ions are usually lost to the wall in less than 100 microseconds. Consequently, ion accumulation appears unlikely in the ALS, except in the many-bunch operating modes.

Should ion trapping occur in the many-bunch mode, linear and non-linear numerical simulations indicate it may be possible to remove ions by leaving a single large gap in the train of electron bunches. For example, one could have 250 consecutive electron bunches followed by 54 empty rf buckets. The ions are propelled outward by the series of converging lenses, and they are lost as the gap passes their azimuthal position. This strategy has been used successfully at DORIS.

ALS Lattice

The lattice of the ALS electron storage ring is designed to accommodate a large number of radiation-source insertion devices, to produce a very low electron beam emittance, to have favorable values of the various lattice functions at the long straight sections, to have an acceptable natural chromaticity, to have a high periodicity to reduce structure resonances, and to have low beta functions to minimize beam loss due to gas scattering.

The ring is divided into twelve superperiods, and it contains twelve 6-meter straight sections for undulators, for wigglers, and for injection. The beta functions and the dispersion function are shown in Figure 3-6. The dispersion is zero in the long straight sections to minimize source widths and angular divergences. Furthermore, because the wigglers and undulators are located where the dispersion is zero, they will actually tend to reduce the electron-beam emittance. Figure 3-7 shows the overall layout of the ALS storage ring and the many long straight sections, which are the dominant feature of this lattice design. Figure 3-8 shows a more detailed view of the major magnets in a portion of this ring.

The unusually low emittance of the ALS storage ring is achieved by arranging to have low values of momentum dispersion and horizontal beta function in the bending magnets. Because the behavior of this dispersion is controlled solely by the single quadrupole, QF, located between each pair of dipoles, the tune and beta values may be controlled independently (within limits) by the quadrupole triplets located near the long straight sections. Studies have shown that this lattice can readily be retuned to compensate for the substantial vertical edge focusing of a superconducting wiggler.

The design of the ALS lattice leads to reasonable values of the natural chromaticity and also provides appropriate locations to place sextupole magnets for correcting this chromaticity.

The required vacuum-chamber aperture in the ALS, sometimes called the "beam stay clear", has been set at ± 32 mm horizontally and ± 24 mm vertically. These parameters were selected after considering the betatron oscillations of electrons, the momentum dispersion in the storage ring, the aperture requirements for injection, and an allowance for closed-orbit errors.

Particle-tracking studies using the computer program PATRICIA [10] have been conducted to study the useful aperture of the ALS, which is defined as the maximum amplitude of stable transverse oscillations. Results show that the useful aperture is about twice that required for beam injection into the storage ring and about 100 times the root-mean-square amplitude of the damped beam; the useful aperture is also roughly equal to the physical aperture given above.

Magnet construction errors, magnet setting errors, and closed-orbit errors can all produce a growth in the electron-beam emittance. A preliminary numerical simulation of these effects has been completed, and the case considered was one in which closed-orbit errors (± 3 mm horizontally and ± 1 mm vertically) were produced by random transverse offsets of quadrupoles and in which the sextupoles were set to correct the chromaticities to zero. No significant emittance growth was found. We plan to perform more detailed simulations in which the effects of closed-orbit corrections, magnet errors, and wigglers are all taken into account.

Ring Magnets

The magnets for the ALS electron storage ring present no unusual engineering difficulties. Although the accurate construction and alignment of storage-ring components will be crucial to the proper operation of the ALS, existing storage-ring technology (described below) is equal to this challenge. The ring magnets consist of four basic types: dipole magnets to bend the beam, quadrupole magnets to focus the beam, sextupole magnets for chromaticity corrections, and

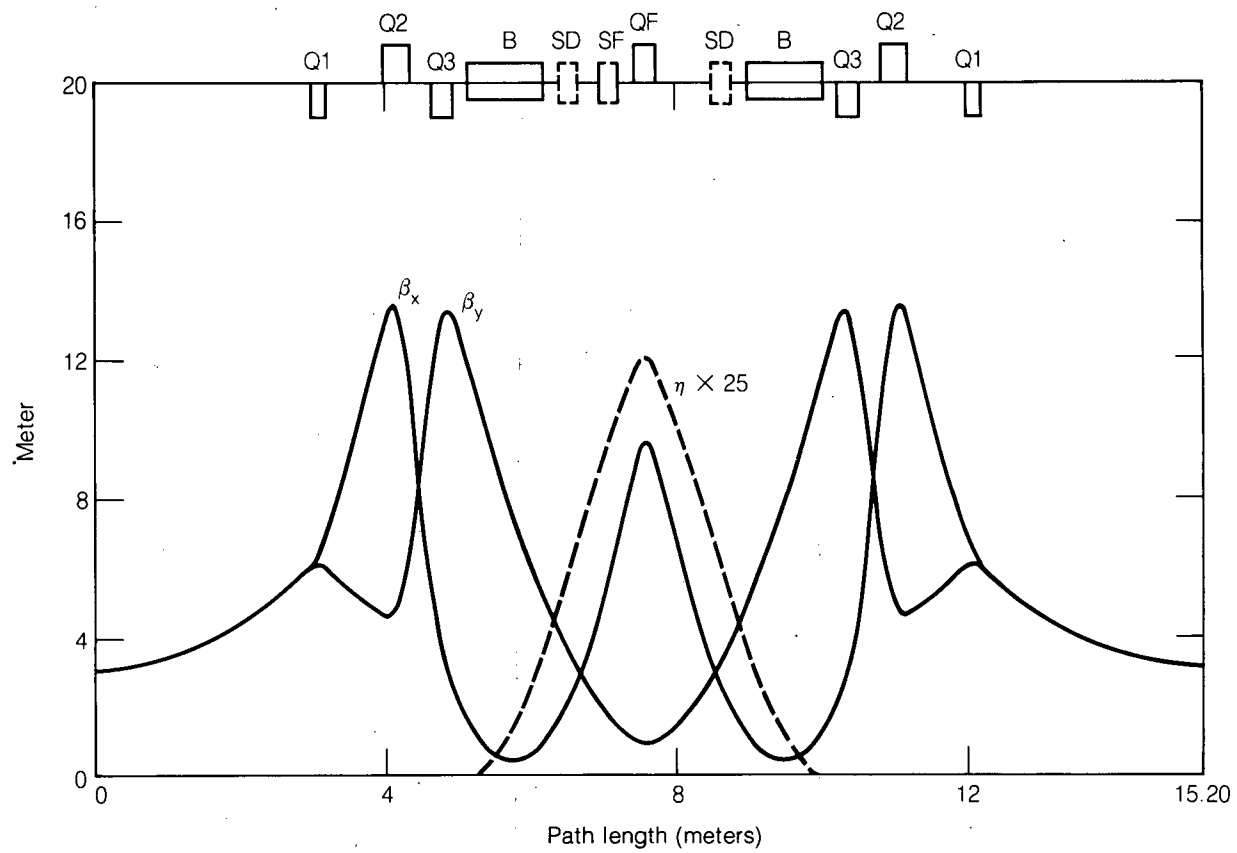


Figure 3-6. Storage Ring Lattice functions.

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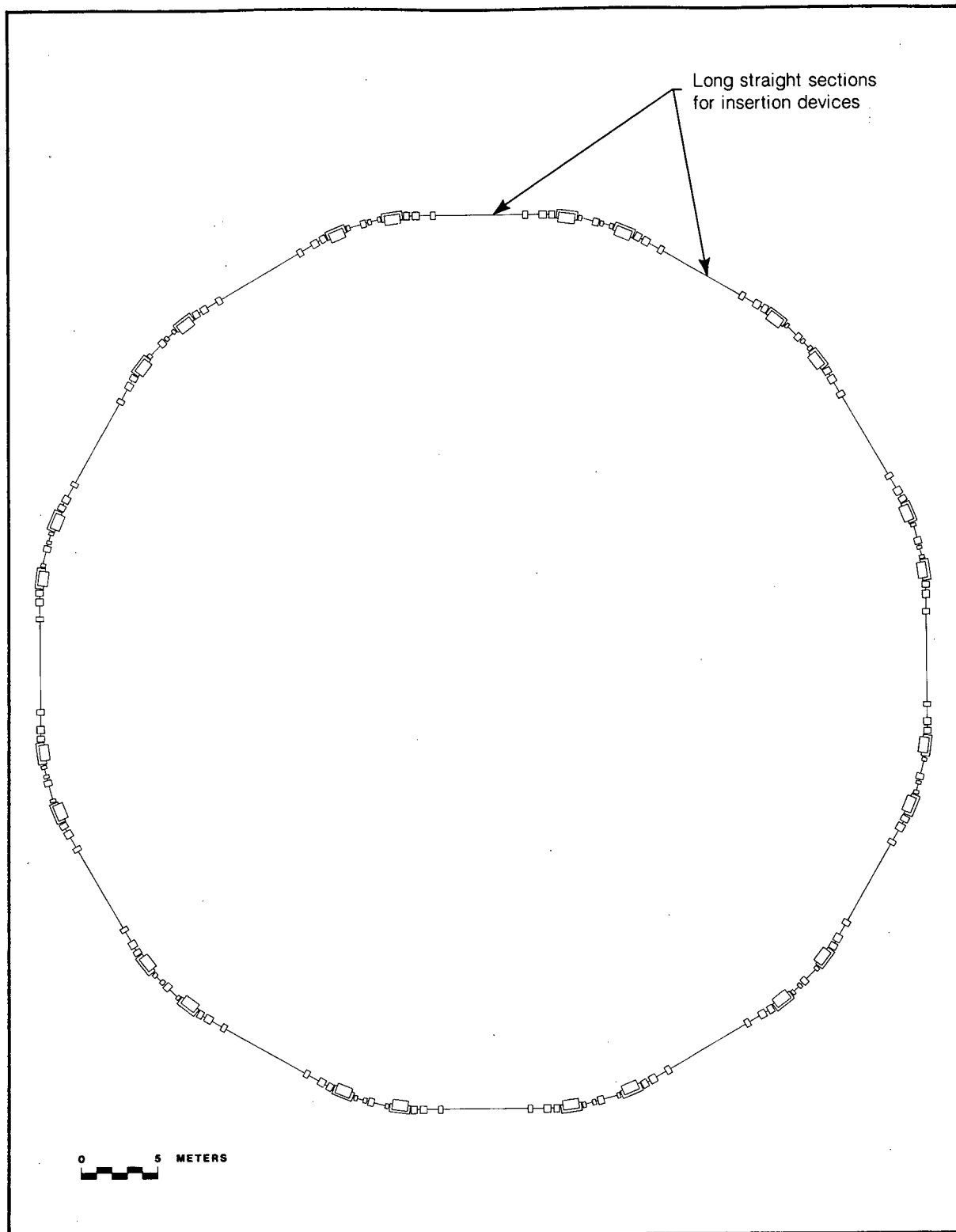


Figure 3-7. Storage ring.

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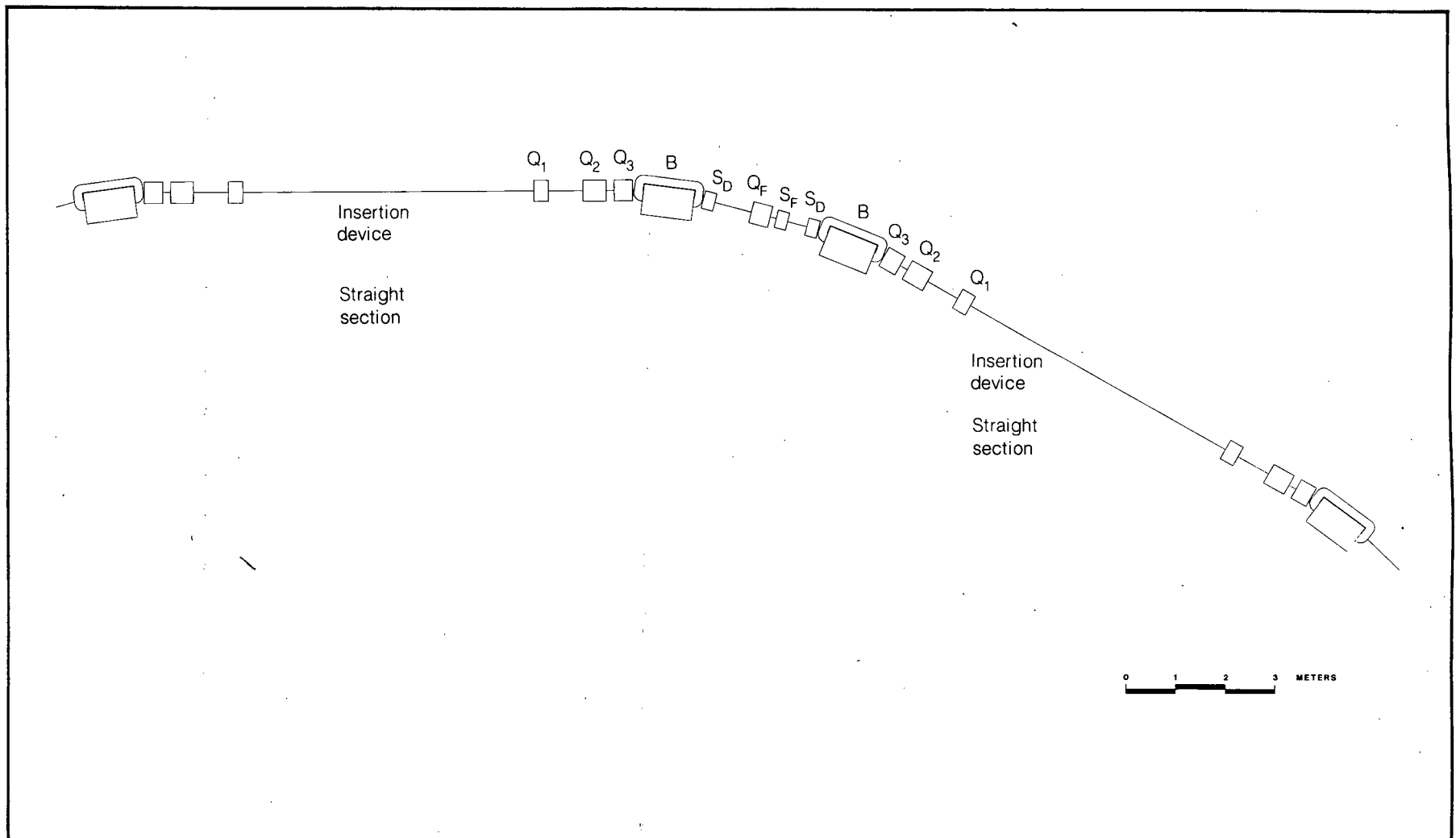


Figure 3-8. Detail of storage ring.

XBL 833-8931

small dipole magnets for beam steering.

The storage-ring bending magnets are "C" magnets (see Figure 3-9) to permit the convenient extraction of the synchrotron radiation. Since the synchrotron-radiation beam and the electron beam leave a straight section along the same path, they separate only at the next bending magnet, where the beam ports for the photon beam lines are located. The magnets are straight, and the sagitta required for the curvature of the electron beam trajectory is accommodated by a large pole area. These bending magnets are laminated, and the entire "C" shape is punched in one piece to ensure structural rigidity and to maintain the required high precision poletip contour. Table 3-5 is a short list of storage-ring bending-magnet parameters for 1.9-GeV operation.

Table 3-5
Storage Ring Dipole-Magnet Parameters

Number required	24
Bending angle (degrees)	15
Field, 1.9 GeV (T)	1.6
Gap (cm)	6.5
Magnetic length (m)	1.04
Current (A)	958
Voltage, per magnet (V)	22.1
Power, per magnet, 1.9 GeV (kW)	21.2

There are a large number of quadrupole magnets in the ALS electron storage ring because of the need to provide very strong focusing. These quadrupoles may be divided into four groups by magnet lengths: 20, 37, 29, and 30.5 cm. The aperture diameter is 6.5 cm for all magnets, as shown in Figure 3-10. In the ALS design, the synchrotron radiation from a wiggler or undulator passes through three quadrupole magnets before it leaves the ring at a bending magnet. Therefore, the quadrupole magnets must be designed to accept a vacuum chamber that is horizontally enlarged to transmit a wide, flat "fan" of synchrotron radiation. Some key parameters of the quadrupole magnets at 1.9 GeV are given in Table 3-6.

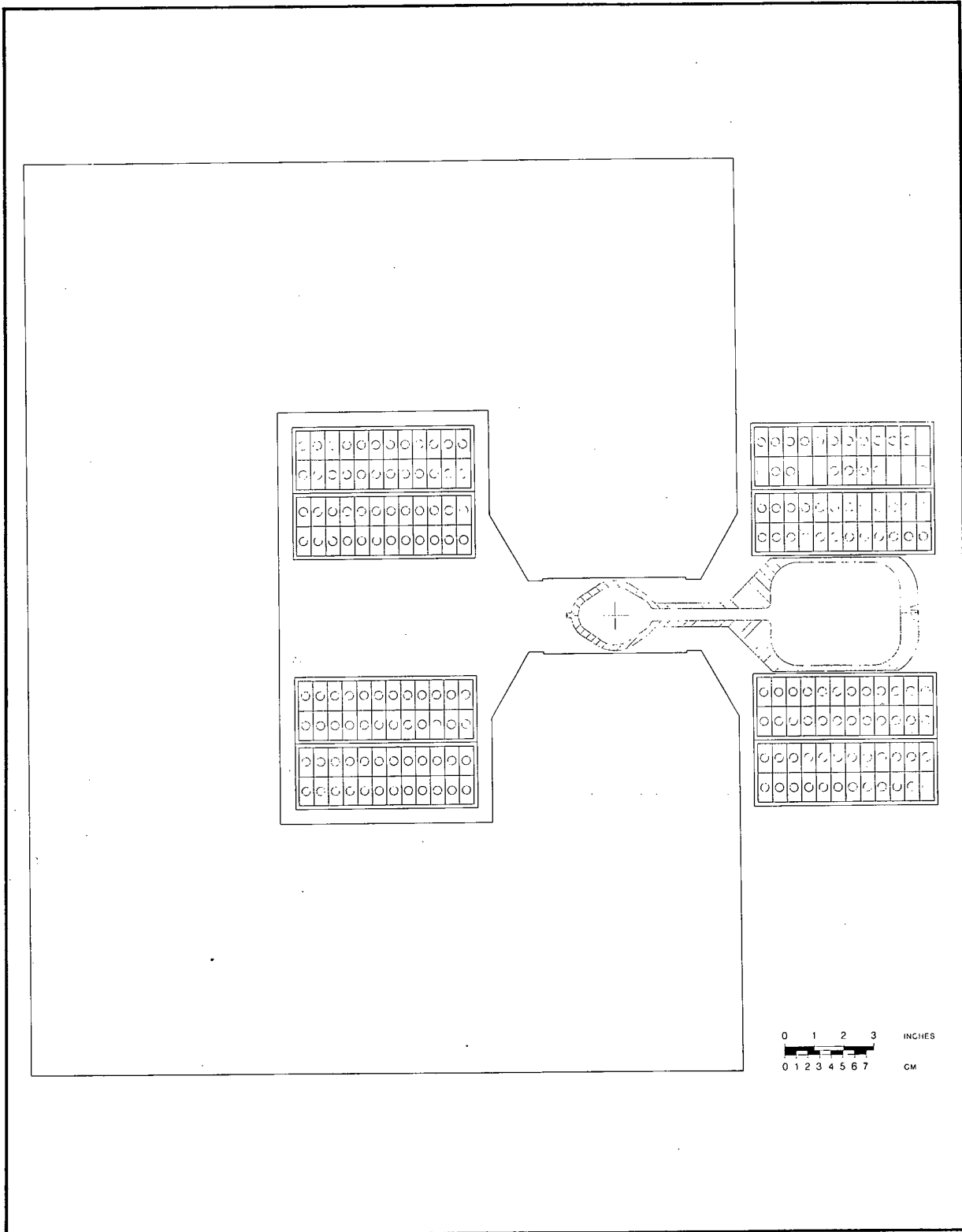


Figure 3-9. Storage ring bending magnet cross section.

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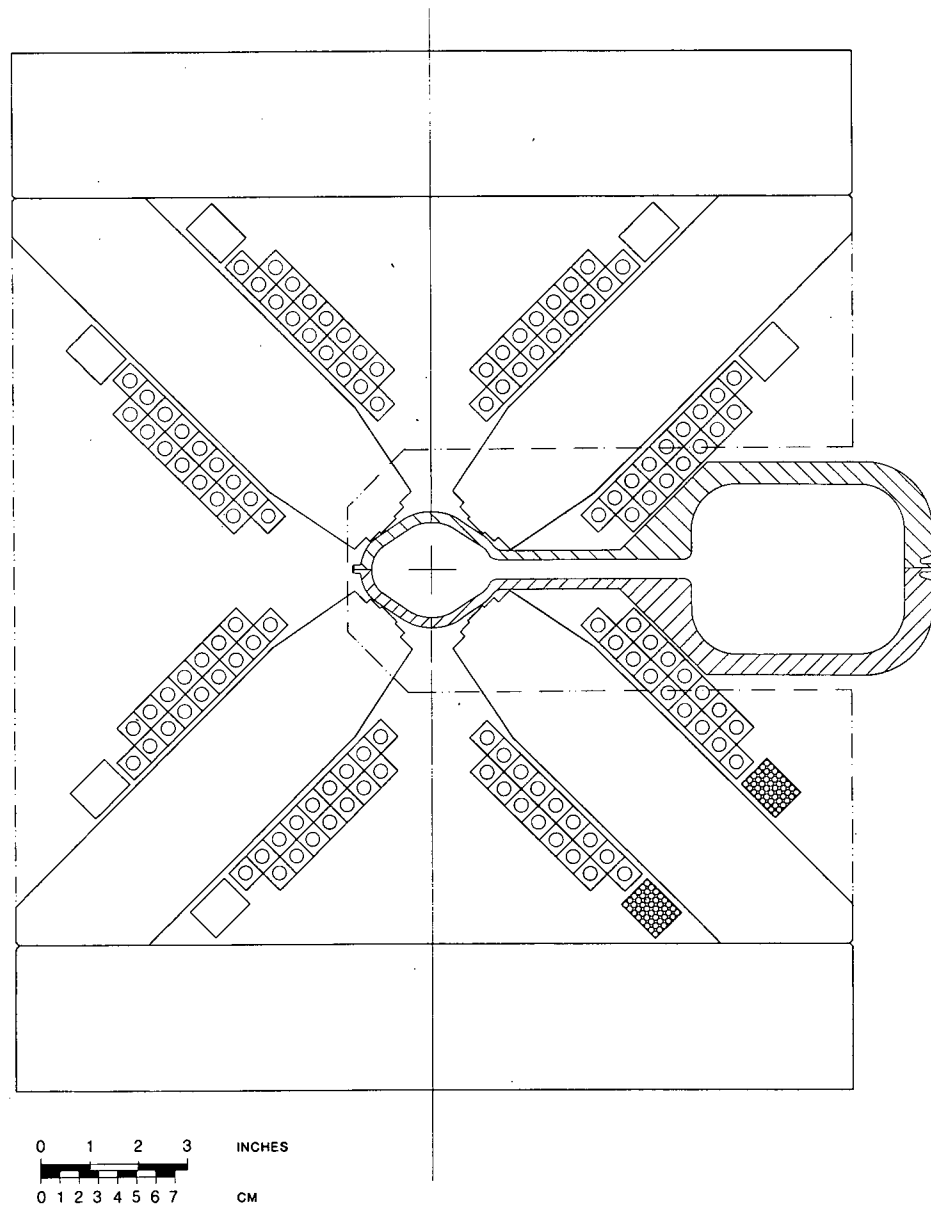


Figure 3-10. Storage ring quadrupole magnet cross section.

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Table 3-6
Ring Quadrupole-Magnet Parameters

Quadrupole Type	Q1	Q2	Q3	QF
Number Required	24	24	24	12
Aperture Diameter (cm)	6.5	6.5	6.5	6.5
Effective Length (cm)	20.0	37.2	29.1	30.5
Maximum Gradient, 1.9 GeV (T/m)	10.7	22.8	22.8	22.8
Current (A)	280	630	630	630
Voltage, per magnet (V)	1.8	7.0	5.8	6.0
Power, per magnet, 1.9 GeV (kW)	0.5	4.4	3.7	3.8
Total Power for Circuit (kW)	12	106	88	46

Thirty-six sextupole magnets are used to correct the natural chromaticity of the storage ring. These magnets also have a 6.5-cm-diameter aperture (see Figure 3-11) and are approximately 20 cm long. They are designed to accept a horizontally enlarged vacuum chamber, therefore they are constructed in three sectors and are supported in such a manner as to provide complete open access along the outer radius. The poletip field is 0.44 T, and the power dissipation is less than 2.5 kW per magnet.

Steering magnets are used to correct the closed-orbit errors in the ALS electron storage ring and to adjust the electron-beam position and angle at the insertion devices. Each of the 24 storage-ring dipole magnets is fitted with a separate trim winding for horizontal steering. An additional 24 steering-magnet modules (each with one horizontal steering magnet and one vertical steering magnet) are installed around the storage ring to provide a complete steering capability. Each steering magnet is about 15 cm long, has a maximum effective field strength of 0.01 T-m, and has a power dissipation of less than 0.15 kW.

The support and alignment of the magnets are crucial to proper ALS operation. The magnet support system must provide adjustments for three translations and three rotations. These six adjustments are made through three vertical and three horizontal struts. Where practical, several magnets share a common base frame. A multi-magnet package can then be aligned in the laboratory and this prealigned package located in the ring with the six struts. Provision for thermal expansion is provided in all supported elements.

All beam elements, including the linac, the booster ring, the storage ring, and the photon beam lines, must be aligned accurately. To do this, a network of accurately surveyed monuments is strategically placed throughout the ALS area. The horizontal alignment of beam elements is then based upon the monument locations. The vertical alignment of beam elements depends on reference elevations provided by a permanently installed liquid level. This system was developed for the PEP project and is both precise (± 0.10 mm) and quick to use.

Each beam element is located relative to the two nearest survey monuments. Offsets are measured from the line of sight between adjacent survey monuments to each beam element. Elevations are measured relative to the liquid level. A combination of conventional optical tooling instruments and proven distance-measuring devices is used in the gathering of survey data.

Distances between adjacent beam elements and distances to the survey monuments are entered into a small on-line computer for analysis. An important benefit of an on-line computer

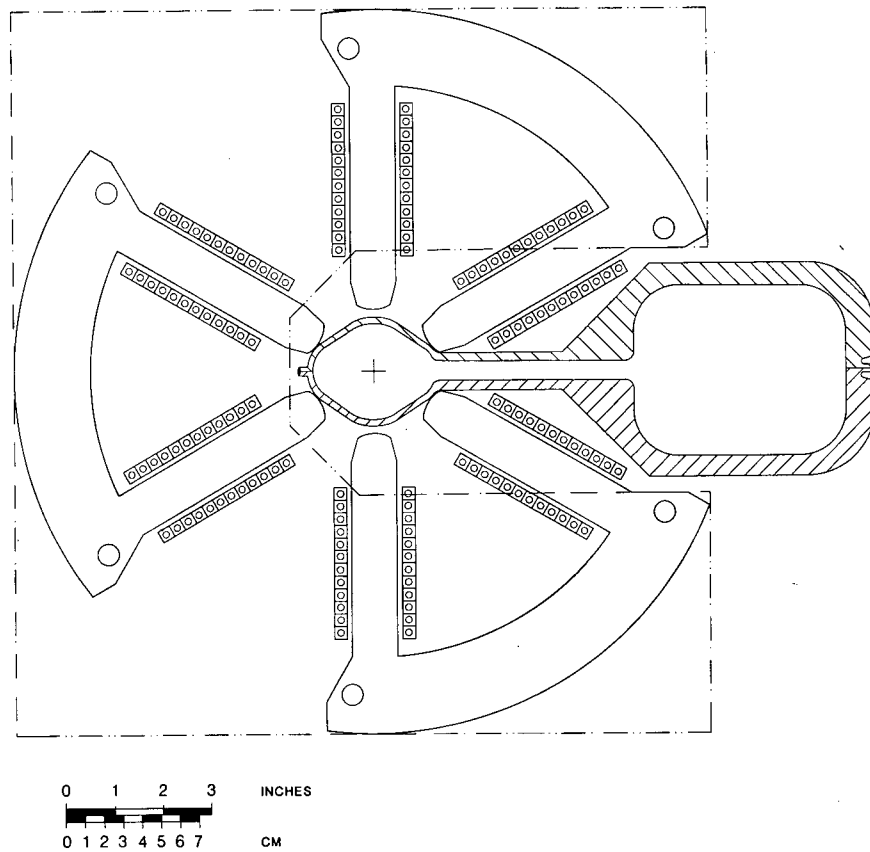


Figure 3-11. Storage ring sextupole magnet cross section.

XBL 833-8934

is the efficient use of survey data. After a group of components has been completely surveyed, the computer is used to calculate the support-stand adjustments which are required. The use of stacks of calibrated shims in the support struts permits these adjustments to be made accurately and with very few iterations. This adjustment scheme was very successfully used at PEP.

Vacuum System

A vacuum of 10^{-9} torr or less is required in the storage ring to obtain adequate electron-beam storage times. Achieving this pressure is relatively straightforward in the absence of stored electrons. However, with a stored electron beam, the dominant gas load is caused by the following two-step process. The synchrotron-radiation photons produce photoelectrons at the surface of the vacuum-chamber wall, and these electrons in turn cause desorption of gas molecules, the most significant of which is carbon monoxide.

This photodesorption process has produced copious amounts of gas during initial operation of existing electron storage rings corresponding to pressures of the order of 10^{-6} torr at full electron beam current. As time passes, the photodesorption process gradually "scrubs" the impinging surfaces causing the photodesorption rate to decrease slowly. Typically, it has taken many months (and sometimes years) of operation for existing storage rings to achieve reasonable beam lifetimes ($\sim 10^{-8}$ torr) at full beam current. If similar techniques were used for the ALS, a pressure of $\sim 10^{-8}$ torr could be expected in a few months but it would take well over a year to reach the vacuum goal of 10^{-9} torr. Better performance is clearly needed.

The vacuum-chamber configuration under consideration for the ALS storage ring is shown in Figure 3-12. The electron-beam circulation region is connected by a long slit to an "antechamber" region containing a water-cooled target upon which the synchrotron radiation impinges. Thus, the gas molecules desorbed by the synchrotron radiation are released into the antechamber region. The antechamber has a large amount of distributed pumping, so that 95% or more of the gas molecules desorbed by synchrotron radiation are pumped within the antechamber and never reach the electron-beam region. Therefore, the gas load at the electron-beam region is reduced by a factor of 20. However, the distributed pump in the antechamber provides as much pumping for the electron-beam region as is available in conventional designs, so that the gas pressure in the electron-beam region is improved by at least a factor of 20.

The height of the slit is not very critical from vacuum considerations, but it must be large enough to transmit the synchrotron radiation from an electron beam which exhibits some uncorrected closed-orbit errors. On the other hand, the slit should be small in order to minimize the rf coupling between the electron-beam region and the antechamber, except at extremely high frequencies.

The antechamber containing the photon absorbers can also contain permanent continuous electrodes to be used for ion cleaning. The usable photons from the insertion devices and the bending magnets emerge from the storage ring and pass into the photon beam lines through slits in the outer radius of the antechamber. Gas contamination from the photon beam lines into the storage ring is attenuated by a factor of 20 by the high-speed pumping and by a geometry that reduces the gas desorbed by surfaces illuminated by synchrotron radiation.

The photon absorbers in the antechambers are copper, water-cooled, and separate from the vacuum wall. The vacuum chambers between straight sections are milled from two 30-ft long plates of high-strength aluminum and welded at the median plane. This technique permits the manufacture of chambers with gently changing cross sections, reduces high-order-mode losses,

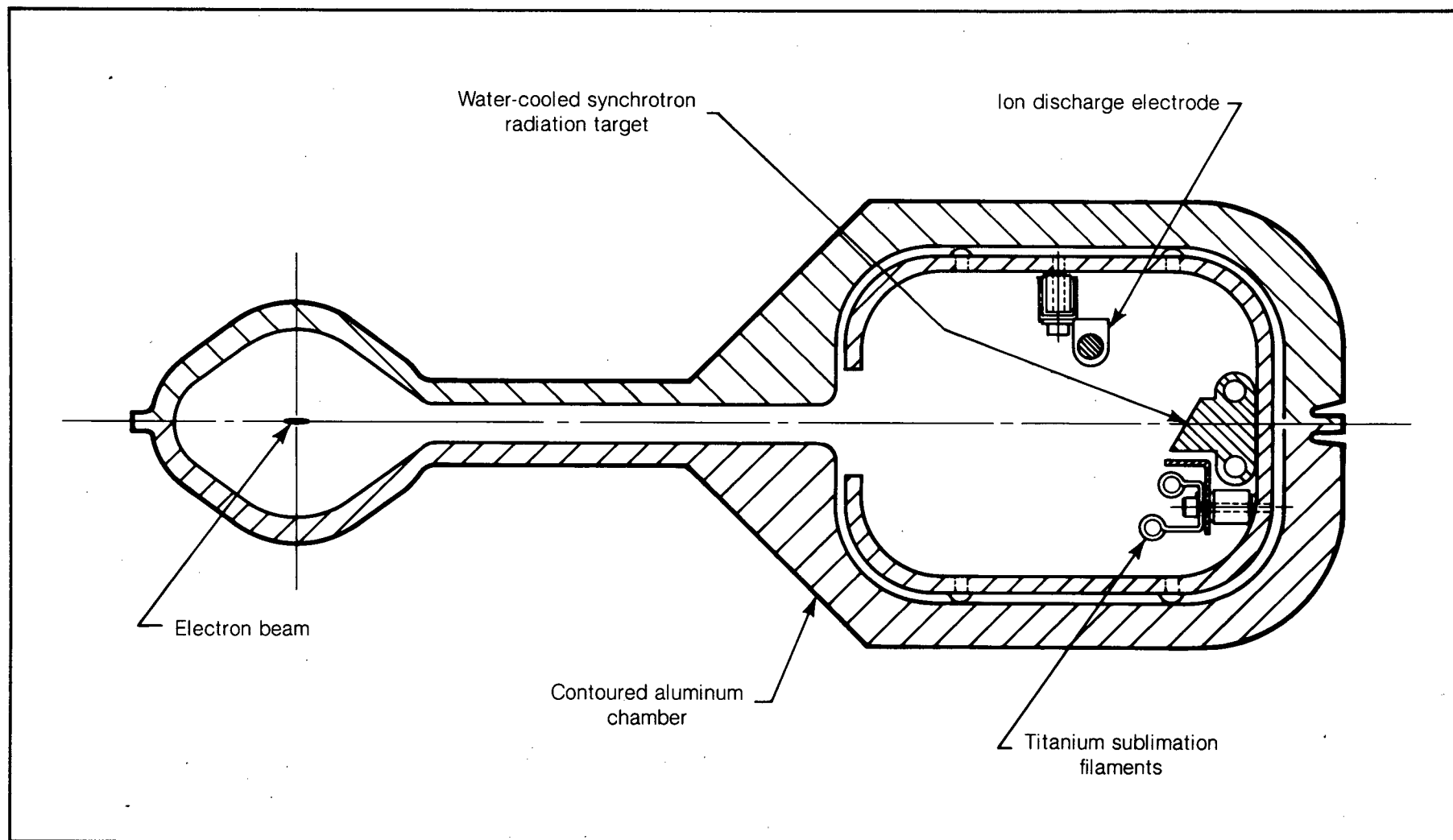


Figure 3-12. Storage ring vacuum chamber.

XBL 833-8935

and insures accurate location of the beam line and its associated components.

The storage ring is pumped by 30,000 l/s of distributed pumping at the antechambers plus appendage ion pumps. Oil-free turbo molecular pumps backed by cryogenic absorption pumps will be used to "rough" pump the storage ring and to pump it during baking and ion cleaning.

Magnet Power-Supply System

The storage-ring and booster power-supply system is based upon the one used at the PEP storage ring. Major magnetic elements (dipoles and quadrupoles) are current regulated by choppers fed from large dc power supplies. The numerous trim and steering requirements are provided by current-regulated bipolar transistor actuators. The reference and monitoring system from the central computer is locally represented by microprocessors interfaced to the current regulators through appropriate DA and AD converters. The major magnet currents are controlled and monitored by 16-bit devices and are regulated to an accuracy of $\pm 1 \times 10^{-4}$. The trim currents and steering-magnet currents are regulated to $\pm 1 \times 10^{-3}$ and are controlled and monitored by 12-bit devices.

The storage ring has four families of quadrupole magnets and one dipole-magnet family. Choppers feeding four of these families are all at the same location, each mounted in a single cabinet adjacent to the dc feeder supplies. The two feeder supplies are rated at 200 kW and 400 kW, with a maximum terminal voltage of 260 V (see Figure 3-13).

The ALS choppers are similar to those which have been used successfully at the PEP storage ring. Using a common dc supply minimizes the cost of dc power and allows the use of choppers running at 2.16 kHz and a current-loop unity-gain bandwidth of over a kilohertz. The corresponding high performance of the chopper system has been well documented at PEP. The remaining quadrupole family, Q1, is driven by a 280-A silicon-controlled-rectifier (SCR) power supply, except for the two quadrupoles, Q1' (in the superconducting wiggler straight section), which will be separately powered. The storage ring also has two families of sextupole magnets, designed for a maximum current of 320 A. These are powered from SCR power supplies. Other SCR supplies are used to power the bending, septum, and quadrupole magnets in the transport line between the booster and storage rings.

