Fermi National Accelerator Laboratory

FN-510

Accelerator Health Physics at DOE Laboratories: a Characterization

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April 12, 1989

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Acknowledgements

The information collected in this report could not have been obtained without the help and cooperation of the radiation protection personnel at each of the DOE laboratories. We thank them for their patience and tolerance during our site visits to each of their facilities and the openness with which they discussed their radiation protection and health physics programs, problems, and needs.

This work was funded by the Department of Energy through the Battelle, Pacific Northwest Laboratories, as part of DOE Program No. HA-01-09-05.

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I. INTRODUCTION

In January 1986 the Department of Energy designated Fermilab as the Lead Laboratory for Accelerator Health Physics Research (AHP Lead Lab). One of the primary purposes of AHP Lead Lab is to advise DOE of those areas of accelerator health physics research which should be pursued, and to help prioritize them. As a first step toward providing such advice visits were made to the various DOE laboratories which have accelerator facilities to observe and tour the facilities, discuss problem areas with accelerator health physicists, and to solicit opinions for improving health physics programs. The visits covered only the technical aspects of such programs. Compliance or regulatory issues were not discussed.

The Department of Energy administers eleven laboratories that have significant activity associated with accelerator-based research. (A twelfth, the Superconducting Super Collider (SSC), is only a R&D project at present and is therefore not discussed in this report.) Accelerators at these labs present a wide range of physical parameters. The energies vary from the TeV to the keV range; beam current from pico- to kilo- amps; particle types from electrons to uranium ions. Accelerator sizes vary from "room size" electrostatic devices through cyclotrons and linacs to a four-mile circumference synchrotron. Some of the accelerators are used by several hundred experimenters from around the world while others involve a few in-house physicists performing applied research.

The differences in accelerator types and properties should be manifest in variations in the characteristics of the radiation fields and the kinds of radiation detection problems encountered at the facilities. Discussion, during the visits, centered on the facilities themselves and the characterization of the radiation fields, instrumentation both for general radiation monitoring and for research, personnel dosimetry and associated concerns, health physics related research done and in progress, and future needs. The emphasis on one or another of these broad areas was in large part determined by each laboratory's health physics staff members themselves.

The body of this report is a summary of these discussions. There are sections on the facilities, which describe the accelerator complex, the characteristics of the radiation fields, the kinds of instrumentation in use to define and quantify the fields, and the personnel dosimetry programs currently in place. Each section contains an introduction which is a summary for all the labs, followed by specific features germane to each facility. The descriptions are not meant to be exhaustive or to even give a complete picture of the total health physics program. It is hoped however that these summaries do provide in a single place a comparison of some aspects of the health physics activities at each lab in which both the similarities and differences are displayed. A final section reports on accelerator health physics research activities, and a preliminary assessment of research needs in this area.

II. FACILITIES

A. Introduction

The accelerators at the DOE Laboratories that were visited are briefly described in this section. The laboratories themselves are introduced below.

Argonne National Laboratory (ANL) is a multiprogram facility operated under contract with the DOE by the University of Chicago. The laboratory supports applied research and development programs in reactor development, nuclear energy, biomedical and environmental research, and basic research in nuclear and high-energy physics, chemistry, biology, and materials science. While the Lab has a facility in Idaho, its main site is a 1700 acre tract, 28 miles southwest of Chicago, Illinois.

The Bates Linear Accelerator Center (BATES) is operated by the Massachusetts Institute of Technology and is located 25 miles north of Boston in Middleton, MA. The facility is used in high-energy and nuclear physics research.

Brookhaven National Laboratory (BNL), operated for the DOE by Associated Universities, Inc., is a multipurpose laboratory located on Long Island, NY, about 60 miles east of New York City. The program includes basic research in nuclear and high-energy physics, chemical and biological effects of radiations, and research and development in various energy systems.

The Continuous Electron Beam Accelerator Facility (CEBAF) is a single purpose laboratory for basic research in intermediate energy and nuclear physics to be located in Newport News, VA. It is run by Southeastern Universities Research Association (SURA) for the DOE, and is expected to be operational by 1994

Fermi National Accelerator Laboratory (Fermilab, FNAL) is a single purpose facility for basic research in high-energy physics. It is an international user facility managed for the DOE by the Universities Research Association (URA), a consortium of 54 universities in the USA and Canada. It is located on 6800 acres near Batavia, Illinois, 35 miles west of Chicago.

The Clinton P. Anderson Meson Physics Facility (LAMPF) is a national user facility for experimental intermediate energy nuclear and particle physics, nuclear chemistry, radiation effects, and radiobiology. It is part of Los Alamos National Laboratory (LANL), a multiprogram facility, covering 37 square miles 95 miles north of Albuquerque, NM. It is operated by the University of California under contract with the DOE.

The Lawrence Berkeley Laboratory (LBL) is a multiprogram laboratory with major efforts in accelerator and fusion research, biology and medicine, energy and environment, materials science, nuclear science, physics, computer science, and mathematics. It is located in Berkeley, CA, and operated for the DOE by the University of California.

The Lawrence Livermore National Laboratory (LLNL), operated by the University of California for the DOE, performs research on nuclear weapons, magnetic and laser fusion, biomedical and environmental sciences, and applied energy technology as well as basic research in chemistry, materials science, computer science, engineering, and physics. It is located about 40 miles east of San Francisco, CA.

Oak Ridge National Laboratory (ORNL) is a multipurpose facility located in eastern Tennessee, and operated by Martin Marietta Energy Systems for the DOE. The major programs are nuclear energy development, basic energy sciences, biomedical and environmental research, and magnetic fusion energy.

The Stanford Linear Accelerator Center (SLAC), operated by Stanford University for the DOE, is located in Menlo Park, CA. It is an international user facility for experimental and theoretical research in high-energy physics, and new techniques for particle acceleration.

Sandia National Laboratories (SNL) is a multiprogram facility operated for the DOE by AT&T Technologies, Inc. Its headquarters is in Albuquerque, NM. The lab's main effort is research and development of nuclear weapons systems.

B. Descriptions of Accelerator Facilities

1. ANL (Figs. 1, 2)

The IPNS (Intense Pulsed Neutron Source) is a 500 MeV rapid-cycling synchrotron fed by a 750 keV Cockcroft-Walton preaccelerator and 50 MeV proton linac. Usual operating conditions are 450 MeV with a proton current of 14 µamps at 30 Hz repetition rate. The beam is transported to a shielded enriched uranium target where $\sim 10^{14}$ neutrons per proton pulse are produced by spallation and fission. These are moderated to thermal energies for neutron scattering and material science research. A parasitic neutral particle beam (H^o) is used on a part-time basis for Strategic Defense Initiative (SDI) related studies. There are 12 neutron-beam ports available for research but typically only 2 to 4 experiments are operated simultaneously. Over 200 experiments are performed each year. The facility operates 5 to 6 months per year on IPNS and 2 to 3 months on associated neutral particle beam experiments.

ATLAS (Argonne Tandem-Linear Accelerator System) consists of a 9 MV tandem accelerator followed by two superconducting linacs which make use of niobium split-ring resonators and superconducting solenoid focusing elements. The machine can accelerate heavy ions ranging from ^{7}Li to ^{127}I to energies up to 20 MeV per nucleon with pulsed-beam currents up to 70 particle-namps. The beams are transported into two experimental areas for heavy ion research that includes quasielastic scattering, fission and fusion reactions, nuclear structure studies, and atomic physics. Only one experiment can be performed at a time although there are twelve separate beam lines. The machine operates 11 months out of the year during which time about 40 experiments are performed. A new electron-cyclotron resonance ion source and superconducting pre-accelerator are being installed.

The Electron Linac, a conventional L-band linear accelerator, can operate in two modes. In pulsed-mode operation the machine provides a 21 MeV electron beam with a peak current of ~20 amps and pulse widths between 4 and 100 nsec. In "steady state" operation pulse widths are 10 µsec and maximum energy is 14 MeV. The electron beam can strike thick high-Z targets to provide bremsstrahlung and photoneutron beams, but is now used only for radiation chemistry studies that include pulse radiolysis, radical reactions, gas phase energy studies, etc. There are 12 beam holes, and about 200 experiments can be done in year, but only one at a time.

The 60" Cyclotron accelerates light ions; protons to 11 MeV with intensities up to 200 µamps, 20 µamps of deuterons to 22 MeV, and alpha particles to 43 MeV at beam currents of ~100 µamps. There are no extracted beams, although there are two beam ports. The accelerator is used exclusively for isotope production for research, engineering, and medical studies. About 36 experiments are done in a year.

Argonne also operates a variety of smaller accelerator facilities for basic and applied research activities. These include a 4.5 MV dynamitron that can accelerate light and molecular ion beams to a few hundred µamps, an 8 MV tandem-dynamitron which accelerates protons and deuterons to produce fast neutrons for applied reactor applications, a 2 MV pelletron-tandem for material science research, a 3 MeV electron Van de Graaff machine, and a number of 150-300 keV electrostatic accelerators for positive ions.

2. BATES (Fig. 3)

The facility consists of a 500 MeV electron linac about 600 feet in length with a one-time recirculation of the beam to produce a "theoretical" 1000 MeV final energy. The maximum energy achieved is actually about 870 MeV. Beam intensities are typically 20 milliamps at frequencies of 200 to 1000 Hz but with the capability to go to 5000 Hz. Beam power is 50 to 100 kW with a maximum of 200 kW. Pulse widths are up to 50 µsec. A polarized electron beam is also available. There are two major experimental halls housing large magnetic spectrometers, and a smaller secondary hall. Beam is directed to only one experiment at a time. The facility operates about 2500 hours per year divided between a fall and spring running cycle.

3. BNL (Figs. 4-6)

The Alternating Gradient Synchrotron (AGS) is a 30 GeV strong focusing synchrotron about 800 meters in circumference, fed by a 200 MeV linac, for basic research in high-energy and nuclear physics. While originally intended only as a proton accelerator, it has recently been used to accelerate fully stripped heavy ions (e.g., ^{16}O and ^{28}Si) (obtained from the dual tandem Van de Graaffs via a newly constructed transfer line) to energies of 15 GeV per nucleon and polarized protons up to 24 GeV. The AGS operates in both fast spill (2 microsecond wide beam pulse extracted every 1.5 sec) and slow spill (1.5 sec extraction time every 3 seconds) modes. The typical per pulse beam intensity is 1.4×10^{13} protons, 10^{10} polarized protons, and 3×10^{10} heavy ions. Up to 8 of the 16 external beam lines at the AGS can be used simultaneously for running experiments. Typically 25 experiments are conducted each year. The AGS running period varies from four to eight months during the year.

Excess beam from the 200 MeV Linac AGS injector is used at the Brookhaven Linac Isotope Production (BLIP) facility, the Radiation Effects Facility (REF), and the Neutral Beam Test Facility (NBTF). The BLIP facility is used to generate radioisotopes using spallation reactions for medical diagnostics and therapy. At the REF, radiation damage studies of electronics, explosives, and other equipment will be pursued along with determining signatures of target materials. At the NBTF, preparation and propagation of neutral beams will be studied. The latter two facilities are related to the SDI effort.

The National Synchrotron Lights Source (NSLS) is a user facility that provides synchrotron radiation for research into atomic and condensed matter physics, chemistry, materials science, metallurgy, biology, and medicine. The facility includes two electron storage rings and associated injectors. One, the VUV (vacuum-ultraviolet) ring, operates at 750 MeV electron energy with a circulating current of 1000 mA, and provides photons in the energy range from 1 eV to 5 keV. The other, called the x-ray ring, operates at 2.5 GeV and 200 mA, with photons in the energy range from 1 to 20 keV. Both rings utilize an injector consisting of a 75 MeV linac feeding a 750 MeV booster synchrotron. Addition of insertion devices (undulators and wigglers) is increasing beam brightness by orders of magnitude. In addition, a high-energy photon source provides up to 500 MeV photons by Compton backscattering UV laser photons from the 2.5 GeV circulating electron beam. The high-energy photon beam intensity will be about 3×10^7 photons per second. The 16 beam ports on the VUV ring and 28 on the x-ray ring can all be used simultaneously. Typically one to four experimental stations are located on a beam line. Each ring currently has about thirty stations in use, for a total of sixty. Essentially all experiments can be run simultaneously. About 900 experiments are performed each year, with the facility operating six to ten months per year.

Two tandem Van de Graaffs are operated by the Physics Department. The two machines combined will provide up to approximately 38 MeV for protons at uA currents, and up to 1.9 MeV/amu for gold at nA currents. The machines can be operated individually or together, and can send beams into three target rooms or into a transfer tunnel leading to the AGS.

Several other accelerators at BNL include a 3.5 MeV Van de Graaff that can provide a tritium beam with currents up to 25 uA, two proton cyclotrons (60" and 41") that are used to produce short-lived positron emitters for PET studies, and a 3 MeV electron Dynamitron recently converted to a positron accelerator with pA currents by the installation of a 350 mCi ^{22}Na source. Also, a prototype x-ray Lithography Storage Ring (XLS) is being developed for industrial production of large scale integrated circuits with very small component size. A high brightness, low emittance electron test accelerator is under construction, as well.

4. CEBAF (Figs. 7, 8)

The facility will be a 4 GeV, 200 μA, continuous beam electron accelerator. It will consist of two anti-parallel 0.4 GeV superconducting linac segments (each 200 m long) connected by recirculator beam lines to allow five passes, in a racetrack configuration. The injector is a linac with superconducting cavities to accelerate electrons to 45 MeV. Beam extraction will allow the simultaneous delivery of up to three beams to three experimental areas. End Station A will have two matched high-resolution spectrometers, while End Station B will be designated for large acceptance photo- and electro-nuclear studies. End Station C will accommodate experiments initiated and mounted by users. CEBAF is expected to be available for experiments in 1994.

5. FNAL (Figs. 9-11)

The TEVATRON, a superconducting synchrotron about 2 km in diameter, is designed to accelerate protons up to 1 TeV. The acceleration process starts with a 750 keV Cockcroft-Walton H^- ion injector which delivers beam to a 200 MeV linac. Following linac acceleration the ions are stripped and injected into an 8 GeV Booster synchrotron, and then into the Main Ring, a conventional (room temperature) synchrotron housed in the same tunnel with the TEVATRON. The Main Ring accelerates protons to 150 GeV after which they are injected into the superconducting TEVATRON for acceleration up to the final energy, typically 800 GeV for fixed target operations.

In the Fixed Target mode of operation, with a maximum intensity of 1.7×10^{13} protons per pulse (a repetition rate of one pulse per minute), the beam is extracted from the TEVATRON, split into several lower intensity beams, and transported down external beam lines to secondary targets or experimental halls. There are 15 beam lines, each servicing at least one high-energy physics experiment (which can all take data simultaneously) and featuring a wide variety of secondary beams (pions, muons, kaons, electrons, photons, neutrons, and neutrinos).

In Colliding Beam mode the TEVATRON is used as a storage ring for protons and anti-protons with beam energies up to 900 GeV. The anti-protons are produced when a 120 GeV proton beam from the Main Ring strikes a heavy metal target. They are collected and stored with the aid of two additional rings, the Debuncher and Accumulator, which comprise the Anti-proton Source. After injection into the TEVATRON the anti-protons and a counter-rotating beam of protons are simultaneously accelerated, bunched and made to collide at selected locations around the ring where detectors are located to study the products of the collisions. There are at present 4 experiments setup at various stations around the ring to take data simultaneously; the largest involves the massive CDF detector located at the B0 straight section. A second very large collider experiment will use a depleted uranium-liquid argon calorimeter. The D0 detector to be located at the D0 straight section is under construction. The TEVATRON typically runs about 6 months in each operating mode, separated in time by up to 4 months (for the changeover and studies).

6. LAMPF (Figs. 12, 13)

The LAMPF complex, at Los Alamos National Laboratory, consists of three 750 keV Cockcroft-Walton accelerators, one for each kind of ion (H^+, H^-, polarized H^-), that inject beam into a 62 m long drift tube linac which accelerates particles to 100 MeV. This in turn injects into the final stage, a side-coupled-cavity linac, which accelerates the ions to an energy between 300 and 800 MeV over a 731 m length in 750 μsec wide pulses with currents of 1 mA. After acceleration the particle beams are separated in a switchyard and directed into three main beam lines and experimental areas. There are about 40 secondary beam lines or ports for a variety of experimental activities. Twenty-eight experiments can be performed simultaneously in the three major areas. LAMPF operates for about 6 months out of the year.

In Area A, the highest intensity primary beam is used to produce pions and accompanying muons for nuclear and particle physics in 4 major experimental spectrometers. After passing through this area the beam is absorbed in a beam stop where neutrons and neutrinos are produced. An isotope production and radiation effects facility lies adjacent to the dump. Downstream is a heavily shielded experimental area for neutrino research.

The second primary beam, usually H^-, at an average current up to 10 μamps, or polarized H^- up to 10 namps average current, passes into Areas B and C. There it is split into a number of secondary beams for both charged particle and neutron physics experiments, including neutron time-of-flight studies.

The third primary beam, with an intensity of about 10% of the total LAMPF beam, consists of H^- ions directed to the LANSCE/WNR (Los Alamos Neutron Scattering Center/Weapons Neutron Research Facility) complex. This area includes a 90 m circumference proton storage ring that converts the 750 μsec LAMPF beam pulse into short (250 nsec) intense bursts, and directs it to a shielded high-Z target/moderator assembly to produce slow neutrons from spallation reactions for material science, condensed-matter physics, chemistry, biology, and National Security science programs. The H^- beam into this complex can be bypassed around the storage ring to strike a bare (unmoderated) target to produce fast neutrons. A number of instrumented neutron flight paths exist for various weapons-related research (WNR).

Los Alamos National Laboratory itself (not LAMPF) also operates a three-stage Van de Graaff facility. This consists of a single-stage Van de Graaff injecting into a tandem accelerator. It has been used to accelerate protons, deuterons, and (almost uniquely) tritons up to about 22 MeV.

7. LBL (Figs. 14-16)

The Bevalac is an accelerator complex that consists of the Super HILAC used as an injector into the Bevatron. The Super HILAC itself is a heavy ion Alvarez-type linear accelerator that can operate in a time-shared mode at energies up to 8.5 MeV/nucleon. There are three high-voltage injectors so that three distinct beam species can be used at the same time on a pulse-to-pulse basis. Operating currents are in the μamp range; beam intensities range from 10^{11} to 10^{14} particles/sec. While 8 experiments can receive beam simultaneously, there are (typically) 2 to 4 running at any one time, including injection into the Bevatron. The Super HILAC has accelerated uranium ions but more commonly runs with neon or argon projectiles. The research program includes the study of a variety of heavy ion nuclear physics phenomena, such as production of new heavy elements, fusion and fission reactions, and the characteristics of nuclear structure at high excitation energies.

The Bevatron is a synchrotron that accelerates heavy ions from the Super HILAC or its local injector to energies up to 2 GeV/nucleon, and with external beam currents up to 1 μamp. Although several large detector facilities exist, including HISS, a heavy ion superconducting spectrometer with a large area detection system, the single biggest user of the Bevatron is the Bio-Med Department which utilizes heavy ions in a program of cancer therapy and medical research. The accelerator operates 8 to 9 months out of the year.

The 88-Inch Cyclotron is a high-intensity variable-energy sector-focused cyclotron. It accelerates protons to 60 MeV, deuterons to 65 MeV, α-particles to 130 MeV, and heavier ions (up to xenon) to over 100 MeV with external beam currents in the 5 to 100 μamp range. (There are also plans to accelerate tritium in the future.) The primary ion source is a unique "Electron Cyclotron Resonance" injector which can select high charge states for a wide range of ions. The experimental area consists of 12 target stations in 8 shielded caves. Three experiments are usually performed simultaneously. Most of the research is in nuclear physics and nuclear chemistry - scattering and reaction studies. A specially equipped high-level cave is used for isotope production.

8. LLNL (Figs. 17-19)

The 10 MV Van de Graaff, a model FN tandem, is used for low energy nuclear and atomic physics research. It can accelerate a wide range of low mass heavy ions from mass number 1 to 19 amu. A beam current up to 20 microamps and beam energy of 75 MeV for a ^{12}C beam is a typical example. Several experimental beam lines are available.

A 100 MeV electron linac provides a 45 kW maximum power electron beam in either a pulsed or DC mode of operation. Secondary beams of bremsstrahlung x-rays, neutrons and positrons are also utilized. Long neutron time of flight beam lines are available.

The Rotating Target Neutron Source (RTNS II), now shutdown, is a facility designed to provide an intense source of fusion neutrons for studying their effects on reactor materials. It consists of a 150 mamp, 400 keV deuteron beam, provided by a Cockcroft-Walton accelerator, bombarding a rapidly rotating water-cooled solid target consisting of a copper alloy coated with titanium tritide. The targets typically contain 6 to 8 kCi of tritium. The D-T reaction in the target produces a high intensity beam (about 2×10^{13} n/sec) of 14 MeV neutrons. The facility includes two heavily shielded target/irradiation rooms.

The Flash X-ray facility (FXR) is a 20 MeV induction linac accelerating electrons which strike a target and produce x-rays. Beam currents of up to 4000 amps per pulse are produced at a three second repetition rate. Pulse widths are about 90 nsec. The x-rays are used for radiography of rapidly evolving events such as detonations of explosives. The radiography is typically done outdoors.

The DC Linac is a 50 to 105 MeV electron linac similar in construction to the 100 MeV linac described above. It is used primarily for outdoor x-ray radiography. Beam currents are typically three amps per pulse with repetition rates variable from one to ten pulses per second, and pulse widths varying from 0.2 to 27 microseconds.

The Advanced Test Accelerator (ATA) is a 50 MeV induction linac accelerating electrons. The average beam power is 125 kW. The beam intensity is about 10 kamps per pulse with a repetition rate of one pulse per second and a pulse width of about 50 nsec. The accelerator is currently used for free electron laser research and for studies of beam propagation in air that relates to the SDI program as well as general development and improvement in induction linac technology. The accelerator and associated experimental areas are located underground.

9. ORNL (Figs. 20, 21)

The Holifield Heavy Ion Research Facility (HHIRF) operates two accelerators for research in heavy ion physics. One is a tandem Van de Graaff designed to operate with a maximum terminal potential of 25 MV. The second is the Oak Ridge Isochronous Cyclotron (ORIC), a K=100 cyclotron originally designed for light ion studies but now used in either a stand-alone mode or as an energy booster for heavy ion beams from the tandem. The tandem, built in a vertical, folded configuration, is designed to provide beam intensities up to 1 particle μamp (about 6.2 x 10^{12} particles-sec^{-1}) for some ion beams; ion species ranging from protons to gold have been accelerated. In general, energies range from ~15 MeV per nucleon for A=16 to 3 MeV per nucleon for A=200. In coupled operation (with ORIC) the available energy range is 25 MeV per nucleon (A=16) to 4.5 MeV per nucleon (A=200) with intensities a factor of 10 less than from the tandem alone. Coupled operations represent about 30% of total beam time. There are about 13 beam lines which deliver beam to experimental apparatus that include magnetic spectrographs, scattering chambers, a velocity filter, an on-line isotope separator, and gamma ray facilities. Typically only one experiment operates at a time.

ORELA (Oak Ridge Electron Linear Accelerator) is an 170 MeV L-band electron linac designed to produce intense pulses of neutrons from 10^{-3} to 10^{8} eV from a water cooled Ta (or Be-backed Ta) target. Beam pulse widths vary between 3 nsec and 1 μsec at a repetition rate of 1 KHz. The maximum beam power on the neutron production target is about 62 kW, with typical intensities of 10^{11} neutrons per pulse (into 4π solid angle). There are 10 neutron time-of-flight paths and 18 experimental stations with two or three in use at any given time. Various moderators and filters tailor the neutrons to the experiment. The accelerator operated for 4500 hours during 1986; typically 20 experiments are done per year.