The booster ring has three families of quadrupole magnets, two families of sextupole magnets, and one dipole-magnet family. To meet the pulsing rate of 1 Hz required of the booster, the net voltage needed in the dipole circuit is 2100 V at a current of 820 A. The 2100-V requirement is best met by four 600-V supplies distributed around the ring, because the voltage above ground can then be limited to 600 V. Only one of the four 600-V supplies needs to be current regulated; the other three will be used as rectification or inversion supplies as required during the rectification, flat-top, and the inversion portions of the pulsing cycle. The current-regulating unit is a chopper, powered from a 630-V dc supply. The three families of quadrupole magnets are each powered with two power supplies in one circuit, in order to provide the desired waveform during the booster cycle. A chopper rated at 260 V and 1000 A provides current regulation, and in addition there is a 600-V voltage-controlled SCR power supply. The dc feeder supplies are rated at 630 kW and 780 kW, respectively (see Figure 3-14).

Booster-ring sextupole circuits are rated at 200 A and 310 A and are fed from SCR power supplies. The septum magnet, the magnets in the transport section between the linear accelerator and the booster, and the solenoids between the electron source and the linac will all be powered by commercial supplies.

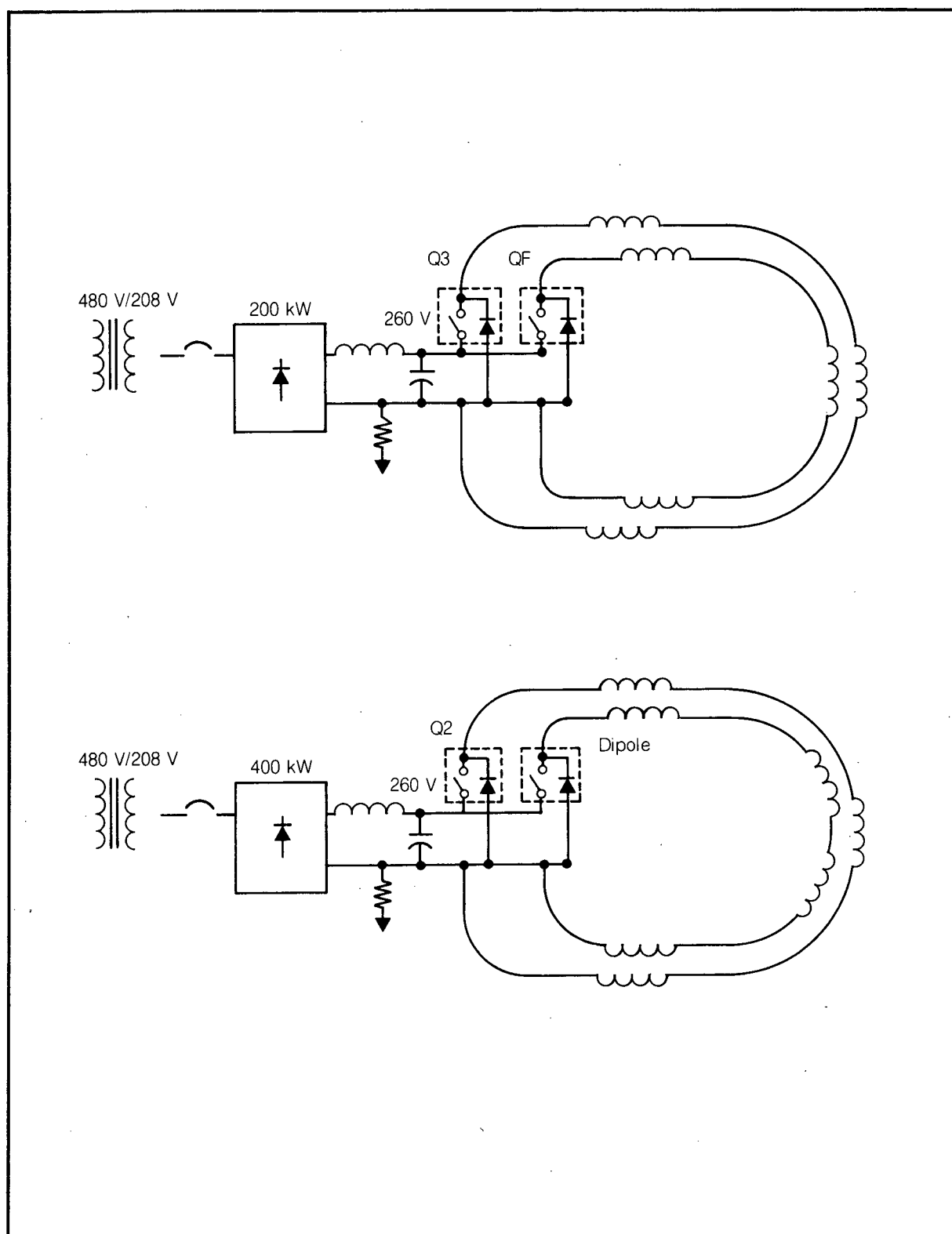


Figure 3-13. Storage ring magnet power supply.

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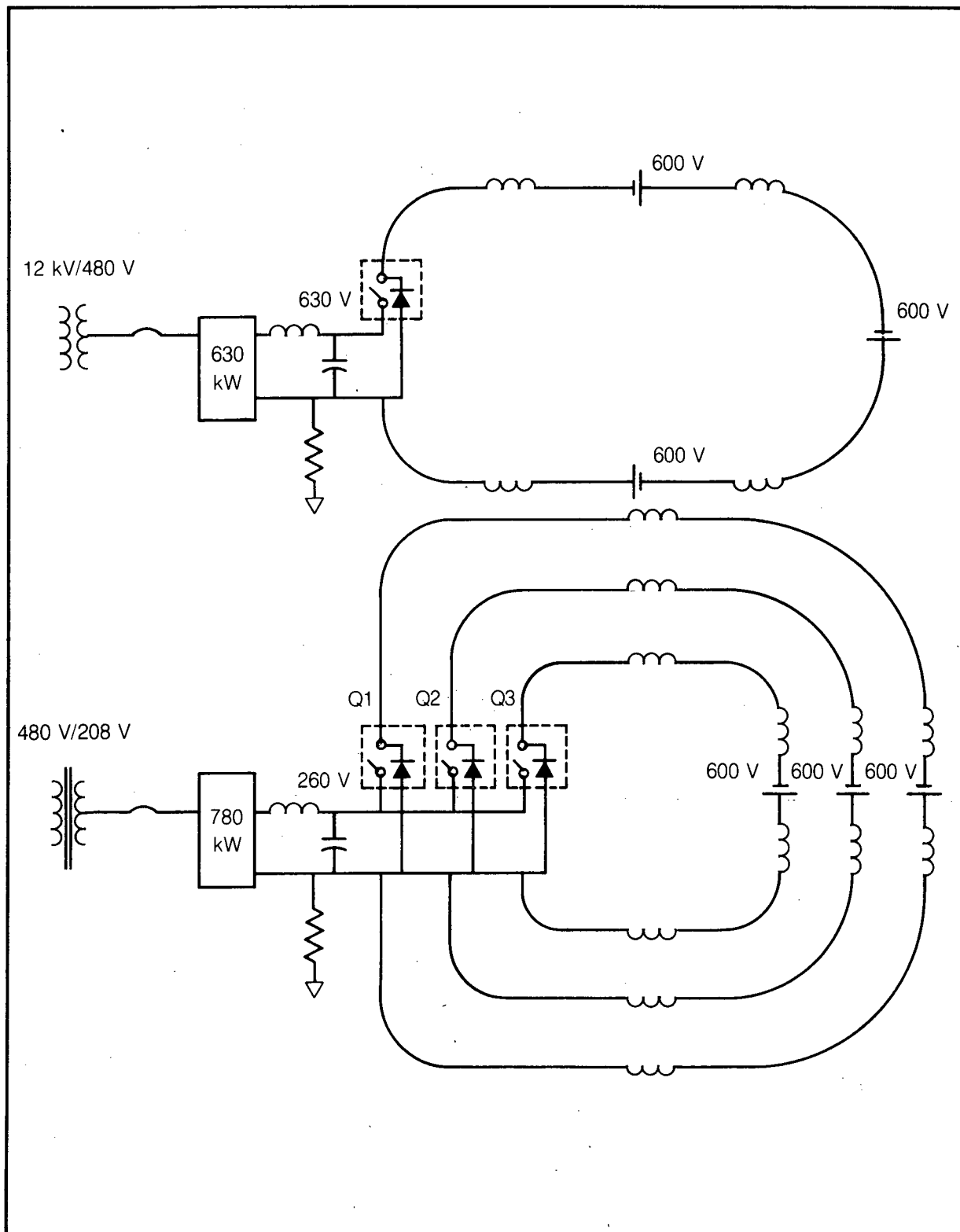


Figure 3-14. Booster magnet power supply.

XBL 833-8937

There are numerous steering-magnet supplies used at the ALS. Table 3-7 lists the supplies needed.

Table 3-7
Required Steering Magnet Power Supplies

Location	Type	Number of Supplies
Storage Ring	vertical	24
Storage Ring	horizontal	48
Booster to Storage Ring	vertical	4
Booster to Storage Ring	horizontal	1
Booster	vertical	8
Booster	horizontal	14
Linac to Booster	vertical	3
Linac to Booster	horizontal	1
		103

The requirements of all the steering systems can be met by standard SuperHILAC steering-magnet power supplies. These are rated at 100 W and are packaged with four units in one chassis.

All of the above systems will be provided with appropriate safety interlocks and monitoring devices to protect both personnel and equipment. All of the magnet systems will be grounded through low resistance circuits that can detect ground currents.

RF System

The functions of the radiofrequency accelerating system in the storage ring are to bunch the beam and to restore the beam energy lost through synchrotron radiation in the wigglers, undulators, and bending magnets. The rf system consists of four cavities driven by klystrons. The cavity gap voltage must be high enough to offset the beam energy loss and to produce very short electron bunches. Table 3-8 gives some parameters of the rf system for the storage ring. In this table, the total effective shunt impedance is given by

$$Z_{\text{eff}} = Z T^2 L ,$$

where Z = cavity impedance per meter (Ω/m)
 T = transit time factor
 L = cavity length (m).

The fundamental mode cavity dissipation is given by

$$P = \frac{(VT)^2}{Z_{\text{eff}}} ,$$

where V = peak cavity gap voltage
 T = transit time factor.

Table 3-8
RF-System Parameters

Frequency	499.65 MHz
Harmonic Number	304
Nominal Bunch Length (2σ)	35 ps
Peak Cavity Gap Voltage	4.4 MV
Transit Time Factor	.683
Peak Electron Energy Gain per Turn	3 MeV
Beam Current	400 mA
Synchrotron Radiation Power	200 kW
Power Loss to Parasitic Modes	25 kW
Total Effective Shunt Impedance	32 M Ω
Fundamental-Mode Cavity Dissipation	280 kW
Total rf Power Installed	600 kW

The rf system is divided into two identical rf subsystems. The major components of an rf subsystem (see Figure 3-15) include two single-cell accelerating cavities, a 300-kW klystron amplifier, a high-voltage power supply and crowbar unit, regulation and control circuitry, and a phase-stable reference line. These will be described below.

The single-cell accelerating cavities have low-loss, semi-spherical designs, and they are very similar to those used at the KEK Photon Factory. The single-cell cavity design was selected because it has fewer potentially troublesome higher order modes, as compared with higher-impedance, multi-cell designs.

The cavities are mounted on the common support girder with the other beamline components. Alignment of a cavity to the beam center line is not critical, since it has only a second-order steering effect on the beam.

Vacuum pumping is provided by a single 100-l/s ion pump on each cavity. Vacuum monitoring is handled by an ion gauge mounted in the rf feed section.

A constant-temperature cooling-water system minimizes the radiofrequency drift during running periods. The water temperature is controlled by a local-station computer.

The cavity tuners are similar to those developed for the LBL Bevatron RFQ project, except for the addition of a bellows-type seal. During operation, these tuners are automatically adjusted to compensate for reactive beam loading, and they provide stability against phase oscillations.

The cavities are coupled to a WR-1800 aluminum waveguide through a cavity transition piece joined to the wide face of the guide. The vacuum window is in the waveguide section. The gas pressure in the waveguide is maintained at slightly more than atmospheric pressure, and it is carefully monitored. In the event of a loss in pressure (indicative of a waveguide leak), the system is automatically shut down. A WR-1800 Magic Tee is used as a power divider between the two cavities. A waveguide penetration in the concrete shielding completes the connection to the power amplifier.

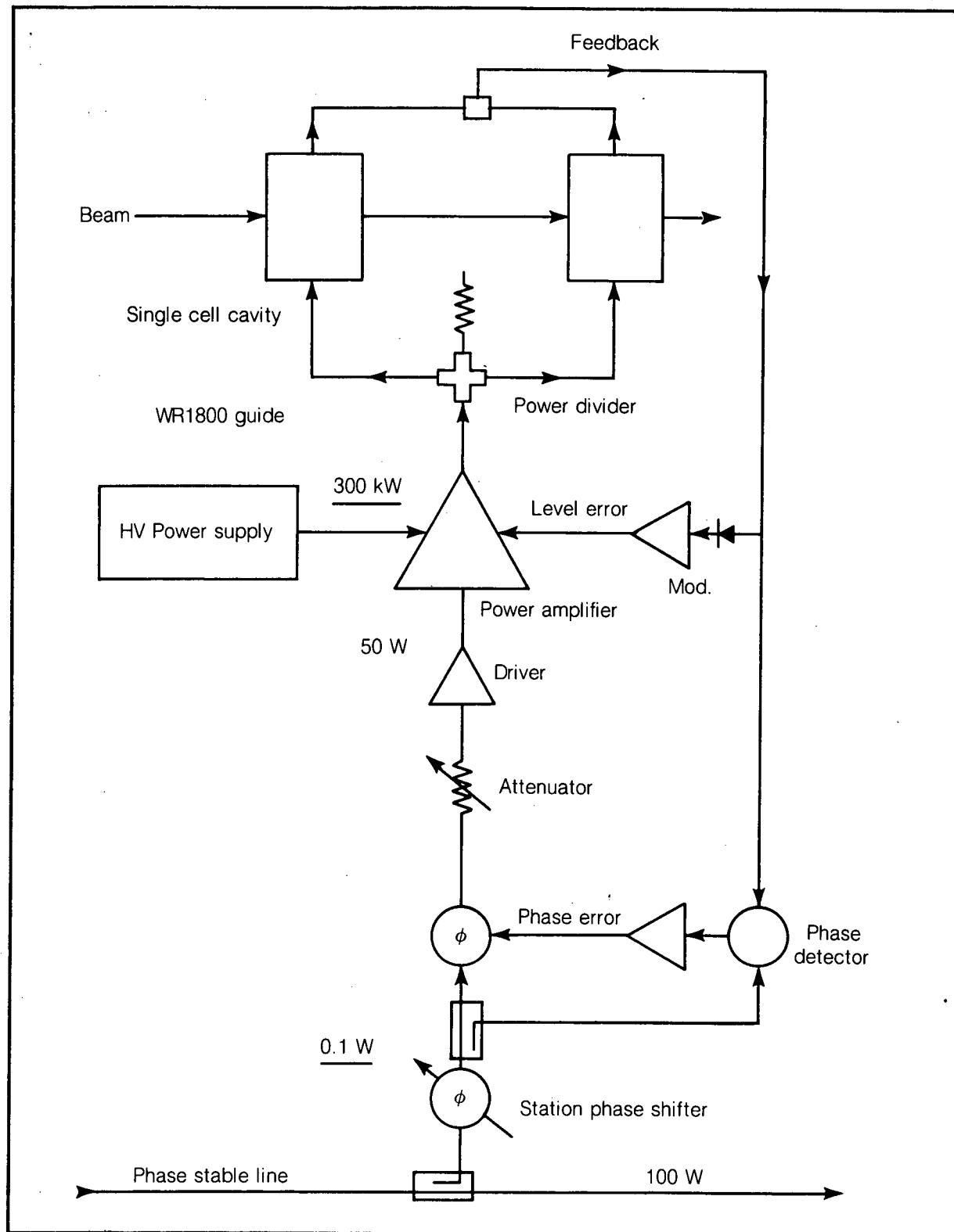


Figure 3-15. Storage ring RF station.

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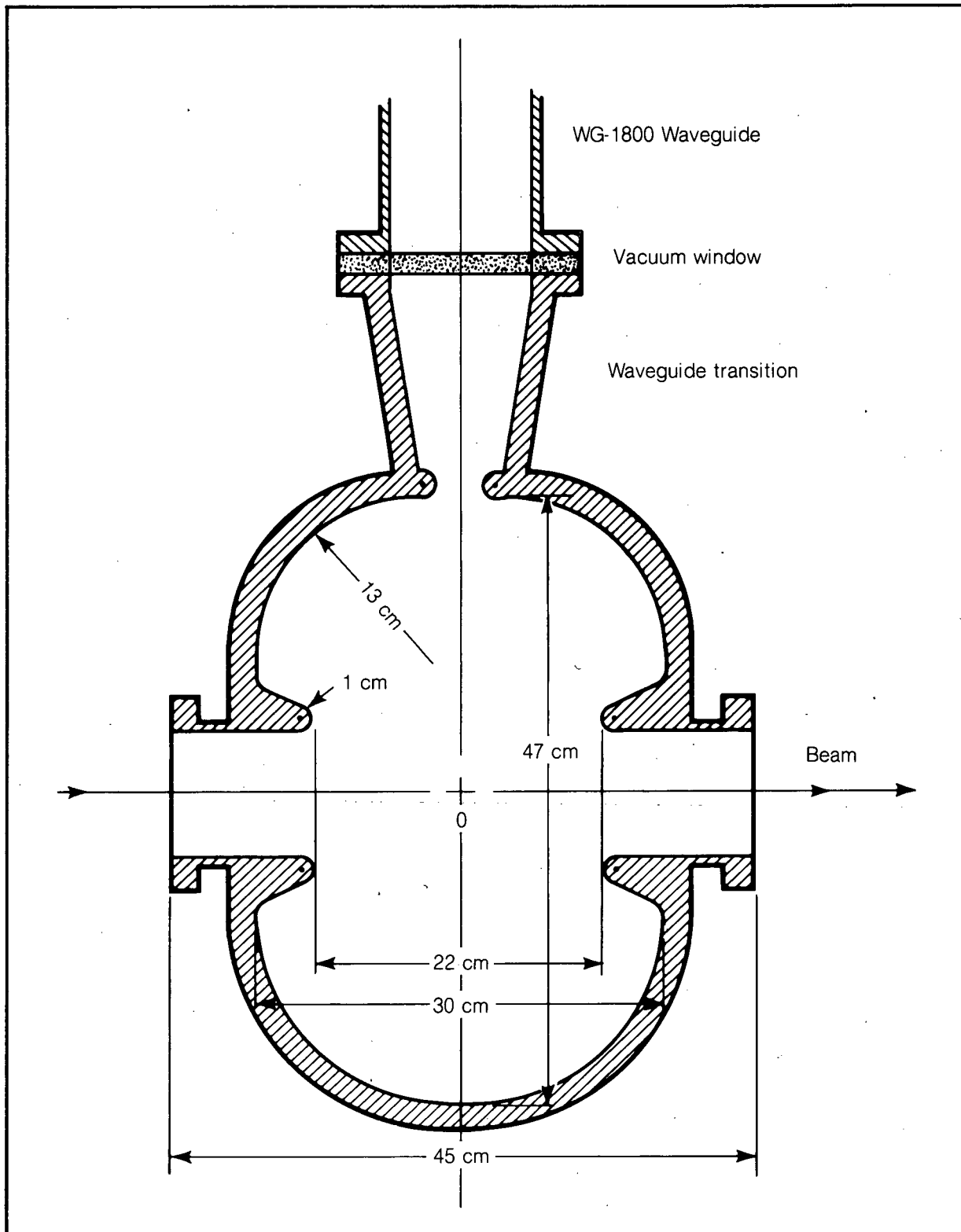


Figure 3-16. Single cell RF cavity.

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An rf isolator or automatic load matching tuner may be used in the waveguide between the klystron and the accelerating cavities. The function of this isolator is to maintain a constant load on the klystron for all beam loading conditions at the cavity. The purpose is to prevent klystron damage and to enhance system stability.

The power for acceleration is provided by a Varian VKP-8259 klystron amplifier (located outside the shielded area for ease of tuning and maintenance). The VKP-8259 delivers up to 300 kW of CW output power at 500 MHz, and the tube has a modulating anode for ease of control. Klystron beam power required is 45 kV at 15 A, which is supplied by a standard pad-mounted power supply and crowbar unit. The beam voltage is controlled by a variable voltage transformer (VVT) and vacuum contactor located adjacent to the power supply. The VKP-8259 requires only about 50 W of drive for fully saturated output, and this can easily be obtained from a standard communications-type solid-state amplifier.

Proper operation of the storage ring requires accurate control of the relative phases and the amplitudes of the output of the two radiofrequency subsystems. A controller chassis very similar to the one developed for the LBL Uranium Beams Project controls the relative phases to ± 1 degree and the amplitude to ± 1 percent.

All accelerator and experimental areas are served by a phase-stable reference system, composed of a stable master oscillator operating at 499.65 MHz followed by a 100-W amplifier. Each drop from the stable reference cable is by a 30-dB coupler, which prevents any one user from causing system errors in the event of equipment malfunction. A user is thus provided with a very stable rf signal phase-locked to the circulating beam in the accelerator. Other timing signals (see the following section) are also transmitted to allow the user to identify any individual radiofrequency bucket.

All parameters involved with personnel safety (e.g., high-voltage barriers) are controlled with a hardware interlock chain. All other system-performance information is collected and processed by a local controller, the Input Output Micro Module (IOMM) described in the section on the control system. This IOMM performs such important functions as adjusting the VVT to minimize energy consumption, monitoring the klystron temperature profiles, and ensuring proper system performance. Additionally, there is a fast crowbar controller to detect klystron-window and gun arcs and remove all power within microseconds to prevent equipment damage. The local IOMM also monitors the performance of the crowbar controller and can turn off the high voltage in the event that its operation is unsatisfactory.

Ring Low-Level Electronics

In designing the ALS facility, great care has been taken to provide the capability to monitor properly and to control the beam and the various components of the accelerator itself. For the first task, instrumentation such as Faraday cups, current transformers, beam position-monitoring electrodes and synchrotron-light monitors are required, whereas the second task requires the use of vacuum monitoring equipment and various computer-controlled synchronization and monitoring devices. In addition to those systems directly concerned with accelerator operation, there are other categories, such as communications and safety-related systems, which also play an important role in the running of a large accelerator complex. Each of these systems is described briefly below.

Wall-current monitors composed of resistors shunting a gap in the beam tube are used to measure beam intensity and position in the injector linac and transfer lines. Signals from these

monitors are available in the control room for observation on fast oscilloscopes. The position signals are processed to generate x and y positions normalized to beam intensity. A computer reads these data and generates a display of beam position for the operator.

A high-frequency Faraday cup in the beam line between the linac and booster is used to determine beam intensity and time structure. A similar cup is used in the transfer line between the booster and storage ring. Suitable electronics for using the cup signals as input to a computer are included.

Beam position and beam size at several locations in the linac and transport lines are monitored with scintillators and TV cameras. Television monitors in the control room are used to display the scintillator images.

Average beam intensity in the booster and storage ring is measured with current transformers surrounding a metallized ceramic portion of beam pipe. The metallic layer is thin enough to permit the lower-frequency components of the circulating beam to couple to the transformers.

At 16 locations in the booster and 84 locations in the storage ring, beam-position monitoring electrodes are installed. Each monitor consists of four button-electrodes, electrostatically coupled to the beam. Signals from the electrodes are processed to obtain the beam center-of-charge. The resulting x-y position signals are sent to a small computer where the beam positions in the booster and the storage ring may be scanned quickly to determine the closed-orbit distortions of the electron beam. Fast signals from selected button-electrodes are also available in the control room for display on a high-frequency oscilloscope.

Synchrotron-light monitors are installed at the booster and storage rings. These consist of photomultiplier tubes, fast photodiodes, and TV cameras. A suitable mirror directs the visible portion of the synchrotron light to the monitors through quartz viewing ports, while the bulk of the synchrotron light passes through the mirror to a photon beam dump. The synchrotron-light monitor is especially useful for detecting low levels of beam, calibrating beam transformers, and detecting beam structure.

Electrodes and driver amplifiers are installed in the booster and storage rings to permit excitation of beam resonances. Signals from position electrodes in the rings are sent to a spectrum analyzer in the control room so that beam instabilities may be studied.

Ion pumps on the storage ring are energized by multichannel power supplies in equipment racks distributed around the ring. Ion gauges at 36 locations around the storage ring are used to measure ring pressure. The ion-gauge power supplies are scanned by a computer so that a profile of ring pressure can be generated. To protect the storage ring vacuum, a system of fast pressure sensors and fast valves is installed at the photon ports. Ion gauges are also used to monitor the pressure in the injector system.

The booster magnetic field, electron source, linac rf, bunchers, and kickers are synchronized such that any number of bunches from 1 to 304 may be accumulated in the storage ring. To accomplish this, a special timing system is provided with inputs from the 500-MHz reference system, the booster magnetic field, and the beam-position monitors in the booster and the storage ring. The stored bunches are "tagged" to allow the injection system to stack a specified number of them. A particular injection scenario is loaded into the control computer via a touch panel, and the computer then sets up the timing system for the appropriate synchronization. Experimenters are also provided with synchronizing pulses so that they can anticipate the arrival of a photon burst. Main-control-room oscilloscopes are provided with synchronizing pulses to enable observation of beam- and machine-related signals.

Real-time observation of beam-related signals is essential for accelerator operation. Very-fast oscilloscopes are installed in the control room for such work. Spectrum analyzers are used to monitor rf parameters, whereas relatively low-frequency beam instabilities are monitored with wave-form analyzers or low-frequency spectrum analyzers. Low-repetition-rate signals, such as the booster guide field, are displayed on a digitizing oscilloscope. TV monitors and video switches are also provided for observation of synchrotron-light and scintillator images.

As mentioned above, the communications system plays an important role in the smooth operation of the ALS facility. The overall system consists of a local ALS public address system and a Laboratory-wide public address system, which allow voice communications to any point in the facility, and a headset intercom system. All three systems are powered from an emergency generator to prevent loss of communications during a power outage.

The ALS headset intercom system will be especially useful during the installation of the magnets, vacuum systems, and other accelerator-system components. This system includes 24 stations with 12 channels available at all stations. Locations are distributed throughout the ALS facility including the storage-ring, injector, insertion-device, and photon-beam-line areas and the control room. Conversations are duplex, with provisions for any number of stations to be on a given channel while other conversations are being carried on simultaneously.

The ALS safety system is a multi-purpose system designed to ensure that personnel are not exposed to ionizing radiation, non-ionizing radiation, electrical shock, or other hazards. In addition, it provides protection against damage to equipment. The system consists of a pair of redundant, hardwired, fail-safe electro-mechanical circuits connected to controlled devices via an enclosed (and locked) cross-connect system. All semiconductors used are redundant and self-checking. The system is on emergency power to ensure uninterrupted interlock-status information. System status is available to the computer control system, but the computer will not be able to override any fault condition. In the event of an unexpected entry into a protected area, the following equipment will be turned off:

- all magnet power supplies
- all rf power supplies
- all inflection power supplies
- all extraction power supplies
- all electron-source power supplies

Normal entry, except for well-controlled variances, requires that all of the above be in the safe condition.

Other personnel-safety features include emergency "crash-off" boxes located not more than 100 feet apart. These "crash-off" boxes will cut all ALS power, except for emergency power.

Injection System

The injection system for the ALS consists of a 50-MeV electron linear accelerator and a 1.3-GeV booster synchrotron. High-energy injection into the electron storage ring was chosen to minimize for experimenters any possible interruptions caused by the filling process. Injection at the normal operating energy will help to avoid small, but disruptive, changes in the beam-spot positions that can be produced by energy ramping.

Booster

The booster synchrotron accepts the 50-MeV beam from the linac, accelerates it to 1.3 GeV, and transfers it to the storage ring. The booster cycles at 1 Hz, each cycle consisting of a 0.35-second accelerating ramp, a 0.2-second flat top for allowing the beam to damp completely, a 0.35-second descending ramp, and a 0.1-second quiescent period.

The booster can be operated in several modes. For the many-bunch mode of operation in the storage ring, 92 of the 112 rf bucket are filled, leaving a 40-ns gap during which the injection kicker magnet turns off and the extraction kicker magnet turns on. In this mode the filling time of the storage ring to 400 mA is about 2.75 minutes assuming a 20-mA beam from the 50-MeV linac, single-turn injection into the booster, and a 50% overall transfer efficiency.

For the few-bunch modes of operation in the storage ring, the linac is pulsed to produce a series of 21 short (2-ns) but intense (40-mA) beam pulses spaced at 32-ns intervals. A three-turn mode of injection is used to inject these bunches into 7 of the 112 rf buckets in the booster. During the 0.2-second flat top of the booster cycle, all 7 of the loaded buckets can be sequentially transferred to just one of the buckets in the storage ring; a waiting period of approximately one damping period (25 ms) must be allowed between transfers. This transfer scheme is a principal reason for choosing the booster-to-storage-ring circumference ratio of 7/19.

To load the storage ring to 400 mA in this few-bunch mode takes 289 booster cycles (assuming an overall transfer efficiency of 50%), or 4.8 minutes. Since each booster cycle can be individually timed and the seven beam bunches can be distributed in the storage ring in a number of ways, a large number of "few-bunch" modes of operation are possible in the storage ring.

The lattice of the booster synchrotron is shown in Figure 3-17. It is similar to the lattice of the storage ring in that it is made up of a series of achromatic cells with intervening long straight sections. There are six such achromatic cells, and the six long straight sections are each 2.4 meters long. The circumference is 67.2 meters (7/19 of the storage ring circumference). This lattice was chosen over several others that were studied because it has the following favorable properties: convenient injection and extraction; low emittance; low dispersion; high superperiodicity; adequate space for sextupoles, beam monitoring equipment, and correction magnets; and efficient use of space. These properties tend to minimize the injection- and extraction-magnet requirements, the required apertures, and the required rf voltage. They also permit a convenient location of the booster within the existing building.

The major parameters of the booster synchrotron are given in Tables 3-9 and 3-10.

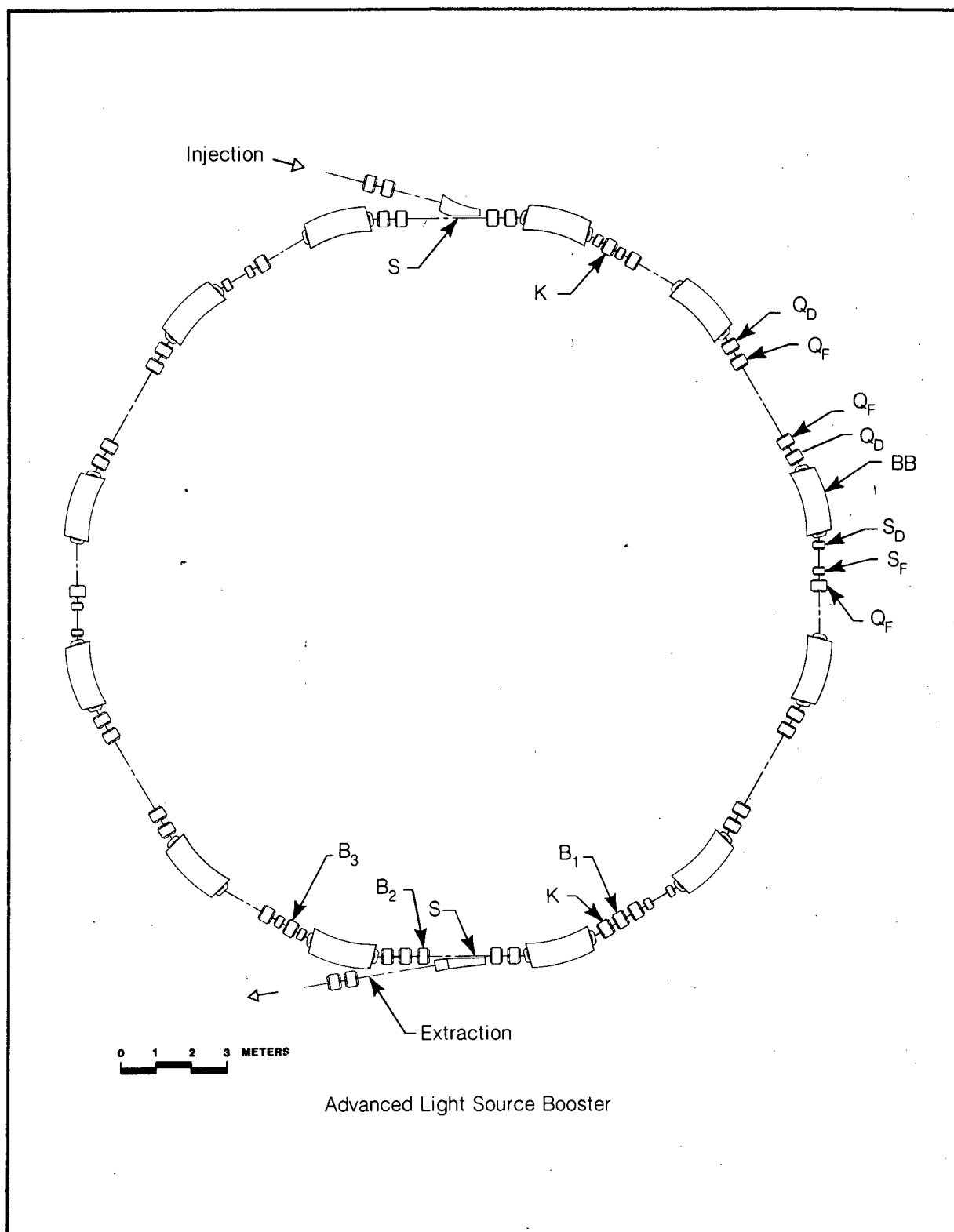


Figure 3-17. Booster synchrotron.

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Table 3-9
Booster Synchrotron Design Parameters

Electron Energy (GeV)	0.5 – 1.3
Electron Current, Many-Bunch Mode (mA)	13
Electron Current, Few-Bunch Mode (mA)	7
Cycle Rate (Hz)	1
Beam Particles	$1.0 - 1.8 \times 10^{10}$ electrons
Circumference (m)	67.2
No. of Superperiods	6
Horiz. Emittance, 1.3 GeV (π m-rad)	7.5×10^{-8}
Energy Spread, 1.3 GeV	$\pm 0.060\%$
Dipole Bending Radius (m)	3.53
Dipole Length (m)	1.85
Max. Dipole Field (T)	1.227
Quad. Length (m)	0.28
Max. Quad. Gradient (T/m)	13.64
Vacuum Aperture, dipoles (cm)	4×5.5
Vacuum Aperture, quadrupoles	10 cm diameter
Max. Horiz. Beta (m)	11.22
Max. Vert. Beta (m)	15.47
Horizontal and Vert. Tune	4.83, 1.88
Horizontal and Vert. Chromaticity	-7.35, -5.98
Momentum Compaction	0.0149
Revolution Frequency (MHz)	4.46
Radiofrequency (MHz)	499.65
Harmonic Number	112
Max. RF Voltage, peak (kV)	200
Synchrotron tune, ν_s	0.0062
Energy Gain per Turn (keV)	0.81

Table 3-10
Booster Parameters at Different Energies

	50 MeV	1.3 GeV
Radiation Loss per Turn	0.16 eV	72 keV
Energy Spread ($\Delta E/E$)	$\pm 7.5 \times 10^{-3}$	$\pm 6.0 \times 10^{-4}$
RF Bucket Half-Height ($\Delta E/E$)	$\pm 3.9 \times 10^{-2}$	$\pm 6.4 \times 10^{-3}$
Damping Times:		
Horizontal	141 s	8.0 ms
Vertical	144 s	8.2 ms
Energy	72 s	4.1 ms

The booster synchrotron magnet system includes 12 bending magnets, 30 quadrupole magnets, 12 sextupole magnets, and 24 steering magnets (12 horizontal, 12 vertical). The booster bending magnets have a laminated-yoke construction to minimize eddy current problems and to maintain good field penetration and field quantity during the acceleration ramping of the injection cycle. The booster ring generally requires larger magnet apertures than does the storage ring but does not require access through the bending magnets for synchrotron radiation beam ports.

The bending magnets will be of an "H" type construction with flat pancake coils encircling the poles. The "H" shape will be punched as a single piece from the steel lamination to produce good magnetic field uniformity and good structural rigidity. Coils will be sized to fit through the magnet gap for insertion during magnet assembly. The magnets will be curved to follow the beam trajectory and will have an effective magnetic length of 1.85 m. The magnet cross section is shown in Figure 3-18. The nominal operating parameters of the dipoles for booster operation at 1.3 GeV are shown in Table 3-11.

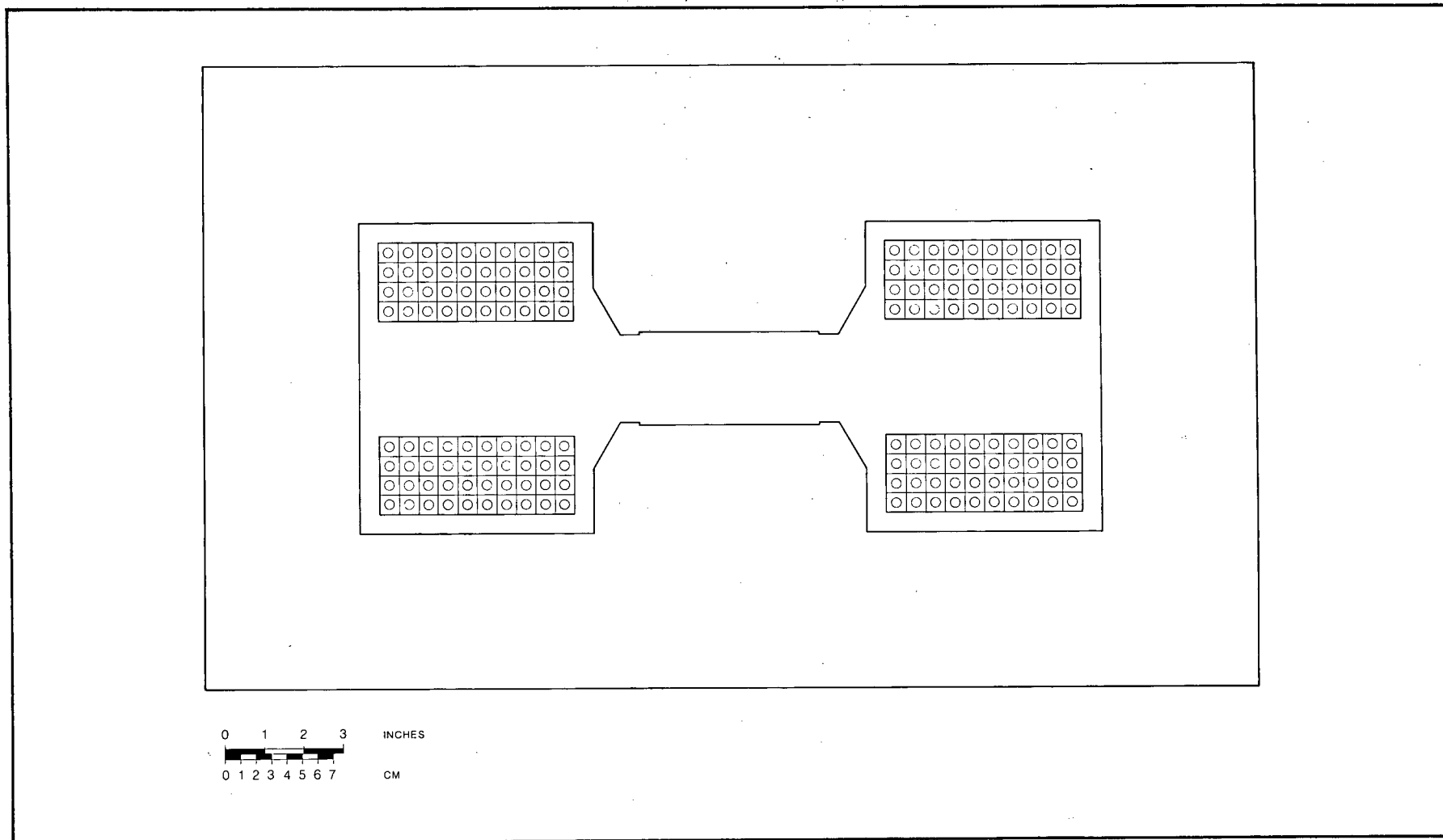


Figure 3-18. Booster bending magnet cross section.

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Table 3-11
Booster Dipole-Magnet Parameters

Number Required	12
Bending Angle (degrees)	30
Field (T)	1.23
Gap Height (cm)	6.0
Good-field Width (cm)	5.0
Length, Magnetic (m)	1.85
Stored Energy (J)	1.65×10^4
Inductance (H)	5×10^{-2}
Resistance (Ω)	0.0665
Current, Peak (A)	818
Voltage, dc (V)	54
Voltage, ac, Peak (V)	115

The quadrupole magnets have an effective length of 28 cm and a maximum design gradient of 17.7 T/m. The design uses a split-yoke assembly with essentially parallel-sided coil slots, as shown in Figure 3-19. A single-piece lamination is not attractive here, because it does not allow adequate clearance for coil insertion through the aperture during assembly and requires very difficult coil fabrication procedures. Using a smaller coil is unattractive because of the need for very-high current densities in the conductors. The space between the coils along the horizontal midplane provides convenient clearance for the deflected electron beam in the extraction channel. Furthermore, the quadrupole side yoke can be easily modified to provide even greater horizontal beam space, if required. The operating parameters for each of the three quadrupole families are given in Table 3-12.

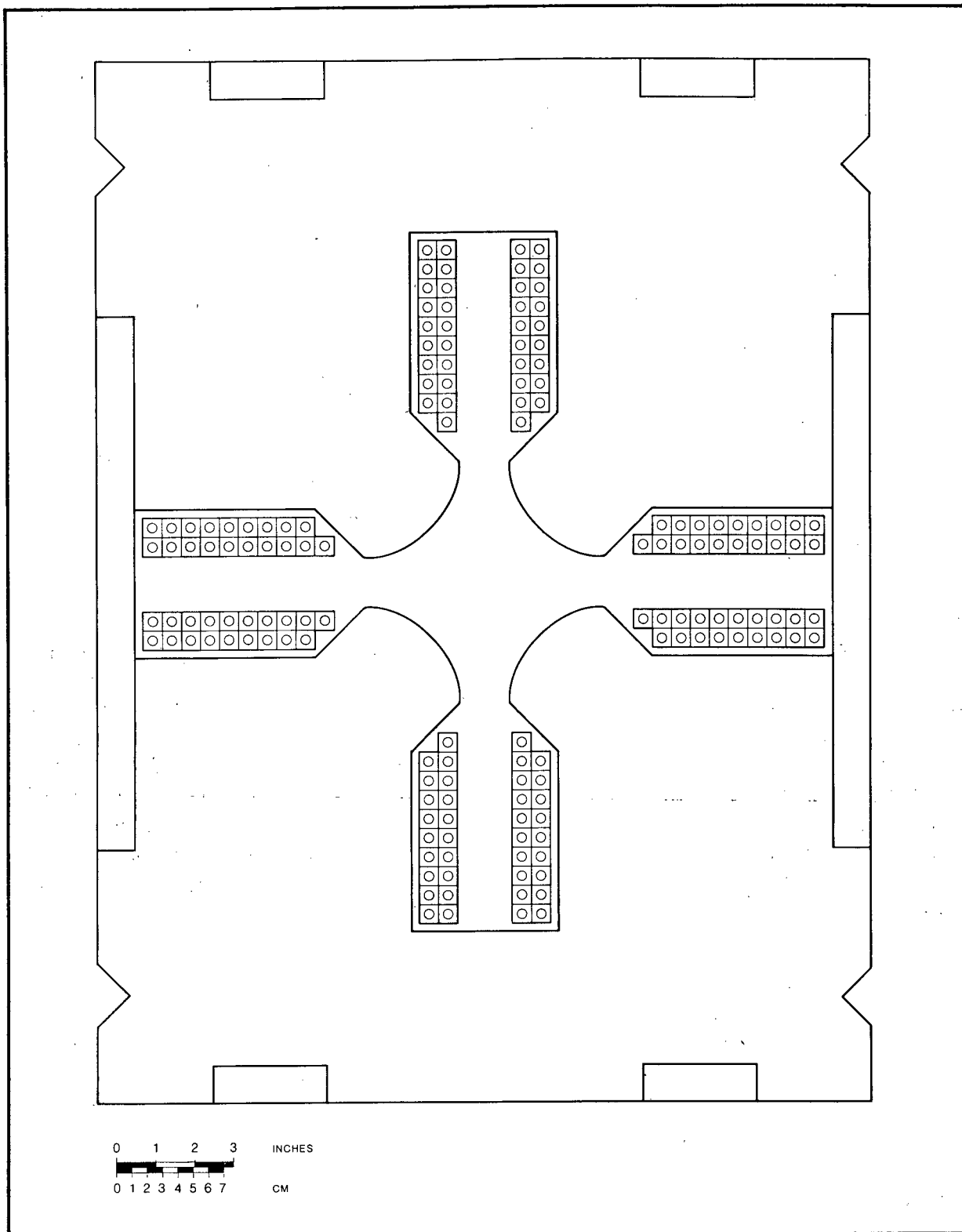


Figure 3-19. Booster quadrupole magnet cross section.

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Table 3-12
Booster Quadrupole Parameters

Quadrupole ID	QF1	QD2	QF3
Number Required	12	12	6
Aperture Diameter (cm)	10.0	10.0	10.0
Effective Length (cm)	28.0	28.0	28.0
Maximum Gradient (T/m)	16.8	15.4	17.7
Current (A)	900	830	960
Voltage, dc (V)	14	13	15
Power, dc (kW)	13	11	15

The booster sextupole and steering magnets are of similar construction to those of the storage ring (described in the Section on Ring Magnets). There will be a total of 12 sextupoles and 24 steering magnets in the booster lattice. A booster sextupole magnet is shown in Figure 3-20.

The booster vacuum chamber consists of 1-mm-wall-thickness stainless steel tubing, except in the injection and extraction regions, where ceramic sections are required. The relatively modest vacuum requirement of 1×10^{-7} torr in the booster ring can be obtained with four 220-l/s ion pumps distributed around the booster. The transfer line between the booster and the storage ring has a pressure gradient of 10^{-7} to 10^{-9} torr, but its relatively small diameter and great length make it possible to maintain this gradient with a 100-l/s ion pump. An isolation valve separating the two rings is needed for booster maintenance and for protection against vacuum accidents.

The pulsed kicker magnets and the narrow septum magnets are described in the following Section on the Beam Transfer System. Similarly, the booster-magnet power-supply system is described in the Section on the Magnet Power-Supply system.

The rf system for the booster synchrotron uses a single rf resonator of construction similar to that of the main-ring resonators. The few kW of rf power is easily supplied by a commercial UHF transmitter, modified to our requirements. The phase- and gradient-control system is identical to that used for the storage ring. The rf signal is fed from the phase-stable reference system.

Beam Transfer System

The beam transfer system for the ALS consists of the following subsystems: 50-MeV beam transport from the linac to the booster; single-turn and multi-turn injection into the booster; beam extraction from the booster; 1.3-GeV beam transport from the booster to the storage ring; and injection into the storage ring.

Beam transport of the 50-MeV electron beam from the linac to the booster requires three bending magnets and four quadrupoles. The beam line that transports the 1.3-GeV beam between the booster and the storage ring requires four bending magnets and seven quadrupoles. The quadrupole design is the same as that for the storage-ring quadrupoles.

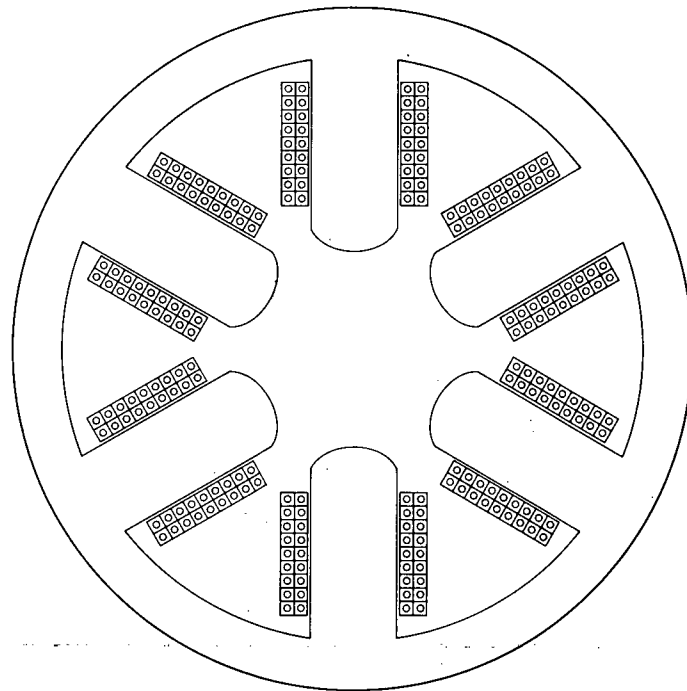


Figure 3-20. Booster sextupole magnet cross section.

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Beam injection and extraction from the booster synchrotron are accomplished using similar components in opposite straight sections of the booster. The injector uses a septum magnet and a fast kicker for single-turn injection (see Figure 3-21). The same septum magnet, along with three bump magnets, is required for three- or four-turn phase-space stacking of the injected beam in the booster ring. These bump magnets are excited with a current waveform that rises to full field and decays in roughly stepwise fashion to zero during four revolution periods in the booster. This mode of stacking in betatron phase space works well if the fractional part of the betatron tune is approximately 0.25. Figures 3-22 and 3-23 show details of the kicker magnet; Figure 3-24 shows a septum magnet; and Figure 3-25 shows a bump-magnet power supply.

Beam extraction from the booster (see Figure 3-26) requires a fast kicker, three bump magnets, and two septum magnets. The three bump magnets establish an offset equilibrium orbit for roughly 100 revolution periods. When the bump-magnet current reaches its peak, the fast kicker steps the beam across a narrow copper septum. In the many-bunch mode, the kicker risetime is less than 40 ns to fit into the 40-ns gap in the booster beam. In the few-bunch mode, the kicker rise and fall times must be less than 32 ns, the spacing between the seven filled buckets. After extraction the beam is deflected beyond the yoke of the last quadrupole in the straight section by a thicker magnetic septum. Two septum magnets are required because of current-density limitations in the thinner septum.

Bucket-to-bucket transfer of the electron beam bunches from the booster to the storage ring is made possible by using the same radiofrequency (500 MHz) in the two rings. In the many-bunch mode, the beam bunches in the 92 filled buckets of the booster are transferred to 92 of the 304 buckets in the storage ring. The consecutive transfer cycles are randomly synchronized, so that eventually the filling of all the rf buckets in the storage ring becomes reasonably uniform.

In a typical transfer cycle, the electron beam being injected into the storage ring is launched into a horizontal coherent oscillation with an amplitude that is much larger than the width of the beam already stored. (Because transverse damping times are about 25 ms in the storage ring, the stored beam has time between injection cycles to damp to its equilibrium size.) The equilibrium orbit of the stored beam is moved to within $4\sigma_x$ of the injection septum when the injected beam is launched on its initial trajectory. A half-wave bump is used to make this shift in the equilibrium orbit. A fractional horizontal tune near $1/4$ or $3/4$ is used. Consequently, to avoid having the injected beam hit the septum during the fourth revolution, the half-wave bump must be turned off in $2.2 \mu\text{s}$. This is a standard method of injection into electron storage rings. Details of the storage ring injection system are shown in Figure 3-27.

The booster fast kickers for injection and extraction require fall times for injection and rise times for extraction of approximately 40 ns in the many-bunch mode of operation. The flat tops for both these magnets are approximately 185 ns long. In the few-bunch mode, the same extraction kicker magnet is used but with a different modulator to provide a faster risetime and a shorter pulse. The three injection bump magnets and three extraction bump magnets for the booster ring and the three injection bump magnets for the storage ring are pulsed with roughly half-sine waveforms a few microseconds long. All the fast kickers and bump magnets have ferrite cores, wound with one-turn current-sheet conductors. In the case of the fast kickers, the modulators are mounted adjacent to the magnet. All the pulsed magnets are powered separately, and the currents of these magnets must be adjusted to accommodate the tune of the synchrotron ring. The pulsed magnets are fitted with ceramic beam tubes having a thin conductive metal

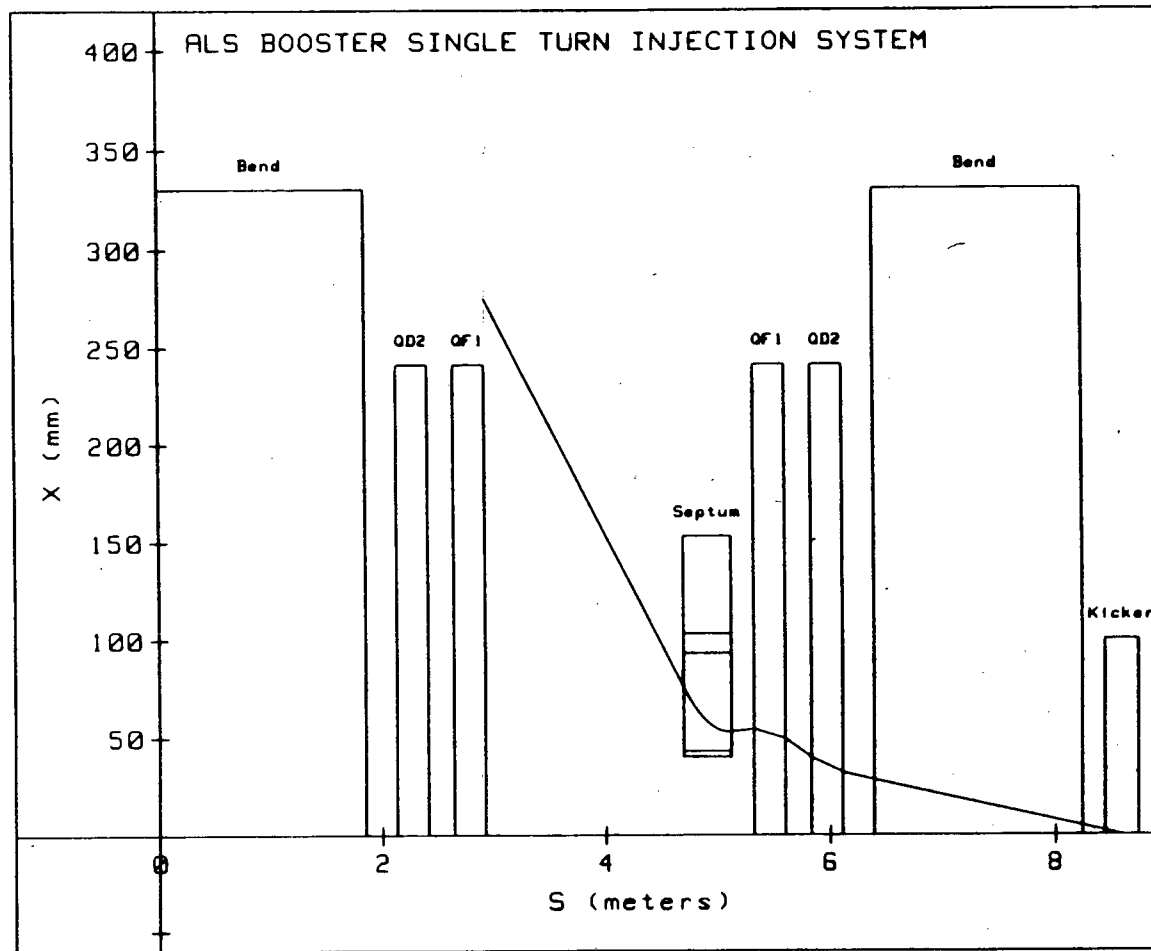


Figure 3-21. Booster beam injection system.

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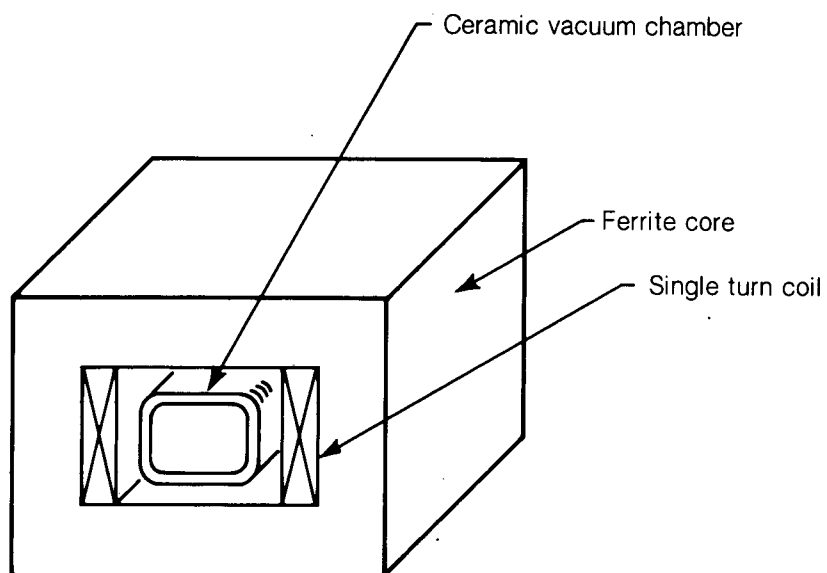


Figure 3-22. Kicker magnet.

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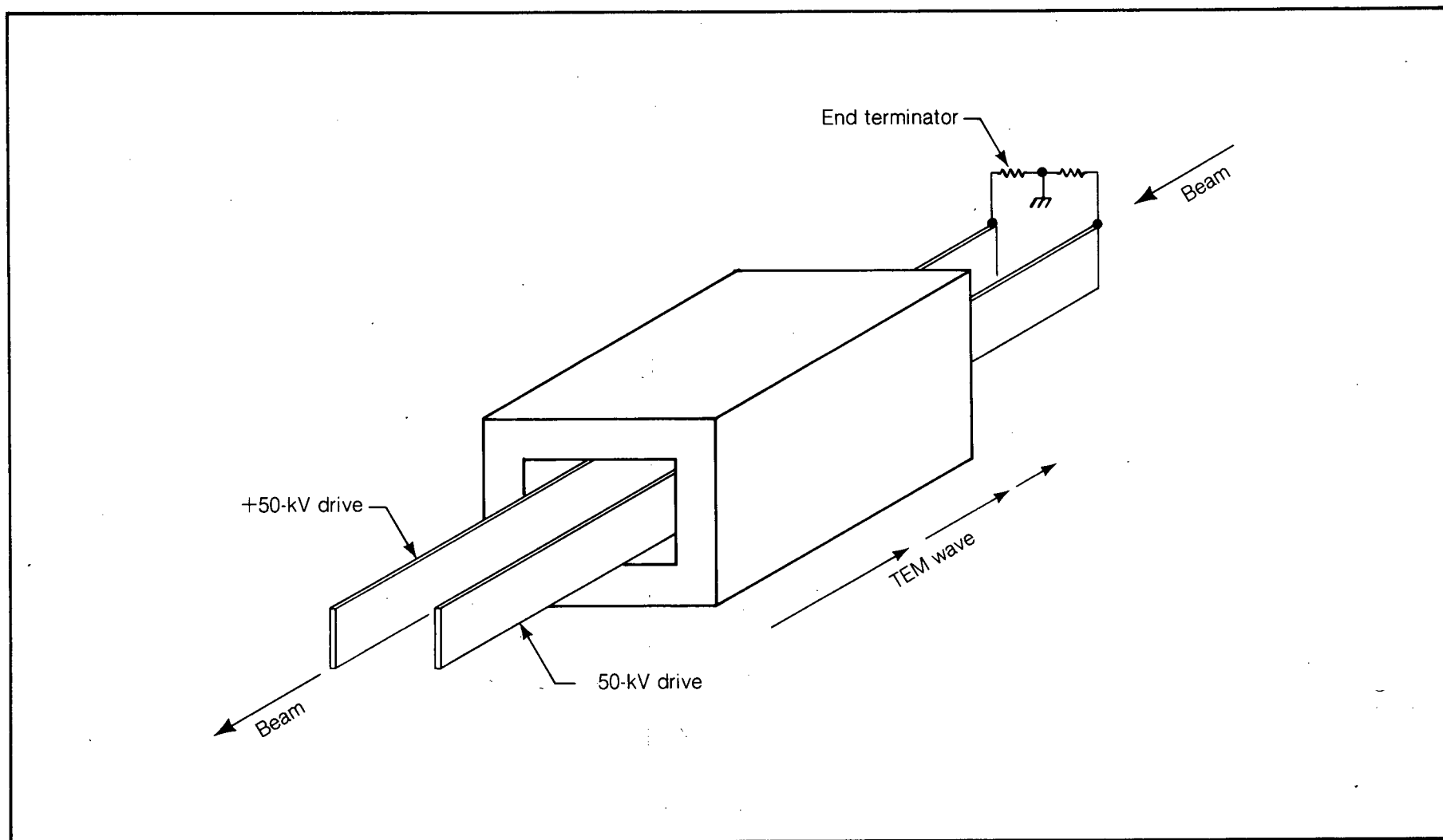


Figure 3-23. Fast beam kicker ferrite-loaded strip-line magnet.

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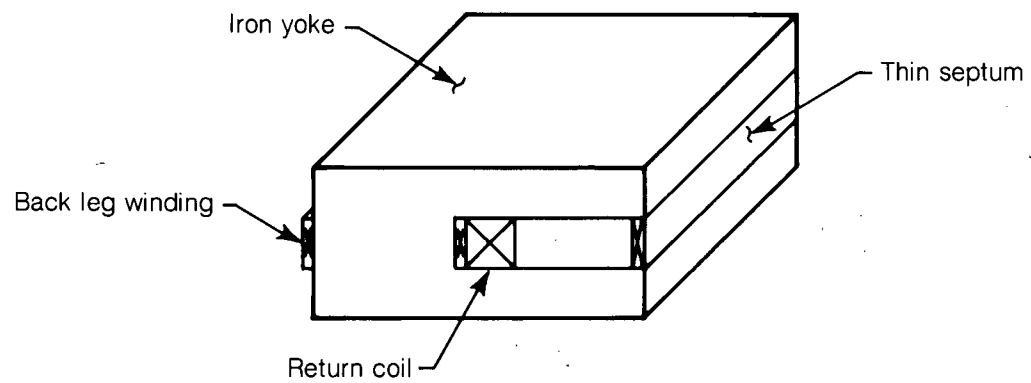


Figure 3-24. Injection/extraction septum magnets.

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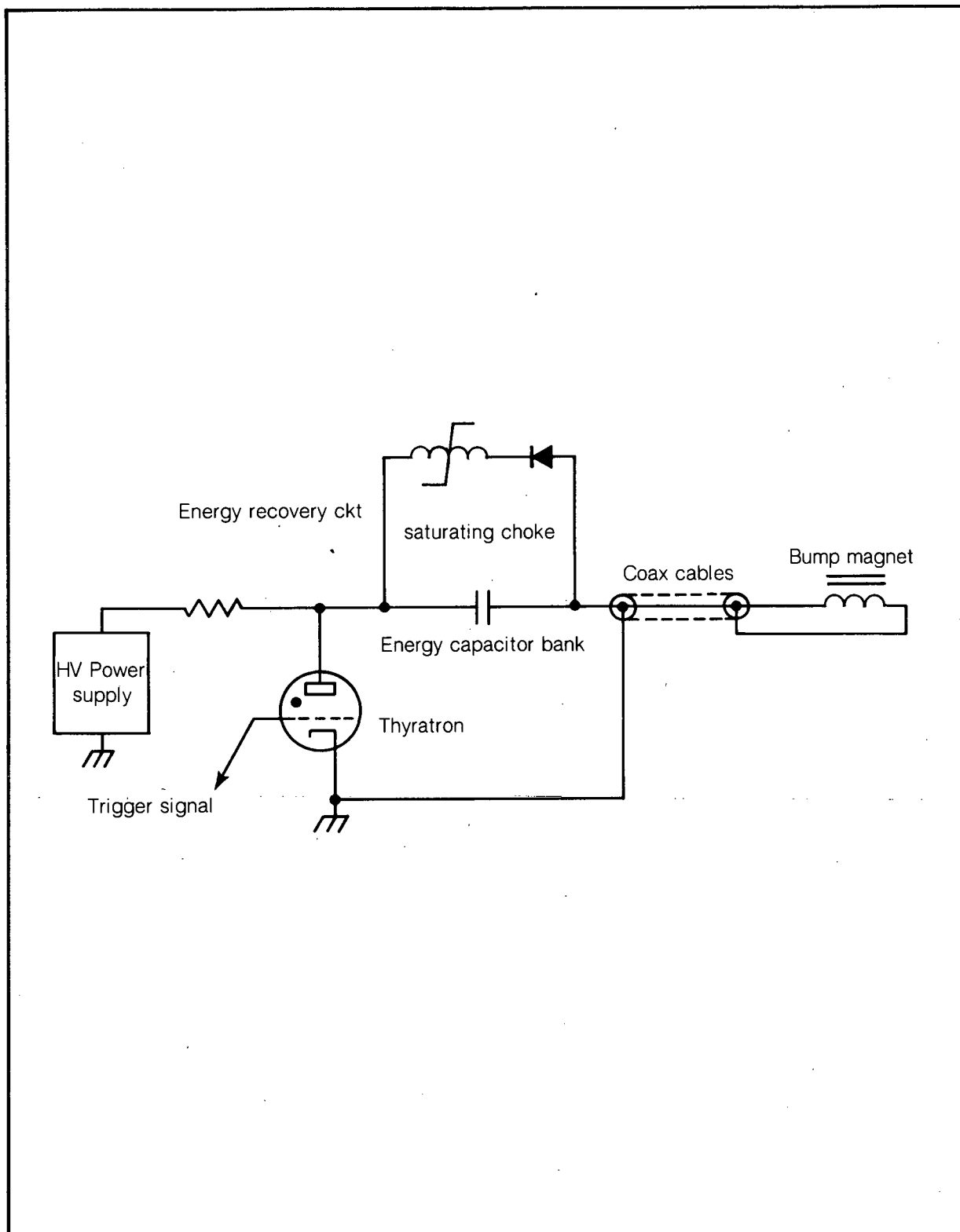


Figure 3-25. Medium-speed "beam bump" magnet power supply.

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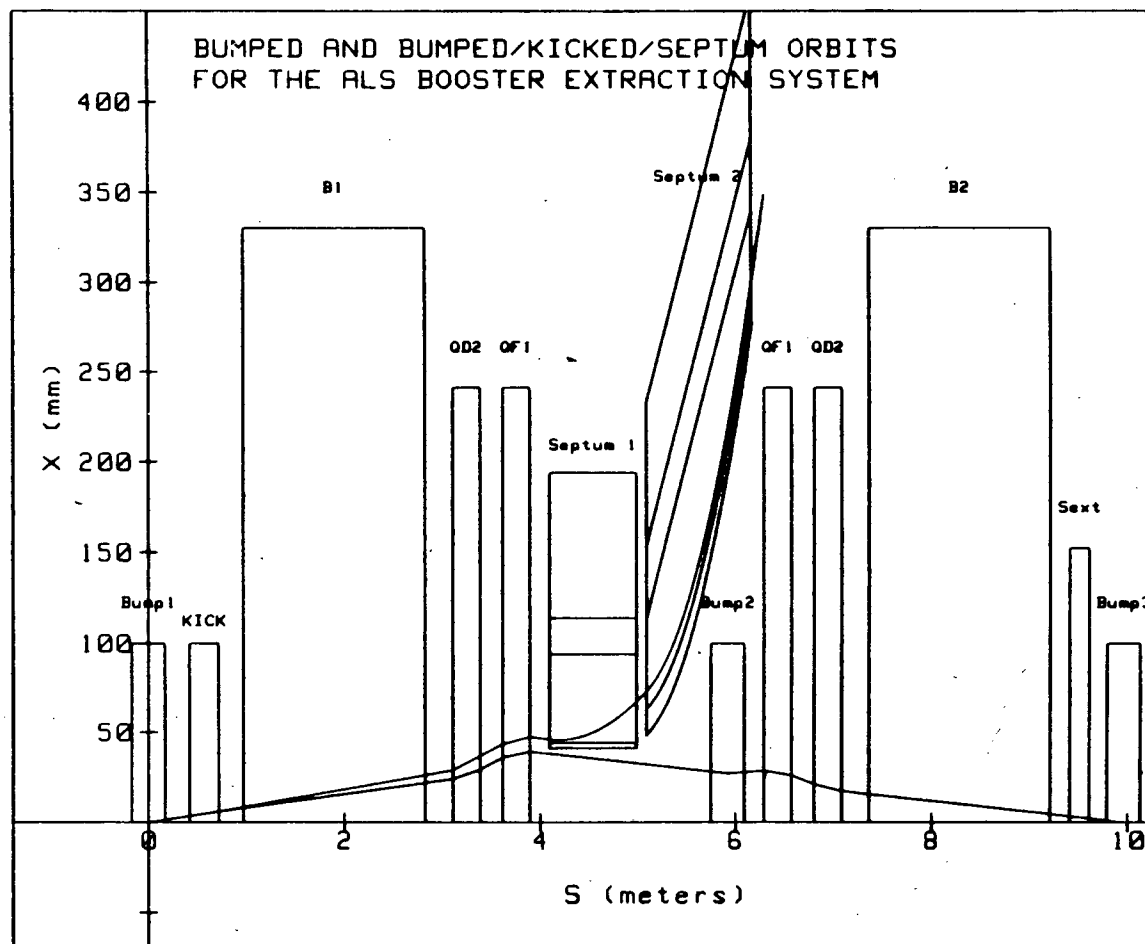


Figure 3-26. Booster beam extraction system.

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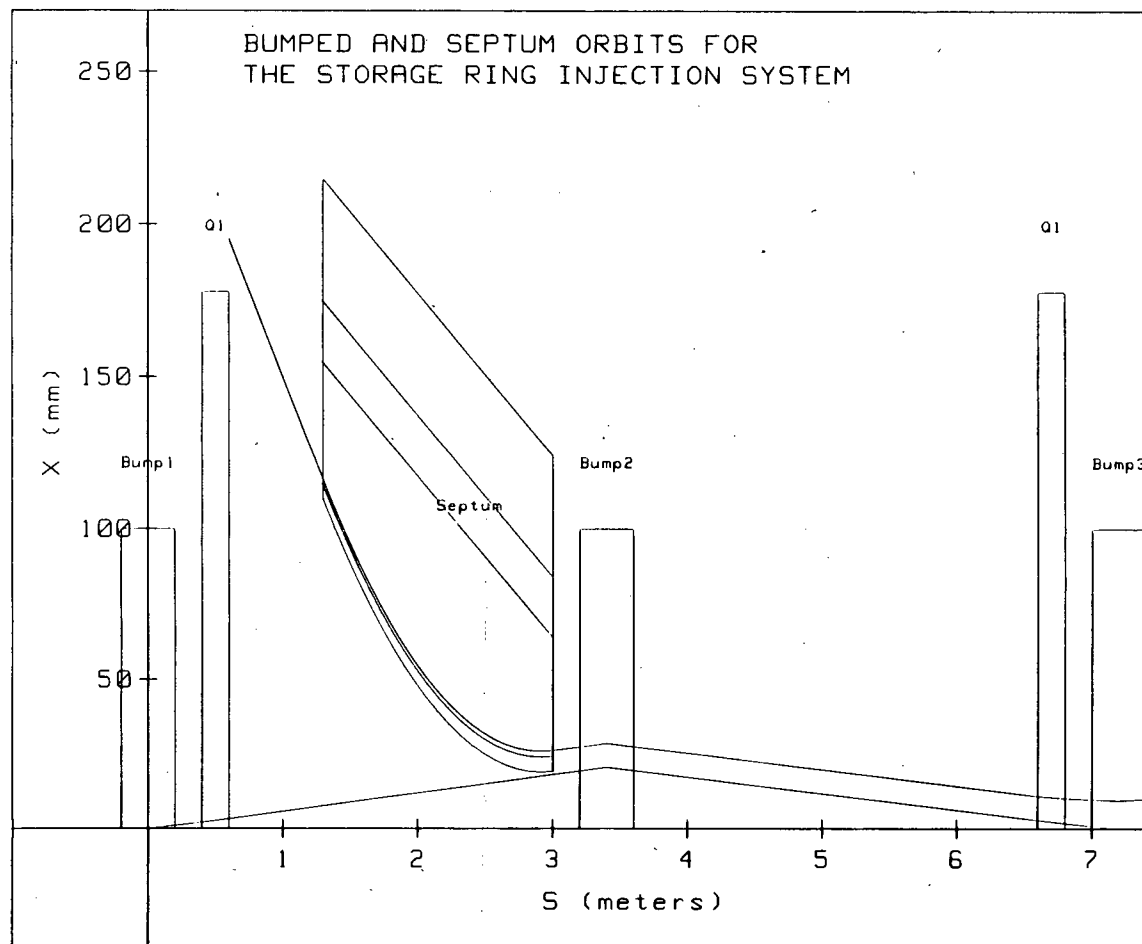


Figure 3-27. Storage ring injection system.

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coating. The conductive coating allows the pulsed magnetic field to penetrate the vacuum chamber without interrupting beam-image currents.

The magnetic septa for injection and extraction have conventional designs and operate continuously during the injection cycle. Coil ends are terminated in iron field clamps, and back-leg windings are incorporated in the design to minimize perturbations of the booster and storage-ring circulating beams.