10. SLAC (Figs. 22-24)

The primary accelerator facility at SLAC is a 51 GeV maximum energy electron linac about two miles in length. The linac can run up to 180 pulses per second with an average beam power of up to 400 kW. In addition, there are two electron-positron colliding beam storage rings (called SPEAR and PEP). SPEAR typically runs with 2.5 GeV per beam (maximum of about 3.5 GeV) at intensities of about 10^{13} particles per beam. PEP can run up to 18 GeV per beam with intensities of 2.5 x 10^{12} particles per beam. There are two interaction regions for SPEAR. Six regions are available for PEP although only one is currently being used for experiments. The SPEAR ring is filled twice a day while PEP is filled three or four times a day.

A fixed target facility for nuclear physics research is located in End Station A which contains three large magnetic spectrometers for electron scattering experiments. A Nuclear Physics Injector (NPI) was recently built to provide beam for this area with energies from 800 MeV to 5 GeV. This injector is located about five-sixths of the way down the linac; it eliminates the need to accelerate beam in the first half of the linac and then decelerate it in the second half. Typical beam parameters for nuclear physics research are 50 mA peak currents, 1.6 microsecond pulse widths, and 180 pulses per second.

A Synchrotron Radiation Laboratory (SSRL) utilizes photons from the SPEAR and PEP storage rings. The available spectra of photons spans a wide range of wavelengths, from the visible into the x-ray region. There are 10 primary "beam ports" from SPEAR, with more than 20 experimental stations. Two ports are available from PEP with one beam line each.

The major new facility at SLAC is the Stanford Linear Collider (SLC), a single pass e^+-e^- linear collider. Electrons and positrons that have been accelerated by the linac are transported through two separate arcs and brought into collision at a single interaction region. The expected maximum energy per beam is 50 GeV with intensities of 5 x 10^{10} particles per pulse and 180 pulses per second (about 72 kW average power).

11. SNL (Figs. 25-27)

Sandia operates electron/ion accelerator facilities for the DOE Office of Military Applications. Research and development activities are directed toward feasibility studies of controlled thermonuclear fusion, for nuclear weapon effects simulation, and for directed-energy weaponry for SDI. The major accelerators are sources of electrons, x-rays, and γ-rays for high dose rate radiation damage effects studies. The laboratory also operates reactors, both pulsed and steady state, for neutron irradiations. A number (about 15 in total) of Van de Graaff generators, an 8 MeV tandem, and other low energy (hundreds of keV) electrostatic devices are used as ion-implantation accelerators for material science and radiation hardening studies as well.

The principal accelerators are pulsed, very high current electron or bremsstrahlung x-ray/γ-ray devices. The main components are Marx generators (i.e., banks of capacitors charged in parallel and discharged in series) and pulse-forming networks based on Blumlein transmission lines. With these devices low-voltage stored energy is converted to a high-energy very short duration voltage pulse. This voltage pulse is then impressed across a vacuum tube diode that consists of a field emission cathode and an anode. The type and thickness of anode material determines whether electron beam or bremsstrahlung x-radiation mode of operation is desired. The frequency of operation of these devices varies from a few "shots" per day to one-shot every few weeks. There are (or will be) 7 to 10 of these accelerators. To get a feel for their characteristics some are described below.

HERMES II (High-Energy Radiation Megavolt Electron Source) produces a peak voltage of 10 MV, a peak current of 100 kA, a pulse width of 100 nsec, and can operate at 3 pulses/hour. In the bremsstrahlung mode (e.g., using a thick Ta anode as converter) it produces a dose of 70 krads (10^{12} rad/sec dose rate) in a 65 nsec wide pulse. As an electron accelerator it transports 60 kJ of energy for rapid energy deposition (in ~60 nsec) or for electron propagation experiments (e.g., in air).

SPEED (Short Pulsed Experimental Electron Device) provides a peak voltage of 1 MV, and a peak current of 1.2 MAmp in a 20 nsec wide pulse. It delivers x-ray doses of 20 to 40 krads at a rate of 2 x 10^{12} rads/sec.

HYDRAMITE II is a 2 MV, 350 kAmp source of x-rays and electrons. It produces 35 ns wide pulses and peak x-ray doses of 60 krads at 1.5 x 10^{12} rad/sec.

PBFA II (Particle Beam Fusion Accelerator) is expected to demonstrate inertial confinement fusion by use of particle beams. It is a circular machine 108 feet in diameter that consists of 36 identical modules of Marx generators and pulse-forming lines that will impress a 20 nsec long 30 MV voltage pulse on to a diode to produce a beam of lithium ions. These are then focussed onto a target which, ultimately, will be deuterium and tritium. Maximum energy output is 3.5 x 10^6 joules in the 20 nsec wide pulse.

III. CHARACTERISTICS OF RADIATION FIELDS

A. Overview

Radiation shielding at most of the accelerator facilities consists of poured concrete, compacted earth, and steel and concrete slabs/blocks. Generally there is roof shielding over the accelerators themselves, but not necessarily over the experimental halls and caves. Accelerator enclosures and high-intensity beam lines are, generally, personnel exclusion areas; dose rates in the beam can be very high. Most radiation measurements for protection purposes are performed outside of the primary shielding, and in and around secondary beam lines.

Radiation outside of the shielding consists mostly of neutrons and, at the higher energy accelerators, muons. Charged hadrons and photons are generally absorbed within the shields, or at least, the intensity of those that do leak through is very much less than for the neutrons.

The direct neutron component of the radiation field outside of shielding creates dose equivalent rates generally less than 5 mrem per hour except where the shielding is inadequate, and/or when light ions (deuterons, ^{3}He, e.g.) are accelerated. Under such conditions higher dose rates - up to 50 mrem per hour - have been observed for short times even in accessible areas. Spectral measurements, based on multi sphere spectrometer studies, suggest average neutron energies less than 1 or 2 MeV, although in the acceleration of heavy ions neutrons with energies above 15 or 20 MeV have been identified. High-energy muons, because they interact only weakly with matter (that is, mostly by atomic ionization and excitation), have long ranges in earth. Direct muon exposure even out to site boundary locations (~2 miles from production targets in some cases) can give measurable annual doses up to 10 mrem for normal yearly running periods. Direct x-ray exposures up to ~200 mR per hour (not necessarily accelerator beam related, however) have been observed near some machine components.

Skyshine neutron fields have been observed in some cases of open experimental area geometry with rates of 1 mrem per hour or even higher when light ions are accelerated. In other situations skyshine neutrons although not yet identified are expected. At SNL skyshine x-ray fields can be so large as to limit accelerator operations because doses approach maximum permissible annual exposure to nearby personnel.

Airborne activation and activated water, produced primarily at beam stops and targets, include sizeable inventories of isotopes of H, C, O, N, and ^{41}Ar at some accelerators. Residual radioactivation of targets and accelerator components can reach values of a few tens to hundreds of R per hour exposure levels at most installations right after the beams are turned off.

B. Radiation Fields Descriptions

1. ANL

Low dose equivalent rates (0.5 mrem per hour) have been observed on the "roof" area above the moderated uranium spallation target at the IPNS, apparently arising from neutrons streaming through cracks in the shielding. Spectral measurements with a Bonner sphere system using thermoluminescent dosimeters (TLD's) as thermal neutron detectors were performed on the "roof" area, near the 2nd floor secretarial rooms and in the 1st floor shops, and revealed dose rates between 0.02 and 0.1 mrad per hour with quality factors between 5 and 6.5, and average neutron energies of 0.1 to 0.5 MeV.

At ATLAS direct neutron doses are so low under normal experimental operations that access is not restricted except when certain light ions are accelerated. There is however a non-beam related source of x-rays up to 250 mR per hour from back streaming electrons within the superconducting resonators. An experiment designed to study the properties of neutrons from heavy ion induced reactions was performed at ATLAS. Oxygen beams were targeted onto a Faraday cup within a shielded area in one of the transfer lines. A Bonner Sphere spectrometer placed about 1 m away at 90° from the target where the dose equivalent rate was ~10 rem per hour revealed both a thermal peak and a peak corresponding to evaporation neutrons (1 to 10 MeV); the latter accounts for practically all of the dose equivalent. During this measurement (but not during normal operation) neutron fields immediately outside of the shielded area were about 25 mrem per hour.

At the 4.5 MeV Dynamitron direct neutrons have been observed in accessible areas when light ions (especially deuterons) are accelerated. Rates of 0.2 mrem per hour per microamp of deuterons were measured outside of the very lightly shielded experimental area. No direct neutron radiation is seen outside of the shielding at the Electron Linac and 60 inch Cyclotron; however, the klystrons at the Linac are a source of x-rays.

Skyshine radiation fields used to be a problem at IPNS before the addition of shielding above the uranium target. No skyshine has been identified at ATLAS but during the heavy-ion experiment mentioned above it is likely that such radiation would have been seen if direct observation had been performed. Skyshine neutrons have been observed in areas around the Dynamitron when intense beams of deuterons are accelerated.

Residual radiation levels are high, up to 50 R per hour at the enriched uranium target at IPNS, at injection and extraction components, and bending magnets. Isotopes such as ^{54}Mn, ^{7}Be, ^{22}Na, ^{60}Co, ^{57}Co, etc., have been identified. Activation is low at the other accelerators except for the 60 inch Cyclotron where levels up to 1 R per hour have been measured after 16 hours cool-off. Airborne contaminants, identified in IPNS stack exhaust, include ^{11}C, ^{7}Be, ^{3}H, ^{82}Br, ^{59}Fe, ^{41}Ar, ^{54}Mn, ^{65}Zn, and Kr isotopes.

2. BATES

There are no significant problems with outdoor dose rates outside of the side shielding at the Bates linear accelerator. Photon dose rates in the laser injector room above the accelerator are typically less than 2 mrem per hour. Direct neutron dose rates are everywhere less than one mrem per hour outside the shielding. Neutron dose rates on the roof of one experimental area may approach 200 mrem per hour under extreme thick target circumstances. Site boundary doses are typically less than 1 mrem per year.

Within accelerator and switchyard enclosures near certain beam line components, dose rates can be quite high. For example, near the tungsten slit in the switchyard the beam-on dose rate can approach megarads per minute. Radiation damage is high in this area, requiring the frequent replacement of cabling. Typical contact gamma dose rates following shutdown in this area may be kilorads per hour while collimator areas in the Linac may have dose rates of a few hundred mrad per hour after shutdown. Residual dose rates within the experimental halls are, typically, much less.

Airborne activity consists of ^{15}O, ^{13}N, and ^{11}C with airflow through the enclosures occurring continuously. Annual doses at the site boundary from airborne radioactivity are typically between 0.01 and 0.02 mrem per year. Radioactive water is not generally a problem. Concentrations are sufficiently low that discharge into surface streams off-site is permitted. Resins from the ion exchange column used to treat cooling water are held for decay. The principle isotope is ^{7}Be.

3. BNL

The NSLS rings have photon and neutron dose rates not exceeding 10 mrem per hour on the experimental floor during injection, with the dose rate being controlled to typically less than 0.5 mrem per day almost everywhere. There is little problem with activation of beam line components. Highest contact dose rates after shutdown due to residual activity are 5 mrem per hour in the linac and booster areas.

Radiation outside shielding at the AGS is composed primarily of neutrons. Muons are a potential problem downstream of the extraction septum and the C' target. On the experimental floor, dose rates in occupied areas including trailers used in experiments range from 0.5 up to 5 mrem per hour. Some low-level amount ($<<1$ DAC) of radioactive air is emitted from target station doors and small amounts ($<10{,}000$ dpm per 100 cm^2) of contamination are found in the primary target caves.

Beam-off radiation levels within the AGS enclosures range from 1 to 10 mrem per hour in walkway areas not close to localized hot spots and up to a few hundred mrem per hour at one foot from hot spots. Following a recent run the hottest spot found within the accelerator tunnel was about 5 rem per hour. Levels in the vicinity of injection, transition, and extraction components and near linac beam stops and the primary target are generally considered high enough to be a maintenance problem (up to 20 rad per hour).

Site boundary doses are less than 5 mrem per year above background as measured with TLDs. Skyshine neutrons may contribute a small amount to this environmental dose but the contribution has not been measured at the site boundary.

No significant radiation fields are generated at the tandem facility during heavy-ion operation; in the past proton and deuteron acceleration produced neutron fields near targets up to 5 rem per hour and gamma fields up to 1 rad per hour. At the 3.5 MeV Van de Graaff radiation levels in the vault area during beam operation have been as high as 200 mrem per hour neutron and 10 mrad per hour gamma. Tritium contamination levels up to several hundred thousand dpm per 100 cm^2 exist in the accelerator vault. At the cyclotrons, radiation levels near the target can be as high as several R per hour gamma and tens of rad per hour beta immediately after shutdown, and inside the machines during maintenance dose rates can be at the R and rad per hour levels with loose surface contamination of tens of thousands of dpm per 100 cm^2 wipe. While radiation levels at the Dynamitron are less than the known background levels because of the small beam currents, the ^{22}Na source reads about 1.2 R per hour per Ci at one meter and thus creates general area exposure rates in the tens of mR per hour range during installation and removal. With the source and insulating gas vessel both in place, rates at the source end of the machine are ~10 mR per hour.

4. FNAL

Direct neutron, muon, and neutron-muon mixed fields have been observed in many accessible beam line enclosures, experimental halls, and accelerator service buildings. Under normal operating conditions dose equivalent rates up to 0.75 mrem per hour (but usually averaging less than 0.25 mrem per hour) are measured in occupied areas. In other accessible but not normally occupied areas mixed field or neutron dose rates up to 7 to 8 mrem per hour have been recorded; muon rates up to 2 mrem per hour have been observed at roads on-site and a maximum rate of ~0.007 mrem per hour above background has been measured at the site boundary about 2 miles from the source. Off-site doses due to muons are usually less than 3 or 4 mrem per year, but reached a high of about 13 mrem during initial operation of the dedicated muon beam line in 1987. Above or adjacent to some beam line enclosures dose equivalent rates of 20 to 100 mrem per hour have been measured but these are fenced and locked exclusion areas.

Neutron skyshine has been identified on at least two occasions during fixed target runs. In one case a dose rate of 1.5 mrem per hour was observed 200 meters from the source, a lightly shielded beam dump; additional shielding reduced this rate by a factor of ten. In the second case, the source was a very large electromagnet unshielded from above, in which the maximum dose rate of iron "leakage" neutrons at a distance of ~75 meters was only ~0.01 mrem per hour.

Neutron spectral measurements with a Bonner Sphere - ^{6}LiI scintillator spectrometer have been performed at various locations on-site. For example, in the second leg of a concrete block labyrinth only 26% of the fluence but 84% of the dose equivalent arises from neutrons with energies greater than 100 keV; outside of an Fe and concrete shield 98% of the fluence and 82% of the dose equivalent come from neutrons below 100 keV; outside of earth and concrete shielding above and adjacent to the anti-proton accumulator-debuncher tunnel 53% of the fluence but 93% of the dose equivalent arise from neutrons above 2 MeV. In a collaboration (with LBL) spectral measurements revealed two broad neutron peaks, near 200 keV and at thermal energies, in the TEVATRON tunnel during 900 GeV collider operation with the spectrometer near the concrete wall 2 meters from the beam line.

Residual radioactivity levels are highest at targets and beam stops, particularly in the neutrino beam line and anti-proton source targets. Rates up to a few R per hour after a hour's cool down from a long running period are typical. The activation of the air in these same areas results in the production of ^{11}C, ^{13}N, and ^{41}Ar; for 1987, the total release was 54 Ci from the anti-proton stack and 27 Ci from the neutrino stack. Activated closed loop cooling water systems resulted in a total 1987 release of ~260 mCi of tritium but off-site levels were so low as to be unmeasurable. Other radionuclides produced in the ion exchange resins in the cooling systems, such as ^{7}Be, are removed during regeneration and precipitate out of solution in settling tanks.

5. LAMPF

Direct neutron radiation at dose equivalent rates up to about 2.5 mrem per hour, for accelerator beam currents of 1 mamp, has been observed in accessible (but not necessarily occupied) areas in the meson experimental hall (Area A) and in the LANSCE/WNR facility. Neutron spectral measurements on the experimental floor or in the balcony areas using Bonner spheres usually reveal two broad peaks (near thermal energies and between 0.01 and a few MeV). More specifically, average neutron energies between 0.04 and 4 MeV have been inferred from such data. Higher energy neutrons ($\gtrsim$ 50 MeV) have been seen in the LANSCE/WNR area but only under unusual beam loss situations.

Neutron skyshine radiation fields have not been seen, or at least have not been identified as such. The low rates expected from skyshine could be obscured by the higher dose rates from activated air and other gases, produced primarily at targets and beam stops, and exhausted into the atmosphere through a ventilation stack. Stack emission during 1986 was 42% ^{15}O, 35% ^{11}C, and 19% ^{13}N with smaller amounts of ^{16}N, ^{10}C, ^{14}O, and ^{41}Ar, and gave a measured yearly site boundary dose of about 17 mrem.

Activated cooling water and the residual radioactivity of beam stops and targets represent a large source for potential γ-radiation problem areas. For example, production targets are well over 1000 R per hour on contact even after four-hour cool offs. (Extrapolation from measurements made at large distances indicate rates of ~60000 R per hour at 30 cm from the H^+ beam dump four months after shutdown.) Clearly, remote handling equipment is used extensively. Dose equivalent rates in accessible areas are kept low by local shielding. Closed loop deionized water cooling systems gave a total assay of about 1.5 mCi per liter in 1986; tritium inventory was 200-300 μCi per liter. The activated water is passed though resin columns and ultimately into sewerage lagoons.

6. LBL

Direct radiation dose equivalent rates between 50 and 100 mrem per hour while the beam is on have been observed in areas not normally occupied in the Bio-Med Control Room at the Bevatron; at the console area, rates are lower by more than a factor of 10. The duty factor is low however due to the long setup time required for patient therapy. This field is predominantly due to neutrons that arise from heavy ion bombardments within the treatment room and are observed along a thinly shielded wall. Some spectroscopic measurements employing Bonner spheres, ^{11}C activation, and BF_3 detectors suggest neutrons of fairly high energies in this area. The dose equivalent from neutrons with energies greater than 20 MeV is about 2 times that from neutrons below that energy; in the adjoining (interlocked) room the ratio is ~5 based on ^{11}C activation and BF_3 measurements. Neutron rates of a few tens of mrem per hour have been detected in roof areas of the Bevatron but these are not usually occupied.

Direct neutron fields with average energies of about 1.5 MeV have been observed at the high-energy end of the Super HILAC near the post-stripper RF cavity. Under unusual situations, rates in unoccupied areas of about 40 mrem per hour have been detected. At the upstream end near the Super HILAC injector, 0.2 to 0.5 MeV x-rays, produced from backstreaming electrons, have been measured in corridors outside the 0.5 in. thick steel vacuum wall at rates in excess of 5 mR per hour, but under these conditions occupancy is excluded.

At the 88" Cyclotron, direct neutron dose rates are usually very small except when ^3He projectiles are accelerated. Under these conditions, rates up to 50 mrem per hour have been detected in adjacent experimental caves. (Even so, no neutron exposure has been recorded on personnel dosimeters.) Detailed spectra have not been measured but estimates indicate quite low energies. For example, no counts were observed with a thorium fission counter (which has a 2 MeV threshold). There is some streaming of low energy neutrons through a penetration to the roof as well. A significant number of γ-rays are detected during isotope production runs when up to 10 Ci of radionuclide activity is produced. Researchers in this area may get yearly doses of almost 500 mrem.

Neutron skyshine dose equivalent rates up to 1 mrem per hour have been identified at the Bevatron where external beam experimental caves have no roof shielding. Residual radioactivity at LBL accelerators is measured to be a few hundred mrem per hour at targets after bombardment, and between 50 R and 1 R per hour at the cyclotron vaults and tanks shortly after irradiation. When maintenance needs to be performed, doses can be 200 to 300 mrem per person. Radioactive gases in cyclotron vaults and enclosed areas are vented to the outside by forced air. Soil, air, and water activation present no hazards.

7. LLNL

When in operation, the 10 MV tandem Van de Graaff can provide up to about 20 μamps of beam ranging from mass numbers 1 to 19. Depending on the particle type and energy, secondary production of neutrons and photons can occur. Maximum dose rates observed from secondary radiation are about 30 rem per hour at 1 meter. The facility is only lightly shielded, but areas are fenced to control personnel access. A computer controlled radiation area monitoring system continuously monitors the work environment and automatically suspends accelerator operation if preset radiation levels are exceeded. There is no problem from skyshine or air activation. Residual activation of beam line components is typically less than 50 mrem per hour following shutdown.

The electron linac in Building 194 can provide up to 45 kW of 100 MeV electrons. The accelerator produces secondary beams of x-rays, neutrons and positrons. Beam-on dose rates can approach a megarad per hour at 1 meter from the target, with residual dose rates due to activation of collimators and other beam line components of a few hundred rads per hour shortly after shutdown. Skyshine neutrons are negligible. Airborne radioactivity is primarily due to the production of short-lived ^{13}N and ^{15}O isotopes. About 100 Ci per year per isotope are released through continuous ventilation of the target and beam line areas.

The RTNS II facility is well shielded and neither direct nor skyshine neutron radiation is significant. Residual dose rates were up to 10 R per hour at one foot from the activated components. Airborne activity consisted of HTO and HT as well as activated air. Contaminated tritiated water and titanium tritide from the target were also produced. A few hundred curies of tritium was released annually from the facility. This facility was the largest producer of radioactive wastes and personnel radiation doses among the LLNL accelerator facilities.

Beam-on dose rates at the FXR facility, due to bremsstrahlung x-rays produced in the target, are as much as 500 R per pulse at 0° one meter from the target. In addition some neutrons are produced through (γ,n) reactions. Access to this facility and the surrounding area is restricted. Air activation, residual activation, and contamination are insignificant due to the low duty factor of the machine.

A second "DC Linac" in use for radiographic studies produces a secondary beam of x-rays having a dose rate of about 1000 R per second. Some secondary (γ,n) reactions occur because of the high electron energy. X-ray skyshine is considerable from this machine since it is used for outdoor radiography. Personnel, however, are not exposed because access to the area is restricted. Activated components may be up to a few R per hour on contact. Airborne radioactivity is minor and no contamination is produced from operation of the accelerator.

Beam-on dose rates at the Advanced Test Accelerator (ATA) due to bremsstrahlung reach a maximum of about 2000 R per pulse at 1 meter downstream of the carbon beam dump. Both x-rays and neutrons (from (γ,n) reactions) are produced. Recent research has concentrated on the development of free electron lasers. Considerable activation of beam line components and dumps is produced, with dose rates up to 10 R per hour at 1 meter distance. Activated air in the form of ^{13}N, ^{15}O, and dust is produced. The exhaust from the accelerator cave is filtered through a HEPA filter. About 200 Ci per year of each isotope is exhausted from the facility. Skyshine is not generally a problem since the facility is underground, but there is an outdoor radiation hazard when "beam-in-air" experiments are under way. Contaminated surfaces are rarely a problem.

8. ORNL

Beam-on dose rates are often not high enough to deny access to experimental areas at the Holifield Heavy Ion Research Facility (HHIRF). The governing rule is one of determining the maximum access time allowed to accumulate a 20 mrem dose. If dose rates exceed 20 mrem in five minutes then the area must be interlocked and access completely denied. Average dose rates less than 2.5 mrem per hour allow unrestricted access during an eight hour shift, and for some running conditions, dose rates less than this are realized. In other cases, for example during coupled operations between the cyclotron and the tandem with a high-energy ^{16}O beam, this may not be true and access must be restricted. In the worst case beam-on dose rates of nearly 100 rem per hour might occur. Beam-on dose is due principally to neutrons.

Access to the ORIC cyclotron vault is not permitted during its operation. Dose rates outside the cyclotron are negligible due to the thick shielding of the vault. Dose rates are also negligible outside the tandem vault. Activation products are usually very short-lived - a maximum of 1 R per hour immediately after shutdown decreasing to a few mR per hour after three days. Accessible areas of the cyclotron itself are typically in the few mR per hour range when the beam is off.

Neutron skyshine during operation is not a problem due to the presence of sufficient overhead shielding. Generally contamination is not a problem due to the short-lived nature of most of the activation products. Air monitoring is not done for the tandem area since air activation is thought to be negligible.

Direct neutrons produced from the target at ORELA span the range from 3 keV to 80 MeV depending on the choice of target and associated moderators. Dose rates may approach 50 rem per hour in the neutron beam lines at 10 meters from the target. Personnel generally can work around the long neutron time-of-flight beam lines, however, since the beam is contained in large cross-sectional area pipes that preclude direct exposure. Some accessible areas outside the Linac area are posted with signs indicating dose rates of 20 to 30 mrem per hour. The target and linac vaults are exclusion areas. Residual activity at targets are thousands of R per hour on contact and several R per hour at a few meters distance. Skyshine has not been a problem due to adequate shielding, and no significant modification to the shielding of the accelerator or target have been required.

9. SLAC

The SLAC linac is located underground and is well shielded so that beam-on dose rates external to the shielding are generally negligible. The exception to this is at some penetrations, where dose rates of about 1 mrem per hour have been seen. Residual levels in the linac due to activation are also less than 1 mrem per hour except at well-defined loss points such as scrapers and diagnostic stations where rates are typically 10 to 50 mR per hour following a shutdown, the tune-up dump where rates are a few R per hour, and the positron source target for the SLC which has been as much as 10 R per hour following activation with an electron beam of only 1% of the SLC design power. Air and soil activation are also negligible even in these relatively high loss areas. The klystron gallery can present some x-ray exposure hazard with dose rates up to a few tens of mR per hour in some locations near the energy-doubler, SLED, under unusual operating conditions.

The fixed target area at End Station A has historically been the dominant source of beam-on radiation at SLAC. Typically 1 to 10 kW of beam power are dissipated in the experimental targets, resulting in the generation of skyshine neutrons that has only once exceeded the goal to limit SLAC site boundary radiation doses to 15 mrem per year. The site boundary is about 500 meters from the skyshine source. Residual levels around the targets are typically 100 to 200 mR per hour maximum. Residual levels around the beam dump are tens of R per hour, typically, but very little access to that area is required. Residual long-lived activity in cooling water is primarily tritium - ^{7}Be is removed with a demineralizer system. Air activation is not a problem around either the target or dump. SLAC enclosures are typically sealed during operations and only vented following a cooling period to allow short-lived radioactivity to decay.

The SPEAR storage ring is now used primarily as a synchrotron light source; it is filled about twice a day with electrons from the linac. There is no measurable radiation on the experimental floor during routine operations. During a fill there is a small amount of radiation, but most experimenters who work there a large fraction of the year get no measurable dose, while a few may get 100 mrem per year. There is essentially no residual radioactivity, air activation, or contamination produced. There is no beam dump for the machine. Remaining electrons at the end of a store are simply lost around the ring prior to injection of a new batch for the next store.

PEP, although a higher energy storage ring than SPEAR, has similar radiation field characteristics. Currently, usage is low for high-energy physics operations. There are also two synchrotron-light beam lines associated with PEP. There are no outdoor beam-on radiation problems associated with PEP operations since the interaction regions shielding designs are based on conservative assumptions of a full intensity beam loss at a single point.

The Stanford Linear Collider (SLC) is currently undergoing commissioning. Above ground dose rates from operations are expected to be negligible. Residual activation in the beam transport arcs is expected to be small. In the final focus region some activation is expected, with dose rates as much as a few R per hour. The electron and positron beam dumps are well shielded (far below ground) and water cooled to tolerate the average beam power of 70 kW. Currently, the interaction area shielding is designed to be sufficient even in the event of an accidental loss of the full intensity beam. When the larger SLD apparatus is installed it will be self-shielded.

10. SNL

There are no direct radiation fields outside of shielding since the major Sandia accelerators are sources of x-rays which will not penetrate the shielding walls surrounding the machines. Direct radiation is a problem only when electron beams are "shot" into the atmosphere outside of the lab buildings. The beam from HERMES II, for example, can deposit 60 kJ over an area of 25 cm^2 during a 60 ns wide beam pulse - a peak dose of about 5×10^7 rads (to silicon). Personnel are restricted from the affected area during the duration of the "shot."

X-ray or γ-ray skyshine, on the other hand, is an important radiological concern since there is generally no shielding on the roofs over the accelerators. In fact these radiation fields serve as a limit to the number of "shots" an accelerator can make in a year because of the DOE allowed yearly exposure limit to radiation workers.

Pulsed neutron fields have been detected around PBFA II and HERMES. Skyshine neutrons may become a radiological problem when PBFA II becomes more completely operational. Activation of accelerator components which is only of minimal concern at present is also expected to become more severe due to 14 MeV neutrons that will arise from full operation of PBFA II. No water radioactivity is currently seen; small amounts of ^{13}N and ^{15}O are present in the HERMES cell following a shot.

IV. INSTRUMENTATION FOR RADIATION MONITORING

A. Overview

Measurements to define and monitor accelerator-produced prompt radiation fields are performed primarily for radiation protection purposes and to interpret readings of personal dosimeters. Fixed area monitors are used to record dose, or dose equivalent, associated with the various components of the prompt (beam-on) fields both within and outside of shielded areas, and in many cases provide electrical signals to turn the beam off when the rates rise above a preset level. They, along with portable survey meters, also serve to monitor residual radiation levels after the beam is turned off.

The most commonly used instruments to measure dose are tissue-equivalent ion chambers, with dose equivalent determined through multiplication by an "appropriate" quality factor. For neutron energies ~20 MeV, polyethylene moderated BF_3 tubes are also used. Air filled ionization chambers, Geiger counters, and in some cases NaI scintillators are employed to determine dose equivalent for the charged particle and γ-ray components of the field, and for beam-off applications. Many of the fixed area monitors used at accelerator facilities are "home grown" while most of the portable survey meters are commercial products (from Eberline, Keithley, Victoreen, Ludlum, HPI, etc.). For airborne monitoring both beta particulate and alpha air monitors are employed.

All laboratories have a full complement of calibration sources, at least one of which is traceable to NBS. For calibration of γ-ray instruments ^{137}Cs, ^{60}Co and Ra sources are usually used, while for neutron calibrations AmBe and PuBe standards are commonly employed. Techniques employed for calibration vary from lab to lab. Calibration intervals for most instruments vary between three and six months; in no cases are they longer than one year.

A number of laboratories have experimental apparatus used primarily for health physics research and for defining the properties of the radiation fields rather than as dose or dose equivalent monitors. Included in this group are, for example, the spherical tissue-equivalent proportional counter used as a LET spectrometer to determine the dose equivalent spectrum, a BNL-modified LET spectrometer that provides signals proportional to both dose rate and LET, a recombination tissue-equivalent ion chamber used to determine quality factors, a polyethylene-lined proportional counter for neutron energy flux measurements, and large area plastic scintillator telescopes for muon fluence measurements. For neutron spectral measurements the multisphere technique, based on hydrogenous moderating spheres up to 18" in diameter that house thermal neutron detectors (^{6}LiI, ^{3}He, activation foils, etc.), is the primary method. To extend this technique to higher neutron energies it is often combined with ^{11}C activation, liquid scintillators (NE213, e.g.), and Bi-loaded fission chambers.

B. Instrument Descriptions

1. ANL

Fixed area monitors at IPNS are Ag-wrapped GM tubes in 8" diameter polyethylene cylinders (CRAMS), tissue-equivalent ionization chambers (ERMS), and VAMPS (made by Victoreen) which employ GM tubes for gamma identification. Furthermore, fifteen locations near but external to the IPNS, are routinely monitored with in-house developed albedo neutron dosimeters utilizing TLD 600 and TLD 700 chips. At ATLAS both a GM tube gamma ray detector and a 10" polyethylene-moderated BF_3 counter for neutrons are employed for fixed area monitoring. There are no fixed area monitors at the 60" cyclotron; GM counters and ionization chambers are used at the Electron Linac. A NaI gamma ray detector along with a moderated BF_3 counter are the fixed-area monitors at the 4.5 MeV Dynamitron. Portable instruments - both beam-on and beam-off - constitute a standard set of commercial survey devices; e.g., air-filled ion chambers, standard and pancake GM tube counters, tissue-equivalent proportional chambers (e.g., HPI-1010), and 9" diameter Cd-loaded spherically moderated BF_3 tubes. For air monitoring a fixed stack monitor is employed at IPNS. It utilizes a Pilot B (plastic) scintillator to detect beta emitters trapped on filter paper through which a sample of the exhaust air is passed, a NaI crystal to view a cartridge which collects iodine in the air, and another plastic scintillator to look at any residual activity. Another NaI scintillator is used as a monitor of the fission gas ^{135}Xe. Portable commercially available high volume air samplers are used elsewhere at the lab.

PuBe sources traceable to NBS are used to calibrate neutron detectors. A wide range of γ-ray and beta standards (e.g., ^{137}Cs, ^{60}Co, ^{90}Sr/^{90}Y) are employed for calibration of other instruments. All instruments are calibrated at regular six month intervals.

2. BATES

Beam-on monitors include SLAC-type argon-filled ion chambers and NMC commercial plastic scintillation detector systems interlocked to terminate beam operation if radiation in excess of 100 mR per hour is measured in peripheral regions near the accelerator. Other beam-on instrumentation mainly used for environmental monitoring includes spherically-moderated neutron counters, two 16-liter 1-atmosphere tissue-equivalent ion chambers capable of measuring exposure rates between 0 and 50 μR per hour and 0 and 150 μR per hour, and a high pressure ion chamber. Beam-off instrumentation includes the usual array of commercial survey meters. Exhaust gas in the stacks is monitored by a 9" GM tube.

Instruments are calibrated every six months. There are two PuBe neutron sources, and a number of radium (NBS traceable) and ^{137}Cs sources for gamma detectors.

3. BNL

Beam-on area monitors at the AGS complex are Fermilab-designed tissue-equivalent ion chambers (Chipmunks), 5" and 12" diameter polyethylene-moderated spheres (containing either TLDs or ^{6}LiI scintillators), and commercial (Eberline) 9" diameter spherically moderated BF_3 counters. Commercial instruments such as the HPI 1010 and 1030 are used as portable beam-on survey meters. The BNL invented mixed-field dose equivalent meter (modified Rossi-type tissue-equivalent proportional counter) has not been routinely used because the 1967 electronics are unwieldy. For beam-off monitoring commercial GM instruments and air ion chambers are used. At NSLS, TLD 600 and TLD 700 pairs inside 5" polyethylene cylinders are used for neutron and gamma area monitors.

A PuBe source is used for calibrating neutron instruments. Gamma calibration sources include ^{60}Co and ^{137}Cs with activities below a few Ci, and two Shepherd beam projectors of 130 and 260 Ci. All gamma sources are cross checked with a NBS calibrated R-meter. All portable instruments are calibrated once per year.

4. FNAL

Beam-on area monitors are in-house designed tissue-equivalent ion chambers - a 3.4-liter chamber containing one atmosphere of propane. External signal connectors on the electronics box attached to the chamber provide remote readout, interlock capability, and a digital pulse train for dose integration. In the Chipmunk version, quality factors can take values 1, 2.5, or 5; a high-range Scarecrow version has a quality factor preset to 4. There are about 300 such chambers, many interlocked to the radiation safety system, throughout the accelerator complex and the experimental beam lines. Portable beam-on meters include commercial tissue-equivalent proportional chambers (HPI 1010, FWT REM402), an in-house developed tissue-equivalent ion chamber (TEIR), cylindrical polyethylene-moderated detectors that house Ag-wrapped (DODO) and Ag-and-Sn-wrapped (Albatross) GM tubes (see part 5, LAMPF), and a muon flux monitor consisting of two 2-cm diameter plastic scintillators arranged as a telescope in which counts can be accumulated as both singles and coincidences. A Mobile Environmental Radiation Laboratory (MERL), a four-wheel drive truck instrumented with large-area plastic scintillator counters and a dePangher long counter, is used for site wide and off-site surveys of penetrating (neutrons and muons) radiation. Beam-off instruments include commercial GM counters (normal and pancake tubes), NaI scintillation counters, and air-filled ion chambers, as well as two styles of Fermilab-developed GM tube survey meters. Commercial air monitoring devices (Triton) are used to sample radioactive gases and STAPLEX high volume samplers collect particulates. Stationary monitors are located at the anti-proton production-target stack and the neutrino (center) target enclosure stack, both regions of high radioactivity production. These are commercial thin window GM tubes that detect betas from ^{11}C, ^{13}N, etc.

AmBe sources with strengths between 2 x 10^5 and 2 x 10^7 neutrons per second and a ^{252}Cf source (2 x 10^7 neutrons per second) have recently been obtained to replace PuBe, PuLi, and PuF sources for use in testing neutron counters. ^{137}Cs sources having strengths up to about 600 mCi as well as three beam projector ^{137}Cs sources up to 130 Ci activity are used for both beam-off and beam-on instrument calibration. Victoreen R-meters calibrated by NBS are used to intercompare calibration sources. Calibration schedules vary from once every quarter to once per year depending on the instrument type.

5. LAMPF

Fixed area beam-on instruments are 9" diameter polyethylene-moderated Cd-wrapped BF_3 counters (Eberline RM-16) and the LAMPF-modified, Fermilab-designed Albatross. In this instrument neutrons are detected by subtracting the count rate in a Sn foil wrapped GM tube (a measure of gamma and charged particle radiation) from that in a Ag foil covered GM tube (sensitive to thermal neutrons as well as gammas and charged particles), both positioned at the center of a polyethylene pseudo-sphere. Both instruments are part of the accelerator interlock system. To monitor for γ-radiation a 1" by 0.5" NaI scintillator counter is employed. It provides a local warning but is not part of the beam permit system. Harshaw TLD 600s and 700s are used as radiation monitors in accessible (although not fully occupied) areas along the length of the accelerator tunnel. These are read out three times per year to provide a measure of the integrated dose. Portable beam-on instruments include 9" polyethylene-moderated Cd-wrapped BF_3 counters, battery operated Albatrosses, proportional ion chamber (PIC6), and tissue-equivalent proportional chambers (HPI-1010). For beam-off measurements the usual collection of air-filled ion chambers and Geiger (standard and pancake) tube counters (including Teletectors) are employed. A particularly useful gamma ray monitor at LAMPF is the Teledose by Xetex because it provides wireless relay of dose and dose rate information on personnel working in high radiation areas. For air monitoring purposes a number of large (50 liter) ion chambers are used.

Calibration sources for neutron detectors are PuBe, PuLi, PuF, PuB, AmBe, and ^{252}Cf. For other instruments Ra and ^{60}Co sources are used. Calibration intervals vary from three months to one year depending on the instrument.

6. LBL

Fixed beam-on monitoring instruments are fast polyethylene-moderated BF_3 counters with two gas tube sizes (1" by 5" long and 2" by 9" long) for use at the Bevalac, and normal moderated BF_3 detectors elsewhere. There are 20 to 30 BF_3 counters at the various on-site accelerators. Gamma rays and charged particles are monitored by GM detectors and air-filled ion chambers.

Portable instruments for both beam-on and beam-off application include a wide variety of commercial survey meters (ion chambers of different sizes - both integrating and rate meters - and Geiger counters) and in-house developed instruments. The "workhorses" at the Lab are transportable moderated BF_3 detectors and Andersson-Braun remmeters. In-house developed detectors also include polyethylene proportional counters and bismuth- and thorium-loaded fission counters for specialized applications. Activation techniques with carbon foils (and sometimes Al, In and Au foils) are sometimes used as beam loss monitors in areas accessible to persons. A portable tissue-equivalent proportional counter-microprocessor system has recently been obtained.

PuBe sources with strengths from 1 x 10^5 to 6 x 10^6 neutrons sec^{-1}, traceable to NBS, are used to calibrate and field check neutron detectors every six months. Other PuBe sources from 10^4 to 8 x 10^7 neutrons sec^{-1} as well as PuLi, PuB, and PuF sources are available for non-routine calibrations. Gamma ray instruments are calibrated with ^{137}Cs and Ra sources quarterly; those in the field, every six months. Specialized instruments are calibrated and checked before each use.

7. LLNL

There are two radiation monitoring systems at the 10 MeV tandem; one is a standard hardwired system and the other is computer controlled. Fixed area monitors are ion chambers and GM counters for photons, and polyethylene moderated ^{6}Li detectors for neutrons. The computer automatically maintains a hourly log of radiation levels. In uncontrolled areas near the machine the system allows 1 mrem per hour for both photons and neutrons separately. If the dose equivalent rates exceed 1 mrem per hour the computer shuts the machine off for the rest of that hour. The system is sophisticated and allows operation without excessive control unless demanded by the radiation levels. At the 100 MeV Electron Linac fixed monitors are SLAC-developed ion chambers. For RTNS II both commercial ion chambers (NMC remote area monitors) and Overhoff tritium monitors are used. At the other linacs the NMC remote area monitors are used. At ATA an in-house designed Reuter-Stokes pulse sensitive ion chamber has been installed. Portable instrumentation includes ion chamber, GM counter, and neutron remmeter survey instruments. For air monitoring "standard" 4" paper filters plus air movers are used along with Eberline computer controlled stack monitors. At RTNS II a passive (silica gel) and real time (Overhoff) stack monitor are employed.

Routine calibration is done in wells inside a "world class" calibration facility using ^{137}Cs sources for photon instruments and ^{252}Cf sources for neutron detectors. Each individual instrument is calibrated in the ion scatter cell and its response duplicated in the source wells. Fixed instruments are calibrated every six months, portables every nine months.

8. ORNL

At HHIRF fixed polyethylene-moderated BF_3 counters and Argon ion chambers are used for beam-on monitoring and as part of a "permissive" access system. When a beam-on access is started, a polling circuit begins integrating dose and monitoring dose rate from the highest reading detector in the enclosure. If the total dose reaches 20 mrem in the subsequent 8 hours, or if the dose rate exceeds 240 mrem per hour at anytime during this period, the accelerator is automatically shutoff and cannot be restarted for 8 hours unless a special key is used under strict administrative procedures. In ORELA neutron flight path areas the dose is monitored with moderated BF_3 detectors and proton recoil proportional counters.

Portable beam-on instruments include in-house designed proton-recoil proportional counters and both moderated and unmoderated BF_3 detectors for neutrons. A standard set of beam-off survey instruments (i.e., GM counters, ion chambers, scintillation counters), usually in-house fabricated, are used. Continuous air monitoring for both alphas and beta-gamma is performed with ZnS scintillators and GM counters designed and built at ORNL.

Instruments are calibrated at 3 to 6 month intervals. A ^{238}PuBe source (1×10^6 neutrons/sec) and Ra and ^{60}Co gamma sources are used. Victoreen R-meters (NBS calibrated) are used for instrument and source intercalibration. A new instrument calibration facility has been put into service and accreditation as a NTIS Secondary Standards Lab under a newly established program is being pursued.

9. SLAC

Fixed area monitors are the so-called Beam Shutoff Ion Chambers (BSOIC) of SLAC design and fabrication. They are 10 liter ion chambers filled to 1 atmosphere with ethane. As implied by the name they are interlocked to the accelerators and will shut them off at high dose rates. Sixty such detectors are located at various places in and around the accelerator complex. Portable instruments include SLAC-built ion chambers and plastic scintillators, although the latter are being phased out and will be replaced by commercial (Bicron) air-equivalent plastic scintillators. Other instruments include Xetex CsI scintillation detectors, GM detectors, and moderated BF_3 remmeters (Andersson-Braun type) for neutrons. There are six peripheral monitoring stations around the site, each containing a moderated BF_3 counter and a GM detector.

Calibration sources are ^{60}Co (up to ~300 Ci) and ^{137}Cs (200 Ci) attached to long cables in well holes, and Ra sources calibrated by NBS, as well as a graphite ion chamber (NBS calibrated) and a Victoreen R-meter. For neutrons there is a ^{252}Cf source and a NBS calibrated PuBe source as well as PuF, PuB and PuLi sources. Instruments are currently calibrated at six month intervals; for portables this will be changed to yearly.

10. SNL

Since the major accelerators are high current very short pulse devices, beam-on instruments must be able to respond without overload on times of the order of nanoseconds. The only direct reading (on-line) instrument is a commercially available pulsed x-ray monitor that consists of a 0.6-cc sealed ion chamber in which current can be digitized at a rate of 10^6 rad sec^{-1}. Extensive use is made of TLDs as well. Since there are no accelerator related neutron fields as yet only TLD 700s need to be deployed, but TLD 600s are sometimes used as a check. At the ion implantation accelerators plastic scintillators are used as monitors during beam-on operation. For beam-off monitoring, standard commercial GM and ion chamber survey meters are used.

About 400 instruments undergo calibration at regular intervals. PuBe neutron sources are available as well as a wide array of Cs and Co sources (from 0.06 $mR\text{-}hour^{-1}$ to 2000 $R\text{-}hour^{-1}$) in an excellently designed calibration facility.

V. PERSONNEL DOSIMETRY

A. Overview

Seven of the laboratories surveyed are currently using TLD systems for both beta-gamma and neutron dosimetry. The others use film but at least one (BNL) will switch to TLD's. All laboratories participate, in some way, in the DOELAP testing program.

X-ray and gamma dosimetry, as well as dosimetry for the muons that arise at high-energy accelerators, is easily handled by any of the commonly used systems. X-ray exposures are not generally significant at accelerator labs (SNL excepted), and do not arise directly from particle beam acceleration but are due to machine operating components such as klystrons and RF cavities. Most gamma doses arise from beam-activated accelerator components; isotopes close in mass to iron produce most of the dose equivalent to workers. There is almost no need for beta dosimetry since few long-lived beta-emitting isotopes are made, and what hazard exists is only from those betas near the surface of the bulk-activated material. Most beta dose reported actually arises from the handling of the depleted uranium used in the fabrication of calorimeter modules for high-energy physics experiments, and not from particle beam acceleration. Standard extremity dosimeters (TLD's usually) supplement whole body badges for uranium workers and provide adequate dosimetry for the high-energy betas involved.

Dissatisfaction with neutron dosimetry whether TLD- or film-based is widespread among the laboratories even though neutrons rarely contribute more than 10 to 20% of the total annual person-rem. For NTA film, fading is the primary concern - one lab exchanges badges every two-weeks to minimize this problem. With TLD systems problems arise from their poor spectral response to the broad energy range of the neutron leakage spectrum outside of shielding. All labs expressed the need for neutron dosimeter development and intercomparison studies in known radiation fields, and a number of them are involved in such studies. Currently, interest is high on the possibility of widespread use of bubble-detector dosimeters. CR-39 track etch detectors also appear attractive because of the better high-energy response than TLD's, but there are concerns with their angular response and sensitivity to changes in processing conditions.

For internal dosimetry some labs routinely monitor their accelerator workers by use of either urinalysis or low-level whole body counting; others only do such dosimetry when ingestion or inhalation incidents are suspected. Those labs with extensive depleted uranium activities perform routine urinalysis or whole body counting at regular intervals. Also, there are bioassay programs where significant tritium contamination occurs. For emergencies, decontamination facilities as well as whole body counting facilities with large NaI scintillator detectors are available for at least preliminary dose assessment at most of the laboratories.

B. Dosimetry Descriptions

1. ANL

The lab is currently using a Panasonic Type 413 AS TLD badge for beta-gamma personnel monitoring and an in-house developed albedo dosimeter for neutrons. Additionally, film (Kodak Type II for β-γ, NTA for neutrons), processed in-house, is available for visitors or special applications. A CR-39 dosimeter will soon be available for use in fast neutron fields. They have furthermore developed a "pencil" type albedo dosimeter based on TLD 600/700's called a Hosger; however, this is used mostly for area monitoring. About 1400 whole body and 300 ring dosimeters are issued each month although not all of these are related to accelerator activities. The dosimetry program has actively participated in the DOELAP accreditation effort and has successfully completed the proficiency testing aspect of the program. Additionally, the dosimetry program participates in ongoing dosimeter intercomparisons performed with ORNL and PNL.

Internal dosimetry is based on urinalysis and is done routinely for accelerator workers. Occasional trace amounts of ^{65}Zn are observed; this probably comes from the ^{65}Cu (p,n) ^{65}Zn reaction. Extensive low-level whole body counting facilities are available. Past use has only been when intakes were suspected; a program of routine operational monitoring has been started and several hundred whole body counts are being performed annually.