Linear Accelerator

The electron linear accelerator is a 50-MeV S-band linac about 8 m long. The electron beam from the linac is modulated, or chopped, to provide the required time structure to fill the rf buckets in the booster synchrotron. The use of different operating modes permits varying the number of electron bunches in the booster and in the storage ring. All the rf buckets can be filled with electron bunches (aside from a gap in the train of bunches caused by the injection kicker magnet in the booster), some of the buckets can be filled, or even a single bucket can be filled in the booster and storage ring. To fill all the buckets, a 185-ns, 20-mA linac beam pulse fills 80 percent of the booster circumference, leaving a 40-ns gap for the rise time of the extraction kicker magnet. Fast, single-turn injection is used in this mode. An alternative mode of linac operation is required when the storage ring is to be filled with only a single bunch of electrons, to accommodate experiments that require a long "dead time" between photon pulses. For the single-bunch or few-bunch modes of operation, the linac beam is modulated so that each burst consists of a train of 2-ns pulses at intervals of 32 ns. Multi-turn injection into the booster puts all of these pulses into seven equally spaced rf buckets in the booster.

The linac can deliver up to 50 mA, with a small duty factor. The major beam components of the linac include a chopped electron gun, an S-band buncher phase-locked to the linac, and two sections of standard corrugated-wave-guide (CWG) accelerator. Other major linac components include a 30-MW klystron amplifier and power system, a signal source, and an rf control system.

The electron gun has the capability of producing a pulse of 100-keV electrons with a current of 1 A. The entire electron-gun assembly has a standard commercial design, and it can be readily purchased. A pulser is mounted inside the high-voltage gun structure and is dc coupled so that it can produce either a single 2-ns pulse for single-bunch operation or a pulse train to fill all the rf buckets. The buncher operates at 2856 MHz and is phase-locked to the injector linac. Since only about 1 kW is required, its power is taken from a coupler on the linac input-power transmission line (see Figure 3-28).

The traveling-wave linac consists of two sections of constant-gradient CWG accelerator. We estimate the linac emittance at about $6.4 \times 10^{-6} \pi$ m-rad in each transverse plane.

The very low duty factor in the pre-injector limits the average rf power dissipation in the accelerator components to less than 500 W. A heated-water system operating at 113°F maintains the tuning stability in the CWG sections.

A single commercially available klystron, rated at over 30 MW, provides ample power for all linac rf accelerating structures. The klystron output power is split into two equal parts with a hybrid junction to power the two CWG sections. The outputs of the CWG sections terminate in tapered resistive waveguides. Heated water provides the temperature stability required for the phase stability of all transmission line components. A single window isolates the klystron vacuum system from all waveguide power-transmission components, which will operate within the

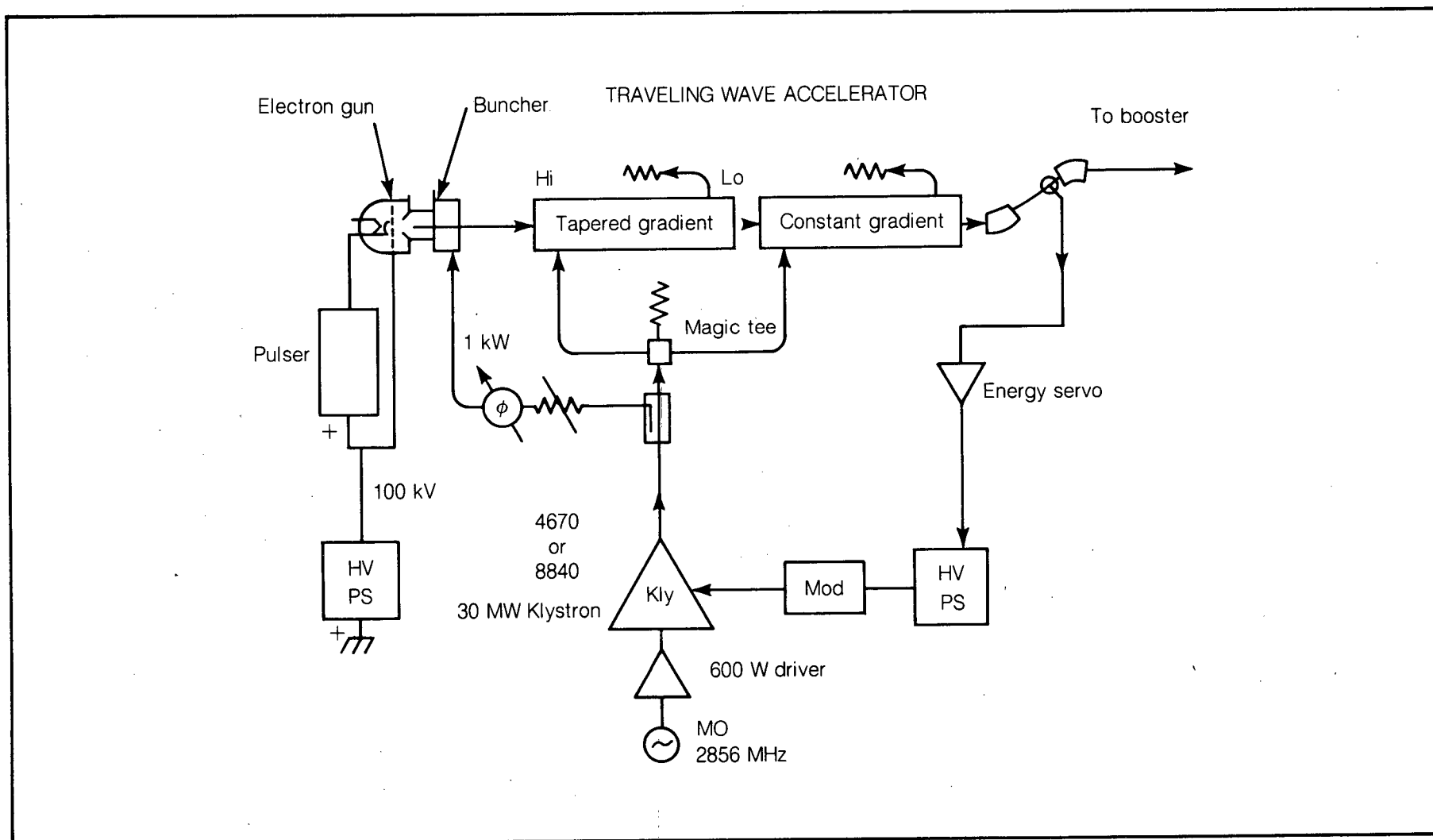


Figure 3-28. Linac RF system.

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linac vacuum.

The main klystron amplifier is powered by a standard line-type modulator of well-proven design. The modulator output drives the primary of a 1-to-10 step-up pulse transformer mounted directly on the tube base. This provides the required beam power of 250 kV at 250 A. The pulse-forming network (PFN) is tuned to a rising output voltage as a first-order compensation for beam loading in the linac. The PFN is designed for a pulse length of about three to five microseconds, to accommodate multi-turn injection. The modulator high-voltage supply is regulated with a signal from an energy monitor in the injection line. This keeps the output energy constant, even if the tuning shifts slightly with time or temperature.

The drive chain consists of a small 1-kW klystron and a stable 2856-MHz signal source, along with several monitoring and control components. The control system provides a gentle turn-on after a fault trip to prevent excessive window and waveguide arcing.

Positron Injection Option

In most electron storage rings the trapping of positive ions produced by the ionization of the residual gas can lead to increased emittance or to shortened beam lifetime. This issue was discussed earlier in the sub-section on "Major Parameters" of the storage ring. It was shown that these problems can probably be avoided at the ALS, because it is likely that the ALS storage ring can be operated in modes in which positive ions are driven to the wall in a time much shorter than the time for neutralization (about 2 seconds at 10^{-9} torr).

In the event that these techniques for avoiding ions are unsuccessful, an alternative approach is to replace the electron beam in the storage ring with positrons. The positive ions are then repelled by the stored beam and, hence, do not present any problem. The positron-beam approach is certain to avoid the positive-ion trapping problem, but it is more complicated than the straightforward electron-beam approach.

Although it appears quite likely that the ALS can be operated successfully with an electron beam, it is not possible at this time to present a definitive argument that positrons will not be required for the ALS to reach all of its performance goals, especially the very small design emittance of the electron beam. It therefore appears expedient to hold open the option of a positron injection system for the present time. However, we anticipate that our ability to predict the necessity for positrons will improve substantially in the coming months. First, operating experience with new storage rings will undoubtedly produce data which will be illuminating regarding these issues. Among such storage rings are Aladdin, the NSLS X-ray Ring, the SRS at Daresbury, the KEK Photon Factory, and the damping rings for the SLAC Linear Collider. Second, we plan to design and to help conduct experiments on existing storage rings, in order to understand better the phenomena of ion trapping and emittance growth. Last, the calculations and simulations discussed earlier will be continued and expanded. To conclude, we believe that the understanding of ion trapping can be developed to the point where a very rational decision can be made concerning the positron injection option for the ALS. This decision must be made approximately one year after start of construction funding. This will leave three years for positron injection system construction before the completion of storage ring construction. The rest of this Section describes a positron injection option and presents the estimated cost in terms of FY83 dollars.

The positron source uses a linac with a folded recirculating configuration in which most of the structure is used once for the acceleration of electrons to the positron converter, and then

once again for acceleration of the positrons. This is shown in Figure 3-29. This positron beam from the linac is fed to the booster and thence to the storage ring.

The electron gun injects electrons into the first section of a two-section linac, and the intermediate-energy electrons are brought around a 180-degree bend to be accelerated further by a second, longer section of accelerator. They are then deflected another 180 degrees and brought to the positron radiator. The positrons are collected in a tapered solenoid and accelerated in a special 50-MeV section in which additional focusing in the form of solenoids and quadrupoles provides the capability to accept the large transverse emittance of the positron beam.

The 50-MeV positron beam is then re-injected into the two sections of linac that had accelerated the original electrons. A simple trio of magnets combines the 50-MeV positron beam and the 100 kV beam from the electron gun. At the 180-degree bend, small magnets separate the trajectories of the positrons and electrons, which have their own 180-degree transport system. The positrons are further accelerated in the second long section of linac and are split off by another trajectory separation magnet.

The parameters of the positron injection option are described in Table 3-13.

Table 3-13
Positron Injection Option

Injector	100 kV, .25A
Pulse length	700 ns, 3 booster turns
First section	100 MeV, 8 MeV/m
Length	12.5 m
Second section	150 MeV, 8 MeV/m
Length	19 m
e ⁻ energy on radiator	250 MeV
e ⁻ spot radius	2 mm
e ⁺ conversion efficiency	0.31 %
e ⁺ accepted momentum	6-11 MeV/c
e ⁺ transverse momentum	.83 MeV/c
e ⁺ charge/pulse	3.6×10^9 /pulse
Third (special) section	50 MeV, 8 MeV/m
Length	6.3 m
Repetition rate	2 Hz
e ⁺ flux	7.2×10^9 e ⁺ /sec
e ⁺ energy	300 MeV
transverse emittance	4.9π mm-mrad
Total linac length	38 m
Total rf power	100 MW

The conversion efficiency calculation comes from the SLAC Blue Book and is consistent with several operating positron sources. In this design, the positron converter operates much as does the SLAC converter, with a momentum acceptance from 6 to 11 MeV/c and a transverse

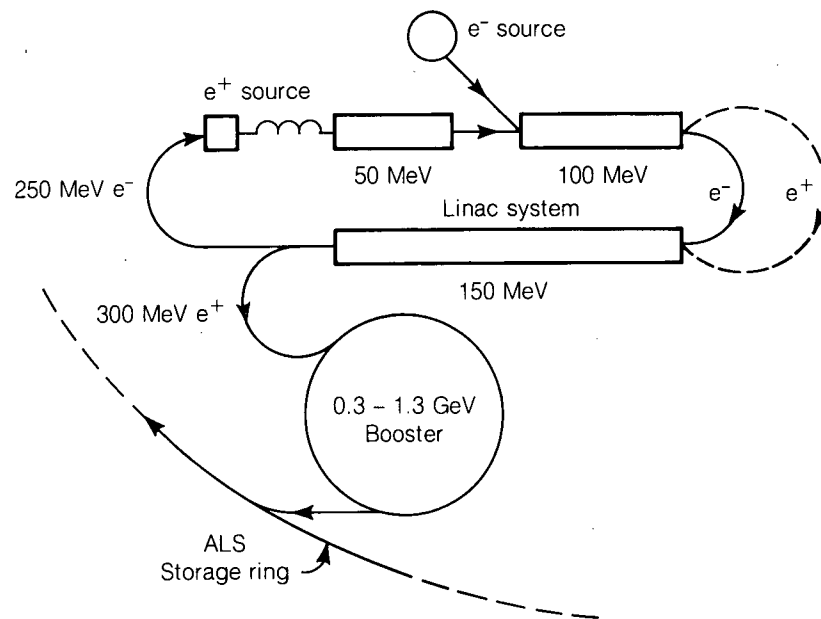


Figure 3-29. Positron injector option.

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acceptance of .83 MeV/c. The spot size of 2 mm represents a lower thermal load on the positron production target than is true for the SLAC device, because of the much lower incident electron energy.

The special 50-MeV section that follows the converter and tapered solenoid is immersed in a focusing solenoid for part of its length, and is constructed in sub-sections to allow the insertion of frequent quadrupole doublets. By the end of the section, the focusing requirements are sufficiently reduced so that the positron beam can share a conventional section of linac with the electron beam.

A further area of optimization and cost savings involves the linac gradient and rf power requirement. The costs are minimized in the very high gradient regime. However, few linacs have actually been built with gradients of 20 MeV/m or greater, although one is being considered for the LEP injector. There is probably little risk in this venture, but for a linac as short as this one, the cost benefit may be marginal. This remains an area open for investigation.

In the positron-injection system shown in Figure 3-29, the 300-MeV, 0.7- μ sec positron beam pulse is fed into the booster by the three-turn method of injection. After acceleration to 1.3 GeV in the booster, the 92 useful positron bunches are transferred to the storage ring, just as in the many-bunch electron-beam mode of operation. With the booster cycling at 2 Hz, the filling time to 400-mA circulating beam in the storage ring is about 16 minutes, assuming 50-percent injection and transfer efficiency both in the booster and in the storage ring.

This positron injection system can also fill the storage ring for operation in the few-bunch modes. However, it can inject beam quickly only for low-current operation.

The estimated incremental cost of the positron-injection system is given in Table 3-14. The 50-MeV linac used in the electron-injection system is assumed to be used for positron injection as well.

Table 3-14
Positron Injection Incremental Costs
(millions of FY83 dollars)

Linac	4.0
Positron converter system	0.4
Beam transport and extra linac focusing	1.1
2 Hz booster modification	0.5
Totals	6.0

The linac costs are based on the cost analysis used for the 50-MeV linac of the electron-injection system. The cost of the positron converter is based on the SLAC estimate for the positron converter in the Stanford Linear Collider Conceptual Design Report [13].

Control System

The ALS has a modern control system based upon the use of a system of microprocessors to provide distributed intelligence. This design strategy was successfully pioneered at LBL on the

Uranium Beams Project. The recent advent of the microprocessor has led to an explosive improvement in computer technology, so that it is now possible to build a highly decentralized accelerator control system that provides exceptional performance at a reasonable price. The current trend is clear indeed: the Positron-Electron Project (PEP) uses a few computers, the Uranium Beams Project uses about 25, and the SLAC Linear Collider (SLC) will use about 100. For the ALS, we plan to use 100 to 200. The major benefits of such a decentralized architecture are a tremendous improvement in system response, an ability to monitor far more variables, and a substantial simplification of programming effort. A basic strategy used successfully for the Uranium Beams Project is to use computer hardware resources to reduce programming costs wherever possible.

Figure 3-30 shows the ALS control system architecture, which will be described from the top down. The highest level of the control system consists of the industry-standard network Ethernet (a trademark of XEROX Corporation). This network uses commercially available hardware to provide communications among the following components of the control system: the Display Micro Modules (DMM's), which drive the accelerator operator consoles; disk storage systems; and several work stations. Disk storage systems are used to record accelerator data, to log errors, to hold data to be printed, and to perform other similar functions. The workstations are used for "number crunching" problems (such as accelerator closed-orbit calculations), which typically require only a modest amount of measured data from the rest of the control system. Work stations are also used for program development and for the diagnosis of problems after beam turn-on. One further function of the network is to provide controlled access by the experimenters to a very few accelerator parameters.

Operating consoles (two are planned) provide the human interface to the control system and to the accelerator, and these consoles are controlled by the DMM's. A very fast control-system response time (about 0.1 second) is highly desirable to avoid objectionable operator delays. To provide this quick response, the DMM incorporates a great deal of computing power in the form of multiple microcomputers, each dedicated to its own tasks. These computers operate in parallel and communicate with one another via MULTIBUS (a trademark of Intel Corporation). We note that a tentative choice of four Intel iAPX-286 microprocessor boards for each DMM provides performance exceeding that of a DEC VAX 11/780 for a very modest price. Each DMM provides operator interface functions, drives the menus, and monitors accelerator problems. The operator console includes six color-TV monitors with touch panels and three knob panels with four knobs each. A substantial programming effort is required to produce the software for the DMM's, because of the complexity of both the calculations and the displays. However, key portions of the DMM software have already been written for the LBL Uranium Beams Project control system.

For the DMM to perform its assigned tasks, it must have access to a complete set of data that describes the current status of the various accelerator systems. These data are stored in the Collector Micro Module (CMM), which provides storage for accelerator data and responds to DMM requests for these data. In addition, the CMM communicates with the Input/Output Micro Modules (IOMM's) and Intelligent Local Controllers (ILC's), which provide the interface to accelerator hardware. This communication is provided by a number of serial links that together can provide the speed required for a quick control-system response time.

The ILC's and IOMM's are local computers (i.e., located near the accelerator) that ensure the proper operation of the accelerator hardware. They are directly interfaced to the accelerator

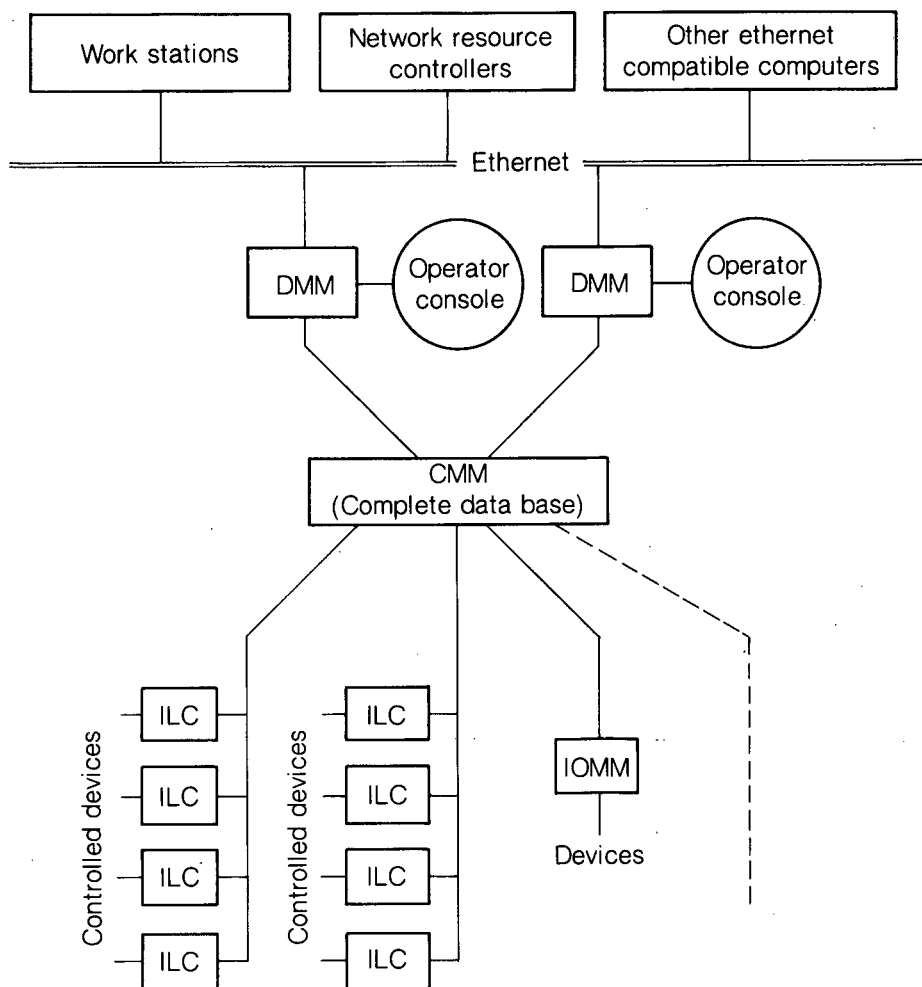


Figure 3-30. Accelerator control system.

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components, and they are provided with considerable computing power (comparable to a 16-bit minicomputer) to perform the following functions: monitoring interlocks, data taking, closed-loop control, data analysis, and error checking. Only analyzed data are sent to the CMM, for the use of the DMM, so the latter is not bogged down with low-level control tasks. The ILC's and IOMM's differ primarily in size and capacity. The ILC's control a few devices with up to about 50 channels of input and output data. The IOMM's, however, are MULTIBUS card cages with up to 16 slots, and they control many devices with up to 250 channels of data. The most powerful IOMM's have multiple microcomputers operating in parallel to perform complex tasks requiring fast response times. A portable console that can interface directly to the ILC/IOMM will be provided for local control or debugging of the ILC's or IOMM's.

In many instances, there are advantages to using several ILC's rather than one IOMM. First, since each ILC deals with only one device, it is easy to provide excess computing capacity. This excess capacity greatly simplifies the programming task, since there is little or no need for the programmer to deal with problems caused by speed limitations of computer hardware. Second, this excess computing speed permits some tasks to be shifted from the DMM, which is the most complex component of the control system, to the ILC, which is the simplest. Examples of such tasks are error checking and conversions of numbers into different representations (from engineering units into ASCII, for instance). The consequences of shifting these tasks are to simplify the DMM software and to reduce software development and maintenance costs. Each ILC is connected to the rest of the accelerator control system through a serial link, so it can easily be isolated from the system during debugging or maintenance.

The use of ILC's also provides considerable flexibility in modifying the control system architecture. Each ILC must constantly refresh about 125 bytes of data at the complete data base stored at the CMM. It is possible for ten ILC's connected to a single 180-kbaud serial link to refresh 1250 bytes of data in about 100 milliseconds. Should it prove necessary, this refresh rate can be increased by reducing the number of ILC's connected to each serial link. In contrast, a similar modification would be difficult to accomplish if IOMM's were used, because the minimum fixed cost of each IOMM chassis is too high for a large increase in the number of IOMM's to be attractive. We estimate that about 27 serial links would be required for 170 ILC's (17 serial links) and 10 IOMM's (10 serial links). Since these serial links operate entirely in parallel, the total system communications capacity is very substantial, almost 5 Mbaud. Note that this is a steady-state speed, not a peak value. If required, about 50 serial links could be used to provide a communications speed of 9 Mbaud.

Computer timing and synchronization are provided by a Manchester encoding system (used for the Uranium Beams Project) with a fiber-optics link. This system provides timing control to a few hundred microseconds.

Insertion Devices

The task of the accelerator design team is to provide an electron storage ring with characteristics (such as low emittance, short bunches, and long straight sections) that permit great flexibility in the selection of insertion devices (wigglers and undulators). The ALS storage ring described earlier meets these criteria. Altogether, 12 long straight sections are available, and 12 insertion devices can ultimately be accommodated. Initially, however, a complement of only six devices (four undulators and two wigglers) is planned.

We have selected a set of possible insertion devices, whose properties are summarized in Table 3-13. We recognize, however, that the users of the facility must be involved in the final choice of insertion devices; and we are leaving open the possibility of modifications to the present list. Details of the various devices are presented below.

Room-Temperature Insertion Devices

The parameters of the six planned insertion devices are listed in Table 3-15. (Note that the undulators U_B and U_C are identical devices.) These parameters are chosen to maximize the high spectral brilliance of the undulation radiation and also to cover the maximum range of photon energies.

Table 3-15
Tentative ALS Insertion Devices (1.3 GeV)

Name	Insertion Device Type	Peak Field (T)	Period (cm)	No. of Periods	Length (m)	E (eV)
U_A	Permanent Magnet Undulator	0.29	16.7	30	5	8 - 200
U_B/U_C	Hybrid Undulator	0.54	5.0	100	5	75 - 3000
U_D	Hybrid Undulator	0.57	3.5	142	5	200 - 5000 (up to 10000 at 1.9 GeV)
W_E	Hybrid Wiggler	1.60	10.0	25	2.5	0.1 - 10000
W_F	Superconducting Wiggler	5.0	14.	14	2	1 - 20000 (up to 40000 at 1.9 GeV)

The high-field wiggler W_F will, of course, use superconducting technology. This device will be described separately in the next Section. The low-field undulator U_A has a field that is low enough to build it as a pure permanent magnet device. The other insertion devices (U_B , U_C , U_D , W_E) will be built as hybrid devices using both samarium-cobalt permanent magnets and vanadium permendur pole pieces. Undulator U_D and wiggler W_E have the smallest pole tip gaps, 1.2 cm, at the indicated fields, which will result in a 1.0-cm minimum beam aperture. These hybrid designs will be very similar to that of the wiggler for the LBL/Exxon beam line at SSRL, which is now close to completion. Undulator U_A is similar to the undulator built by LBL for SSRL two years ago. The two SSRL devices are shown in Figures 3-31 and 3-32. Table 3-16 gives some operating parameters of the ALS insertion devices.

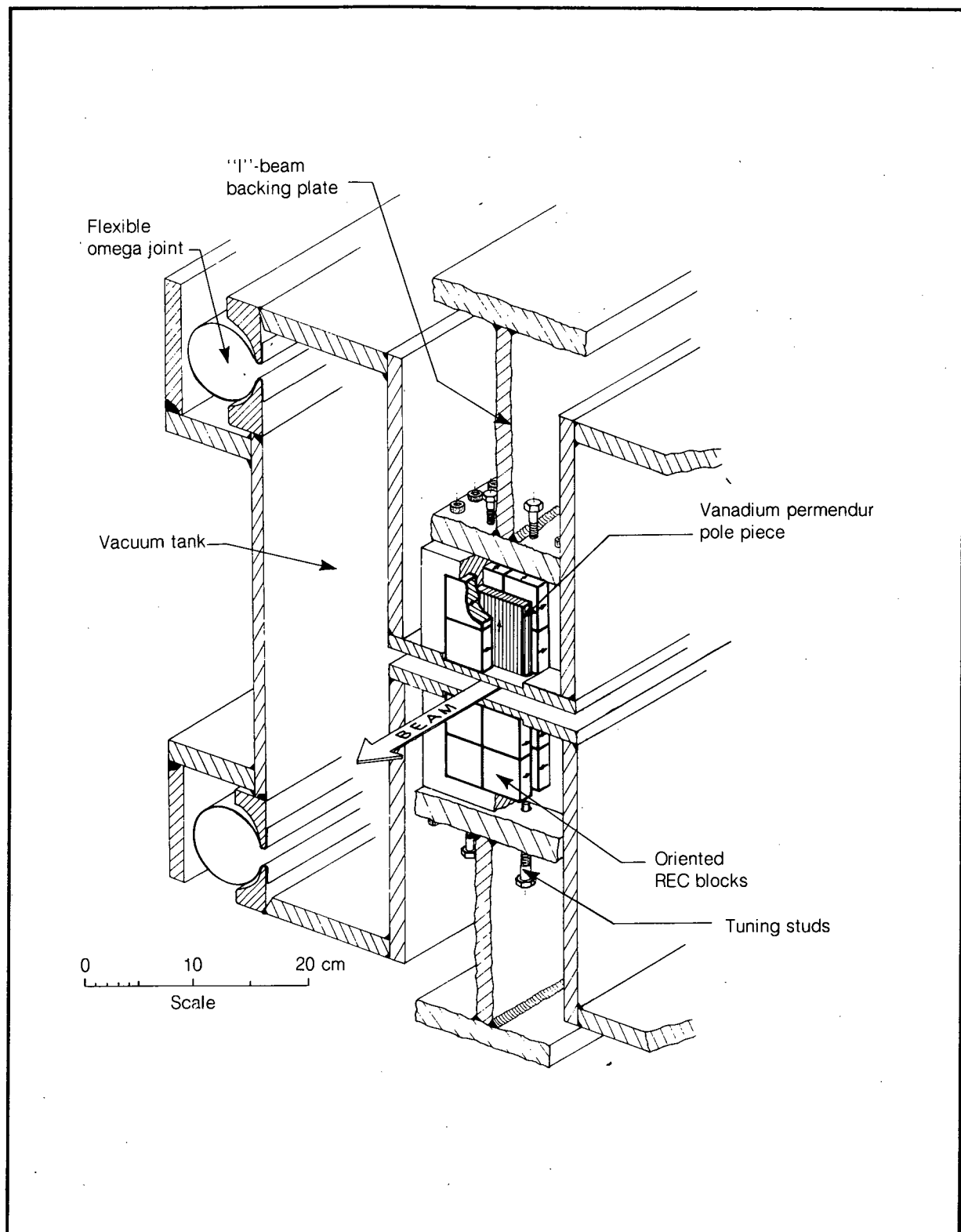


Figure 3-31. Beamline VI wiggler.

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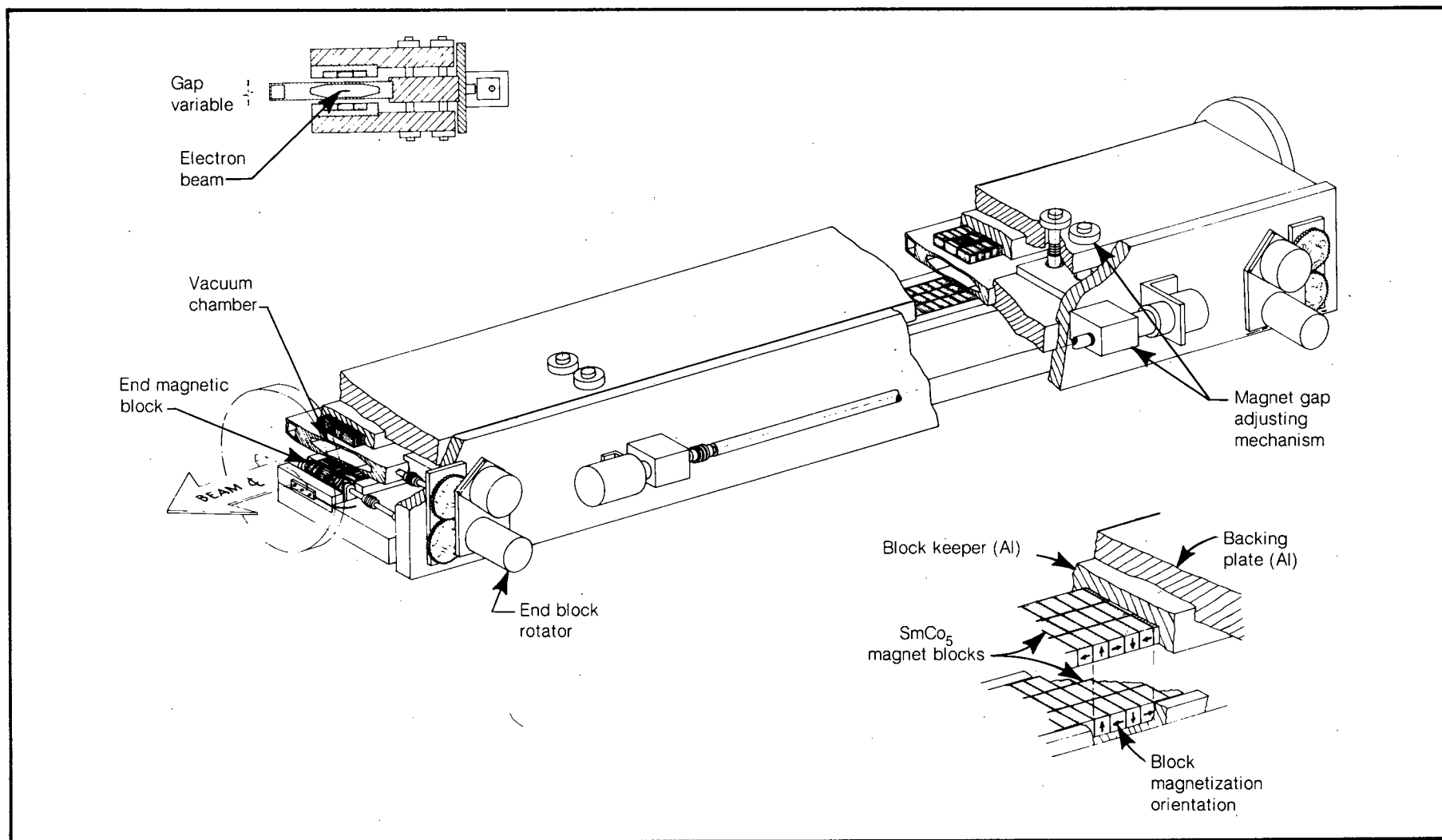


Figure 3-32. LBL-SSRL Undulator.

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Table 3-16
Tentative ALS Insertion Devices Parameters,
Openings Angles and Power Output (1.3 GeV, 400 mA)

Name	K (T-cm)	Magnet Gap (cm)	Critical Energy (keV)	Horizontal Opening Angle ($\pm$ mrad)	Vertical Opening Angle ($\pm$ mrad)	Power (watts)	Peak Power Density (watts/mrad ²)	Peak Power Density @1.9 GeV, (watts/mrad ²)
U _A	4.54	3.0	0.27	1.779	.392	180	107	490
U _B /U _C	2.53	1.75	0.61	0.993	.392	624	666	3040
U _D	1.87	1.20	0.64	.734	.392	696	1001	4563
W _E	14.94	1.20	1.80	5.89	.392	2741	491	2240
W _F	65.66	3.50	5.62	25.71	.392	21412	878	4009

The ALS lattice design, with low electron beam emittance and long straight sections, is ideal for good undulator performance. Figure 3-3 shows the extremely high photon spectral brilliance that the ALS undulators can provide. The range of photon energies available from undulators extends up to 10 keV when the storage ring operates at 1.9 GeV (or up to 40 keV with a superconducting wiggler). The undulator spectrum consists of sharp peaks at discrete energy values, as shown in Figure 3-2. Scanning in energy during an experiment can be achieved by varying the gap size of the undulator to change the magnetic field.

The ALS wigglers provide attractively high photon fluxes for many types of experiments. A representative spectrum is shown in Figure 3-5.

Superconducting Wiggler

Parameters for the first ALS superconducting wiggler magnet have been chosen to supply synchrotron radiation for up to five beam lines for experimenters, with photon energies up to 40 keV. A design minimum of 5 T can be achieved with 4.5-K operation; however, a cryogenic system with 2-K capability is provided to allow operation up to 6 T and to accommodate a short-period, high-field design, if required in the future. The design of the magnet is conservative, using well-known conductor (ductile Nb-Ti alloy) and the same type of 2-K cryogenic system that has been in service at the LBL high-field magnet test facility for two years. In addition, the magnet gap is large enough to allow the insertion of a liquid-nitrogen-cooled beam tube to shield the magnet from image-current heating and possible stray radiation. The fraction of distance along the beam line used for coil thickness (as opposed to pole length) has been optimized to minimize the amount of conductor required. The field distribution along the beam is slightly more sharply peaked than a sine wave. Poles and yoke of magnetic steel are used to control stray fields and to reduce the amount of superconductor required. An important additional advantage of the magnetic yoke is that the forces on the coils in the direction normal to the mid-plane are outward, rather than inward across the magnet gap. This means that no heavy structural elements are required in the gap, and thus the coils can be closer together and be more efficient. To provide pressure integrity of the liquid-helium vessel up to 5 atmospheres, stainless steel walls 5 mm thick are used to span the horizontal aperture. The poles at the entrance and exit are provided with trim coils so that the exit point and direction of the electron-beam orbits

are not changed by the operation of the wiggler. Sensors and controls for the entire system are compatible with central-computer monitoring and steady-state control. If it were possible to decrease the magnet gap, by eliminating the liquid-nitrogen-cooled beam tube for example, it would be possible to increase the magnetic field strength or to reduce the period length. Parameters of the wiggler are listed in Table 3-17.

Table 3-17
Superconducting Wiggler Parameters

Central Magnetic Field, variable with good field quality	3 to 6 T
Length of period (complete cycle of up and down field)	14 cm
K value at 6 T	78
Number of Periods	14
Overall Length	240 cm
Aperture (full)	10 cm horiz. $\times$ 1 cm vert.
Pole Length in Beam Direction	1.5 cm
Coil Thickness in Beam Direction	2.0 cm
Conductor:	
Material	Nb-Ti alloy in Cu matrix, monolithic
Cross Section	1.26 mm $\times$ 1.26 mm
Cu: Superconductor Ratio	1.5:1 (by volume)
Insulation	Formvar
Operating Temperature	2 K (for 6 T) 4.5 K (for 5 T)
Magnet Poles and Yoke Material	magnetic steel
Current Density in the Conductor	470 A/mm ²
Higher performance can be achieved by using two "grades" of wire, one for high maximum field and another for the low-field region of the coil.)	

The construction of the wiggler coil is shown in Figure 3-33. Its 58 identical coils are in the shape of flat "racetracks." The conductors are square with rounded corners and are spaced apart at the rounded ends to decrease the maximum field magnitude in the coil. This will permit permeation by liquid helium throughout the coil. Pole pieces are made of mild steel. The load-carrying yoke pieces can be made of either a laminated steel or a 9-percent-nickel steel, which is a good structural steel at low temperatures.