The DOE Radiological Assistance Team (RAT) is on-site and available for radiation emergencies. Extensive whole body counting apparatus and various decontamination facilities along with on-site M.D.'s with radiation emergency experience are also available.

2. BATES

About 250 TLD albedo dosimeters are issued to permanent radiation workers and read out routinely every month. Short-term workers and visitor badges are read out daily. All processing is done in-house. Typically, no neutron doses are measured except when special tests are performed in the experiment areas. This program is undergoing review for DOELAP accreditation.

3. BNL

Film, processed by a commercial vendor, is used for both beta-gamma (Kodak Type II) and neutron (NTA) dosimetry. Also, Lexan dosimeters are used at the AGS, and Cr-39 at the NSLS and the reactor. About 500 dosimeters are issued to AGS radiation workers, 380 to those at the NSLS, about 1500 to the rest of the Laboratory, and about 400 visitor badges each month. Neutron doses routinely occur in the AGS experimental areas. Lexan dosimeters are used to avoid the biweekly dosimeter exchange and the higher MDL required because of the NTA film fading problem. The lab is currently in the middle of DOELAP qualification - including beta dosimetry categories because of the extensive depleted uranium handling activities associated with calorimeter construction.

Internal dosimetry for uranium handlers involves monthly urinalysis. No exposures greater than the ALI have been detected. Whole body counting with an 8" by 4" NaI detector is available and about 60 routine counts are performed each year; trace amounts of ^{65}Zn and isotopes associated with gaseous or liquid experimental targets have been found.

The whole body counter is also utilized in the case of a radiation accident. The medical staff has expertise in handling radiation emergencies.

4. CEBAF

The dosimetry program started in the fall of 1987 and uses an external organization for a TLD service. During the following year only gamma doses are expected since only testing of RF cavities and low energy parts of the injector system are scheduled.

5. FNAL

A commercial vendor is used to provide standard film badge service for both beta-gamma (Kodak Type II) and neutron (NTA) dosimetry. Doses due to exposure to muons have been found to be monitored accurately with gamma film. For persons who work in areas of known or suspected neutron dose both CR-39 and polycarbonate badges may also be issued. There are about 1500 persons on regular monthly exchange with another 500 badges per month used mostly by visiting experimenters. Accreditation under the DOELAP program is in progress.

Until recently there has been no need for a routine internal dosimetry program. With the start of construction of a large depleted uranium calorimeter several persons involved in its assembly undergo urinalysis at regular intervals, and occasional low-level whole body counting.

For radiation emergencies an 8" by 2" NaI scintillator detector is available for preliminary dose assessment. More complete body counting can be performed by arrangement with ANL. Fermilab personnel may be called on to assist the RAT team located at ANL. A decontamination facility is available on-site.

6. LAMPF

The dosimeter used is a TLD 600/700 albedo system for both beta-gamma and neutrons, exchanged monthly and processed in-house. Everybody at the accelerator complex (about 850 people) is badged - including secretaries and other non-radiation workers - because of exposure to the radioactive gases exhausted up the stack. Dissatisfaction with the poor high-energy neutron response of the TLD system has led to tests with both NTA and CR-39 to improve the neutron dosimetry. The lab has passed the DOELAP qualification.

Internal dosimetry is based on whole body counting. All radiation worker employees are cycled through at a frequency based on their jobs and expected exposure. The few that show positive results consistently display the 511 keV γ-ray from the ^{11}C in the stack gas. Experimenters involved with tritium use have urinalyses at regular intervals.

The whole body counter is available for use in a radiation emergency as is a decontamination facility, and a hospital emergency room equipped for radiation accidents.

7. LBL

The laboratory currently uses film, exchanged monthly and processed in-house, for both beta-gamma and neutron dosimetry. There are about 1200 gamma (Kodak Type II) and 600 neutron (NTA) films used each month. There are plans to switch to a Panasonic TLD system, but NTA or CR-39 will continue to be used for actual neutron dosimetry; the TLD system will be used as a "flag" of neutron exposure. Dosimeter intercomparison studies are being done in neutron fields associated with heavy ion accelerators. All DOELAP performance tests have been passed.

Internal dosimetry is handled by the Medical Services Department. No internal doses directly related to accelerator activities have ever been measured. Persons handling dispersible isotopes, such as target materials, are monitored monthly either by urinalysis or whole body counting.

There is a DOE RAT team in the area to respond to radiation emergencies. A whole body counter facility exists for accidental exposure.

8. LLNL

The laboratory uses the Panasonic TLD system for both radiation workers and other employees. About 1000 radiation worker badges are exchanged monthly, 8000 non-radiation employee badges are read out quarterly, and 1800 visitor badges read out monthly.

About 50 persons who work in potential or actual neutron radiation areas are also badged with CR-39. All processing is done on-site. DOELAP performance tests will be initiated on April 1, 1989.

Tritium is the only source of internal dose associated with accelerator operations. It arises from the RTNS II. For every 100 mrem external dose equivalent measured there is, typically, 15 mrem internal dose from tritium. Weekly urinalysis is required for all employees at RTNS II. Whole body counting is done annually.

9. ORNL

All persons in the accelerator buildings are issued a Harshaw four TLD badge, read out quarterly. In addition workers needing neutron monitoring receive a Panasonic neutron albedo badge that contains six TLD materials and represents an attempt to make the dosimeter sensitive to a number of different neutron-energy ranges. Alternatives for improved neutron monitoring in the future are being investigated. About 10,000 employee dosimeters from ORNL and K-25 are processed in-house each quarter. The lab has applied for accreditation under the DOELAP program.

Whole body counting and urinalysis facilities are located on-site. Medical personnel are equipped and trained to handle radiation emergencies.

10. SLAC

The lab uses a TLD 600/700 system in a matrix of teflon for both gamma and neutron dosimetry. The dosimeter is incorporated into a wallet-sized ID card. For radiation workers the TLD's are read-out quarterly; for others the read-out is yearly. Dosimeter evaluation is done in-house. There are about 250 radiation workers, 1300 other employees, and 1000 users, contractors, or visitors. Based on a series of measurements with Rem meters, a two element neutron-activation spectrometer, and a GM tube for the gamma component, performed over a period of time, the true neutron dose equivalent obtained with these TLD dosimeters may be overestimated by a factor of two or more. Overall about 5% of the beam-on dose equivalent arises from neutrons. Between 30 and 40 persons may get as much as 100 mrem neutron dose equivalent annually. The lab has been partially qualified under DOELAP.

There have been no measurable internal doses. There is no active contamination.

11. SNL

A TLD 600/700 Harshaw albedo dosimeter system is used for both beta-gamma and neutron dosimetry. These are exchanged quarterly and read out in-house. About 2000 persons are issued dosimeters; one-third of these work around accelerators. Until now no accelerator related neutron doses have been observed but PBFA II is not yet fully operational. All exposure arises from x- and γ-rays. The laboratory is in the process of qualifying under DOELAP.

Both whole body counting and urinalysis is available for internal dosimetry, and accelerator workers are occasionally monitored. There has been some tritium uptake during inertial confinement fusion experiments performed on the pulsed accelerators.

VI. CONCLUSION: RESEARCH ACTIVITIES

Health physics related research efforts were discussed during the visits. Most labs would like to participate in research but many feel unable to undertake even modest programs because of time and manpower constraints. It became clear during the discussions that the major accelerator health physics needs are in the areas of neutron dosimetry and instrumentation. Some studies done or in progress include attempts to completely characterize the radiation field in beam enclosures or outside of shielding by measurement of spectral fluence/dose distributions, and then intercompare different dosimeter types in the "known" fields. Other, quite modest, efforts in new instrument development are also under way. The general consensus was that dosimeter and instrument intercomparison should be extended in future research and some considerable effort be devoted to the development of new materials and instrumentation for neutron detection particularly at high-energies in pulsed as well as steady state fields.

Other current research efforts and future suggestions for investigation mirror the more specific interests and health physics needs of each individual laboratory. For example, muon fluence measurements and comparison with production and transport models address important questions about muon dose and related operational health physics concerns at very high-energy accelerators. Other studies in progress include heavy ion stopping power measurements, photon skyshine studies, and instrument tests with a pulsed x-ray source. Future research efforts were proposed to measure both neutron and photon skyshine distributions and develop calculational procedures, to study the chemical and physical properties of the radioactive gas in exhaust stacks, and for LET and general micro-dosimetry studies. A proposal to measure neutron production cross sections and spectra from proton, heavy ion, and electron bombardment of nuclear targets for use in the development of hadronic cascade codes for shielding and other applications is clearly an extensive research program requiring many person-years of effort.

All of the labs enthusiastically support the establishment of at least one accelerator beam line dedicated to health physics related research. While opinions differed as to accelerator energy, beam type, and part of the country for siting the facility, all agreed that the experimental area should be well instrumented for many varied uses. Shielding experiments performed in reproducible geometry, instrument and dosimeter intercomparison, and a whole range of research proposals including those mentioned above should be amenable to investigation.

There are other activities, not specifically research, that would be useful to the whole accelerator health physics community. Some of these suggested during the discussions include a "Code of Good Practices" for synchrotron radiation facilities, the preparation of a radiation data handbook like the Particle Properties Data Booklet ("Blue Book") of high-energy physics, a compilation of a catalog of neutron spectra measured outside of shielding as a function of thickness for different shield materials and source terms, and the development of a high-energy neutron calibration facility sited somewhere in the United Stated.

V. EPILOGUE

We emphasize again that this report does not present a complete picture of the health physics programs at the laboratories visited. Not all of the individual summaries in each section of this manuscript cover the same points. While a general outline was used to open the discussions, the informality of the proceedings often allowed emphasis on items of specific interest. Our notes reflect these specific individual laboratory concerns.

The general picture that emerged from our visits was of health physics staff members diligently coping with their individual operational concerns. The similarities in the techniques used to address these problems seemed to outweigh the differences. The almost complete unanimity that high-energy neutron detection is the single most important need for health physics at accelerators is the major conclusion of this report.

We wish to thank the health physics staffs of all of the DOE laboratories that we visited for their cooperation and courtesy. We commend all of the participants for the openness with which technical aspects of the health physics activities were discussed.

Appendix A: FIGURES

Figures of experimental areas and/or of accelerators at the various DOE labs are presented in this section. The figures were (except for SLAC and LLNL) submitted by each of the participant laboratories in this survey; final selection was made by us.

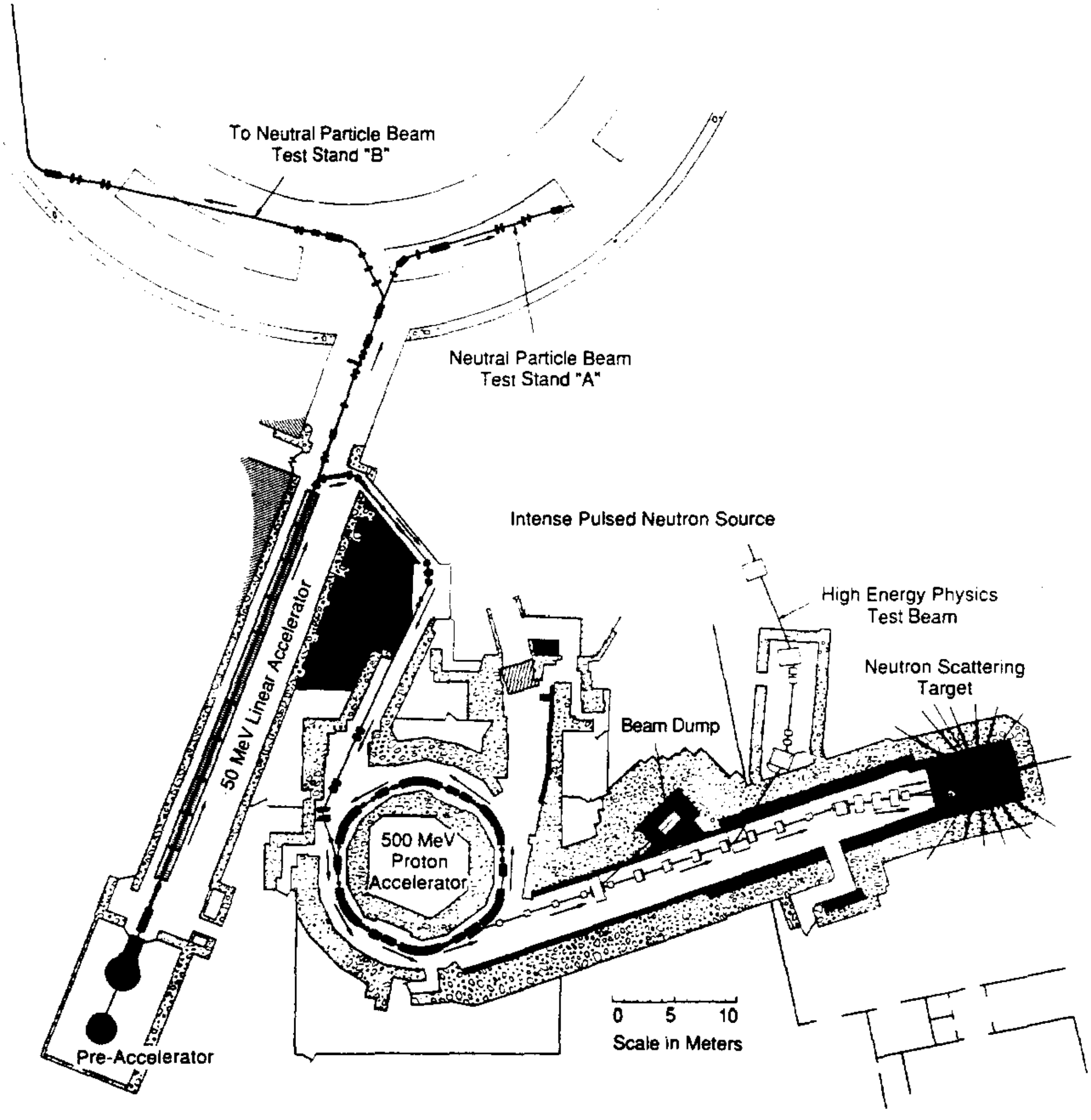


Fig. 1. Layout of the IPNS accelerator system. Also shown schematically is the NPB test facility of the Argonne SDI effort.

Figure 1 ANL:IPNS

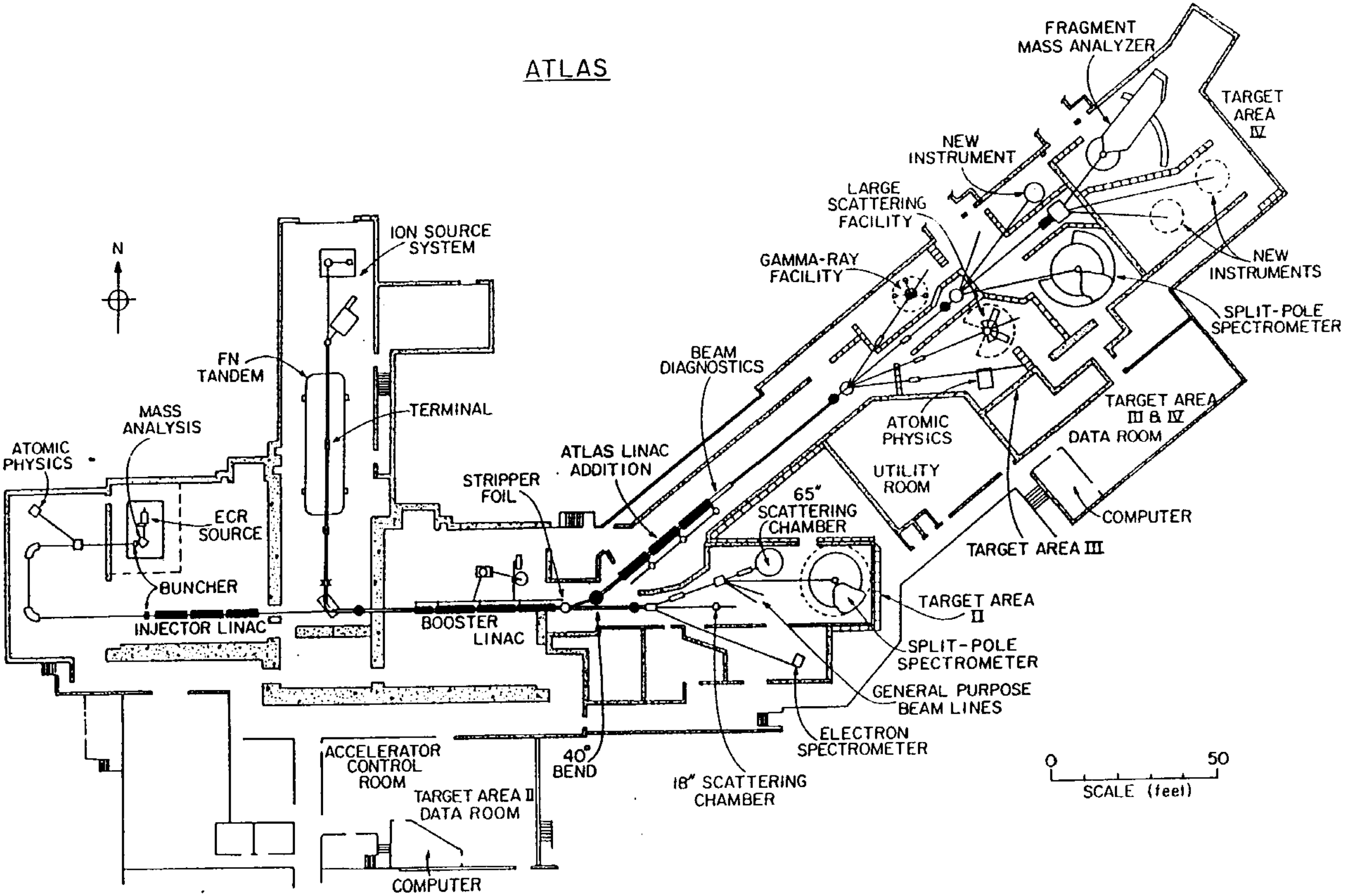
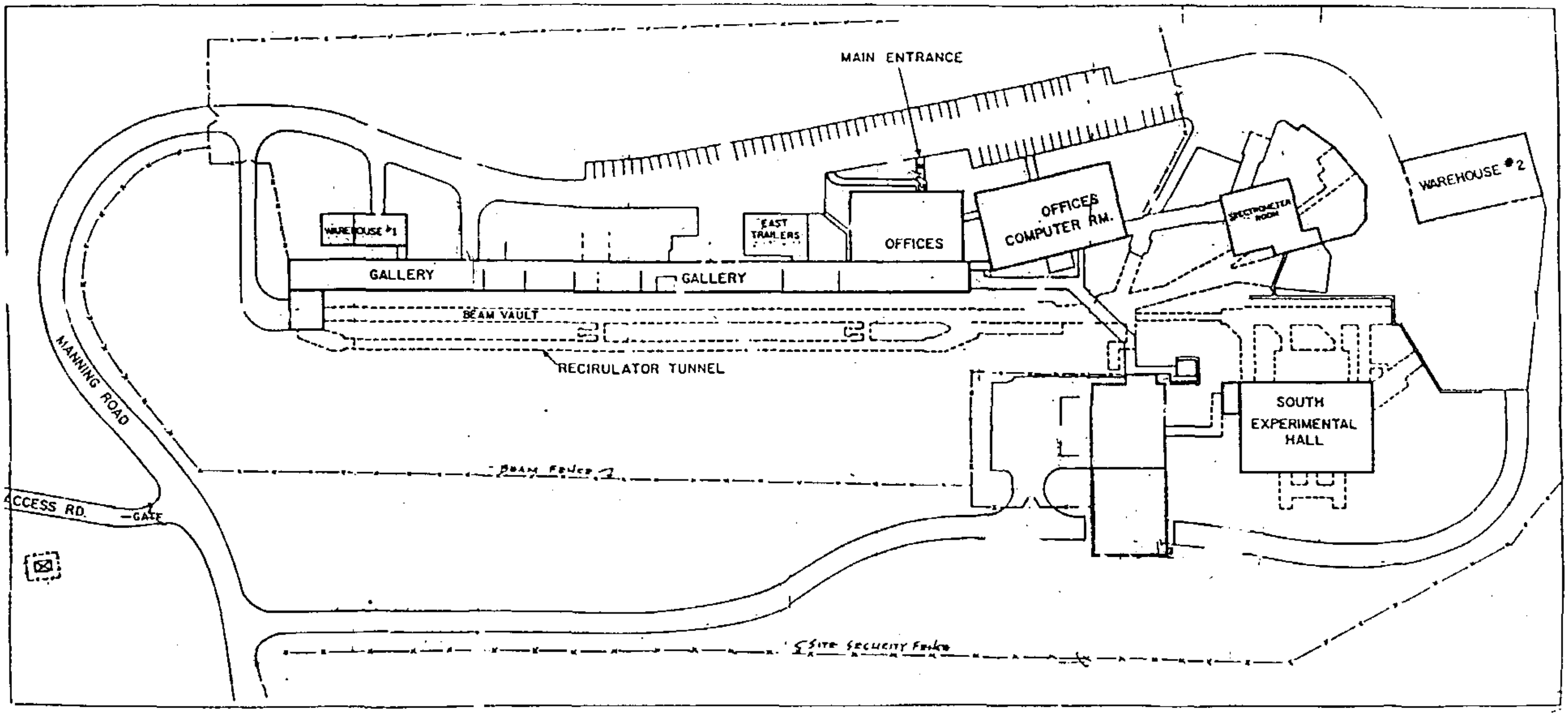
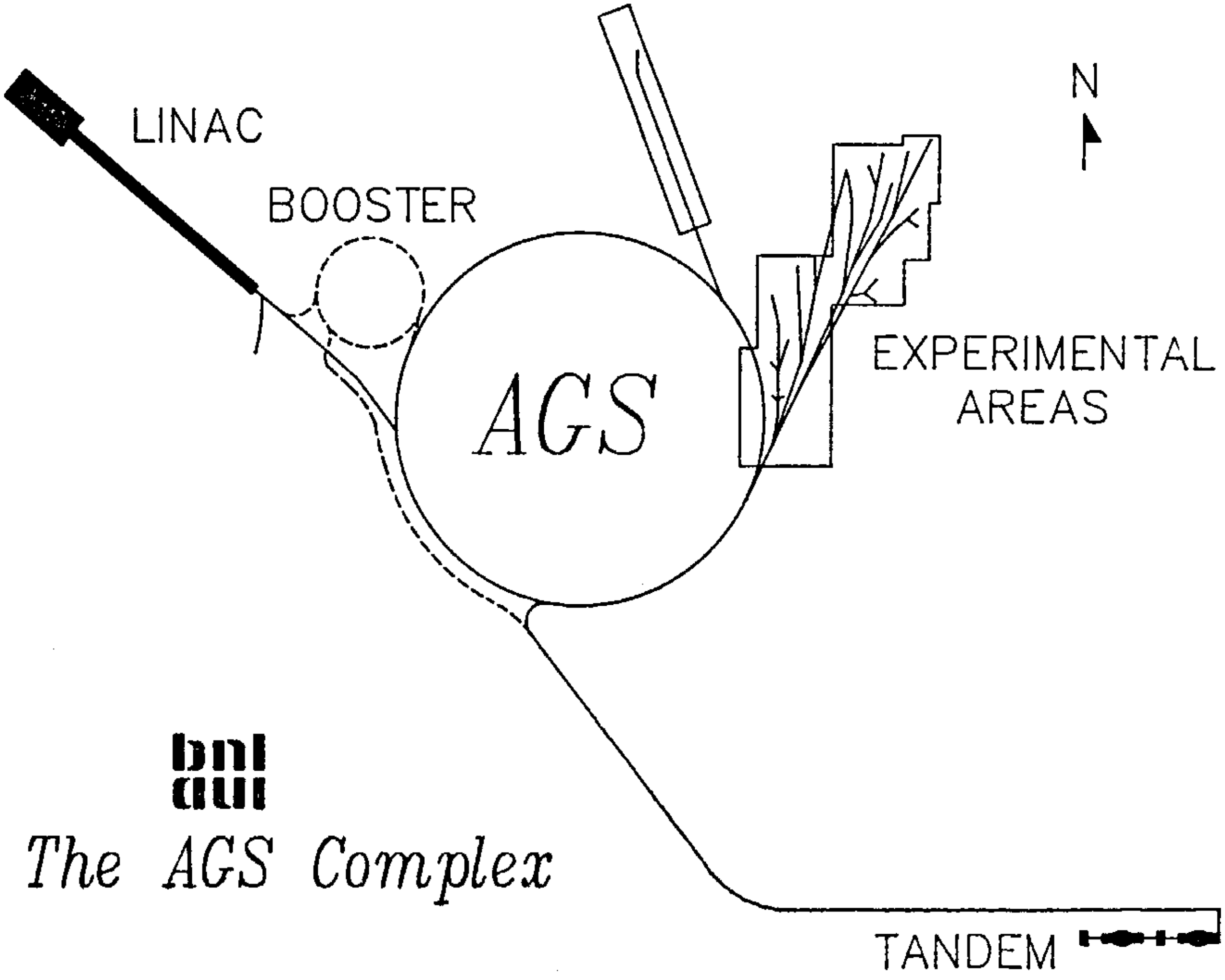


Figure 2 ANL:ATLAS

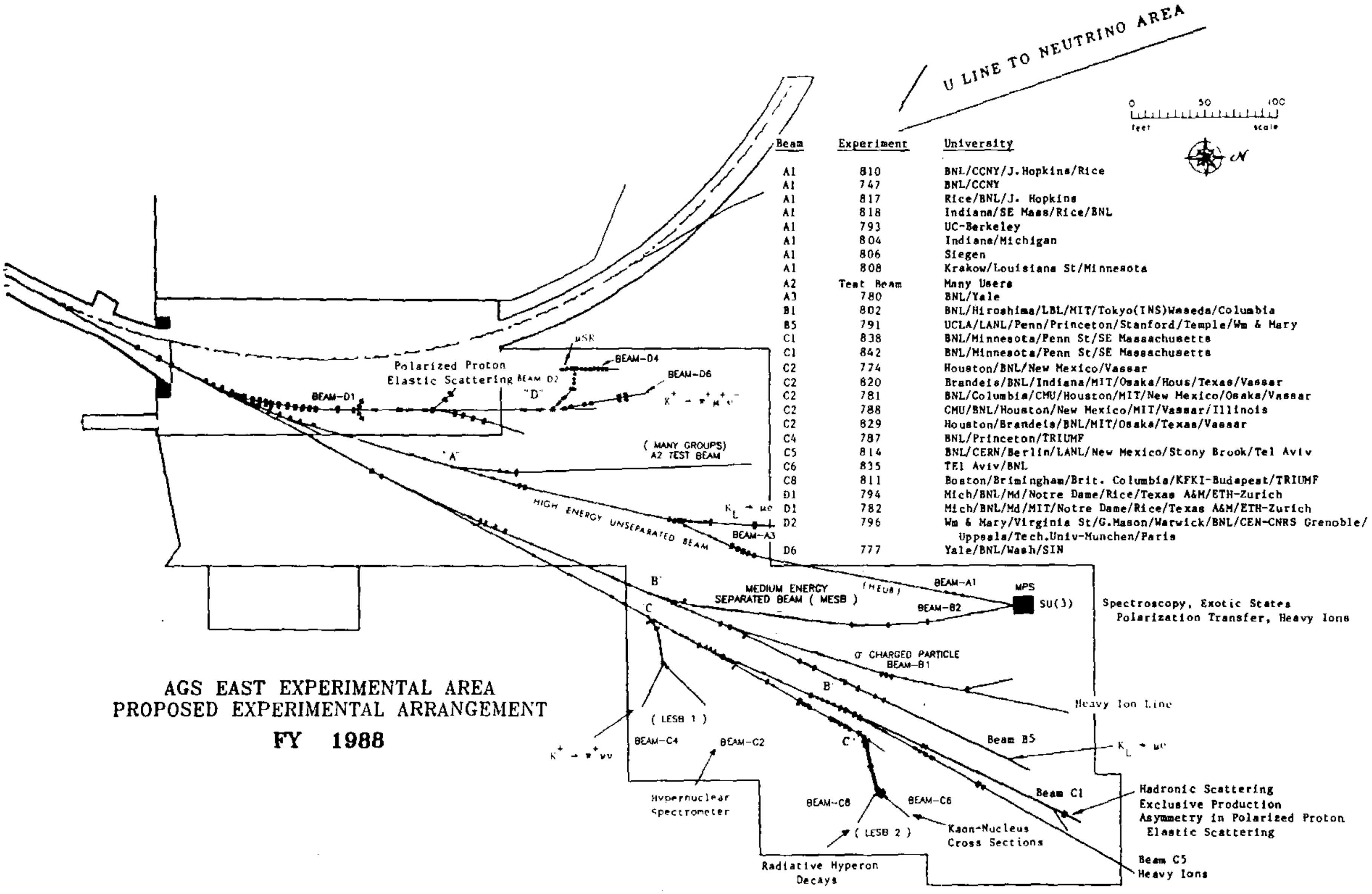
Figure 3 BATES





The AGS Complex

Figure 4 BNL:AGS



AGS EAST EXPERIMENTAL AREA
PROPOSED EXPERIMENTAL ARRANGEMENT
FY 1988

Beam	Experiment	University
A1	810	BNL/CCNY/J.Hopkins/Rice
A1	747	BNL/CCNY
A1	817	Rice/BNL/J. Hopkins
A1	818	Indiana/SE Mass/Rice/BNL
A1	793	UC-Berkeley
A1	804	Indiana/Michigan
A1	806	Siegen
A1	808	Krakow/Louisiana St/Minnesota
A2	Test Beam	Many Users
A3	780	BNL/Yale
B1	802	BNL/Hiroshima/LBL/MIT/Tokyo(INS)Waseda/Columbia
B5	791	UCLA/LANL/Penn/Princeton/Stanford/Temple/Wm & Mary
C1	838	BNL/Minnesota/Penn St/SE Massachusetts
C1	842	BNL/Minnesota/Penn St/SE Massachusetts
C2	774	Houston/BNL/New Mexico/Vassar
C2	820	Brandeis/BNL/Indiana/MIT/Osaka/Hous/Texas/Vassar
C2	781	BNL/Columbia/CMU/Houston/MIT/New Mexico/Osaka/Vassar
C2	788	CMU/BNL/Houston/New Mexico/MIT/Vassar/Illinois
C2	829	Houston/Brandeis/BNL/MIT/Osaka/Texas/Vassar
C4	787	BNL/Princeton/TRIUMF
C5	814	BNL/CERN/Berlin/LANL/New Mexico/Stony Brook/Tel Aviv
C6	835	TEl Aviv/BNL
C8	811	Boston/Brimingham/Brit. Columbia/KFKI-Budapest/TRIUMF
D1	794	Mich/BNL/Md/Notre Dame/Rice/Texas A&M/ETH-Zurich
D1	782	Mich/BNL/Md/MIT/Notre Dame/Rice/Texas A&M/ETH-Zurich
D2	796	Wm & Mary/Virginia St/G.Mason/Warwick/BNL/CEN-CNRS Grenoble/ Uppsala/Tech.Univ-Munchen/Paris
D6	777	Yale/BNL/Wash/SIN

Fig. 3

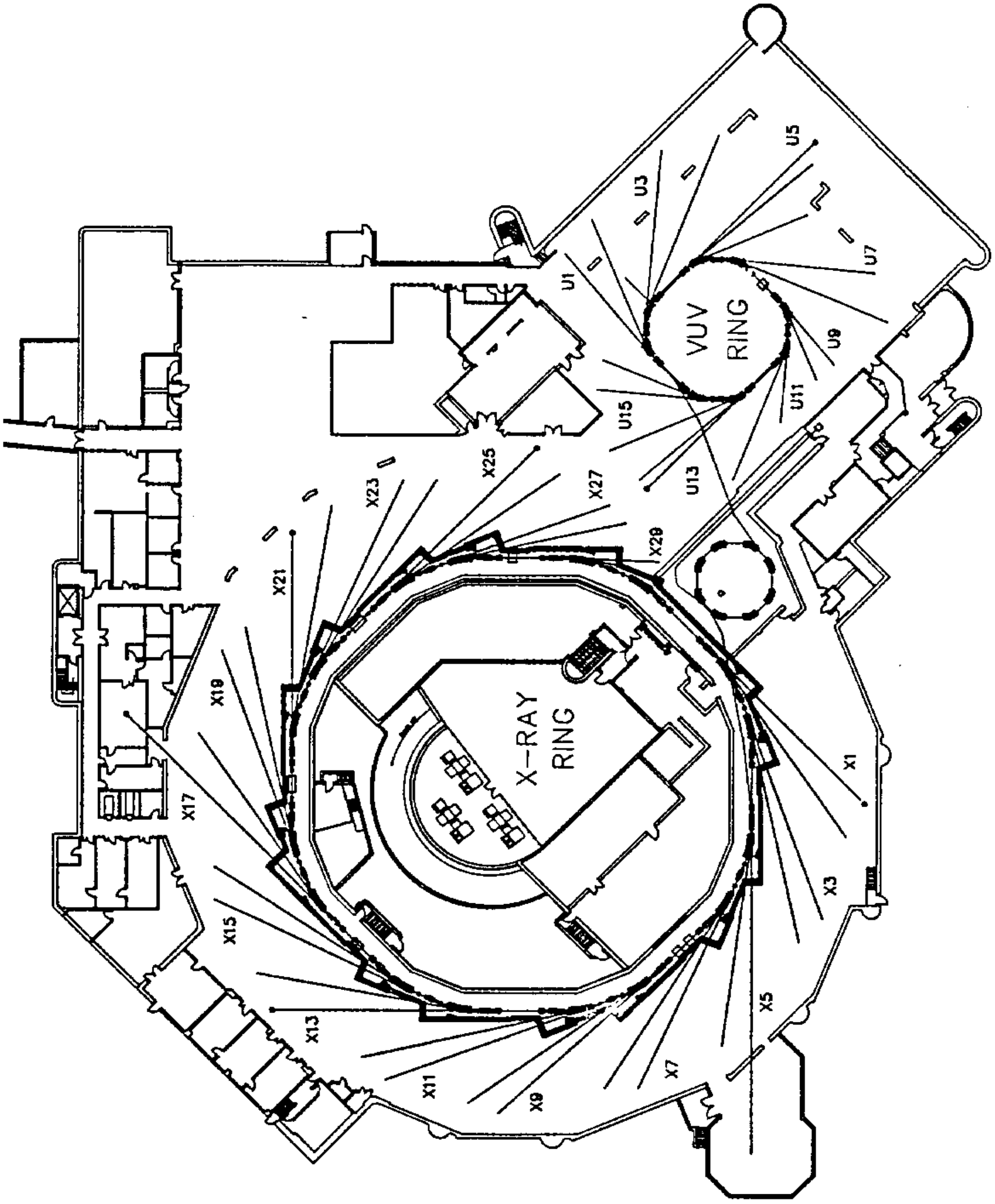


Figure 1. Floor plan of the National Synchrotron Light Source experimental area.