Each coil has 225 turns of 1.26-mm-square multifilamentary wire with a copper-to-superconductor ratio of 1.5. Total stored energy is 1.1 MJ. Each coil is shunted with a protection resistor ($\sim 0.01 \Omega$) with which it is in good thermal contact. A low-voltage (~ 4 -V) power

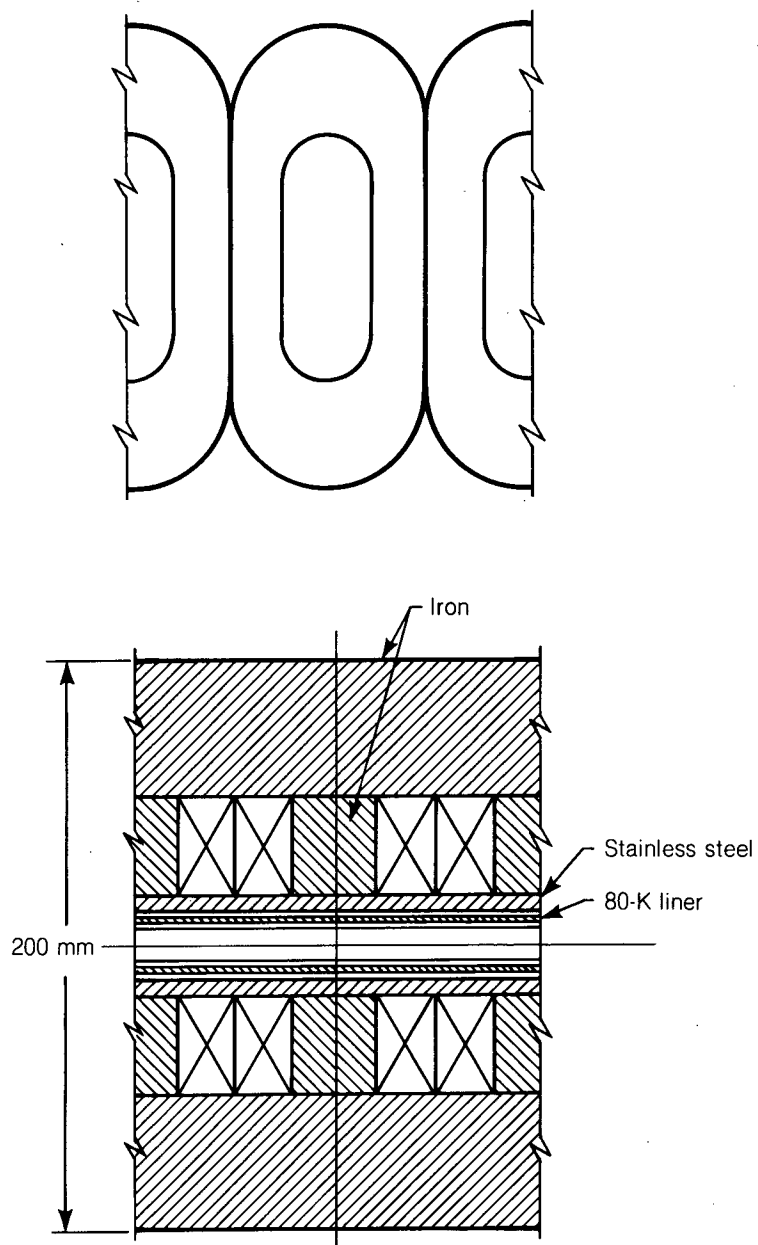


Figure 3-33. Superconducting wiggler magnet coil.

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supply can charge the coils in about 20 minutes.

During accidental quenches, each coil is small enough to discharge safely, depositing its energy internally. Furthermore, the coils are sufficiently coupled inductively to cause a chain of successive quenches that, if rapid enough, could provide a safe discharge without *any* quench protection circuitry. However, for maximum safety the appearance of the additional voltage across a single normal coil (~ 10 V) will trigger the opening of a switch at the power supply. This will cause immediate transfer of current in each coil to its shunt resistor and will decrease the current in the shunt of the normal coil, thus limiting its heating. All coils will be quenched immediately because of heating in the shunts. This is a safe coil-protection system that allows high inductance, low current, and reasonable wire size. Alternative shunting methods, such as the cold diodes used in the FNAL Energy Doubler magnets and the BNL-CBA magnets, could also be used; this would eliminate the need for opening a switch for protection.

The cryogenic system, shown schematically in Figure 3-34, is nearly identical to the system used at the LBL high-field magnet test facility. The system produces helium II in a sub-cooled condition, at a pressure slightly greater than 1 atm, to act as the magnet coolant. The heat leak to the system is calculated to be 70 W for 2-K operation. A suitable liquifier for this service is the Model 1460 (Koch Process Systems, Inc.), a competitively priced commercial unit.

Figures 3-35 and 3-36 show the helium II cryostat closely coupled to a magnet dewar. Depending on space or shielding conditions, the cryostat can also be several meters from the magnet. A special transfer line can be used to carry the coolant, the current leads, and the instrument leads.

Photon Beam Lines

To use the synchrotron radiation efficiently, multiple photon beam lines can be built to use the radiation from a single insertion device. In some cases, the simultaneous operation of multiple beam lines is possible, but in other cases a removable mirror is used to switch the radiation from one beam line to another. Present plans call for fourteen photon beam lines to be constructed (see Figures 3-37 to 3-43) during the startup phase of the ALS; these beam lines will make use of the radiation from the initial complement of six insertion devices. These 14 beam lines have been planned in such a way that an additional 5 photon beam lines can be built at these 6 straight sections. Of course, we recognize that final plans for these experimental areas must be made in consultation with the users of the facility; thus, modifications to the layouts described here will be accommodated as required.

The first optical element of a beam line is usually a mirror. The glancing angle of incidence on the mirror must meet three criteria. First, the cutoff energy must lie above the desired range of the deflected beam line. Second, the thermal loading on the mirror must be within tolerable limits of present technology, i.e., less than about 10 W/cm^2 . Third, enough working space must be provided between the beam lines. The first two requirements tend to make the glancing angle smaller, whereas the third makes it larger. Deflection angles of the ALS beam lines are obtained by balancing the above conflicting requirements.

Undulator radiation achieves its maximum spectral brilliance when observed through a pinhole, which for ALS is a hole 0.6 mm in diameter at 20 m. Therefore, an undulator beam line is provided with a downstream slit assembly. If the main beam line has a secondary line, this means that the deflected and undeflected lines cannot be operated simultaneously. However,

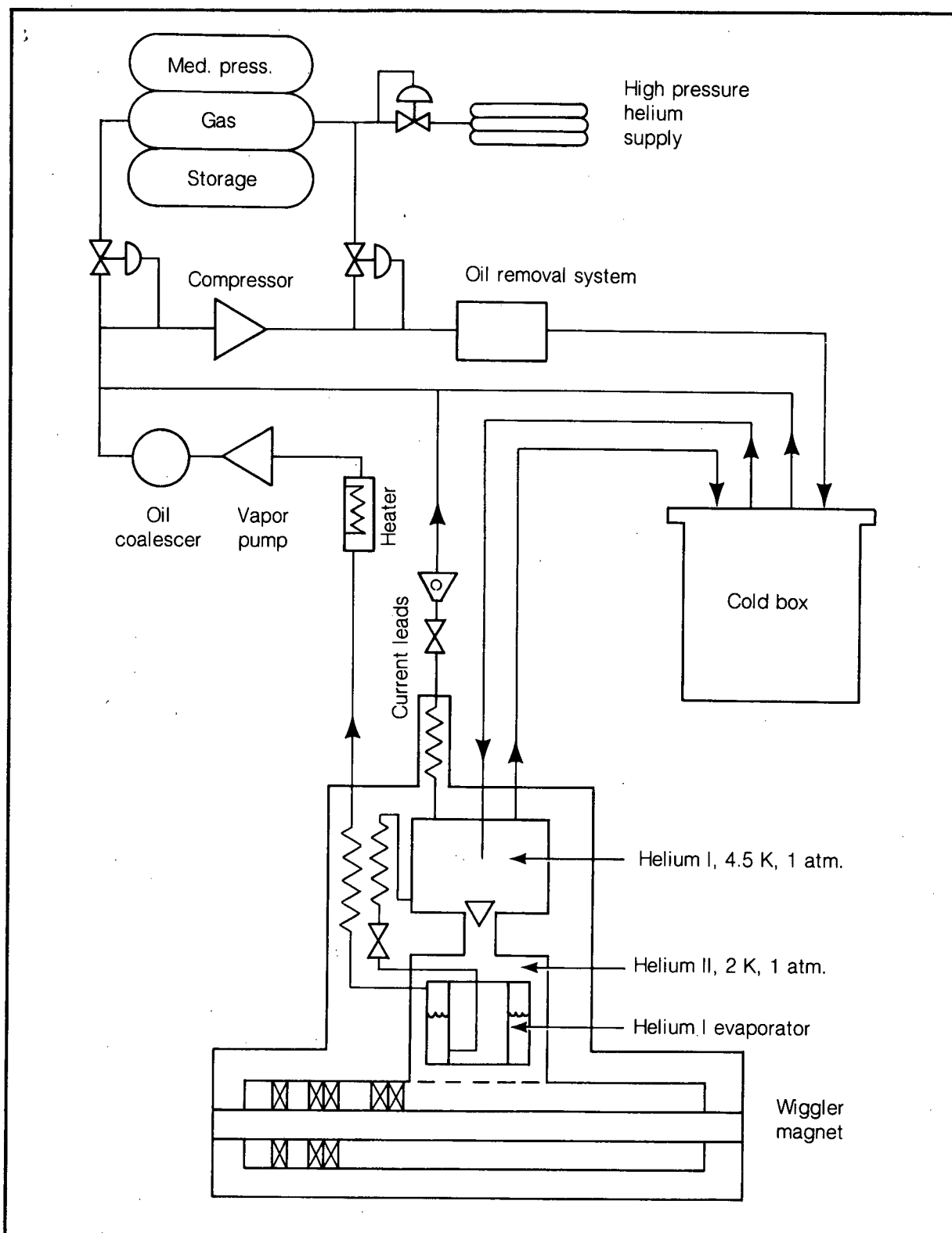


Figure 3-34. Schematic of 2-K helium refrigerator system.

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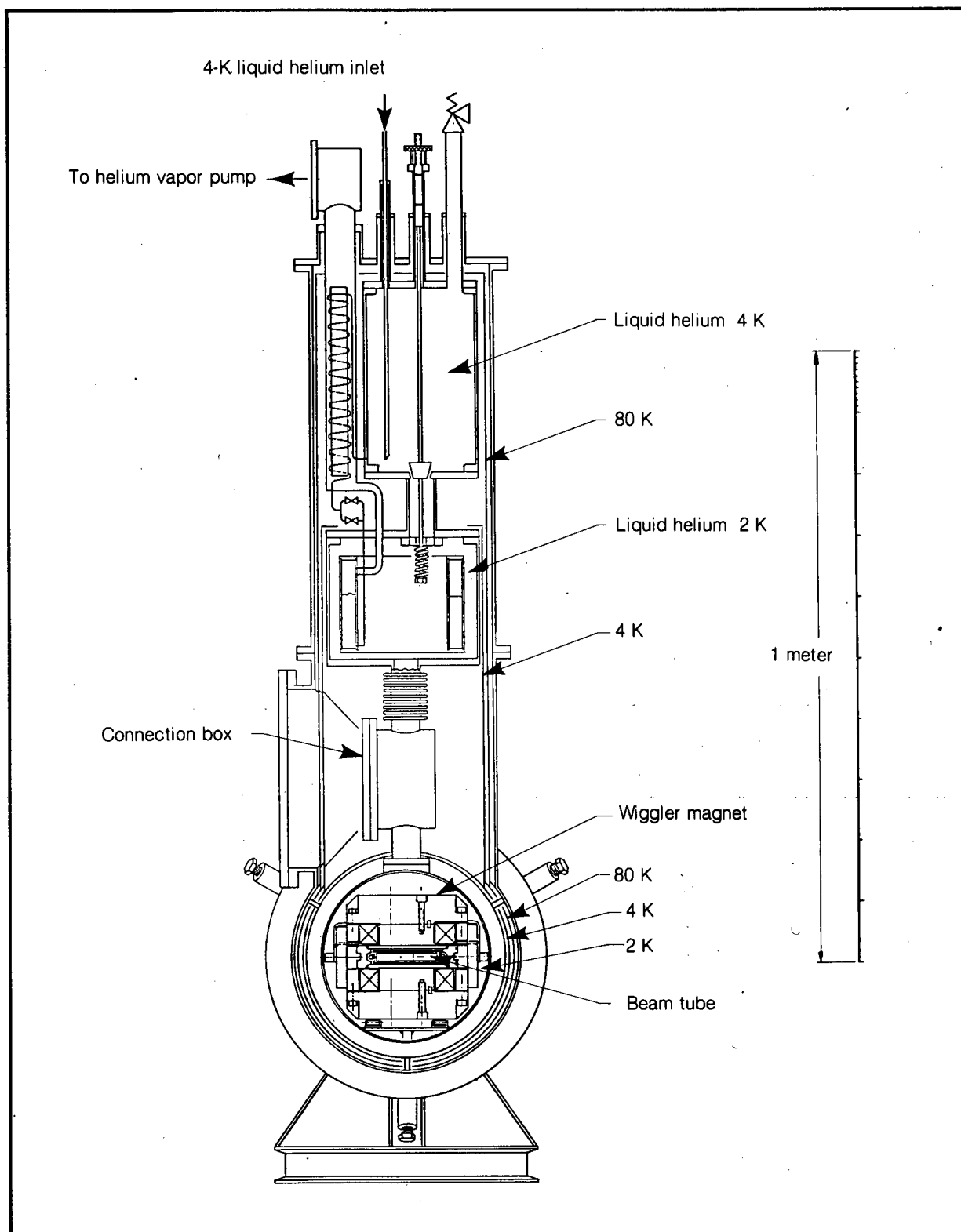


Figure 3-35. Superconducting wiggler cryostat.

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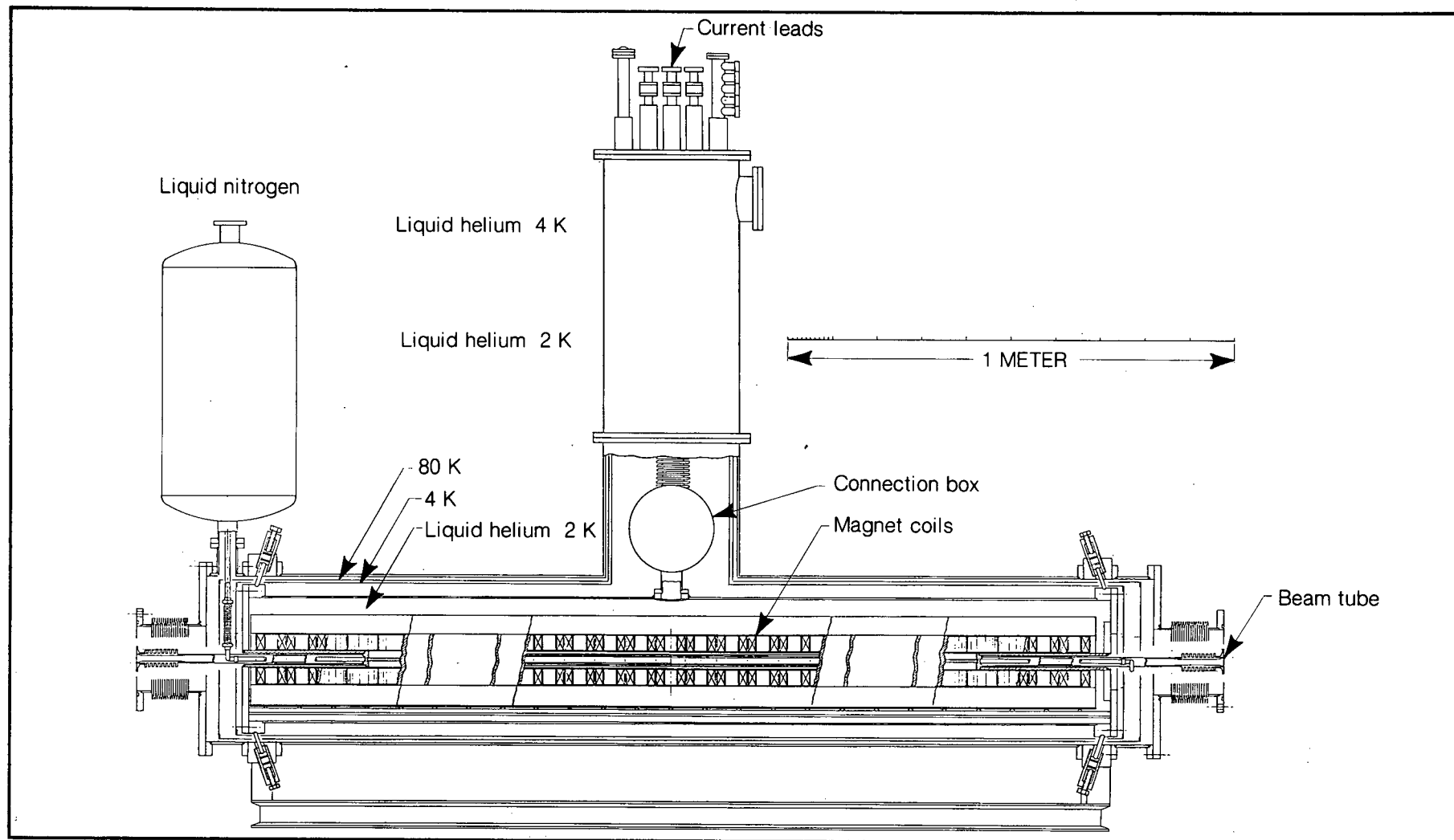
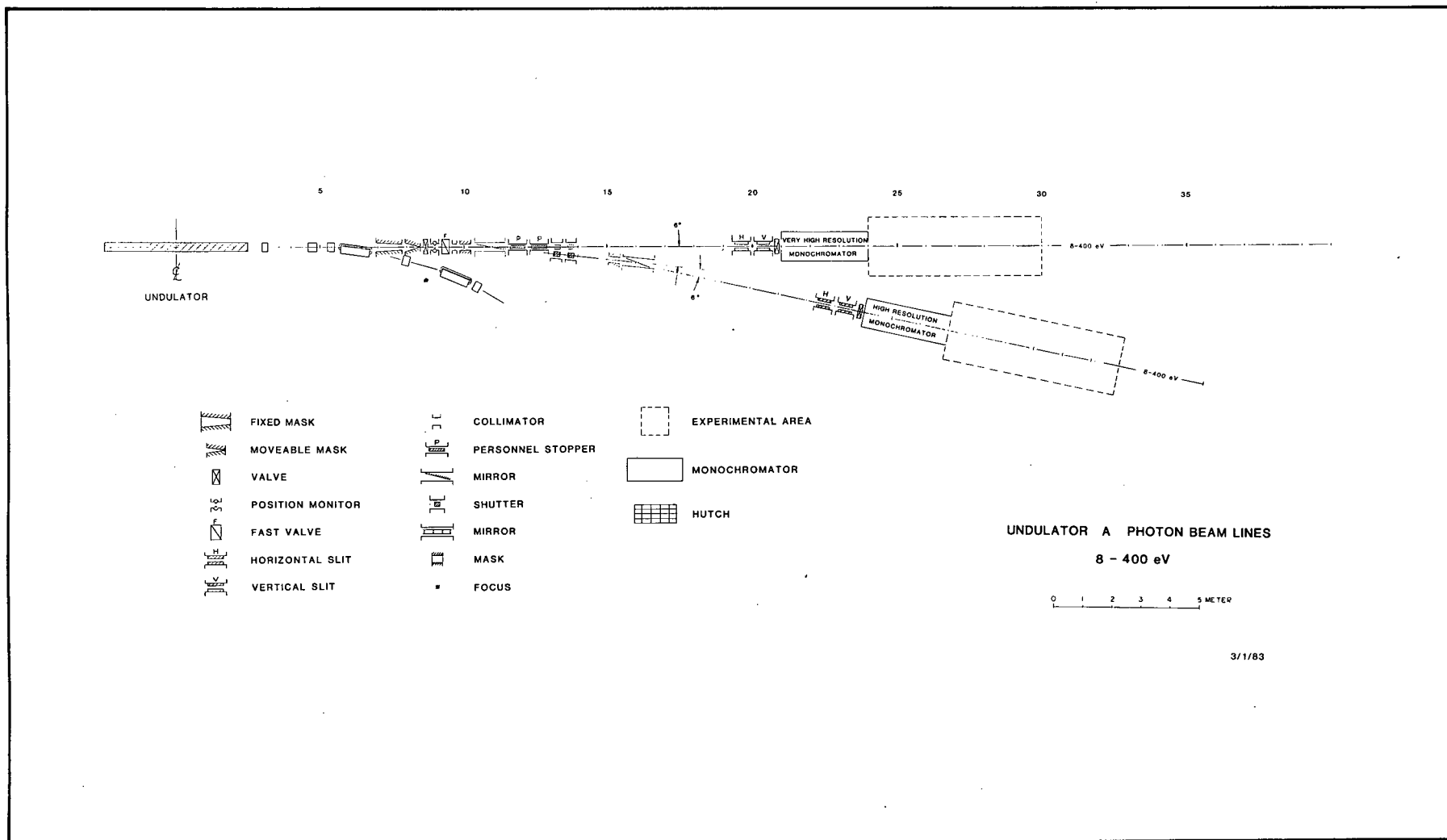


Figure 3-36. Superconducting wiggler cryostat.

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Figure 3-37. Undulator A photon beamlines.

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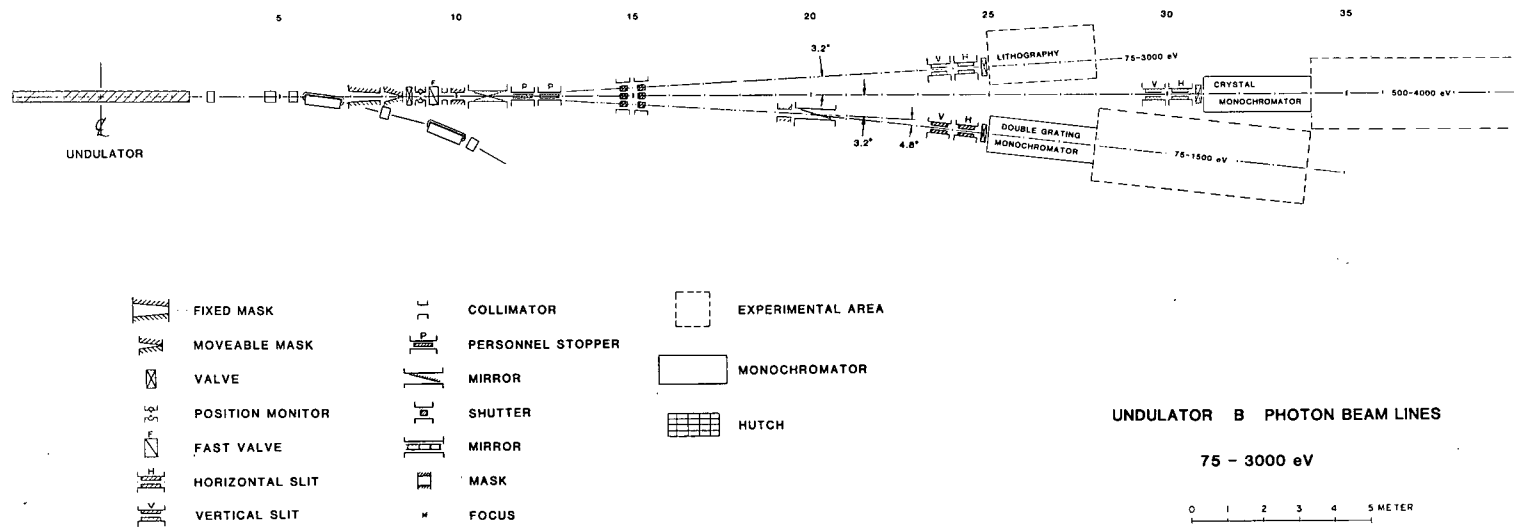
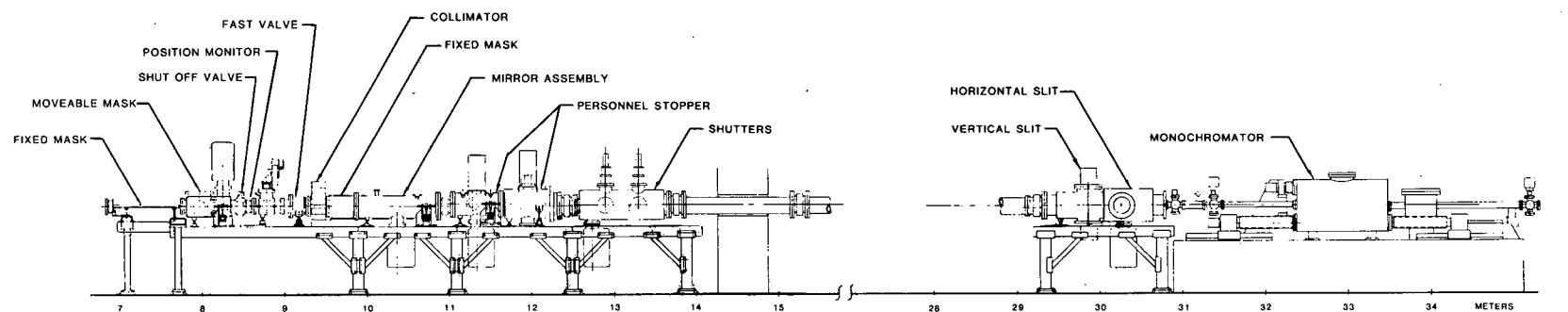


Figure 3-38. Undulator B photon beamlines.

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UNDULATOR B PHOTON BEAM LINE
BRANCH LINE NO.1 LAYOUT
3/1/83

Figure 3-39. Undulator B photon beamlines, elevation view.

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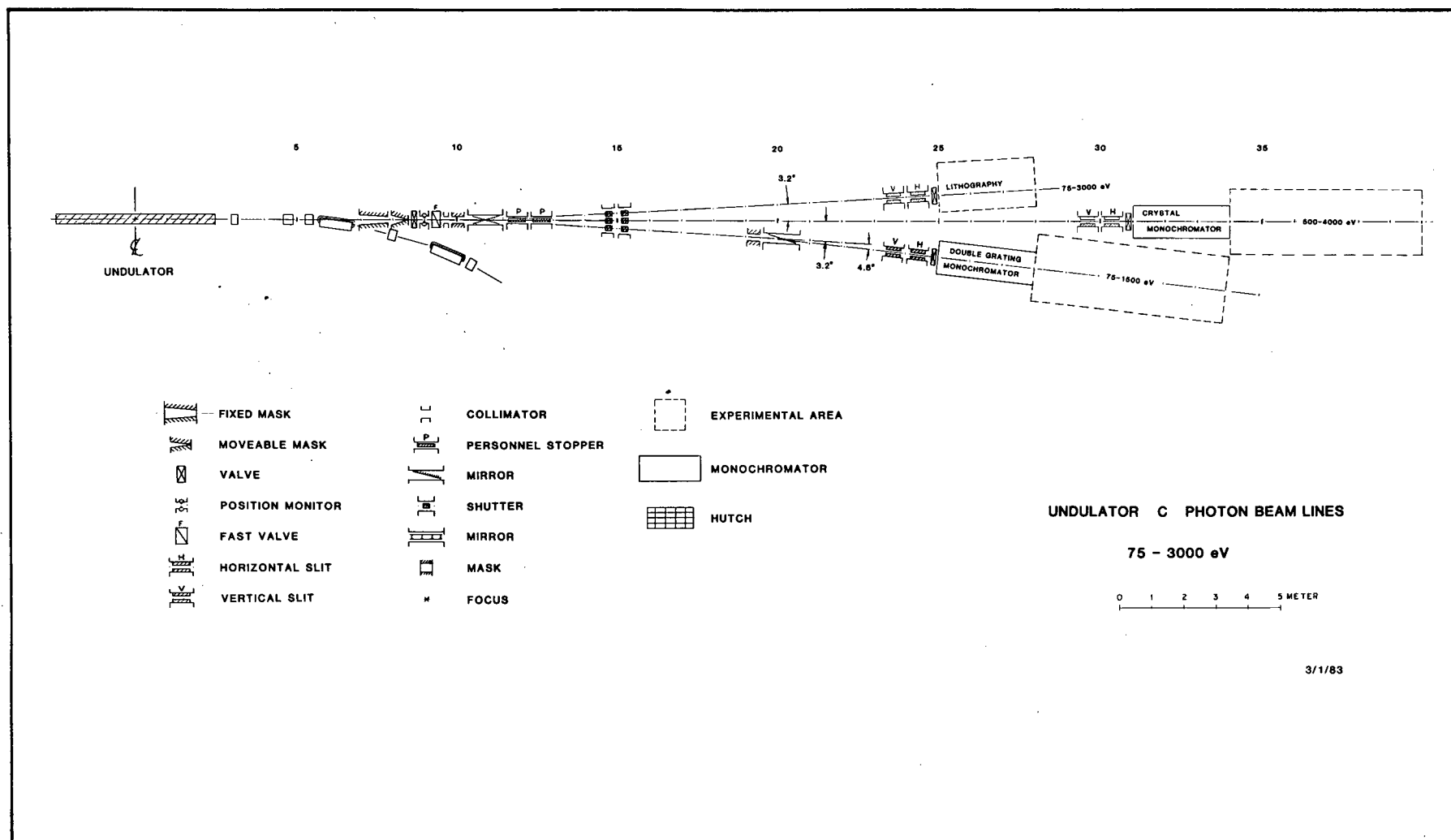


Figure 3-40. Undulator C photon beamlines.

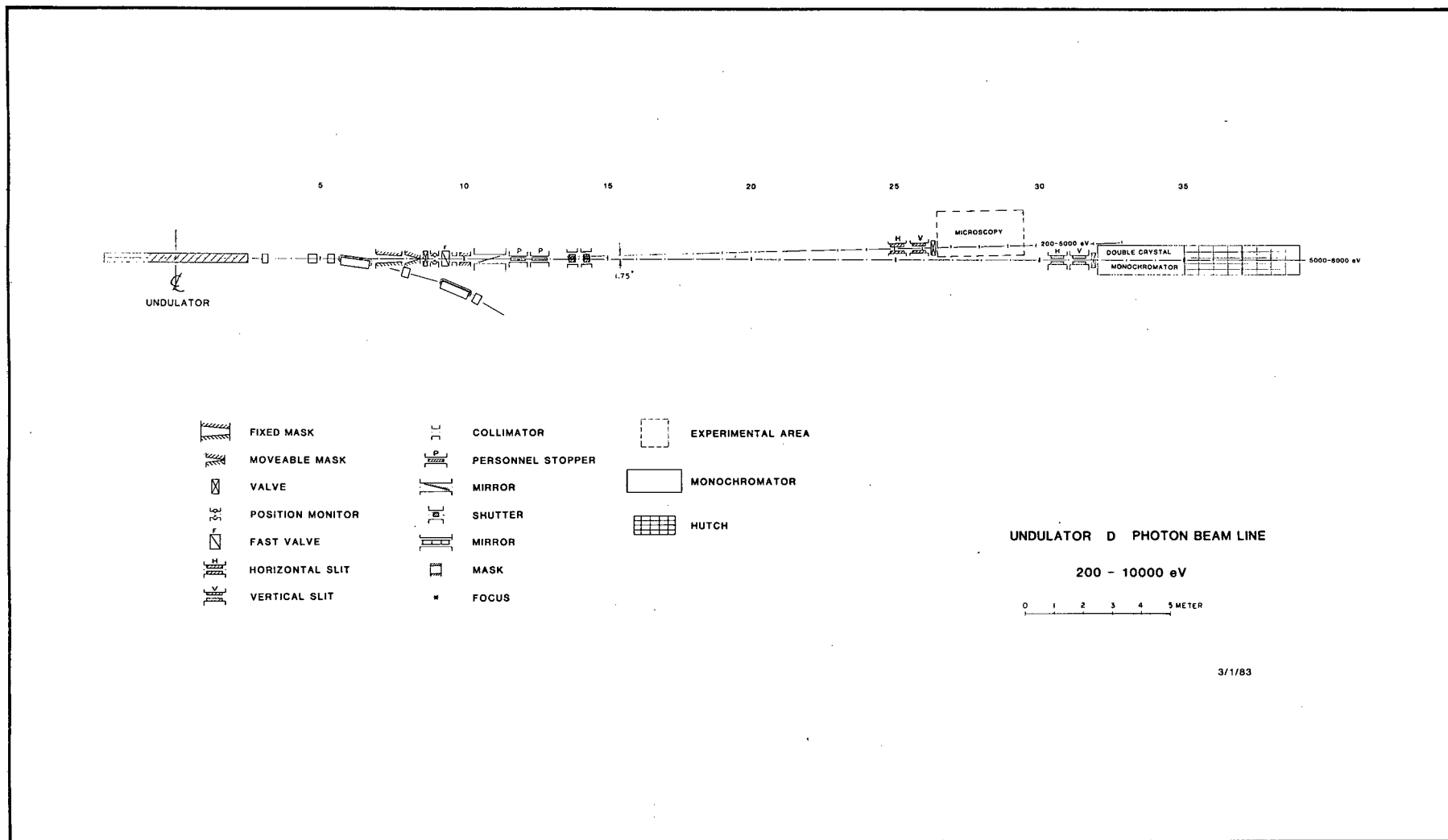


Figure 3-41. Undulator D photon beamlines.

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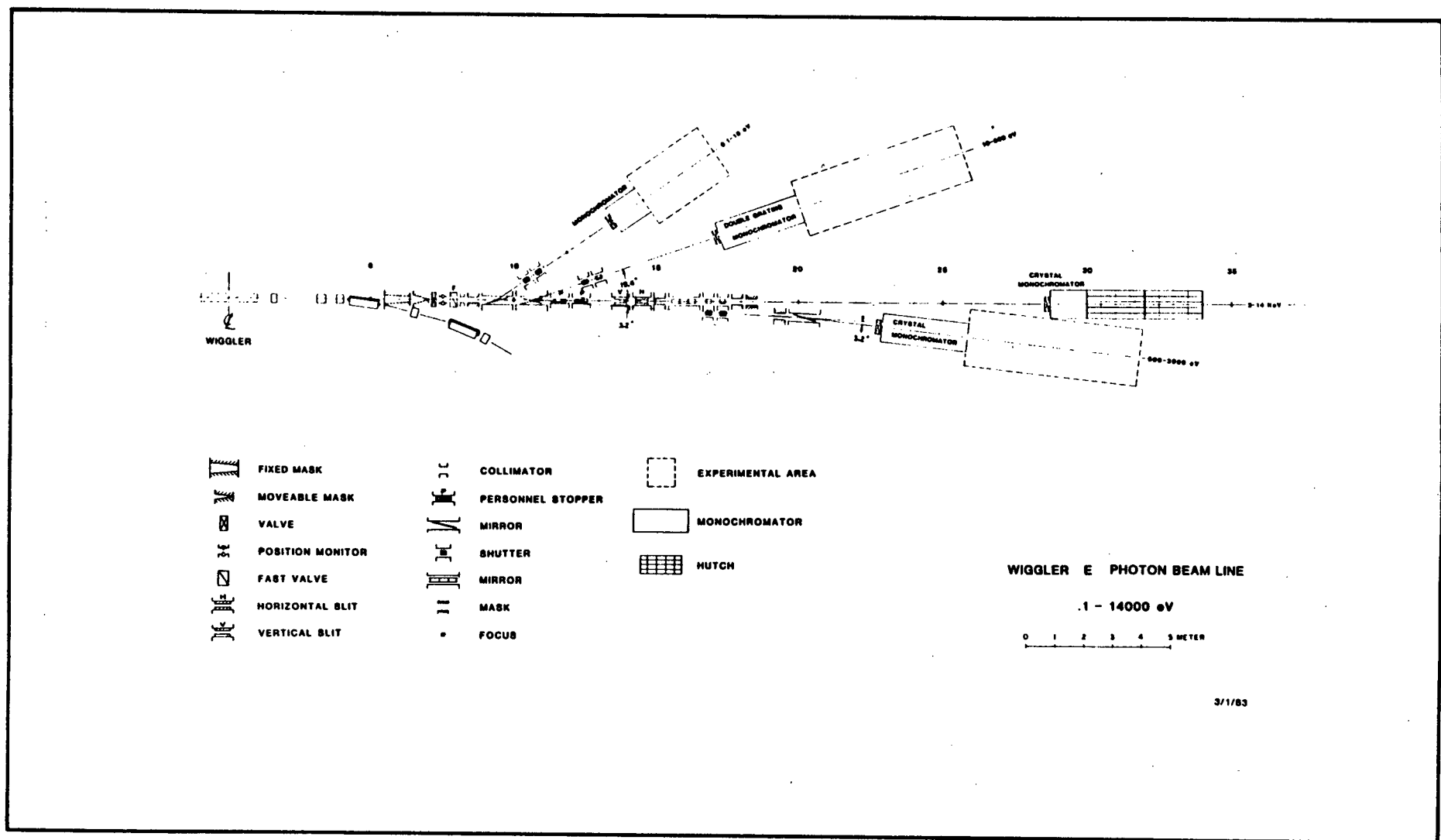


Figure 3-42. Wiggler E photon beamlines.

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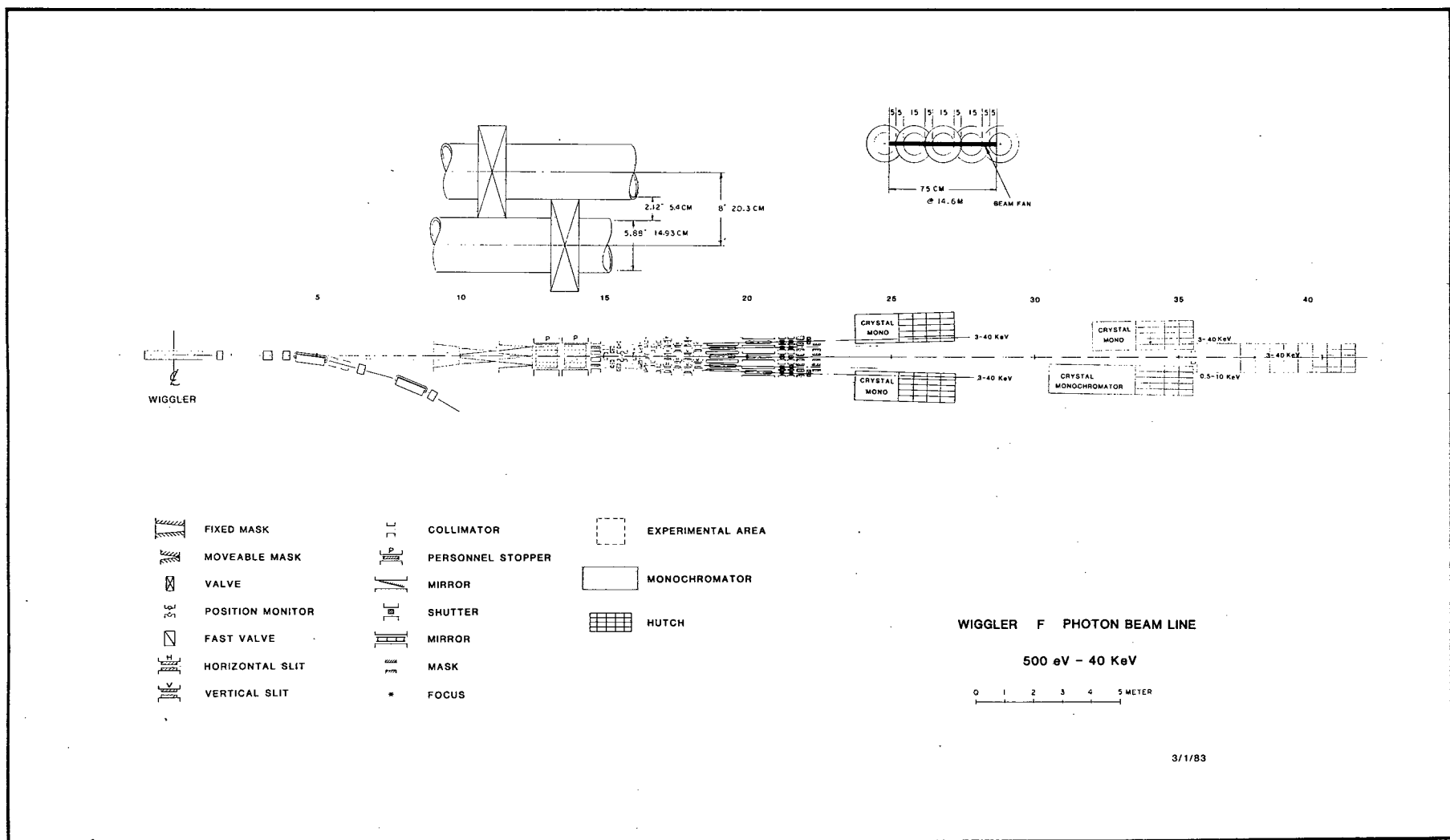


Figure 3-43. Wiggler F photon beamlines.

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efficient use of the undulator line by several experimental groups can be achieved by producing separate monochromators for the main line and the secondary line. One team can then be performing an experiment in the main line while the other team is installing an experiment in the secondary line.

In what follows, possible configurations for the six photon beam lines are presented. These are meant to be illustrative and should not be viewed as final layouts.

Undulator beam line U_A provides very bright photon fluxes in the range 8-400 eV. Two experimental stations are envisioned for this line. The straight-through line does not suffer a loss of flux and is equipped with a very-high-resolution monochromator, such as a double plane-grating monochromator.

Photons reach the secondary station by means of a retractable mirror at the 10-m point that deflects the beam by 6° . The monochromator for the secondary station can achieve a high resolution but also is designed for high throughput running.

A large user demand is anticipated for extremely bright photon beams in the energy range from 75-3000 eV. Therefore, two identical beam lines, U_B and U_C , are provided. Three experimental stations are available for each of the U_B and U_C beam lines: two with monochromators and one "white" beam port for lithography experiments, for example. The main line (undeflected) has a double-crystal monochromator of the JUMBO design which covers the energy range 500-3000 eV.

A mirror that deflects the beam by 3.2° directs the photons to the monochromatic secondary station. The monochromator is a plane-grating type, probably using two gratings for a higher resolution, and covers the 75-1500 eV range. If feasible, an in-vacuum grating/crystal inter-changer will be installed to increase the energy range to 3000 eV. It is expected that the latter devices will appear on other beam lines as the work horses in this energy range.

The U_D beam line has an energy range from 200 to 10000 eV and has the highest brightness of all the ALS beam lines. The main beam line here has a double-crystal, in-vacuum x-ray monochromator. It is also possible to operate this beam line without the monochromator to give higher intensity and lower energy resolution.

A secondary station is provided here for experiments that can use the high x-ray brightness without an x-ray monochromator. Potential experiments on this line are x-ray microscopy and lithography. A mirror is inserted into the x-ray beam at 13 m to deflect beam into the secondary line. This mirror can either be completely inserted for full intensity or be partially inserted to give useful beam in both beam lines.

The beam lines from the W_E insertion device are designed to use the smooth energy distribution of flux from the wiggler magnet. Experiments that scan a large energy range, such as Extended X-Ray Absorption Fine Structure (EXAFS) experiments, can readily use this line. In general, several experiments can run simultaneously with different horizontal sections of the beam.

The main beam line, with a horizontal angle of 12 mr, is an x-ray line that covers the energy range 3 to 10 keV. It is equipped with an x-ray mirror at 14 m to focus and reduce the harmonic content of the beam. This line has an in-vacuum, double-crystal monochromator to resolve the incident white radiation to an energy resolution, $\Delta E/E$, of about 4×10^{-4} . Experiments can be done in either of two 1.5-m by 2-m radiation hutches.

A second beam line, with a horizontal angle of 3 mr, is a soft x-ray beam line that covers the energy range 500-3000 eV. The monochromator on this line will be similar to that provided

for soft x-rays on the undulator beam lines. Experiments on this line, in general, would be scanning the monochromator over a large energy range and would want the flux to vary smoothly over the complete scan.

A third beam line is provided to cover the energy range 0.1 to 10 eV. This line is provided with a mirror and radiation shutters. In this energy range, normal-incidence optics are possible, and there exists a class of good monochromators, e.g., Seya-Namioka.

A fourth beam line is provided for experiments in the 10 to 500 eV range. A high-resolution monochromator of the plane-grating type will serve here.

The superconducting wiggler insertion device (described earlier) on beam line W_F provides an intense beam of photons with an energy range up to 40 keV. The horizontal angle is 51 mr. This line can accommodate up to five secondary beam lines that each take a portion of the wide incident beam. Each beam line has adjustable horizontal and vertical slits for control of beam size and separate beam stoppers for independent operation.

Three similar beam lines use the central part of the beam. Each has a horizontal acceptance of 10 mr and is equipped with an x-ray mirror and an in-vacuum, double-crystal monochromator. One of the three central lines is designed as a soft x-ray beam line and, therefore, has a more complex monochromator to cover the energy range from 500 to 10000 eV. The other two central lines cover the energy range from 3 to 40 keV; they can be operated with the x-ray mirror up to around 30 keV or without the mirror, to above 40 keV. For special experiments, it is also possible to operate without the x-ray monochromator or mirror to provide an intense, wide (40 cm at 40 m) white radiation beam.

Two secondary beam lines for EXAFS experiments can use the edges of the main beam. These lines have an energy range of 3 to 40 keV, and they are also equipped with an x-ray mirror to reduce the harmonic content of the beam. The x-ray monochromator on these lines could be a conventional double-crystal monochromator operating in helium.

So far, we have emphasized the usage of photons from periodic insertion devices. However, valuable photon fluxes can also be collected from the bending magnets around the ring, and they will undoubtedly be utilized in some future beam lines. In the far infrared regions from .001 eV to 1 eV, the bending magnets are especially attractive since the performance of the undulators and wigglers becomes poor in this energy range because of destructive interference.

In an infrared beam line, a large solid angle of photons is collected by an aspheric mirror. The beam is focused at a downstream window assembly and the desired spectrum is transmitted via relay optics to either a Fourier Transform Interference Spectrometer or a diffraction grating spectrometer. It is desirable to operate the line in conjunction with an insertion device beam line, since the intense photons from the latter could be used to excite the samples to be studied.

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4 Advanced Light Source Conventional Facilities

This chapter briefly describes the conceptual design and scope for the modifications to the existing Building 6 and the construction of a new building addition to house the ALS, its beamlines, and its experimental areas. Summary cost and schedule data are included in Chapter 8. The detailed ALS Conventional Facilities conceptual design is presented in a separate handbook, CDR-Volume II, and provides full backup data for scope, specifications, drawings, cost and schedule details, and additional supporting documents.

The Advanced Light Source will be located in the Building 6 area of the LBL site and will utilize many of the services and facilities available at this location. Building 6 presently contains the original 184-Inch Cyclotron and is an attractive site because of its sizable flat hilltop setting with solid foundation conditions and because it is centrally located within the Laboratory.

A plan view of the ALS and the Building 6 site is shown in Figure 4-1. The existing high-bay experimental galleries, surrounding 120 degrees of the southerly perimeter are suitable for housing a portion of the ALS experimental areas. Surrounding the northerly 240 degrees of Building 6, new experimental bays of medium height will be constructed to house a portion of the ALS storage ring and additional experimental areas. The new addition is shaded in the plan view of Figure 4-1. The cross-sectional view of Figure 4-2 shows the elevation view of Building 6, the new addition, and the concrete shielding walls for the electron storage ring tunnel.

The injection system for the ALS, consisting of a linac and a booster synchrotron, will be constructed within Building 6. Power supplies will also be housed within the existing building.

The existing overhead bridge crane will provide service to ALS facilities within the central portion of Building 6. Support facilities for researchers and operating personnel will be maintained within the original Building 6 and space will be included for accelerator support and services including shops, maintenance areas, toilets, utility use, and storage. The mezzanine of Building 80, immediately above the west side experimental area, will provide space for the main control room.

The new addition to Building 6 will comprise approximately 35,000 square feet at grade level. In combination with existing Buildings 6 and 80, this complex will house the Advanced Light Source and all its support facilities. The new building addition will be a steel framed structure, approximately 27 feet high sitting on new concrete footings over a new concrete floor slab.

New exterior walls will be insulated and sheathed with vertically ribbed metal siding. The roofing will be a built-up moisture-proof membrane over rigid thermal insulation on metal

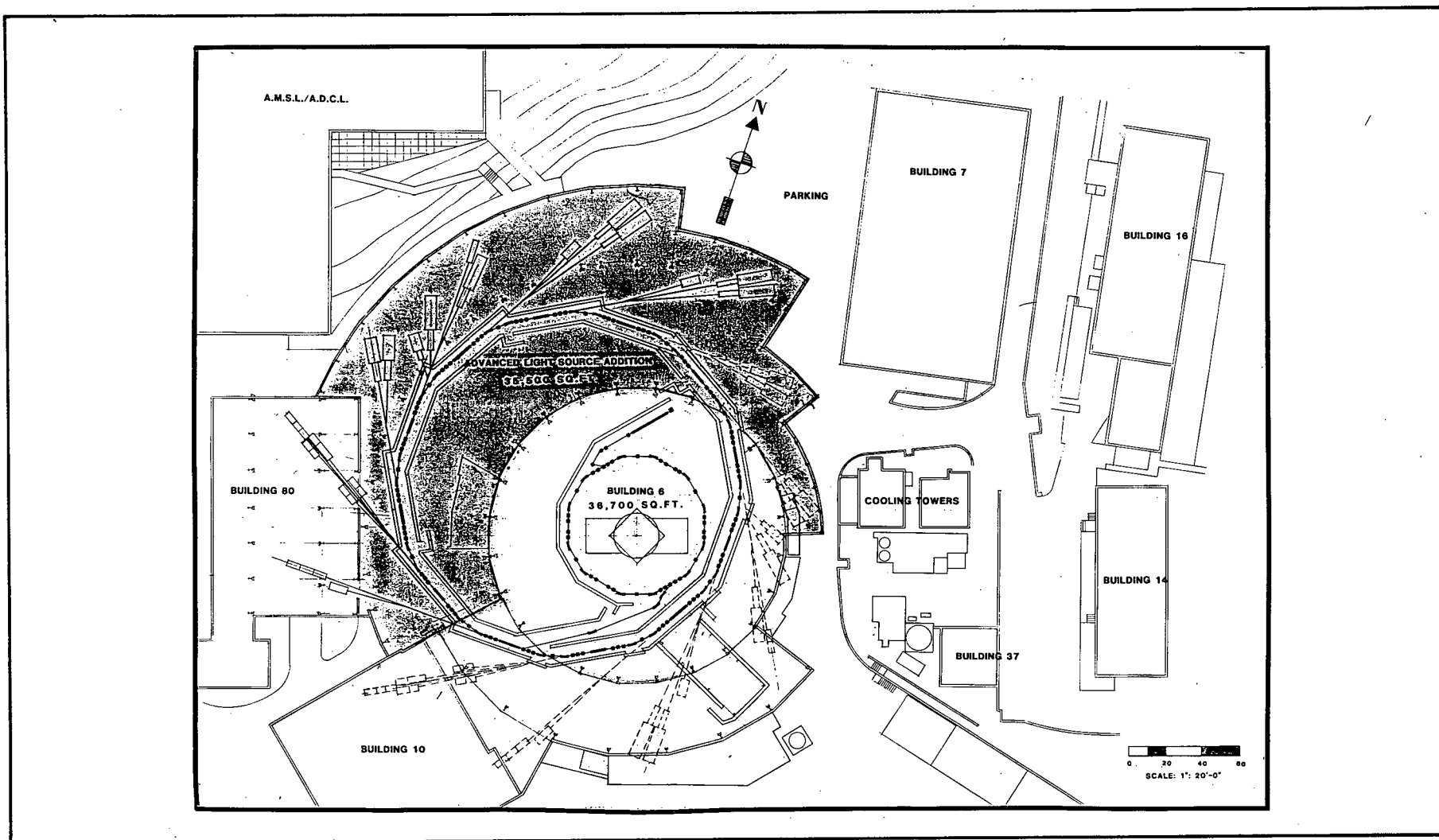


Figure 4-1. Plan view of ALS and Building 6 site.

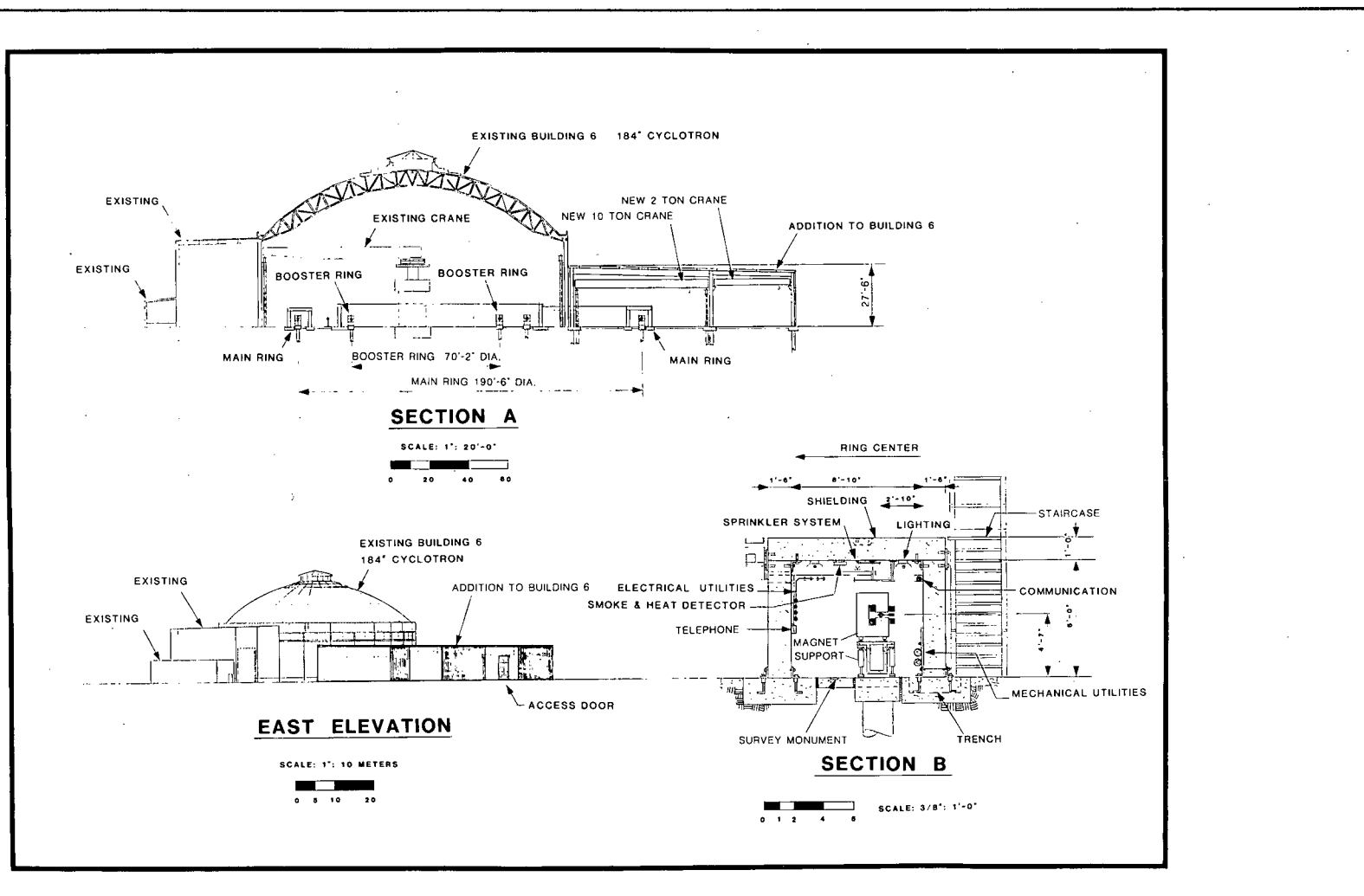


Figure 4-2. Cross-section elevation view of Building 6, new addition, and concrete shielding walls for electron storage ring tunnel.

decking, supported by steel purlins, beams and columns. Roll-up, overhead doors will be provided for vehicular access and swinging pressed metal doors provided for nominal pedestrian access.

A retaining wall extending 150 feet from the northeast corner of Building 80 will support a portion of the perimeter of the building addition. The rest of the building columns will be supported on cast-in-place concrete caissons, interconnected at the building perimeter by concrete grade beams. A new 6-inch slab-on-grade will be cast in the addition.

Lateral forces will be resisted by the roof metal deck diaphragm braced by the structure below. These forces will be resisted in the radial direction by the moment-resisting steel frames. In the tangential direction, the lateral forces will be resisted by vertical steel braced frames.

A new 10-ton crane will cover the areas in the new addition to service the storage ring and its shielding. The crane runway will require separate steel columns from the building steel columns. The crane will be a double-girder, top-riding trolley crane with cab and pendant controls.

A 2-ton crane will be provided to cover the perimeter area of the addition. It will be supported by the steel building columns and will have a pendant control only.

The linac, booster, transport line, and storage ring will be enclosed in concrete shielding tunnels to prevent radiation exposure to personnel working in the area. The tunnel shielding will have nominally 1.5 feet thick walls and 1.0 foot thick roof with special localized shielding required in certain areas, such as injection into the storage ring.

The shielding will consist of precast wall and roof panels bolted together to form a tunnel. The bolted connections will be designed as moment connections to provide lateral seismic stability. The walls will be supported on spread footings except in areas where there are existing heavy duty slabs which will provide adequate support.

Alignment of the storage ring and the experimental beam lines will require some modifications to the existing crane and building columns and lateral bracing at several locations. Some modification of the north end of the existing Neutral Beams Engineering Test Facility (NBETF) experimental cave will be necessary. This modification will require shortening of the cave area and a new shielding wall at the north end. Some relocation of equipment outside the cave will also be necessary. Modifications to Building 80 will provide new entry doors, experimental support areas, and new control room space.

The existing Building 6 was reviewed in 1971 for seismic criteria by the firm of Engle and Engle, Structural Engineers. Their review confirmed that the building meets the LBL lateral force design criteria of 0.2 g equivalent static force and 20 psf wind load. Some remedial work was recommended where the lateral bracing had been altered, and this work was completed. Other items of work involving restraints for the massive shielding blocks were only partially completed; however, since all the existing shielding is to be removed for the ALS the seismic stability of the old shielding is not an issue.

Building 80 was also examined by Engle and Engle for seismic stability. The seismic report required the addition of some tubular steel cross bracing in the exterior walls, and all recommended work was completed. This building now also satisfies the LBL lateral force design criteria.

The mechanical utilities modifications and upgrading required for the ALS are summarized below:

- a. Demolition, relocation or replacement of certain existing mechanical utilities, both above and below ground, in the general project area.
- b. Demolition, modification or extension of existing automatic fire protection systems.
- c. Heating, ventilating, and/or air conditioning system.
- d. All mechanical utilities such as equipment cooling-water systems, instrument-quality compressed air, and domestic water and sewer systems.
- e. Temporary mechanical services to all adjacent buildings and operations affected by construction work on the various mechanical utilities.

In general no utilities will be buried under the new concrete slab-on-grade floor, if possible. Sitewide systems such as high-pressure cold water, natural gas, sanitary sewers and compressed air will be re-routed around the building.

Within the building itself, utilities will be either placed in accessible floor trenches or supported above the floor along utility right-of-ways.

The utility services to be provided include: Low conductivity cooling water, compressed air, domestic hot and cold water, sanitary sewers, and high-pressure fire protection system water mains.

The Heating and Ventilating system will take into account the high bay, open area nature of the building addition, and the pre-emptive right-of-ways of the overhead bridge crane over the entire area.

During the summer season, hot air will be allowed to stratify underneath the roof space to lessen the heat gain through the roof. This hot air will be automatically vented outside whenever it begins to intrude into the occupied space. During the winter season, the overall area will be provided with overhead heaters for general background level heating. At work areas, supplementary heating will be provided by forced-air down-draft tubes which tap the stratified hot air for heating.

The existing 40-feet-high bay adjoining the new building addition will be provided with forced down-draft tubes and the overhead space heaters will be reactivated.

A wet pipe, automatic fire sprinkler system will be provided for the entire area. Special areas such as raised floor plenums in the control room will be provided with halon fire suppression systems.

The electrical utilities modifications and upgrading required for the ALS are summarized below:

- a. Add alternate 12 kV feed from PG&E Bank 1 to the substation at Building 6.
- b. Remove oil-filled transformers and replace with nonflammable liquid-filled or air-cooled dry type.
- c. Extend Building 6 power distribution and grounding system to the ALS addition.
- d. Update interior and exterior lighting systems.
- e. Provide power to new mechanical equipment installations, R.F. amplifiers and magnet power supplies.
- f. Enlarge and expand telephone, public address, fire alarm and computer distribution systems to the ALS site.
- g. Provide wireways for signal, control wiring, magnet cabling and coaxial cables between the control room, R.F. areas and the experimental areas.
- h. Remove unused or abandoned electrical equipment, wiring and right-of-ways.

- i. Relocate as necessary various equipment, conduits, wiring and controls which conflict with the modifications to the existing Building 6 ALS site.

The maximum peak electrical power demand for the Advanced Light Source and experimental apparatus is estimated at 5.7 MW, based on the loads of all ALS components. This is 2.2 MW for booster magnet power supplies, 0.65 MW for storage ring magnet power supplies, 2.3 MW for R.F. components with 0.5 MW for experimenters, house power and lighting.

The transformer site at Building 6 presently contains all oil-filled transformers that feed Building 6 and surrounding buildings. These will be replaced with large, nonflammable liquid-filled or dry type, 12 kV to 480V and 12 kV to 208V transformers. They will be selected to have optimum full load and no load losses. Twelve kilovolt vacuum circuit breakers will control the feed to the primary of these transformers and the secondaries will have main disconnect circuit breakers with shunt trips. The R.F. power and magnet power transformers will have "crash off" buttons connected to their shunt trips as a safety precaution to protect building personnel.

A single 2.5 MVA 12 kV to 277/480V, three-phase, 4-wire, transformer will supply all the needs of the R.F. power system including the linac, booster, and storage ring amplifier and dc plate power supplies. A second 2.5 MVA 12 kV to 277/480V, three-phase, 4-wire, transformer will supply the 1.6 MVA and 1.7 MVA SCR-controlled magnet power supplies. A third transformer of 2.5 MVA 12 kV to 277/480 volt, three-phase, 4-wire, will supply house power, mechanical utilities such as HVAC, pumps, fans, 120V duplex outlets and office lighting, overhead cranes, highbay lighting and 480V distribution panels. These panels will also feed 480V to 208V/120V dry type 45 kVa transformers at each of six experimental areas spaced around the storage ring, providing a source of 480V (3 phase), 208V (3 phase), and 120V, which will be used for beamline vacuum equipment, experimenters instrumentation, control power, building and tunnel lighting.

The existing Building 6 high bay will be retrofitted from incandescent to high-pressure sodium-vapor lamps. The ALS addition will be lighted with high-pressure sodium-vapor lamps, and with fluorescent task lighting wherever practical. Overall lighting will be maintained at 10 footcandles with local or task-supplemental lighting used where needed.

The communications systems in the ALS project will consist of telephones; fire and security alarm and supervision; intercoms, local paging and public address. The building specific components of the overall system are currently in place in Building 6 and 80, and will be modified to meet the requirements of the ALS. Conduits, trays, floor ducts, raceways, junction boxes, and terminal boards will be provided to interconnect the storage ring, injector, R.F., experimental areas, and control systems with the central control and computer rooms.

The existing LBL fire alarm system will be extended to the ALS addition. Fire alarm supervision and system supervision will be transmitted to the LBL fire station via a multiplexed system. The twenty existing zones based upon the current occupancy of Building 6 will be re-assigned to provide protection to the ALS program.

5 Surface Sciences and Catalysis Laboratory Building

The Surface Sciences and Catalysis Laboratory (SSCL) will be located in a laboratory-office building located near and linked to the Material and Molecular Sciences Laboratory, Building 62. This Chapter presents a summary physical description. Summary cost and schedule data for the building are included in Chapter 8. The detailed SSCL conceptual design is presented in a separate handbook, CDR—Volume III, and provides full backup data for scope, specifications, drawings, cost and schedule details, and additional supporting documents.

The facility will comprise about 47,500 GSF and be located near the Material and Molecular Sciences Laboratory, Building 62 and the National Center for Electron Microscopy (NCEM). Laboratories, offices, a conference-seminar auditorium, standard utilities and laboratory services, and furnishings are provided.

Figures 5-1 and 5-2 show the SSCL and its relationship to the LBL site and the adjacent research facilities.

The floor plan is approximately 95×150 feet. The building has a reinforced concrete frame, shear walls, and a waffle-slab roof-and-floor structure supported on spread footings. The building will have three stories plus a partial basement. The auditorium and administrative area will be a steel frame structure with a metal deck roof.

The building will be provided with standard built-up roofing over insulation with exterior walls (non-bearing) of prefinished panels on metal studs (insulated cavity) with gypsum board interior wall surfaces throughout. All interior walls and ceiling surfaces will be gypsum board except where acoustical ceilings are provided in specific areas. Laboratory furniture and fume hoods with acid/alkali resistant tops and construction will be commercial products.

A 6,000-lb.-capacity elevator suitable for carrying freight and passengers will be provided. Central station air handling units with 95% filters, draw-through cooling coils, return fan units, and economizer controls will provide for heating, ventilation, and air conditioning (HVAC) requirements. All supply and return air will be ducted. A new water chiller will replace an obsolete model at Building 62 and will supply the new facility air handling units. The heating system uses gas-oil-fired hot-water boilers. The facility will be equipped with an automatic fire sprinkler and alarm system.

Power and utility systems will be extended from adjacent, existing plant services. Toxic effluents will be contained through high filtration and collection systems.

The chart that follows Table 5-1 provides a listing of programmatic space requirements upon which the final design was based.

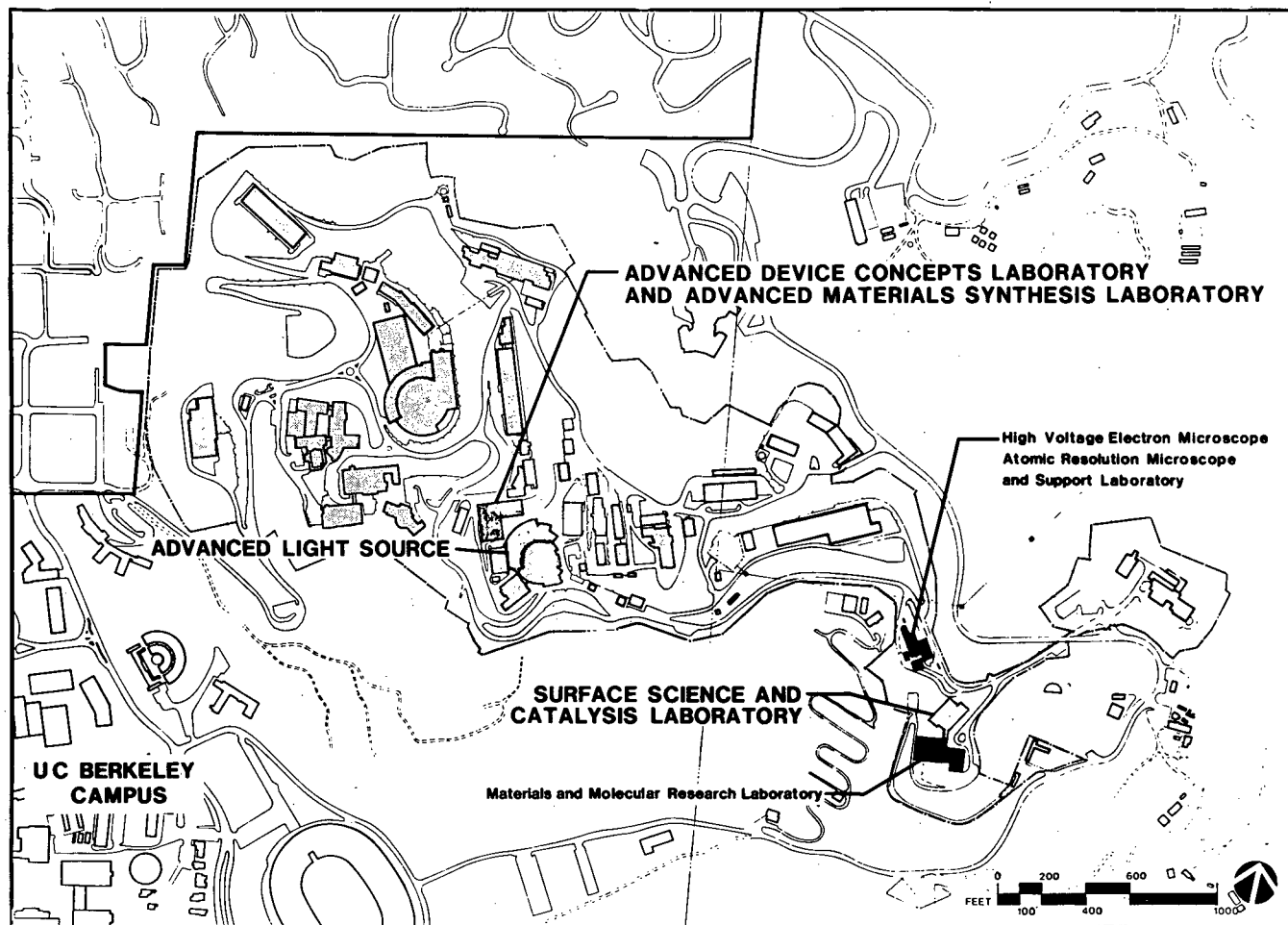


Figure 5-1. Plan view of SSCL and LBL site.

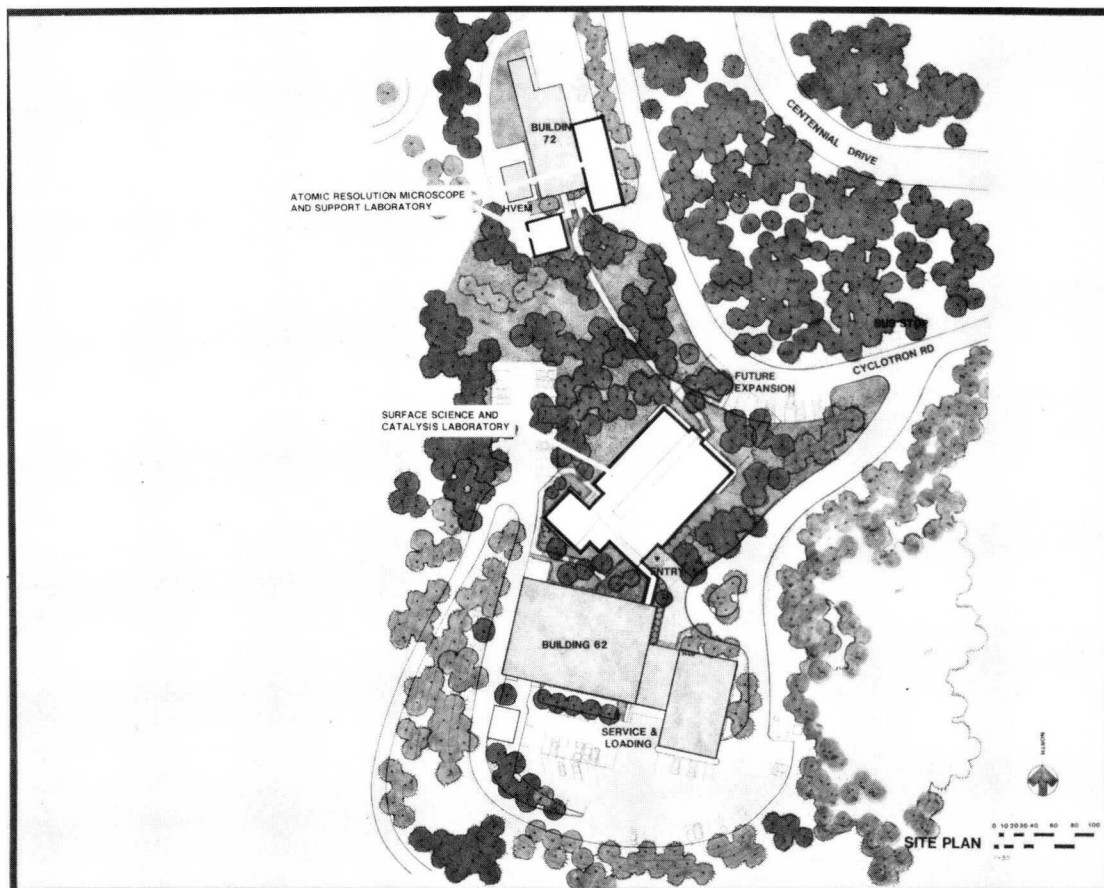


Figure 5-2. Plan view of SSCL and Building 62 area.

Table 5-1
Schedule of Net Areas, Functions and Occupancy

Bldg. 62 Area	Net Area-Sq. Ft.			Occupants
	Labs	Lab Support	Other	
<i>First Floor - Elevation 788</i>				
Lobby			680	
Administration			2,800	14
Organic Catalysis	588	240		4
Surface Physics	819	360		6
Surface Properties under Extreme Conditions	1,128	240		4
Characterization of Zeolites, Innovative Catalysts, and dual-phase catalysts	1,923	1,260		24
First Floor Subtotal:	4,458	2,100	3,480	52
<i>Second Floor - Elevation 803</i>				
Auditorium and Meeting Room Lobbies			520	
Meeting Room			410	
Auditorium			1,875	
Auditorium Projection and Storage Rooms			320	
Photoelectron Spectroscopy and Photonassisted Surface Reactions	3,832	1,600		27
Colloid Chemistry	831	240		4
Second Floor Subtotal	4,663	1,840	3,125	31
<i>Third Floor - Elevation 818</i>				
Solid State and Surface Reactions	2,975	1,560		21
Reactions of Coal and Coal Related Organics	1,935	400		6
Third Floor Subtotal	4,910	1,960		27
Subtotal All Floors	14,031	5,900	6,605	110
Total net functional floor area 26,536 SF				
Gross enclosed area 45,802 SF				
Covered open areas x 1/2 1,963 SF				
Total gross area 47,765 SF				

Title II design of the SSCL Building as presently described has been completed as part of the Chemical and Materials Sciences Laboratory (CMSL) project which was funded in FY80. The original scope of the project included the CMSL addition to Building 62 (now renamed SSCL) and the Atomic Resolution Microscope (ARM) facility at Building 72. In FY81 construction (Title III) funding for the addition to Building 62 was rescinded and the CMSL project was rescoped to include:

- The ARM facility at Building 72
- The ARM Support Laboratory addition to Building 72
- Design only of the addition to Building 62 (SSCL)

Title II design, including construction contract documents for the SSCL Building and related site improvements, is essentially complete. A final construction cost estimate and a critical path network schedule have been submitted by the Architect, MBT Associates. These documents provide an unusually complete basis for the "Conceptual Design Report" required as part of the NCAM project.