Figure 6 BNL:NSLS

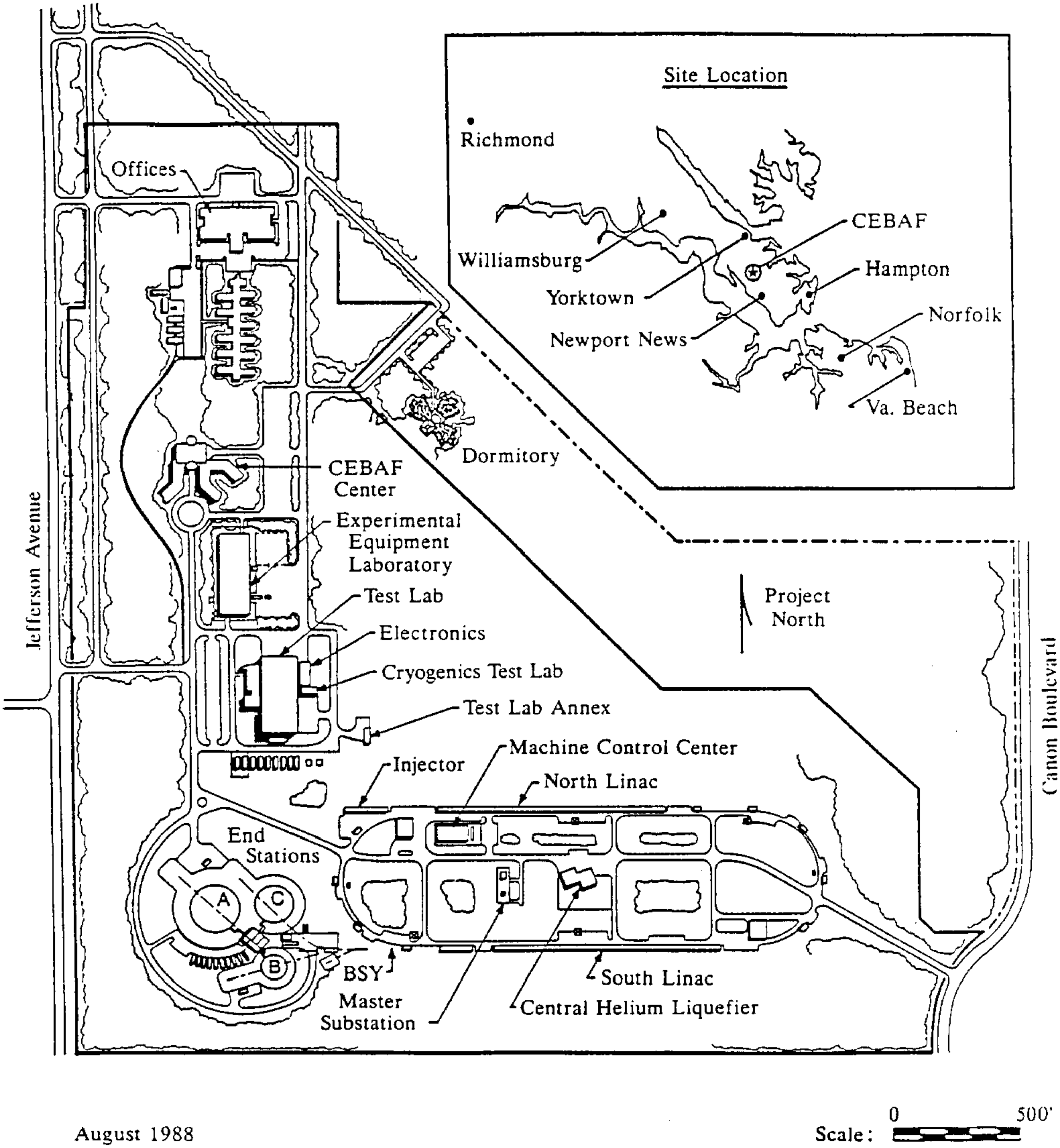


Figure 7 CEBAF:Site

MACHINE CONFIGURATION

CEBAF

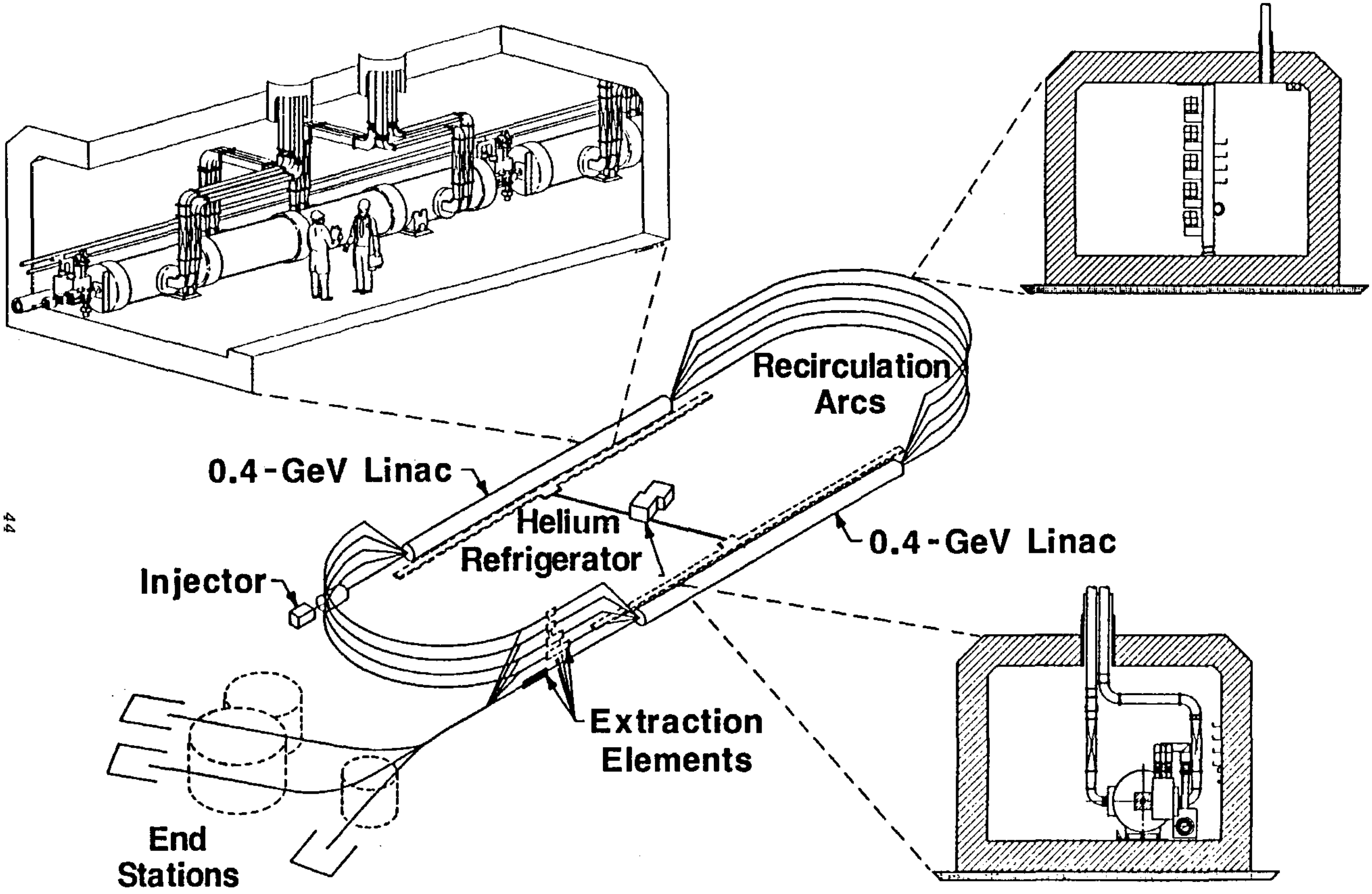


Figure 8 CEBAF:Accelerator

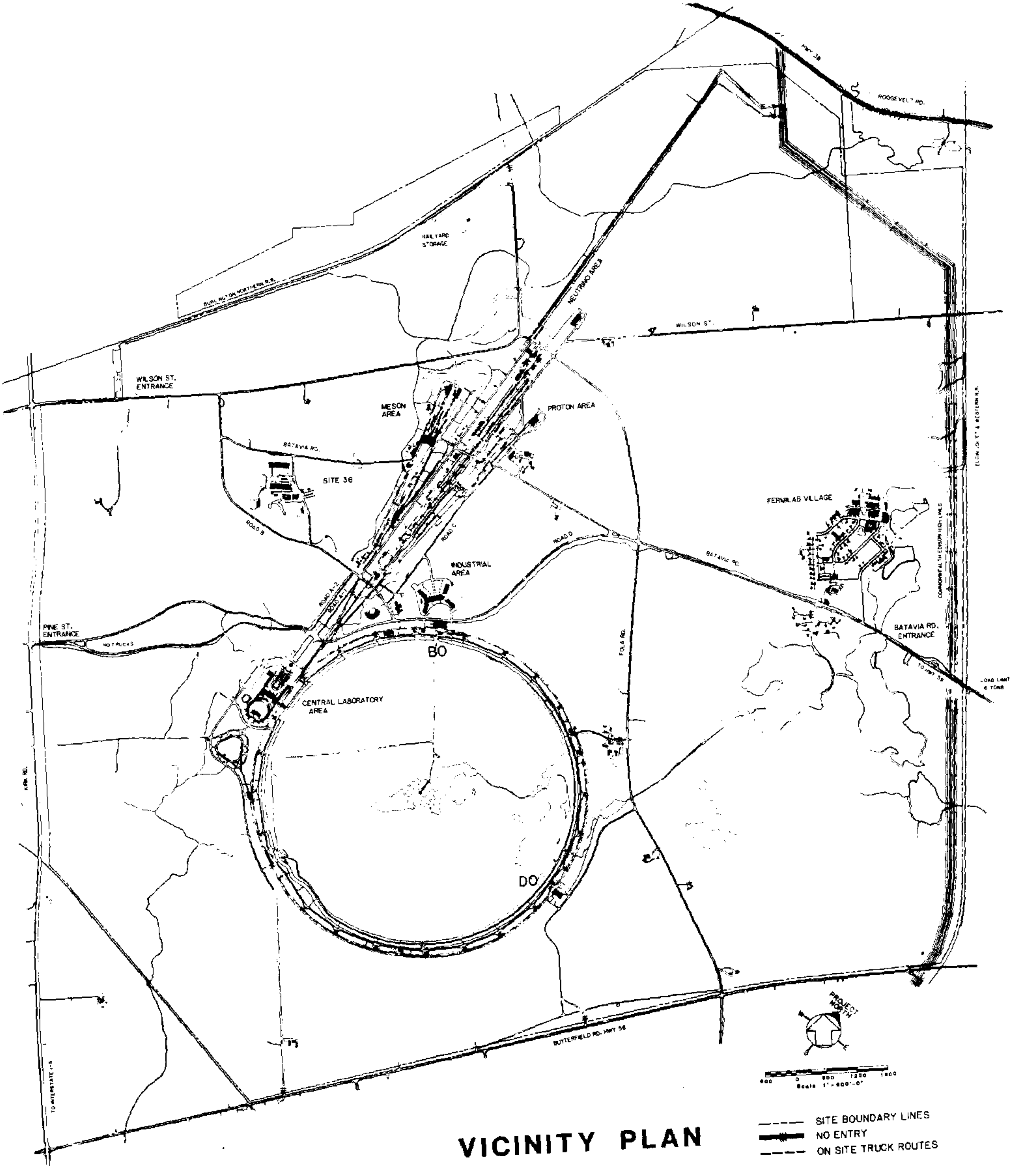


Figure 9 FNAL:Accelerator and Site

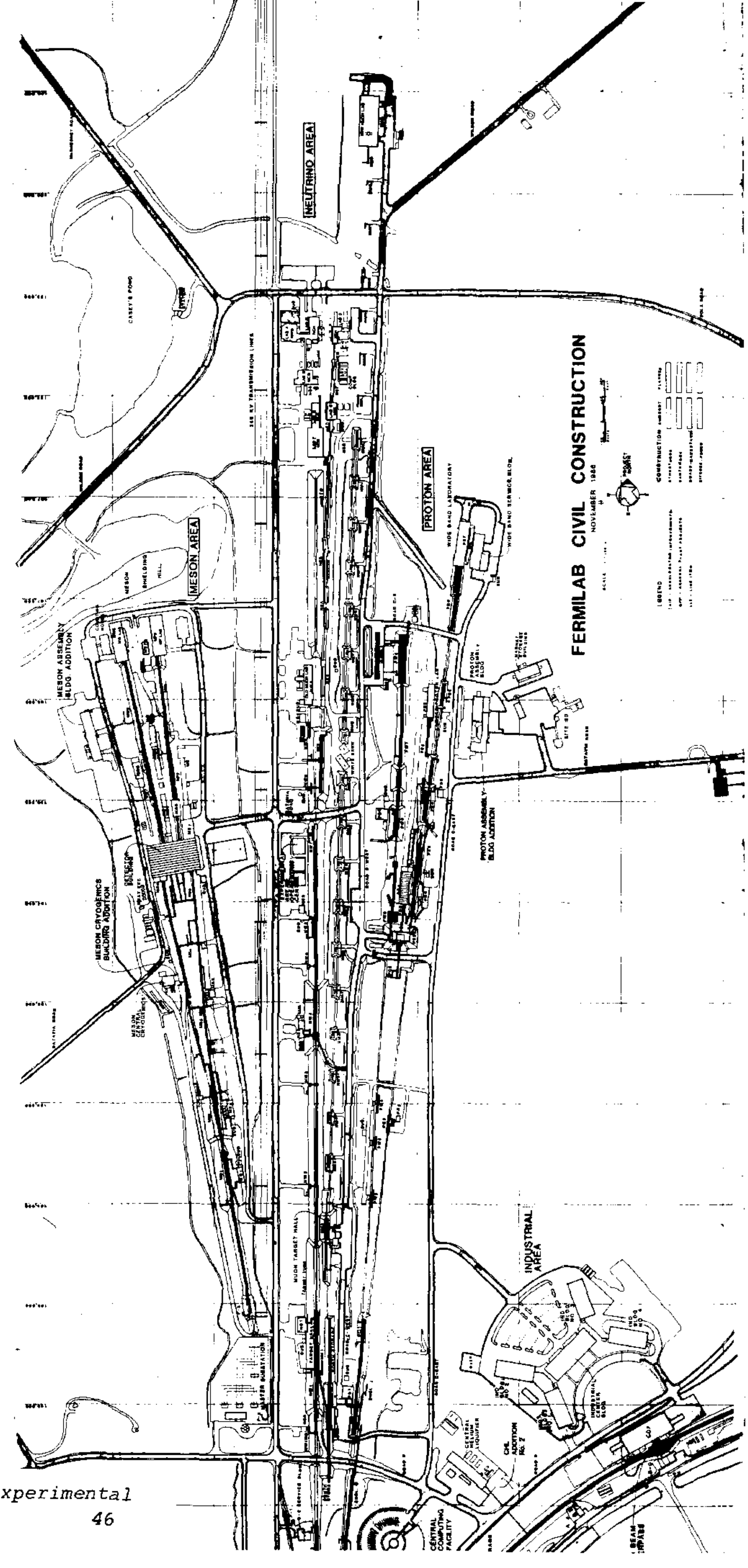


Figure 10 FNAL:Experimental Areas

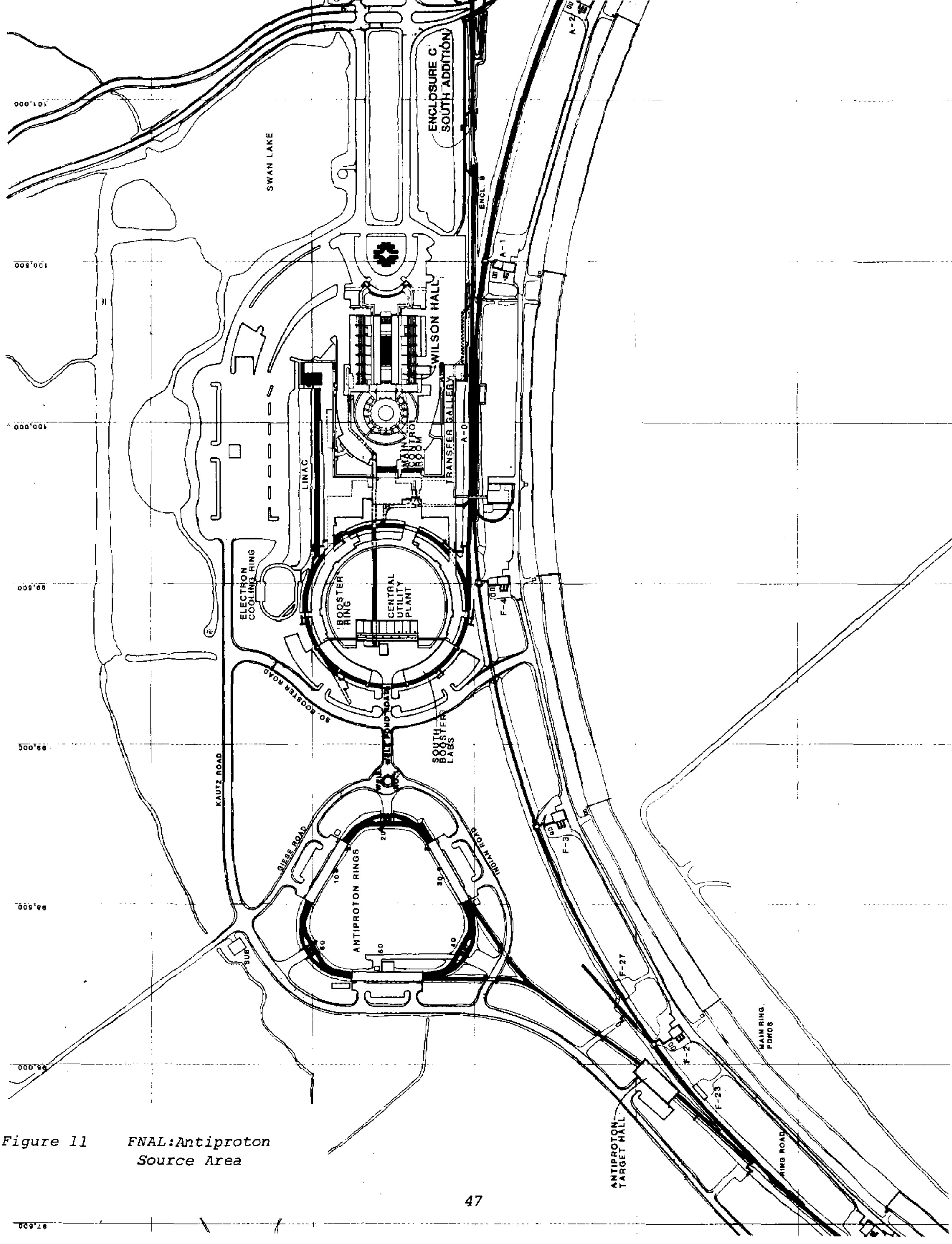


Figure 11 FNAL:Antiproton Source Area

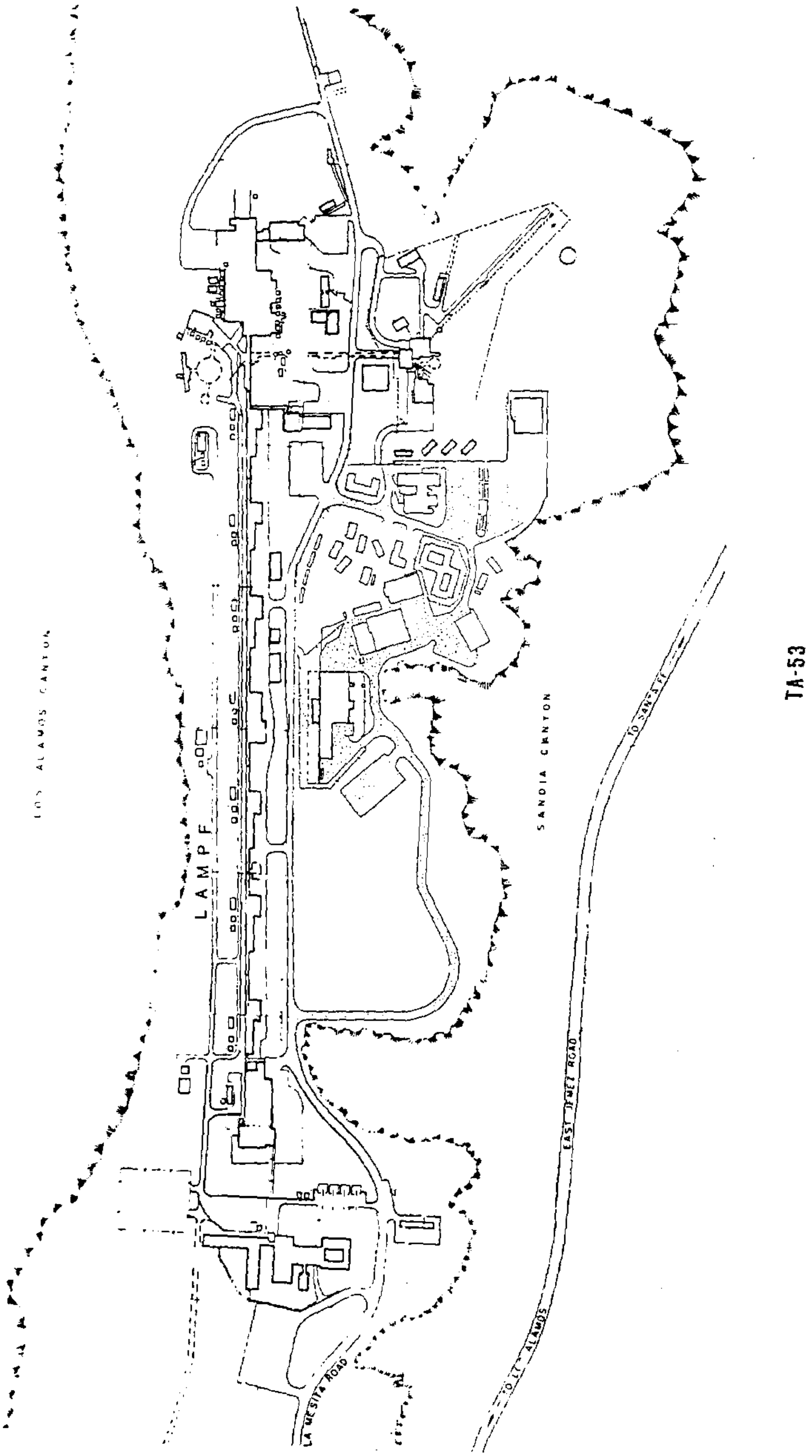
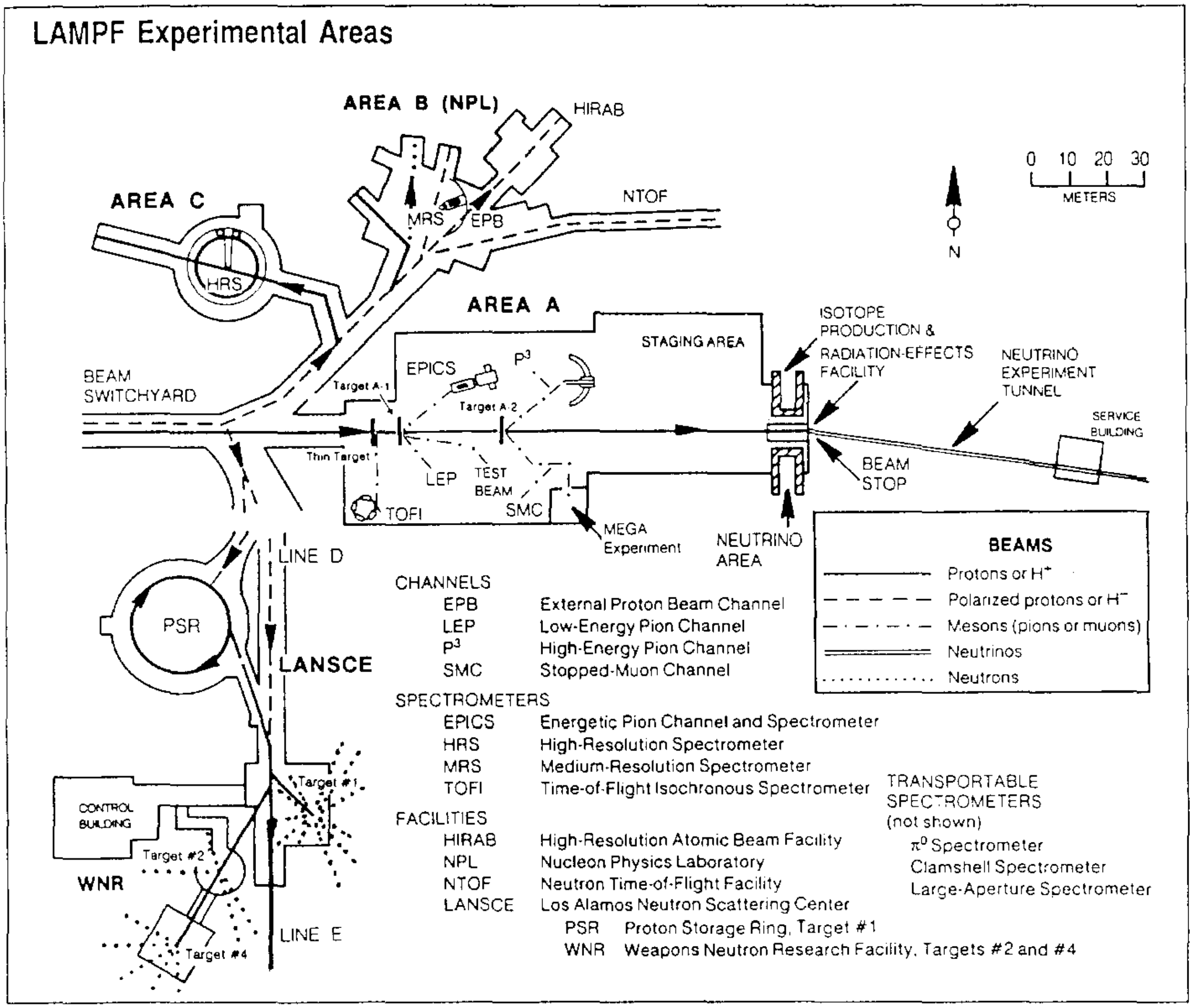


Figure 12 LAMPF:Site

LAMPF Experimental Areas



CHANNELS

EPB	External Proton Beam Channel
LEP	Low-Energy Pion Channel
P³	High-Energy Pion Channel
SMC	Stopped-Muon Channel

SPECTROMETERS

EPICS	Energetic Pion Channel and Spectrometer
HRS	High-Resolution Spectrometer
MRS	Medium-Resolution Spectrometer
TOFI	Time-of-Flight Isochronous Spectrometer

FACILITIES

HIRAB	High-Resolution Atomic Beam Facility
NPL	Nucleon Physics Laboratory
NTOF	Neutron Time-of-Flight Facility
LANSCE	Los Alamos Neutron Scattering Center
PSR	Proton Storage Ring, Target #1
WNR	Weapons Neutron Research Facility, Targets #2 and #4

TRANSPORTABLE SPECTROMETERS
(not shown)
- π^0 Spectrometer
- Clamshell Spectrometer
- Large-Aperture Spectrometer

Figure 13 LAMPF:Experimental Areas

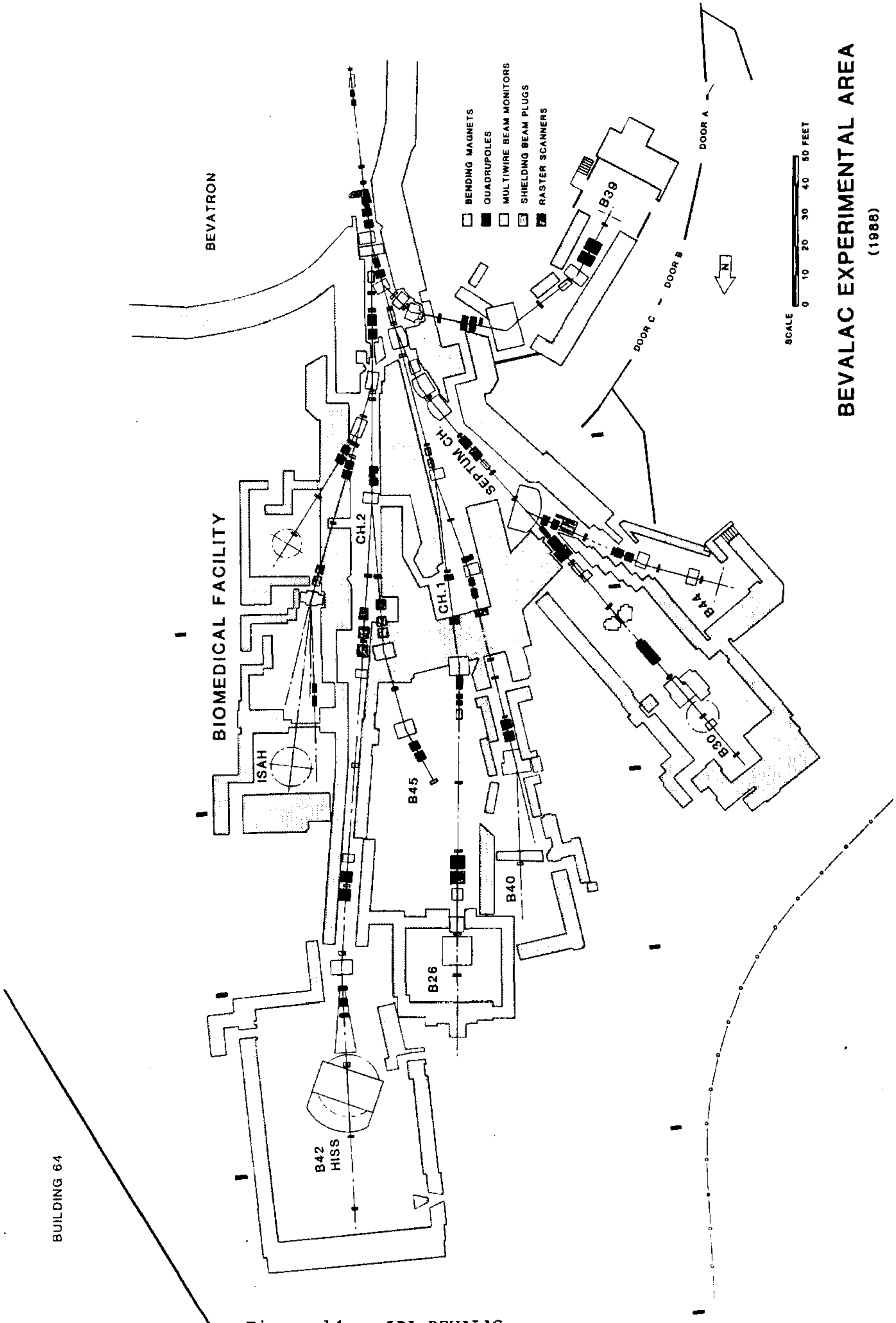


Figure 14 LBL:BEVALAC
Experimental Area

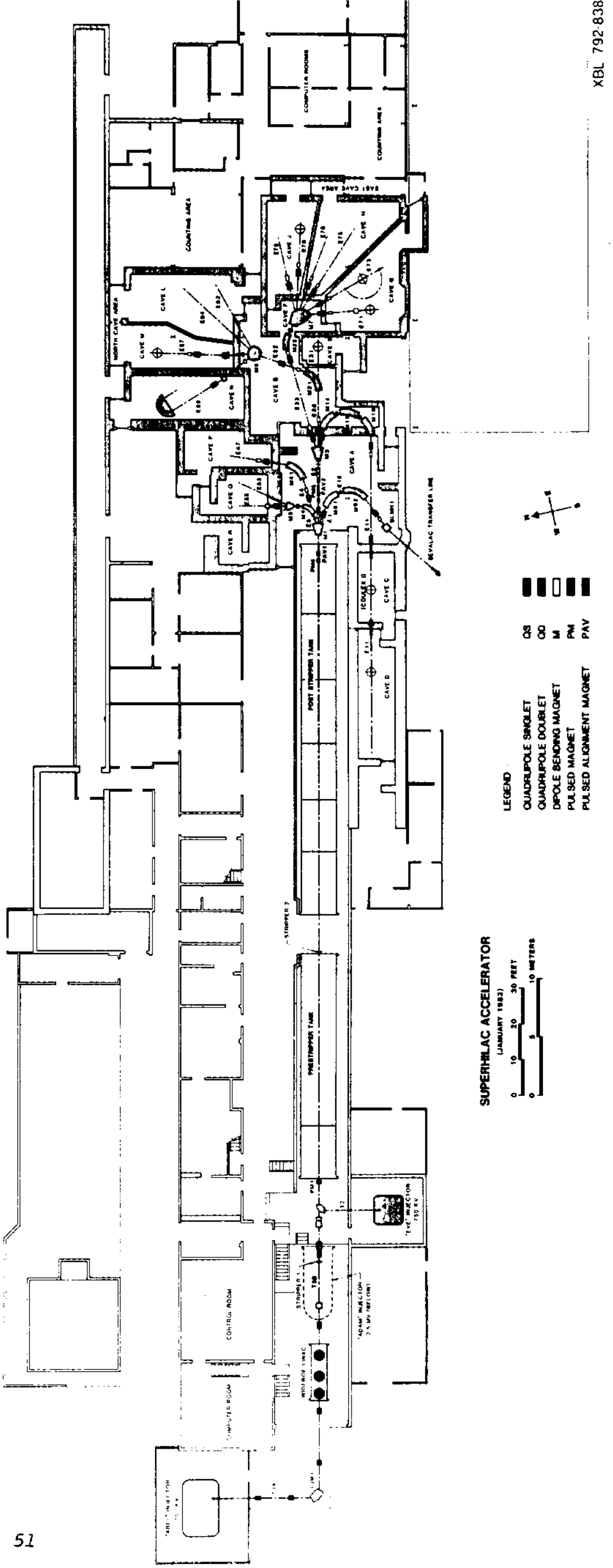


Figure 15 LBL:Superhilac

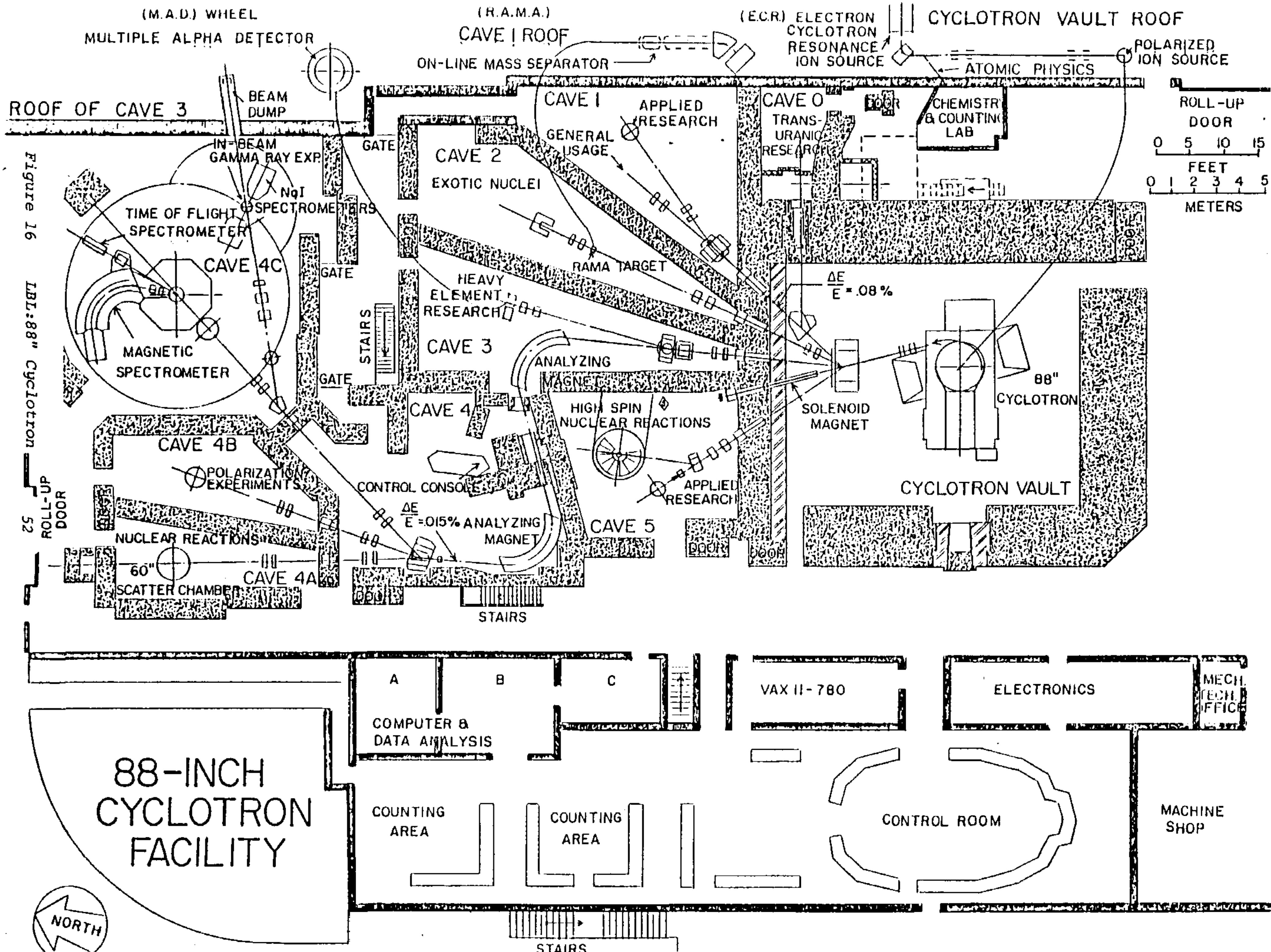

(M.A.D.) WHEEL
MULTIPLE ALPHA DETECTOR
(R.A.M.A.)
CAVE I ROOF
ON-LINE MASS SEPARATOR
(E.C.R.) ELECTRON CYCLOTRON RESONANCE ION SOURCE
CYCLOTRON VAULT ROOF
POLARIZED ION SOURCE
ATOMIC PHYSICS
ROOF OF CAVE 3
BEAM DUMP
IN-BEAM GAMMA RAY EXP.
NaI SPECTROMETERS
TIME OF FLIGHT SPECTROMETER
CAVE 4C
MAGNETIC SPECTROMETER
GATE
GATE
GATE
CAVE 2
EXOTIC NUCLEI
CAVE I
APPLIED RESEARCH
GENERAL USAGE
RAMA TARGET
CAVE 0
TRANS-URANIC RESEARCH
DOOR
CHEMISTRY & COUNTING LAB
ROLL-UP DOOR
0 5 10 15
FEET
0 1 2 3 4 5
METERS
HEAVY ELEMENT RESEARCH
STAIRS
CAVE 3
ANALYZING MAGNET
$\frac{\Delta E}{E}$ = .08 %
88" CYCLOTRON
SOLENOID MAGNET
CAVE 4
HIGH SPIN NUCLEAR REACTIONS
APPLIED RESEARCH
CYCLOTRON VAULT
CAVE 4B
POLARIZATION EXPERIMENTS
CONTROL CONSOLE
$\frac{\Delta E}{E}$ = .015%
ANALYZING MAGNET
CAVE 5
ROLL-UP DOOR
NUCLEAR REACTIONS
60" SCATTER CHAMBER
CAVE 4A
DOOR
DOOR
DOOR
STAIRS
A
B
C
COMPUTER & DATA ANALYSIS
VAX II-780
ELECTRONICS
MECH. TECH. OFFICE
88-INCH CYCLOTRON FACILITY
COUNTING AREA
COUNTING AREA
CONTROL ROOM
MACHINE SHOP
NORTH
STAIRS