6 Advanced Materials Synthesis Laboratory and Advanced Device Concepts Laboratory Building

The Advanced Materials Synthesis Laboratory (AMSL) and the Advanced Device Concepts Laboratory (ADCL) will be located in a single laboratory-office building directly adjacent to and interconnecting with the Advanced Light Source at Building 6. This chapter briefly describes the conceptual design and scope for the building and presents a summary physical description. Summary cost and schedule data for the building are included in Chapter 8. The detailed AMSL/ADCL conceptual design is presented in a separate handbook, CDR-Volume IV, and provides full backup data for scope, specifications, drawings, cost and schedule details, and additional supporting documents.

Figure 5-1 shows the location of the AMSL/ADCL Building at the LBL site. Figure 6-1 shows a perspective view of the building, and Figure 6-2 is a site plan showing the relationships of the AMSL/ADCL Building to the ALS at Building 6 and other physical plant facilities in the area. The floor plan of the two facilities shows how the fourth floor of the laboratory building is interconnected with the ALS experimental area and Building 80. Figure 6-3 is a cross section showing this relationship with respect to elevation. The area surrounding the site for the AMSL/ADCL Building has been studied extensively to detail geology, topography, hydrology, and site utilization. Previous recent work, which included numerous subsurface investigations, has been augmented by specific borings and analyses performed by Harding-Lawson Associates, Engineers, Geologists and Geophysicists. The ELS Design Group (Elbasani, Logan and Severin), Architects and Planners, has studied the older original area of the Laboratory which encompasses the site for this building. A building at this site has been shown in the Long Range Development Plan for the University since 1962. With the advent of the initiative for NCAM, alternative locations were studied for individual buildings for the AMSL and the ADCL before concluding that the proposed site be selected for a single building to house both laboratories. Benefits of this choice include:

- Close proximity and direct access to the ALS complex for optimum integration of associated research and development
- Minimum disruption to existing program activities, utilities, and other site improvements
- Minimal environmental impact

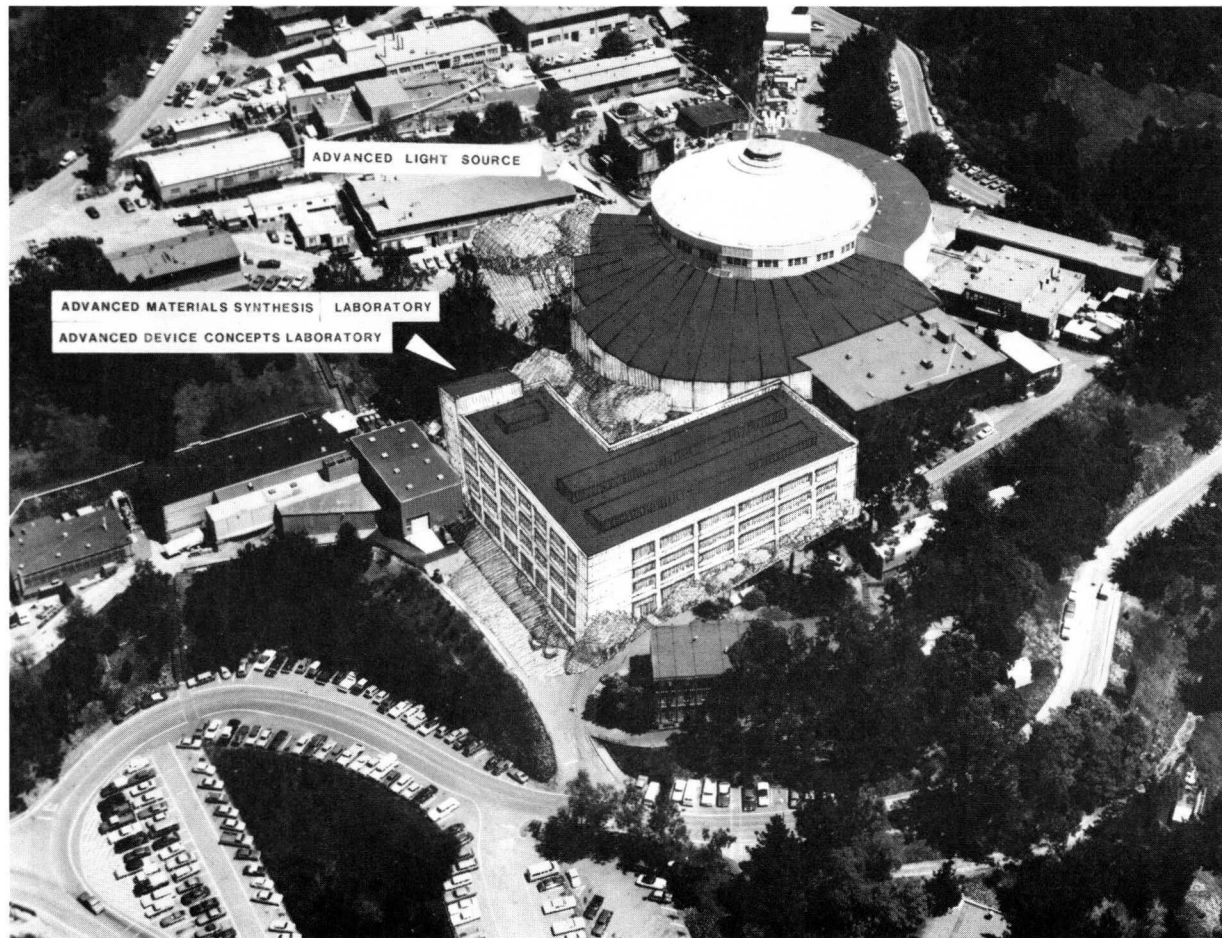


Figure 6-1. Perspective view of AMSL/ADCL Building.

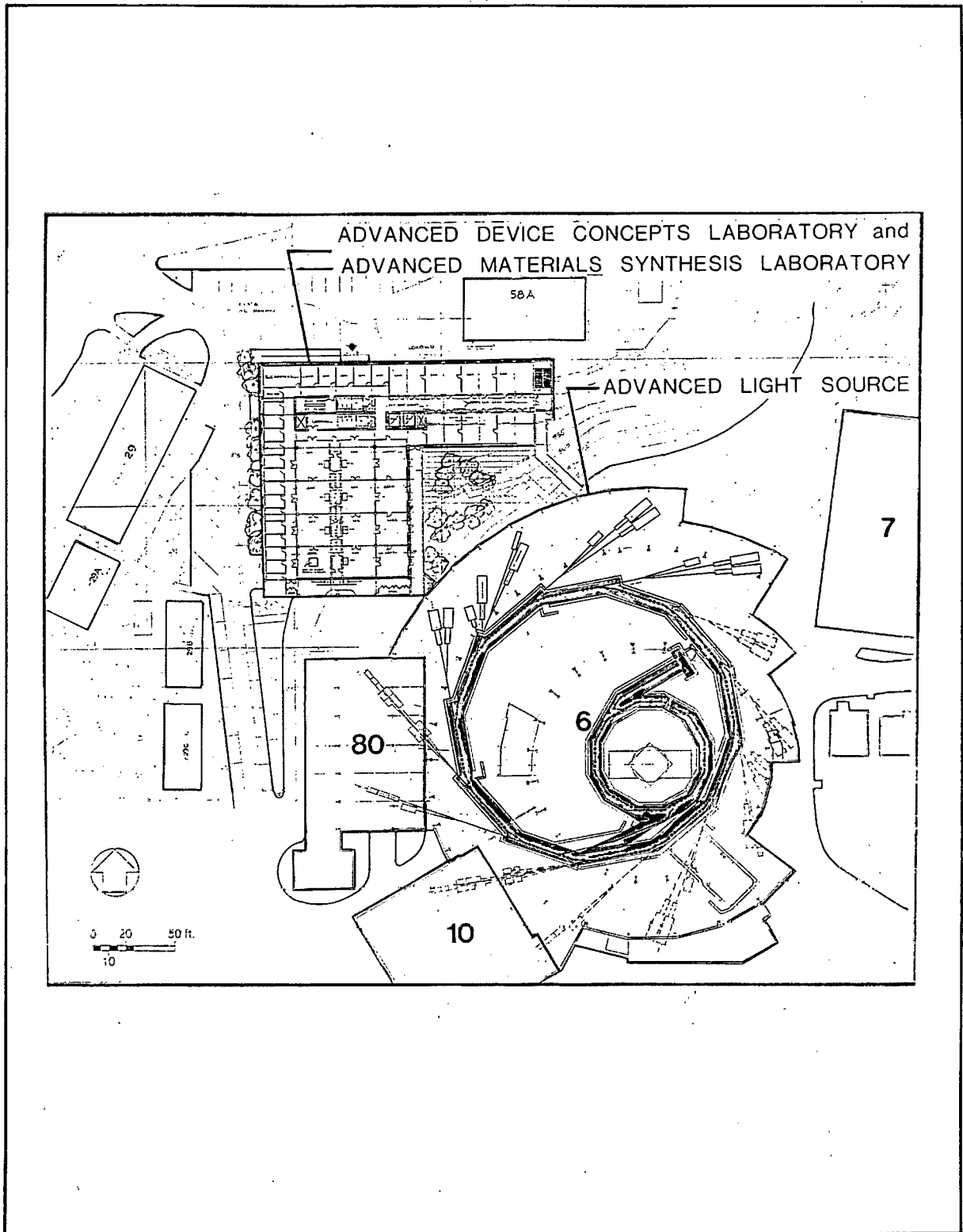


Figure 6-2. Site plan of ALS and AMSL/ADCL Buildings.

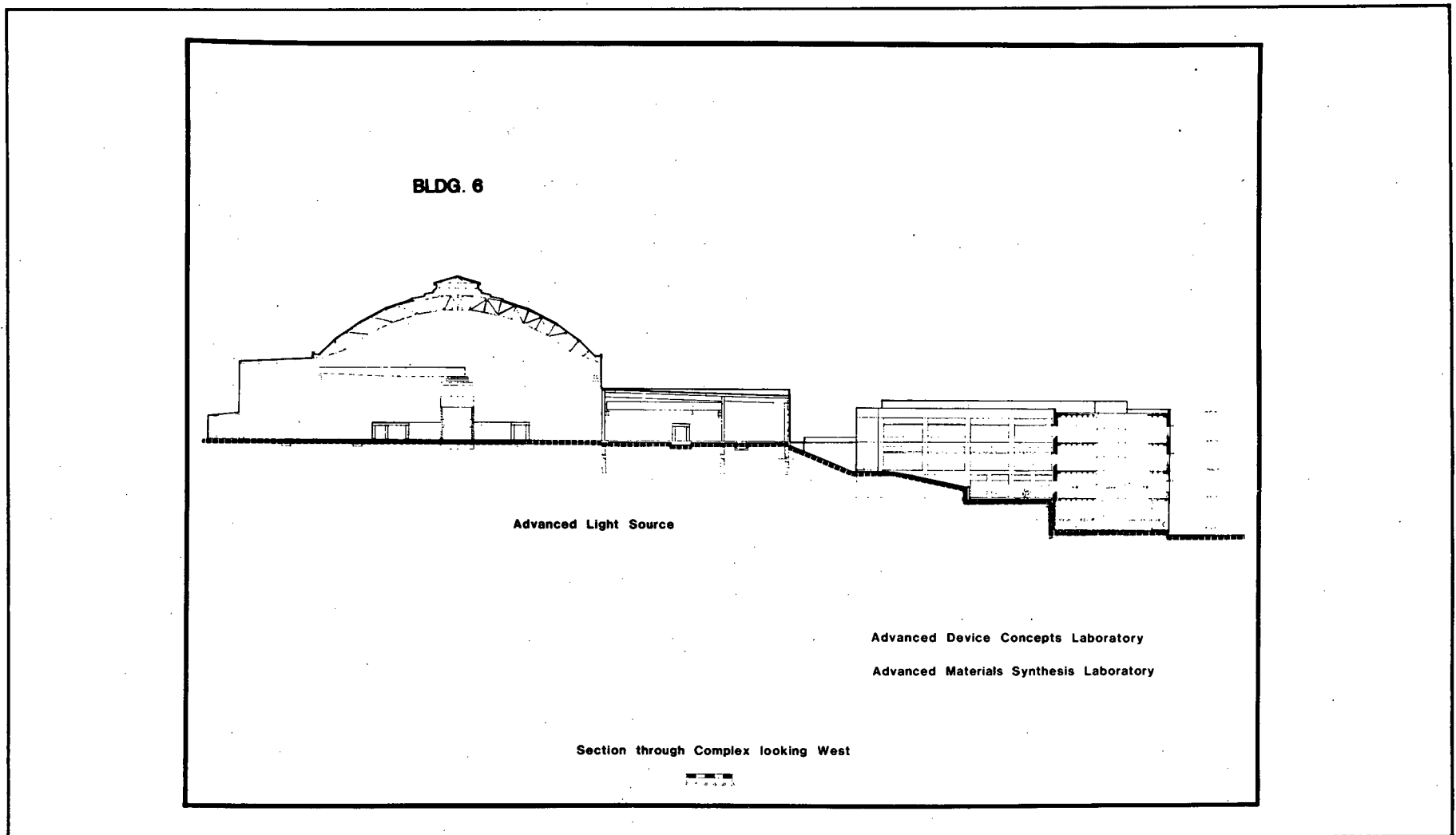


Figure 6-3. Elevation view of AMSL/ADCL and Building 6.

- Good geological stability
- Close proximity to all existing site utilities and services
- Good construction access.

The AMSL/ADCL Building will include office and light laboratory areas with about 82,000 GSF of space. The four-story building will occupy a hillside site, providing a first floor with a main entrance at the grade level of the base of the hill and three full stories above, with the fourth floor entrance at the grade level of the top of the hill. The partial first floor (about 14,156 GSF) will house the reception area, administrative offices, a conference-seminar room, shop, mechanical equipment rooms, a loading dock, and receiving area. The three stories above (each about 22,388 GSF) will house laboratories and support office space. The third floor will align with, and provide direct access to, the lower floor of existing Building 80, a two-story building housing shops, staging areas, and support facilities for the ALS. The fourth floor will align with the upper floor of Building 80, which also matches the main floor level of Building 6 and the ALS. The full floor plan at each level will be L-shaped, about 196 feet long in one direction and 170 feet in the other. The longer element will be 62 feet wide and the other 98 feet wide.

The building structure will consist of a reinforced concrete frame with shear walls and waffle-slab construction of the roof and floors above the base level. Foundations will consist of poured-in-place reinforced spread footings.

Exterior walls (non-bearing) will be constructed with prefinished panels on metal studs (insulated cavity). All interior walls and ceiling surfaces will be gypsum board except where acoustical ceilings are provided in specific areas. Laboratory furniture and fume hoods with acid/alkali resistant tops and construction will be commercial products.

Central station air handling units with filters, draw-through cooling coils, return fan units, and economizer controls will provide for HVAC requirements. Air conditioning will be supplied where an environmentally controlled air supply is required in specific laboratories. All supply and return air is ducted. The heating system will be gas-oil-fired hot-water boilers. The facility will be equipped with an automatic fire sprinkler and alarm system.

Toxic effluents will be contained through filtration and collection systems. Power and utility systems will be extended from adjacent existing plant services in close proximity.

Table 6-1 provides a listing of programmatic space requirements upon which the conceptual design is based.

The AMSL/ADCL Building will be constructed on a sloping site with topography ranging in elevation about 50 feet. The slope varies in steepness from 9:1 (horizontal to vertical) to 1:1. The existing site is primarily undeveloped but does encompass portions of a paved parking area and two relocatable trailer buildings. Ground cover consists of wild grass dotted with several eucalyptus trees of varying size.

Geologically, the building site contains varying soil and bedrock conditions including earth fill, colluvial soil, volcanic rock (Moraga formation) and sedimentary bedrock (Orinda formation). The building will be founded on the Orinda bedrock on spread footings stepped into the hill. The maximum cut will be 18 feet deep in the central portion of the building. An 18-foot-high basement retaining wall will provide lateral support for the cut as part of the building structure.

Harding Lawson Associates, Engineers, Geologists and Geophysicists, performed the geotechnical investigation for the project, including review of previous soils information, drilling

Table 6-1
Schedule of Net Areas, Functions and Occupancy

	Net Area — Sq. Ft.				
AMSL/ADCL Building	Labs	Lab Offices	Other	Occupants	
<i>First Floor — EL.832.5</i>					
Conference Room			1,078		
Reception, Clerical			600		
Administration			1,525		
Shops			1,872		
Shipping and Receiving			194		
Storage Rooms			112		
First Floor Subtotal:			5,381		22
<i>Second Floor — EL.850.5</i>					
Laboratories	10,865				
Laboratory Offices		3,000			
Receiving Area			315		
Storage Rooms			344		
Second Floor Subtotal:	10,865	3,000	659		60
<i>Third Floor — EL.866.0</i>					
Laboratories	11,700				
Laboratory Offices		3,315			
Storage Rooms			344		
Third Floor Subtotal:	11,700	3,315	344		51
<i>Fourth Floor — EL.881.5</i>					
Laboratories	11,700				
Laboratory Offices		3,315	344		
Fourth Floor Subtotal:	11,700	3,315	344		51
Subtotal All Floors:	34,265	9,630	6,728		184
Total Net Usable Area:	50,623 sq.ft.				
Gross Enclosed Area:	81,900 sq. ft.				
Covered Open Area × 1/2:	100 sq. ft.				
Total Gross Area:	82,000 sq. ft.				

and logging of new borings, performing laboratory analysis, and preparation of a report titled "Geotechnical Investigation for Planned Advanced Materials Synthesis Laboratory and Advanced Device Concepts Laboratory at the Lawrence Berkeley Laboratory" dated March 1, 1983. A copy of the report is appended in Section 8 of Volume IV. The report concludes that:

"the proposed site is feasible from a geotechnical standpoint for the planned use and that there are no unusual soil or rock conditions which would place severe constraints on the conceptual design."

Harding Lawson Associates will review final foundation and grading drawings and specifications pertinent to the soil engineering aspects of the project to assure conformance with the intent of their recommendations. Excavation for the proposed AMSL/ADCL Building will be performed using conventional excavating equipment including ripping of the bedrock. The recommended temporary cut slope during construction is 1:1. Flatter slopes or shoring may be required if localized weaker soils are encountered.

A full complement of mechanical utilities will be provided to serve the wide spectrum of basic research that may be done. The following list of services will be provided:

- Cold water, domestic and nonpotable systems
- Storm sewer and sanitary sewer
- Acid waste sewer, including an acid waste retention and monitoring facility
- Natural gas, including a metering station
- Diesel oil underground storage tank, including transfer pumps
- Provisions for a liquid-nitrogen storage tank
- Provisions for central (or local) compressed gas cylinder installations and distribution piping systems for N_2 , O_2 , H_2
- Compressed air
- Low conductivity cooling water, supply and return
- High pressure cold water for fire protection

Within the building a package ion-exchange unit will provide demineralized water. Provisions will be made for a distilled water generator and storage tank.

Electrical Utilities will be supplied to the AMSL/ADCL Building by a 12-kV underground feeder entering from the northeast. The electrical feeder will originate from the Building 6 12-kV switching and power distribution center and will be routed through the existing substation east of Building 58A. This feeder will be installed in a new high-voltage duct bank which will provide improved reliability to the new building and to Buildings 46, 47, 58 and 58A. The Building 58 substation will also be extended to accommodate new 12-kV disconnect switches.

An indoor, self-contained substation will be installed to provide power to the new facility as well as low-voltage power to Building 29 and the Building 29 trailers. The estimated capacity for the new laboratory is 2300 kVA, and for the Building 29 Complex the required capacity is 175 kVA. The new building will have a 200-kW standby generator.

Construction of the AMSL/ADCL Building coupled with the nearby addition to Building 6 for the ALS will necessitate a change in the pattern of access traffic in the vicinity of Building 6. Increased occupancy will also require additional parking. Studies to develop effective access and parking schemes have been carried out in conjunction with near term and long range planning for the older site of the original Laboratory (LBL) which surrounds and encompasses Building 6.

Access to the area will be upgraded by widening the roads around the south quadrant of Building 6 and between Buildings 29 and 80. The parking lot between Buildings 29 and 58A will be enlarged to provide space for access and service to the main entrance of the AMSL/ADCL Building and to maintain the quantity of existing parking spaces. Additional required parking will be developed in several areas within the older original area of the laboratory site nearby.

7 SSRL Improvements

Introduction to SSRL

The Stanford Synchrotron Radiation Laboratory (SSRL) is one of the leading U.S. x-ray synchrotron radiation facilities. As of March 31, 1982, it served 443 senior experimenters and approximately 100 graduate students from 124 institutions. Ninety-three of these institutions are located in the United States, including 53 universities, 29 private corporations and 11 government laboratories. The 31 foreign institutions are located in 13 different countries.

SSRL utilizes the 4 GeV storage ring, SPEAR, to produce synchrotron radiation at 15 experimental stations on 5 beam lines. Three of these beam lines are illuminated by bending magnets while two can be illuminated by either 8-pole wigglers, constructed as a joint SSRL-SLAC project, or by a 30-period undulator, constructed as a joint SSRL-LBL project. Presently being designed and constructed are two new beam lines. One is an LBL-EXXON-SSRL collaboration which will utilize a 54-pole wiggler constructed by LBL. Another is a Xerox-Stanford-SSRL collaboration which will eventually utilize three undulators to provide high brightness in the 100-1000 eV range.

The scientific programs carried out at SSRL span many different scientific areas, as listed below. Those which were originated or developed at SSRL are shown with an asterisk.

Wiggler and Undulator Development*

X-ray Area Detector Development

X-Ray Absorption Spectroscopy

Physics of EXAFS*

Near edge structure (XANES)*

Bulk EXAFS

Fluorescence*

Surface EXAFS*

Photon induced desorption EXAFS*

Time-resolved EXAFS*

X-ray Diffraction

Proteins

Amorphous Materials

Physics of anomalous scattering

Differential anomalous scattering*

Anomalous scattering crystal structure analysis

Two-dimensional systems

Surfaces of 3-dimensional systems

Small-angle scattering including time-resolved

Atomic Physics

Deep shell phenomena

Compton scattering

X-ray Fluorescence Analysis

Extremely dilute species

Photoemission

Physics of photoemission

Band structure analysis

Surface and interface studies

Photoelectron diffraction***X-ray Lithography****Non-invasive Angiography****Time-resolved Fluorescence Spectroscopy**

Semiconductor physics

Biophysics

Goals of the Construction Program

The SSRL-NCAM construction program has the following four goals:

1. To obtain major increases, quickly and economically, in the photon flux and brightness available at SSRL in all spectral regions.
2. To increase the time available for experimentation and to increase its effectiveness.
3. To develop and test new insertion devices as well as the techniques for utilizing many insertion devices on one storage ring.
4. To gain additional experience in the commissioning of low emittance storage rings.

The goals are both supportive of and complementary to those of NCAM and the ALS. SSRL will be the only synchrotron radiation source which will be readily available to NCAM staff and Western United States experimentalists until the ALS is functioning. In order to fully utilize the soft x-ray and vacuum ultraviolet capabilities of ALS, it is important that SSRL and its user community continue to develop in capabilities. The first two goals are consistent with that objective.

ALS is expected to be the first storage ring in the world which will be designed and constructed for the utilization of many insertion devices. It is important to gain prior experience in the functioning of storage rings containing several such devices soon.

Only about five wigglers and undulators have been utilized thus far for the generation of synchrotron radiation on storage rings. It is anticipated that increasing design sophistication will result from their increased utilization. The proposed collaborative development of them by SSRL and LBL will assure more effective utilization of them at the ALS.

It has become apparent from the experiences at the University of Wisconsin and the National Synchrotron Light Source that the commissioning of low emittance storage rings is a complex and difficult task. The SPEAR emittance reduction project will provide some valuable experience locally.

SSRL will provide NCAM staff and the remainder of the SSRL user community with state-of-the-art x-ray beam lines and experimental stations.

Overview of the SSRL-NCAM Project

The goals discussed above will be achieved through:

(a) Construction of a 10,000 sq. ft. addition to Building 131 which will bring the first floor and mezzanine almost all the way around to the SPEAR trestle, as shown in Figure 7-1. By shifting activities from presently existing space to this new space, room will be provided for new insertion device beam lines. The addition will also provide the extra experimental set-up and office space required as a result of the new beam lines.

(b) Alteration of the storage ring SPEAR and its injection system to reduce the emittance by a substantial amount (up to a factor of about 4), bringing it almost to the planned emittance of the NSLS rings. As shown in Figure 7-2, this emittance reduction will increase the brightness of all SSRL beam lines by about an order of magnitude and will allow for the achievement of higher x-ray energies with undulators. The performance of all of SSRL's beam lines will also be improved through the reduction of beam bounce. In addition, increases in the total amount of time during which SPEAR can be dedicated to synchrotron radiation production will be achieved through modifications of an electron gun and injection system proposed for addition to the SLAC LINAC by American University.

(c) Construction and installation in SPEAR of two insertion devices producing ultra-high x-ray and soft x-ray brilliances and photon fluxes. One option being considered is a variable gap, in-vacuum undulator which would reach a photon energy of about 7 keV in the fundamental peak. Experimentation with such a device would yield information about the high photon energy limits of such devices and, therefore, the lowest stored electron (or positron) energies practical for future all wiggler/undulator, x-ray storage rings. Another option is a wiggler designed specifically for x-ray scattering experiments of the type presently being performed on Beam Line VII. We anticipate that this wiggler will have approximately the same magnetic field, but fewer poles than the 54 pole wiggler presently being constructed in the LBL-EXXON-SSRL collaboration. Since, however, the latter wiggler is expected to provide the highest x-ray flux in the world for quite some time, as illustrated in Figure 7-3, this new wiggler will represent a substantial addition to our x-ray facilities.

(d) Construction of an ultra-high brilliance x-ray undulator beam line on PEP. As illustrated in Figure 7-2, this beam line will provide the most brilliant x-ray beam in the world in the 10-30 keV spectral region and will make possible new experiments which are otherwise impossible to perform.

Cost Summary

The costs associated with each major element of the SSRL-NCAM construction program are summarized below.

Building 131 extension	\$2.026 M
SPEAR Emittance Reduction	3.490
Beam Bounce Reduction	0.240
Injection System Modifications	0.072
SPEAR Insertion Devices	2.838
PEP Beam Line	3.964
Total	\$12.630 M

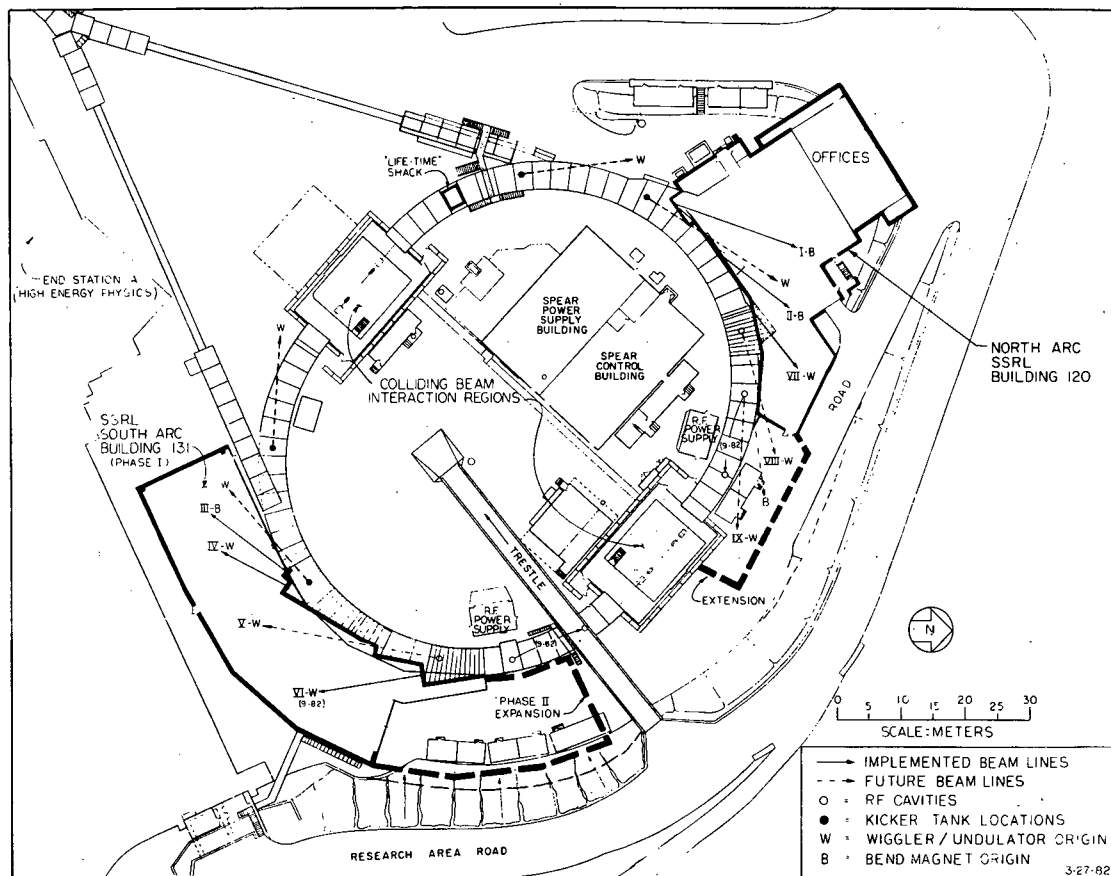


Figure 7-1. Plan view of the SPEAR ring being used by Stanford Synchrotron Radiation Laboratory. Planned construction is dashed.

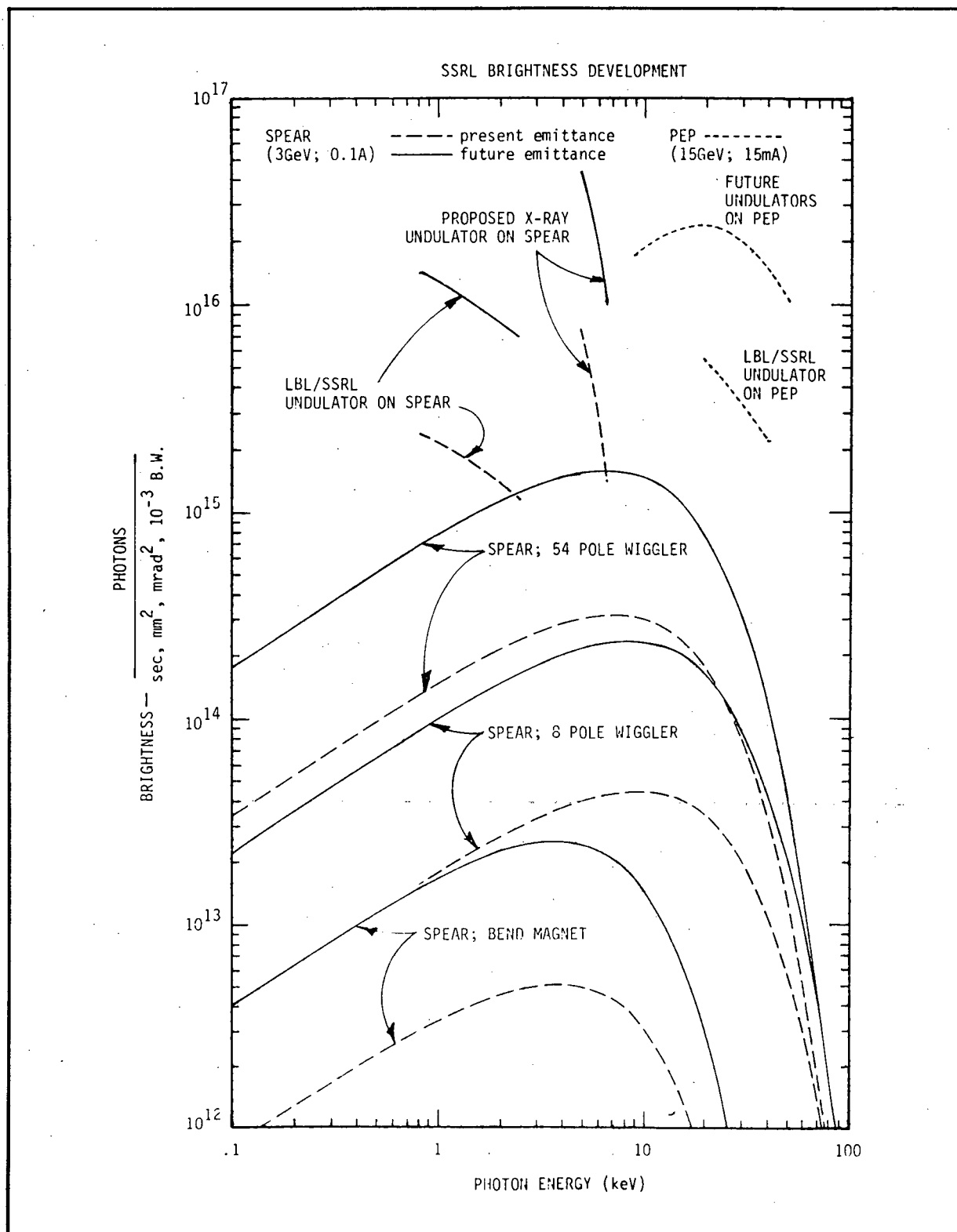


Figure 7-2. Increases in SSRL spectral brilliance expected to occur as a result of the planned improvements.

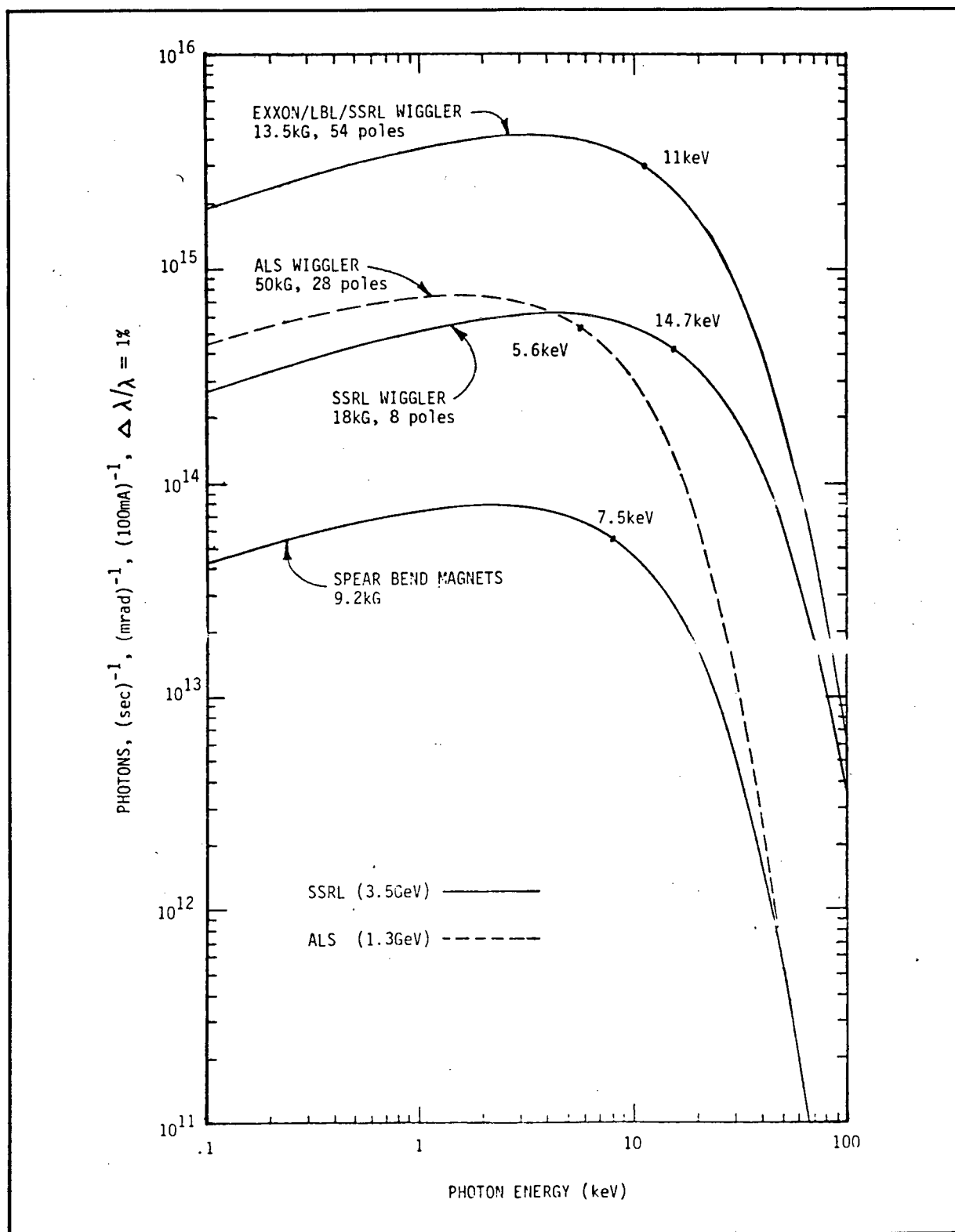


Figure 7-3. Comparison of x-ray fluxes provided by various wigglers.