Figure 16

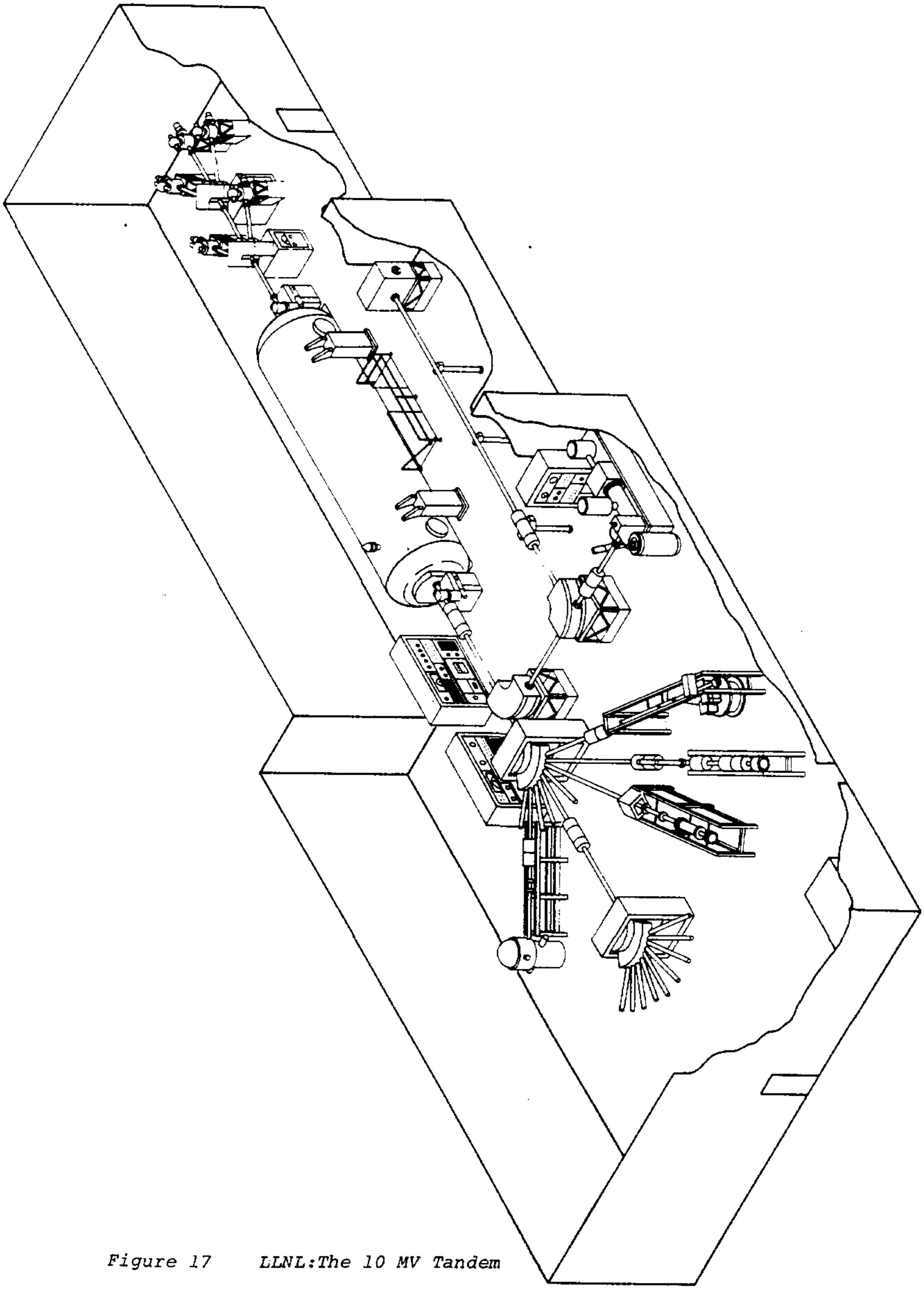


Figure 17 LLNL:The 10 MV Tandem

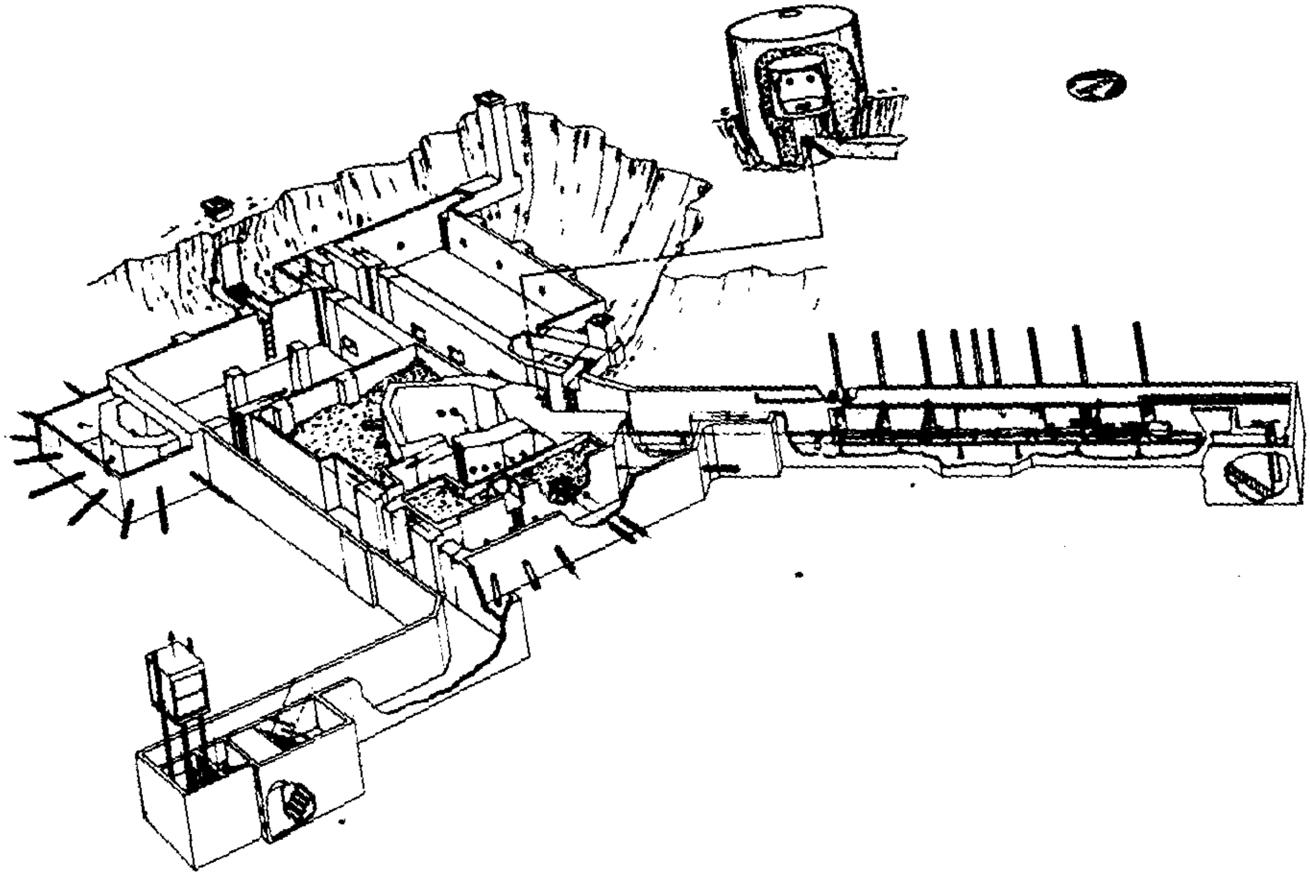
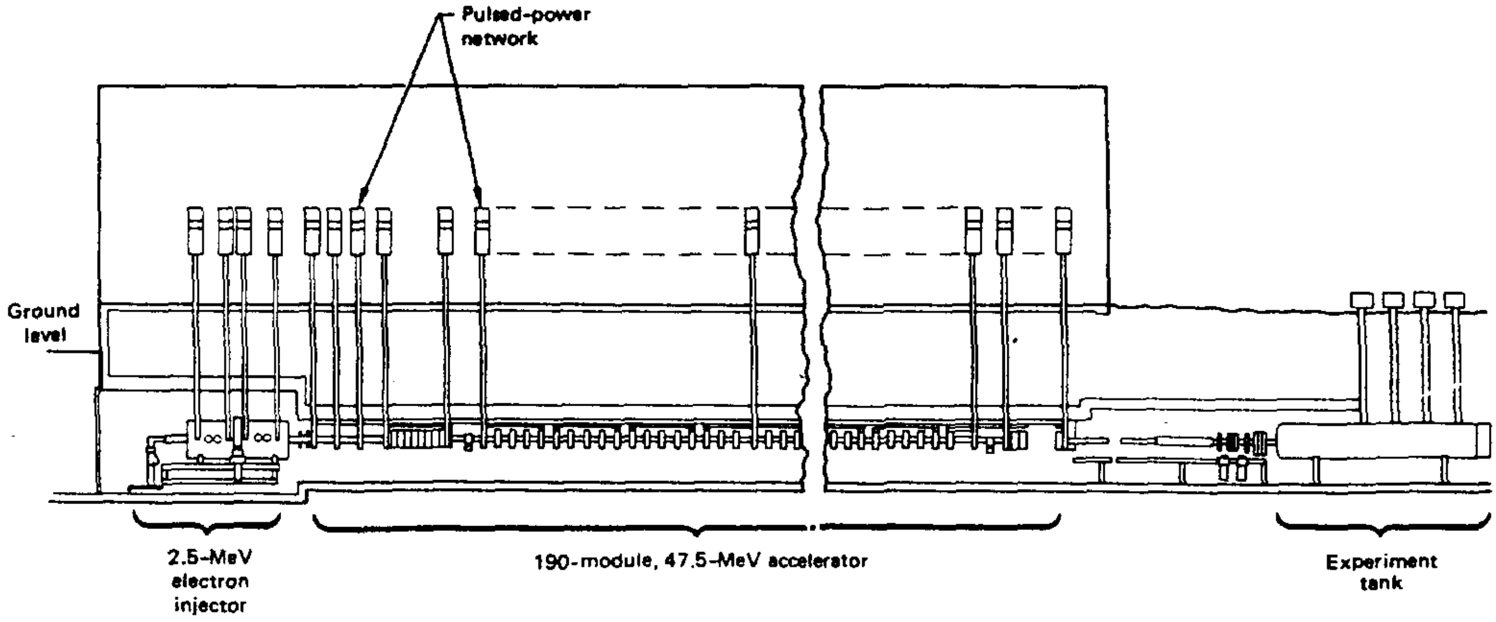


Figure 18 LLNL:100 MeV Electron Linac



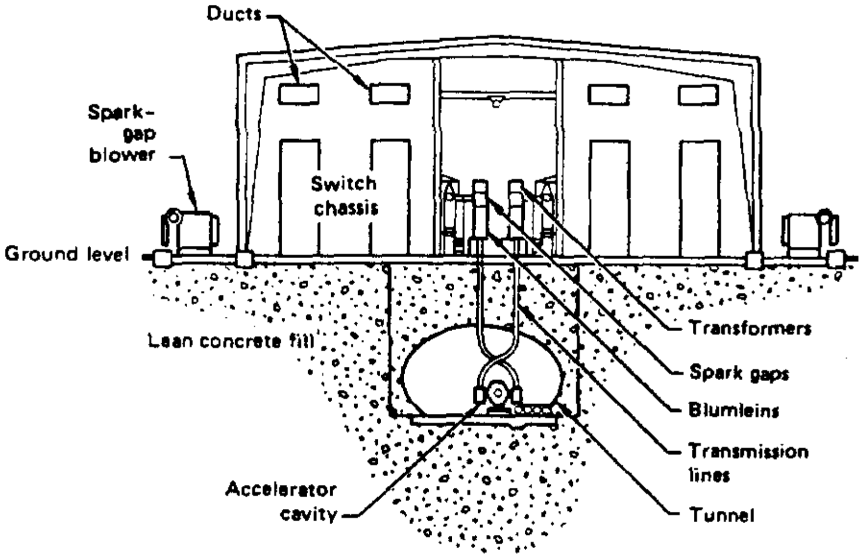


Fig. 3

Sketch of the ATA facility showing arrangement of major components: the pulsed-power network, the electron injector, the accelerator, and the shielded, gas-filled experiment tank. (Many of the vertical elements forming the pulsed-power network have been omitted for simplicity.) This whole assemblage will be 200 m long. The cross-section of the accelerator shows the end of one accelerator cavity, located in an underground tunnel, as well as the Blumleins connecting it to the pulsed-power transformers above ground.