8 Costs and Schedule

The following pages contain tables, charts, and figures presenting summary cost estimate data, funding and expenditure rate profiles, and overall project schedules. The first series of Tables (8-1 through 8-5) provide overall project cost information in actual year (i.e., escalated) dollars. Tables 8-2 through 8-5 show these estimates both as obligation requirements (budget authorization) and expended costs (budget outlay) for each fiscal year throughout the duration of the project. Figures 8-1 and 8-2 are funding profile plans and show the same information graphically.

Table 8-6 presents the Total NCAM Costs in constant FY83 dollars. Table 8-7 compares the total FY83 dollar and cost estimate amounts for EDIA, construction, and contingency with actual year dollar totals. Table 8-8 expands the FY83 dollar cost estimate summary for the Special Research Facilities/ALS Technical Components to three WBS detail levels. Figures 8-3 and 8-4 show the distributed cost data for the ALS in FY83 dollars.

Figures 8-5 through 8-8 are summary schedule charts for the project. The overall major project milestones are shown on Figure 8-5, and the remaining figures show relative phasing and time durations for construction packages for the major elements.

**NCAM TOTAL PROJECT
ACTUAL YEAR M\$
April 1983**

	M\$
NCAM PROJECT (TEC)	138.9
1.0 Engineering, Design, Inspection, & Administration	23.4
1.1 Overall Project Management & Admin.	8.0
1.2 Conventional Facilities	5.0
1.3 Special Research Facilities	10.4
2.0 Construction Costs — Conventional Facilities	40.5
2.1 Surface Science & Catalysis Lab	9.6
2.2 Advanced Light Source Addition	8.8
2.3 AMSL & ADCL Building	22.1
3.0 Construction Costs — Special Research Facilities/ALS	41.9
3.1 Storage Ring	10.7
3.2 Injector	6.2
3.3 Control System	2.4
3.4 Insertion Devices	7.7
3.5 Photon Beamlines	14.9
4.0 Contingencies	20.2
5.0 SSRL Improvements	12.9

Table 8-1. NCAM Total Project

Table 8-2
Obligations and Costs Schedule Detail (M\$)*
NCAM Total Project Cost

Description	Total	FY 1984		FY 1985		FY 1986		FY 1987		FY 1988		FY 1989	
		O	C	O	C	O	C	O	C	O	C	O	C
NCAM Project Management	7.95	1.21	1.21	1.38	1.38	1.50	1.50	1.50	1.50	1.33	1.33	1.03	1.03
ALS Conventional Facilities	11.57	3.40	2.87	5.20	4.66	2.97	4.04						
ALS Special Research Facil.	66.16	5.49	5.08	11.55	10.55	16.68	15.32	15.90	16.43	11.57	13.66	4.97	5.12
Lab Buildings SSCL	11.10	9.30	3.60	1.50	6.00	0.30	1.50						
Lab Buildings AMSL/ADCL	29.19	2.40	1.10	1.39	1.39	2.00	2.40	12.00	9.00	10.40	10.70	1.00	4.60
Subtotal	125.97	21.80	13.86	21.02	23.98	23.45	24.76	29.40	26.93	23.30	25.69	7.00	10.75
SSRL Improvements	12.93	4.10	1.60	5.58	8.08	3.25	3.25						
TOTAL	138.90	25.90	15.46	26.60	32.06	26.70	28.01	29.40	26.93	23.30	25.69	7.00	10.75

*Escalation rates compounded per annum; FY83 8%, FY84 8.5%, FY85 and beyond 9%.

Table 8-3
Obligations and Costs Schedule Detail (K\$)*
Conventional Facilities/SSCL

WBS	Description	Total	FY 1984		FY 1985		FY 1986	
			O	C	O	C	O	C
1.2.1.1	LBL Activities							
	Engineering	70	20	20	30	30	20	20
	Inspection	140	50	50	70	70	20	20
	Consultants	40	20	20	20	20	0	0
	Const. Management	70	30	30	30	30	10	10
1.2.1.2	Architect-Engineer Title III	130	130	50	0	60	0	20
2.1.1	Construction							
2.1.1.1	Construction Contract							
	Site Improvements	410	410	280	0	100	0	30
	Building	7340	7340	2600	0	4400	0	340
	Utilities	190	190	160	0	20	0	10
2.1.2.1	Special Facilities	310	310	0	0	280	0	30
2.1.2	Equipment							
2.1.2.2	Standard Equipment	<u>1360</u>	<u>0</u>	<u>0</u>	<u>1200</u>	<u>500</u>	<u>160</u>	<u>860</u>
	Subtotal	10060	8500	3210	1350	5510	210	1340
	Contingency	<u>1040</u>	<u>800</u>	<u>390</u>	<u>150</u>	<u>490</u>	<u>90</u>	<u>160</u>
	TOTAL	11100	9300	3600	1500	6000	300	1500

*Escalation rates, compounded per annum: FY83 8%, FY84 8.5%, FY85 and beyond 9%.

Table 8-4
Obligations and Costs Schedule Detail (K\$)*
Conventional Facilities/ALS

WBS	Description	Total	FY 1984		FY 1985		FY 1986	
			O	C	O	C	O	C
1.2.2	EDIA	1278	900	540	200	469	178	269
2.2.1	Site Preparations	1452	1452	1452				
2.2.2	Equip. Relocations	622	622	622				
2.2.3	Construction							
2.2.3.1	Site Improvements	43	43	43				
2.2.3.2.1	Structural	2175			2175	2175		
2.2.3.2.2	Cranes	174					174	174
2.2.3.2.3	Interior Rooms	117			117	117		
2.2.3.2.4	Shielding	1775					1775	1775
2.2.3.2.5	Utilities (Mech.)	721			567	351	154	370
2.2.3.2.6	Utilities (Elec.)	1540			1200	703	340	837
2.2.3.3	Building 80 Mods.	<u>141</u>	<u> </u>	<u> </u>	<u>141</u>	<u>141</u>	<u> </u>	<u> </u>
	Subtotal-	10038	3017	2657	4400	3956	2621	3425
	Contingency	<u>1529</u>	<u>383</u>	<u>216</u>	<u>800</u>	<u>703</u>	<u>346</u>	<u>610</u>
	TOTAL	11567	3400	2873	5200	4659	2967	4035

*Escalation rates, compounded per annum: FY83 8%, FY84 8.5%, FY85 and beyond 9%.

Table 8-5
Obligations and Costs Schedule Detail (K\$)*
Conventional Facilities/AMSL/ADCL

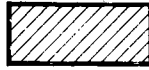
WBS	Description	Total	FY 1984		FY 1985		FY 1986		FY 1987		FY 1988		FY 1989	
			O	C	O	C	O	C	O	C	O	C	O	C
1.2.3.1	LBL Activities													
	Engineering	900	330	330	160	160	190	190	150	150	40	40	30	30
	Inspection	290			30	30	60	60	70	70	80	80	50	50
	Consultants	140	60	60	30	30	20	20	20	20	10	10	0	0
	Const. Management	120	20	20	20	20	20	20	20	20	20	20	20	20
1.2.3.2	Architect-Engineer													
	Titles I & II	1150	1150	500	0	250	0	200	0	200	0	0	0	0
	Title III	220	220	0	0	0	0	40	0	70	0	80	0	30
1.2.3.3	Const. Management†	400	400	50	0	60	0	70	0	80	0	90	0	50
2.3.1	Construction													
	Site Construction													
2.3.1.1	Access and Parking	890			890	590	0	300	0	0	0	0	0	0
2.3.1.2	Site Imp., Utilities													
	Found. & Slabs	1130					1130	900	0	230	0	0	0	0
	Building Construction													
2.3.1.3	Building Stage I	10200							10200	6800	0	3400	0	0
2.3.1.4	Building Stage II	4040									4040	3040	0	1000
2.3.2	Equipment													
2.3.2.1	Special Facilities													
	Stage I Building	300							300	150	0	150	0	0
	Stage II Building	250									250	120	0	130
2.3.2.2	Standard Equipment													
	Stage I	4220									4220	2120	0	2100
	Stage II	770									370	200	400	570
2.3.3	Removals	360					360	360					0	0
	Subtotal	25380	2180	960	1130	1140	1780	2160	10760	7790	9030	9350	500	3980
	Contingency	3810	220	140	260	250	220	240	1240	1210	1370	1350	500	620
	TOTAL	29190	2400	1100	1390	1390	2000	2400	12000	9000	10400	10700	1000	4600

*Escalation rates, compounded per annum: FY83 8%, FY84 8.5%, FY85 and beyond 9%.

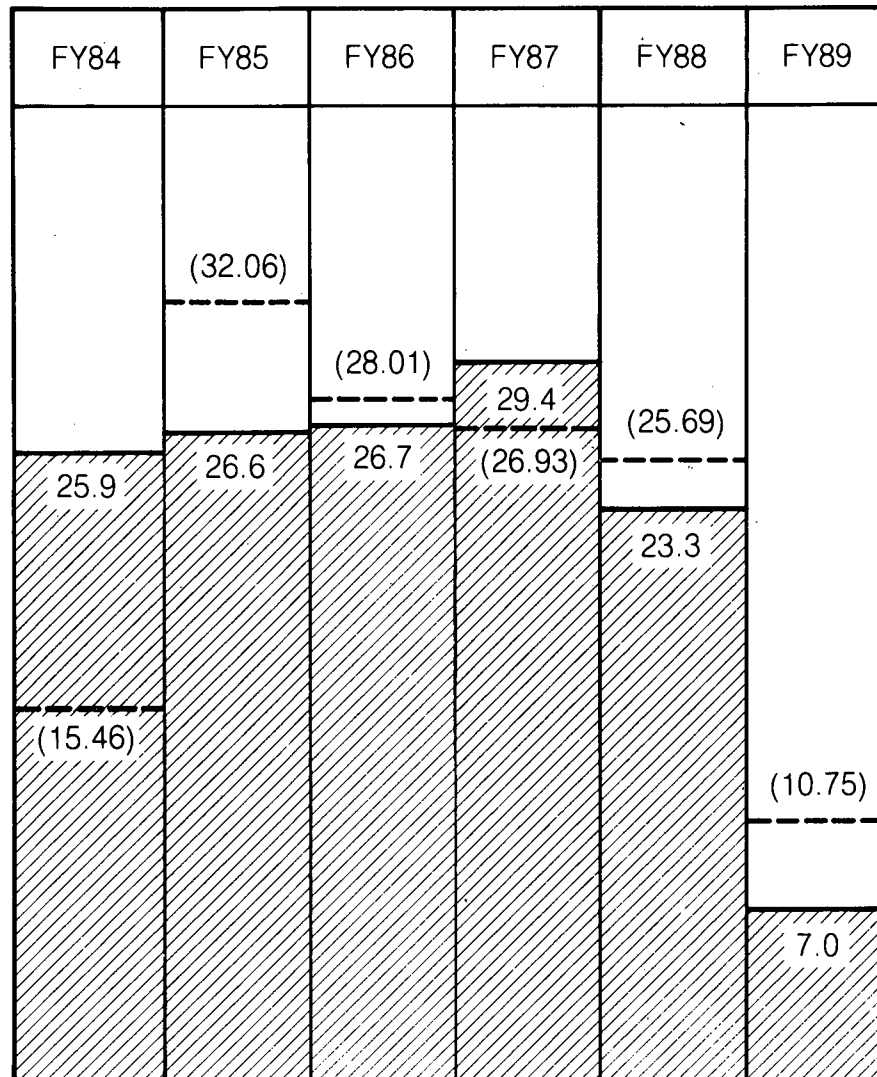
†Construction Management services for all NCAM components.

NCAM FUNDING PROFILE
TOTAL PROJECT
ACTUAL YEAR M\$

Budget Authorization
Obligations



Budget Outlay
(Costs)



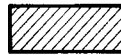
TOTAL COST 138.9 M\$

Figure 8-1. NCAM total project funding profile.

NCAM ELEMENT FUNDING PROFILE
ACTUAL YEAR M\$

8-8

OBLIGATIONS



COSTS,



	FY84	FY85	FY86	FY87	FY88	FY89	TOTAL M\$
Project Management	1.21	1.38	1.50	1.50	1.33	1.03	7.95
ALS Conventional Facilities	3.4	5.2	2.97				11.57
ALS Special Research Facilities	5.49	11.55	16.68	15.9	11.57	4.97	66.16
SSCL	9.3	1.5	0.3				11.10
AMSL/ADCL	2.4	1.39	2.0	12.0	10.4	1.0	29.19
SSRL	4.10	5.58	3.25				12.93

Figure 8-2. NCAM major elements funding profile.

NCAM TOTAL PROJECT
FY83 M\$
April 1983

	<u>M\$</u>
NCAM PROJECT (TEC)	138.9
1.0 Engineering, Design, Inspection, & Administration	17.7
1.1 Overall Project Management & Admin.	6.1
1.2 Conventional Facilities	3.7
1.3 Special Research Facilities	7.9
2.0 Construction Costs — Conventional Facilities	30.8
2.1 Surface Science & Catalysis Lab	8.2
2.2 Advanced Light Source Addition	7.4
2.3 AMSL & ADCL Building	15.2
3.0 Construction Costs — Special Research Facilities/ALS	31.6
3.1 Storage Ring	8.7
3.2 Injector	5.3
3.3 Control System	1.9
3.4 Insertion Devices	5.3
3.5 Photon Beamlines	10.4
4.0 Contingencies	14.9
5.0 SSRL Improvements	10.9
6.0 Escalation*	33.0

*Escalation rates compounded per annum; FY 83 8%, FY 84 8-1/2%, FY 85 and beyond 9%.

Table 8-6. NCAM Total Project

Table 8-7
NCAM Project Cost Summary,
FY83 and Actual Year Dollars Comparison.

	Project Management	ALS		Laboratory Buildings			SSRL Upgrade	TOTAL
		Conventional Facilities	Special Research Facilities	SSCL	AMSL/ADCL	Subtotal		
FY83 K\$								
EDIA	6050	1111	7913	390	2208	17672	1750	19422
Construction	—	7407	31654	8195	15192	62448	7000	69448
Contingency	—	1278	10032	915	2642	14867	2180	17047
Total	6050	9796	49599	9500	20042	94987	10930	105917 (FY83K\$)
Actual Year K\$								
EDIA	7953	1278	10442	450	3220	23343	2070	25413
Construction	—	8760	41856	9610	22160	82386	8270	90656
Contingency	—	1529	13862	1040	3810	20241	2590	22831
Total	7953	11567	66160	11100	29190	125970	12930	138900 (TEC)
Escalation	1903	1771	16561	1600	9148	30983	2000	32983 (Escal)

*Escalation rates compounded per annum; FY83 8%, FY84 8.5%, FY85 and beyond 9%.

Table 8-8
Special Research Facility/ALS
Cost Estimate FY83 dollars.

WBS	Description	FY83K\$
3.0	Construction Costs— Special Research Facilities/ALS	31654
3.1	Storage Ring	8692
3.1.1	Ring Magnets	2714
3.1.2	Ring Vacuum System	1902
3.1.3	Survey & Alignment	322
3.1.4	Ring Magnet Power System	645
3.1.5	Ring RF System	1765
3.1.6	Ring Low Level Electronics	1344
3.2	Injector System	5346
3.2.1	Booster Magnets	1373
3.2.2	Beam Transfer Magnets	599
3.2.3	Vacuum System	525
3.2.4	Booster Magnet Power Systems	735
3.2.5	RF System	323
3.2.6	Beam Transfer Power Systems	629
3.2.7	Linear Accelerator	792
3.2.8	Low Level Electronics	370
3.3	Control System	1922
3.3.1	Network & Work Stations	384
3.3.2	Consoles	144
3.3.3	Display & Collector Micro-Modules	686
3.3.4	Input/Output Controller Modules	640
3.3.5	Timing & Synchronization	68
3.4	Insertion Devices	5337
3.4.1	Undulator A	468
3.4.2	Undulator B	859
3.4.3	Undulator C	859
3.4.4	Undulator D	887
3.4.5	Wiggler E	573
3.4.6	Wiggler F	1691
3.5	Photon Beamlines	10357
3.5.1	Beamline A	1681
3.5.2	Beamline B	1193
3.5.3	Beamline C	1193
3.5.4	Beamline D	1257
3.5.5	Beamline E	2786
3.5.6	Beamline F	2247

Table 8-8(continued)
Total ALS Technical Components Cost

	<u>FY83K\$</u>	<u>Actual Year K\$*</u>
EDIA @ 25%	7914	10442
Construction	31654	41856
Contingency @ 25%	10032	13862
TOTAL	49600	66160

*Escalation: FY83 8%, FY84 8.5% , FY85 and beyond 9%.

**ALS FUNDING PROFILE—
SPECIAL RESEARCH FACILITIES**

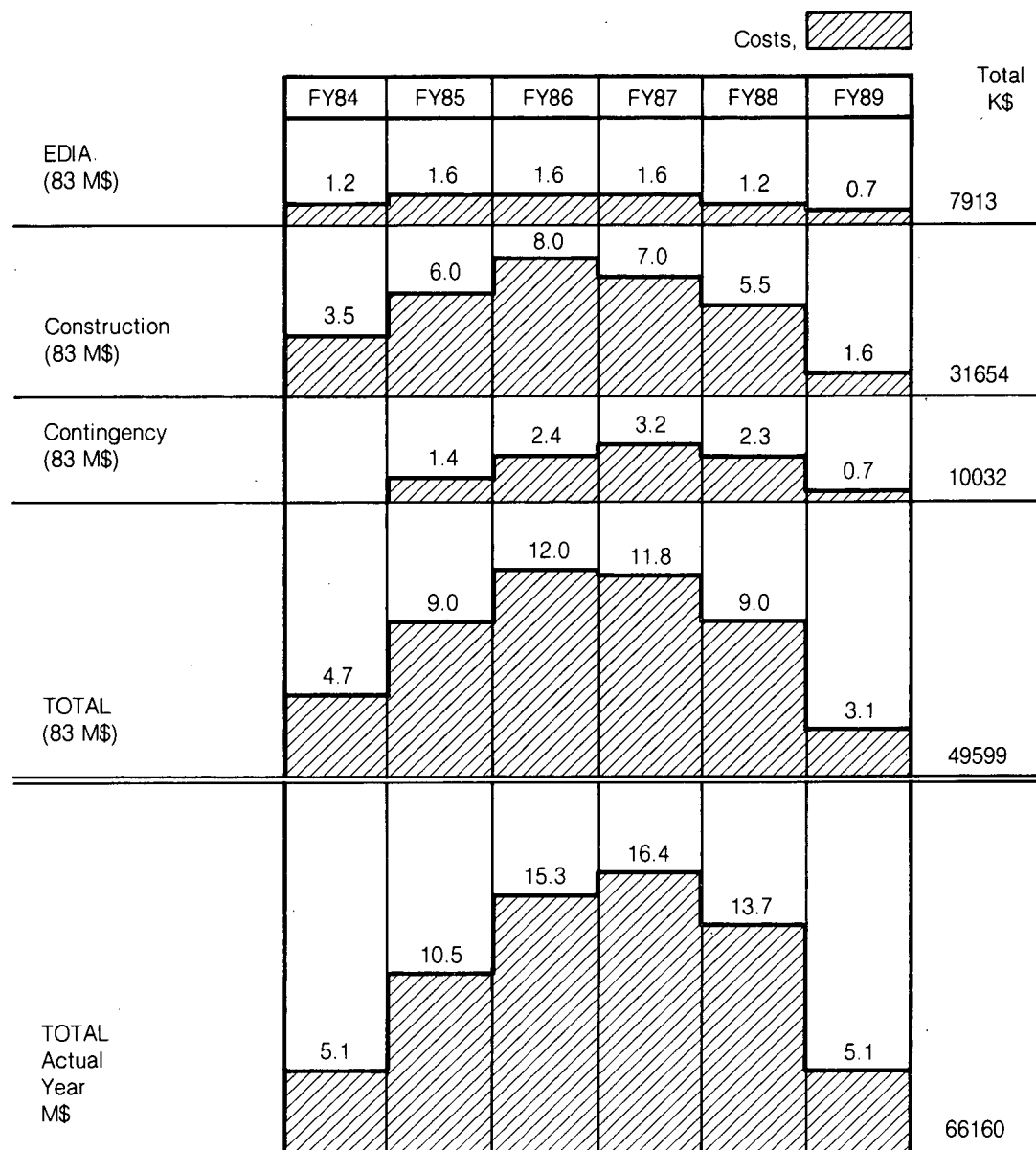


Figure 8-3. ALS funding profile—special research facilities.

ALS FUNDING PROFILE— TECHNICAL COMPONENTS						
Construction costs FY83 M\$	FY84	FY85	FY86	FY87	FY88	FY89
Storage Ring	1.2	3.0	3.1	1.4		
						Total K\$
						8692
Injector System	2.0	2.5	0.8			
						5346
Control System	0.3	0.5	0.6	0.5		
						1922
Insertion Devices			1.3	1.5	1.9	0.6
						5337
Beamlines			2.2	3.6	3.6	1.0
						10357
Total Construction Costs	3.5	6.0	8.0	7.0	5.5	1.6
						31654

Figure 8-4. ALS funding profile—technical components.

OVERALL PROJECT SCHEDULE

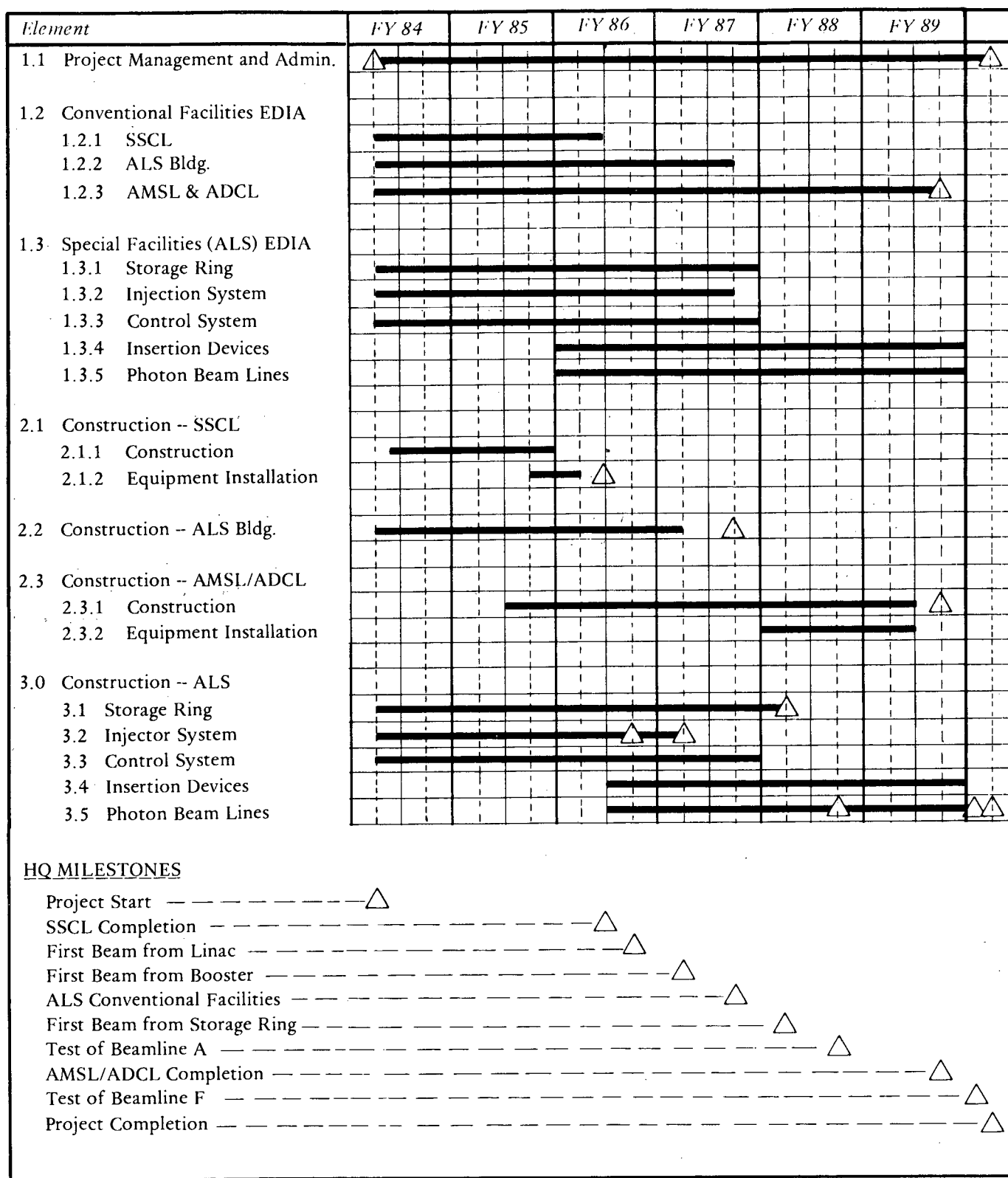


Figure 8-5. Overall project schedule.

ENGINEERING, DESIGN, INSPECTION, AND ADMINISTRATION

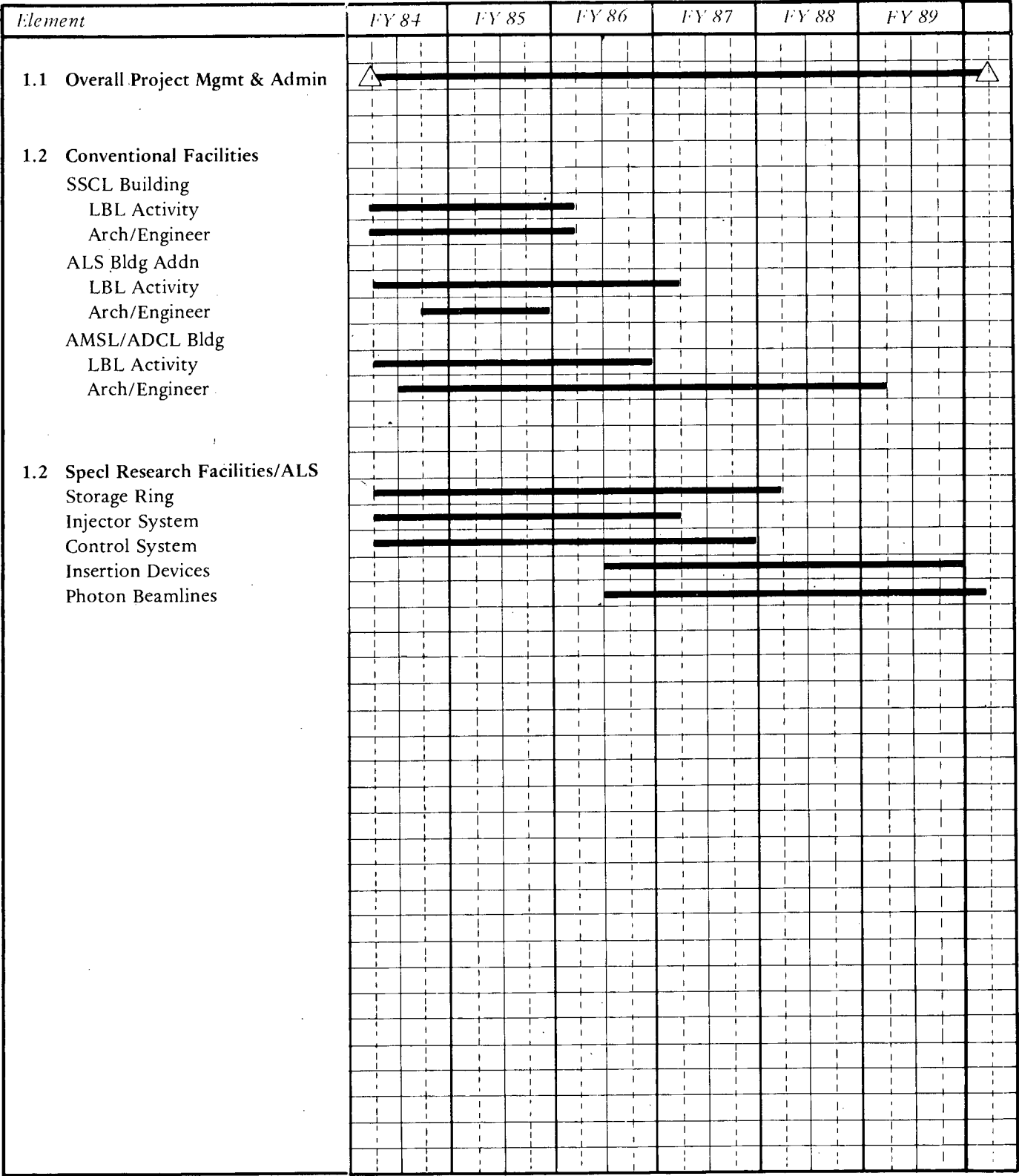


Figure 8-6. EDIA schedule.

CONSTRUCTION - CONVENTIONAL FACILITIES

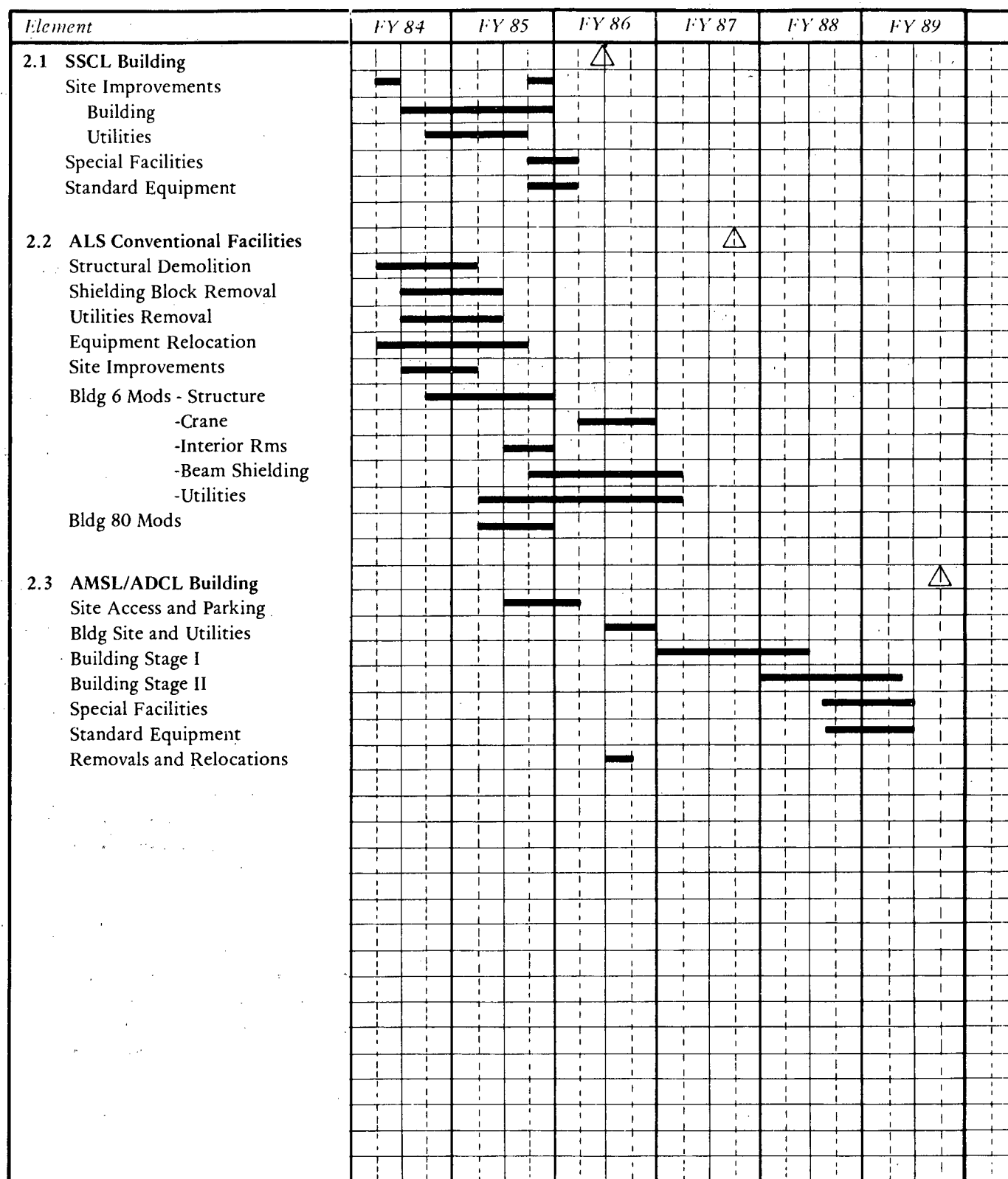


Figure 8-7. Conventional Facilities schedule.

CONSTRUCTION – SPECIAL RESEARCH FACILITIES/ADVANCED LIGHT SOURCE

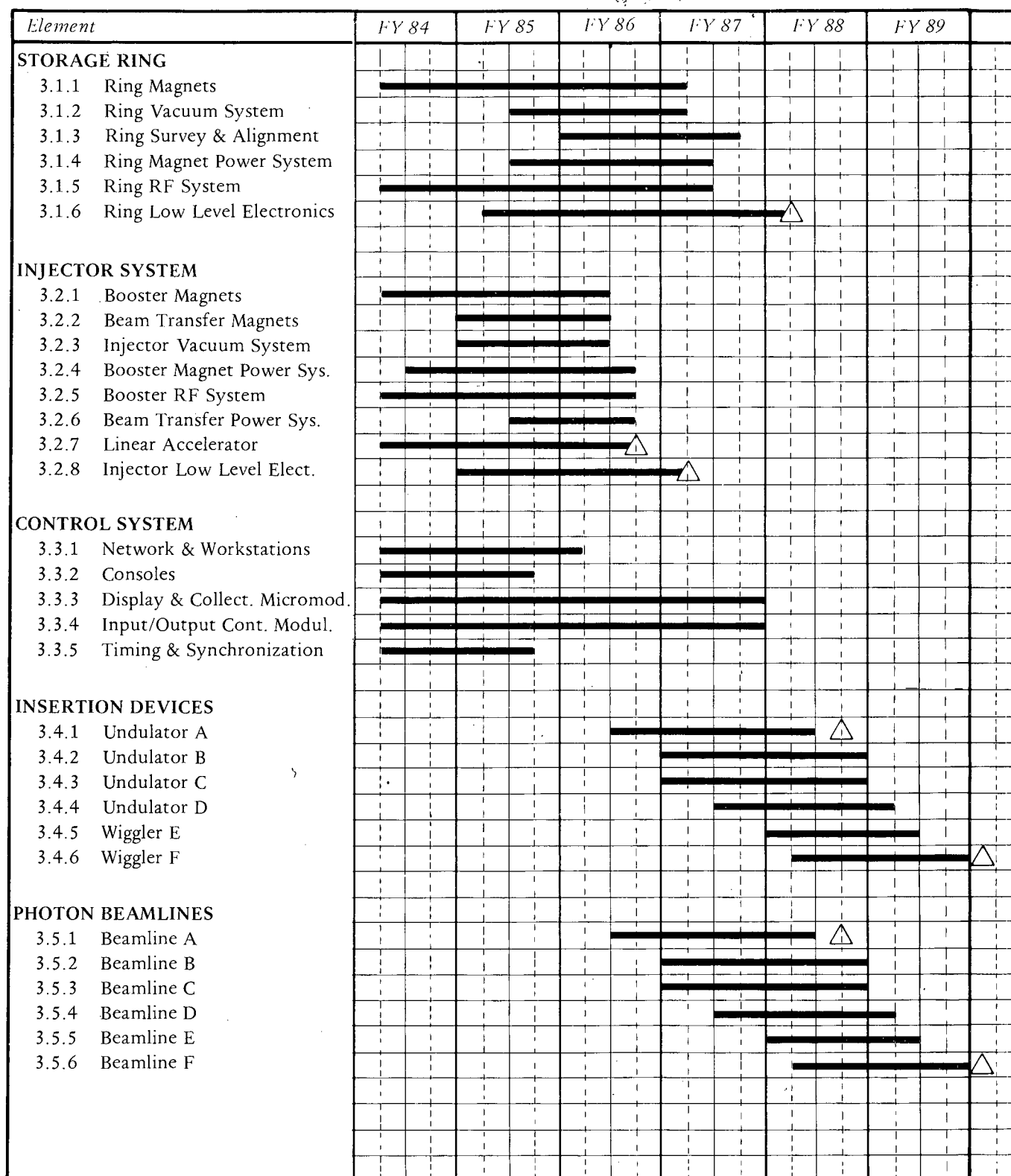


Figure 8-8. Special Research Facilities/ALS schedule.

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