Figure 19 LLNL:ATA, The Advanced Test Accelerator

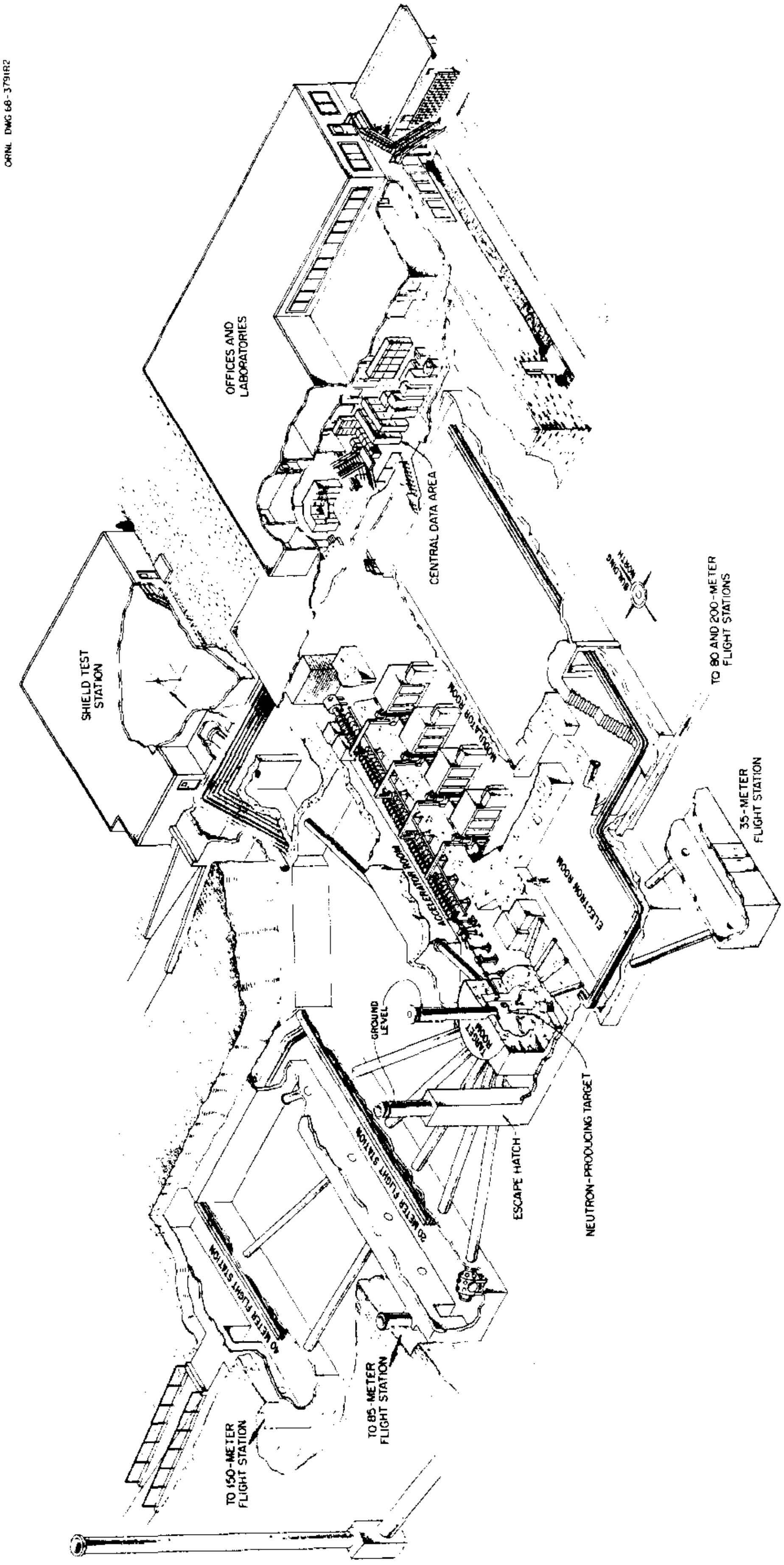


Figure 20   ORNL:ORELLA

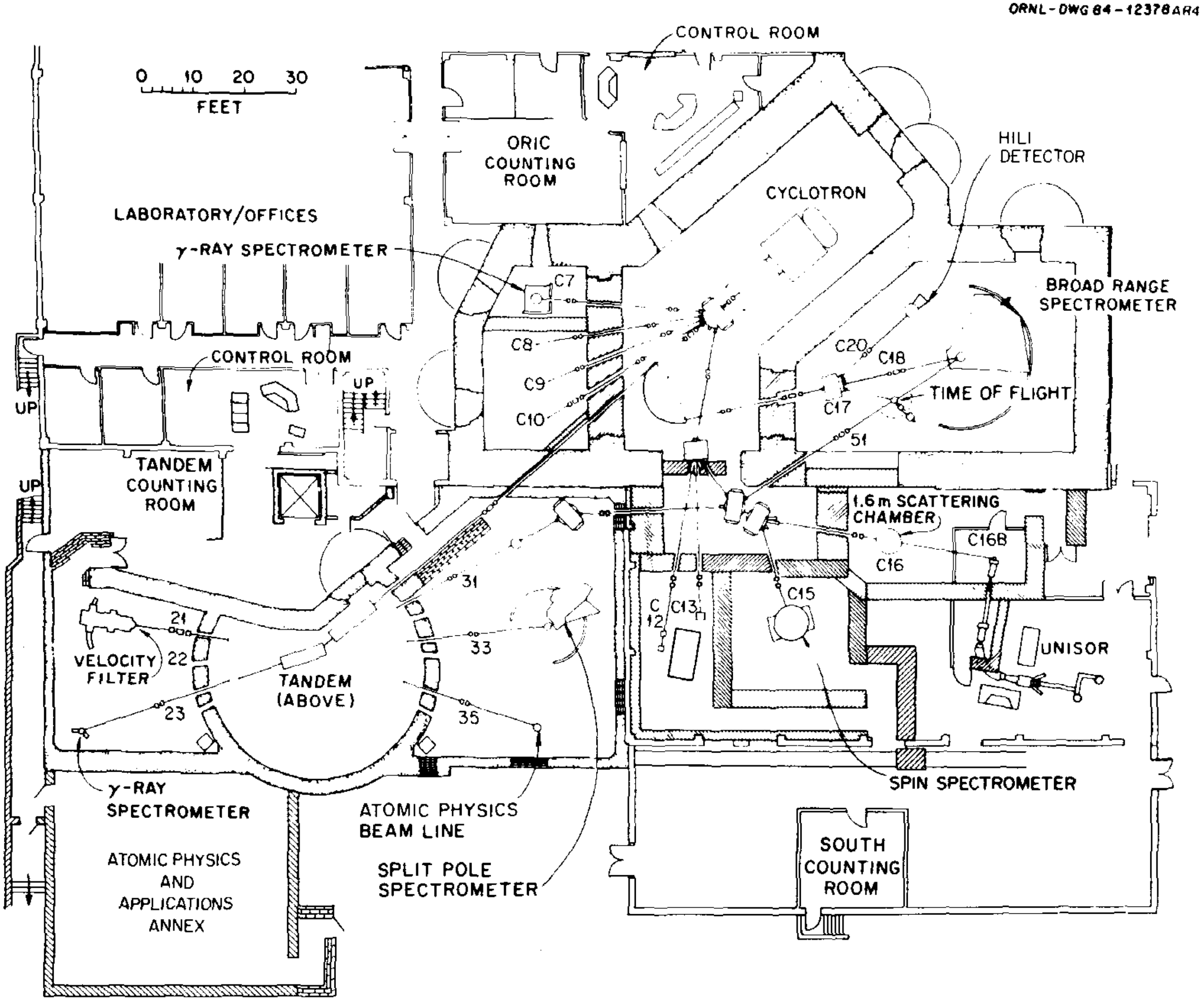


Figure 21 ORNL:HHIRF

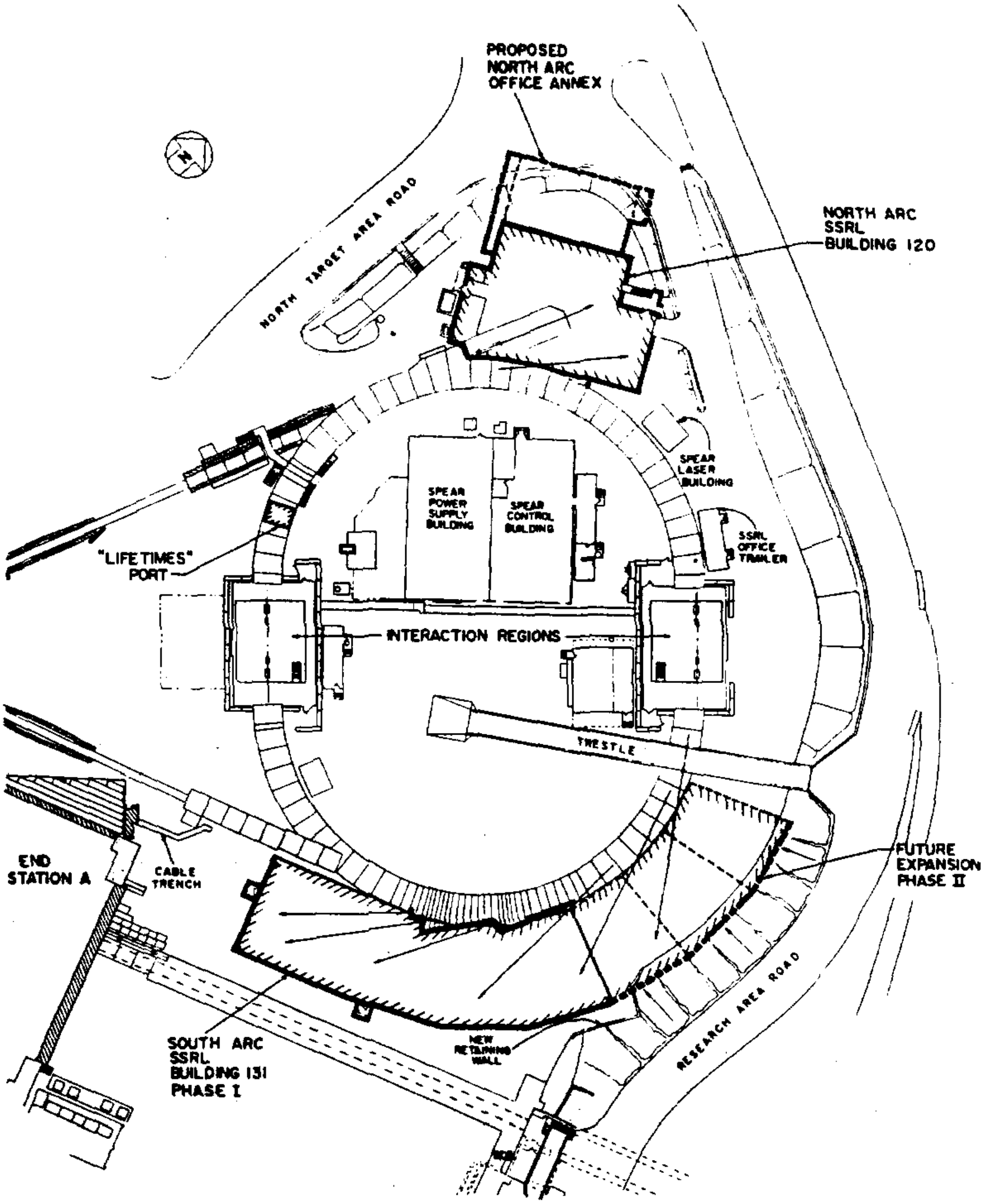


Figure 22 SLAC:SPEAR Ring

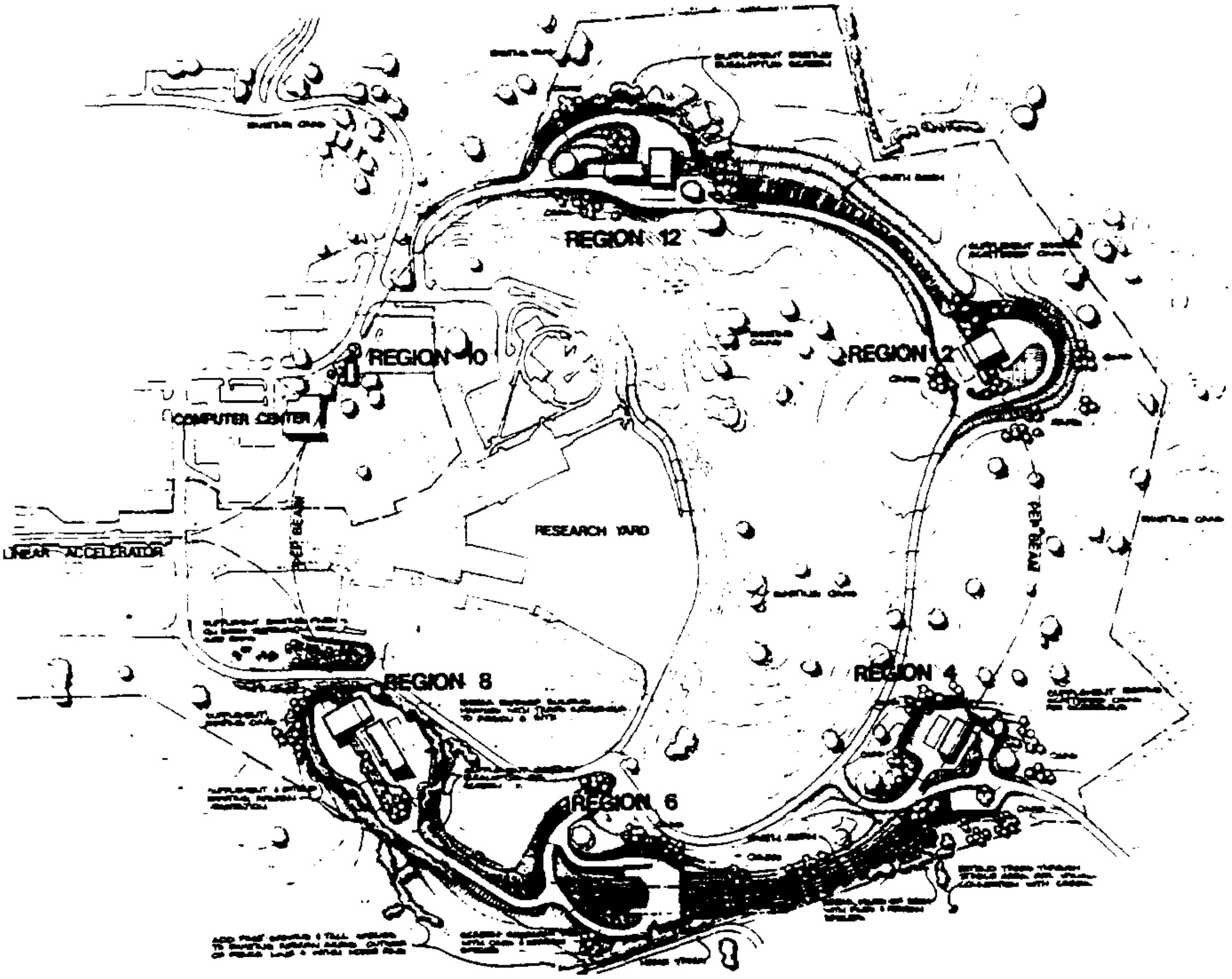
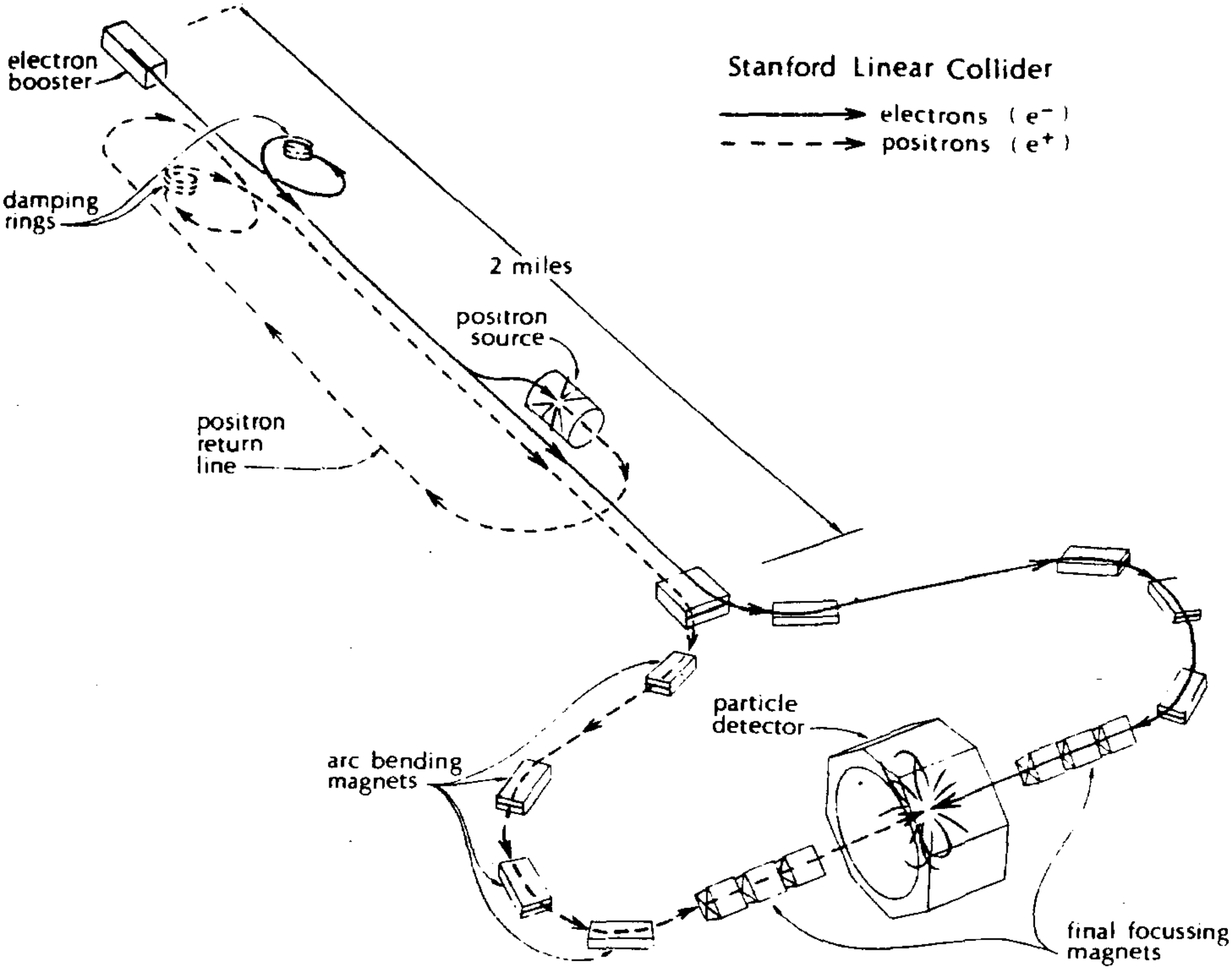


Figure 23 SLAC:PEP Ring



Artist's conception of the SLC. Electrons and positrons are accelerated to almost 50 GeV in the linear part, then guided and focussed by magnets until they collide head-on. Surrounding the interaction point, the Mark II detector records the tracks and energy deposits of particles emerging from these collisions. (Drawing by Walter Zawojski.)

Figure 24 SLAC:Linear Collider

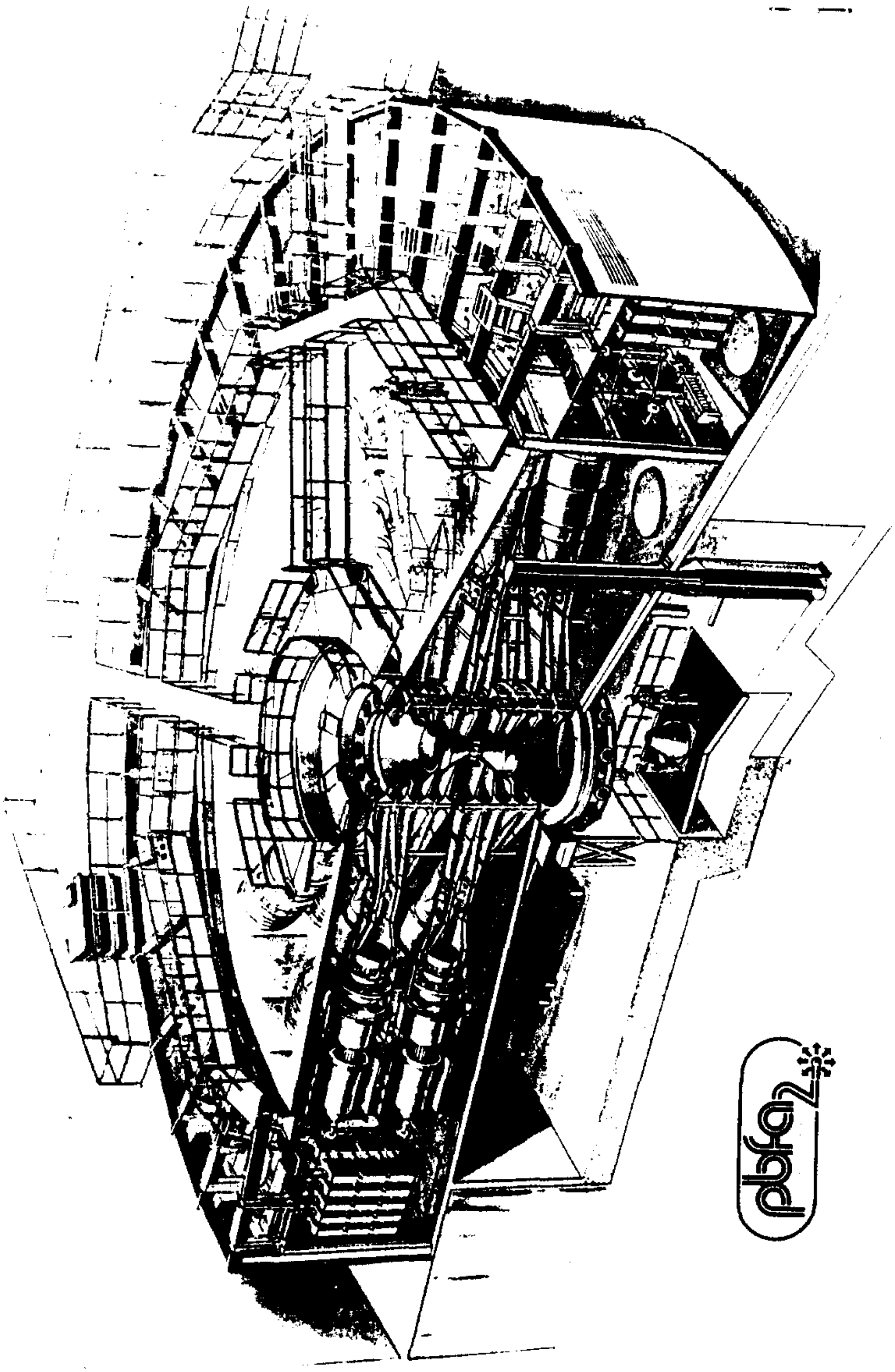


Figure 25 SNL:PBFA2

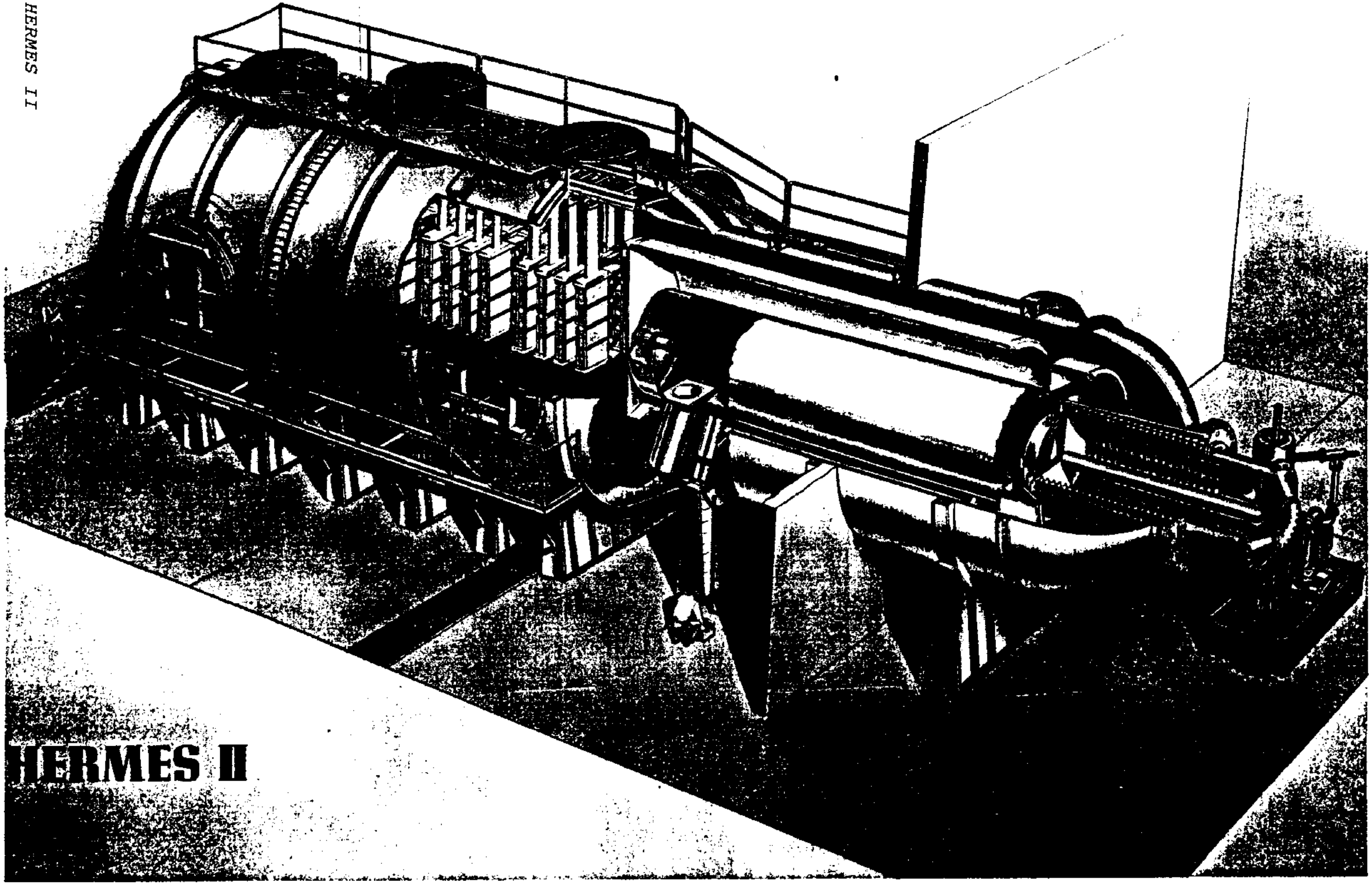


Figure 26   SNL:HERMES II

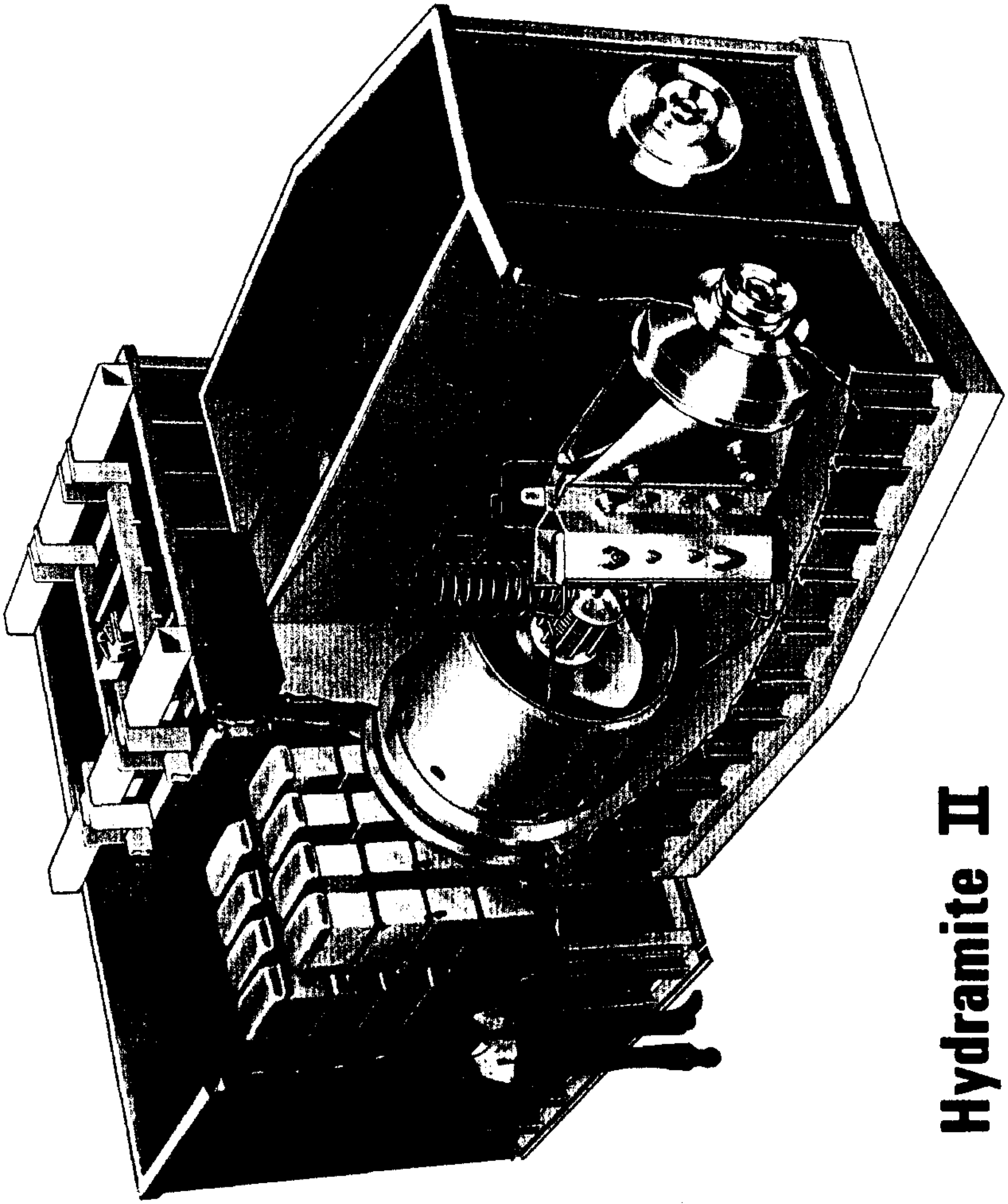


Figure 27 SNL:Hydramite II

APPENDIX B: PARTICIPATING PERSONS

A list of the persons at the various laboratories who participated in the discussions are presented below. While most are health physicists, or participate in health physics activities, some represent other disciplines at their respective laboratories.

1. **ANL**
   E.H. Dolecek, W. Fairman, A.L. Justus, H.J. Moe, R.E. Toohey, V.R. Veluri, R Wynveen

2. **BATES**
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3. **BNL**
   J. Baum, W.R. Casey, A. Kwehner, E. Lessard, D. Lowenstein, S. Musolino, N.R. Rohrig, C. Schopfer

4. **CEBAF**
   T. Hassler, G. Stapleton

5. **FNAL**
   S. Butala, J.D. Cossairt, L.V. Coulson, A.J. Elwyn, W.S. Freeman, M. Gerardi, W.C. Salsbury, P. Yurista

6. **LAMPF**
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7. **LBL**
   T. deCastro, A. Greenhouse, J. Haley, J. McCaslin, G. Schleimer, W. Swanson, R. Thomas, J. Young

8. **LLNL**
   C. Graham, K. Haslam, S. Homann, J. Mecozzi, D. Myers, M. Treat

9. **ORNL**
   J.F. Alexander, C.M. Jones, T.A. Lewis, R.L. Mlekodaj, W.F. Ohnesorge, K.M. Wallace

10. **SLAC**
    D. Busick, T. Jenkins, R. McCall, R. Nelson

11. **SNL**
    W. Burnett, T. Simmons, D. Sinton, A. Stanley, D. Thompson, G. Tucker