THE GENERAL ATOMIC COUPLED ELECTRON LINEAR ACCELERATOR

D. R. Adcock, J. R. Beyster, J. L. Cole

General Atomic Division
General Dynamics Corporation
San Diego, California

Summary

The General Atomic Linear Accelerator Facility consists of two L-band linear accelerators which can be operated independently or coupled together to form one machine. The first accelerator is a single section powered by a 20-MW klystron and is capable of operating over an energy range of one MeV to 17 MeV. Peak currents of 16 A at 12 MeV and 40 ns pulse length have been obtained with the first Linac.

The second Linac, which is built in line with the first machine, consists of three sections powered by one 10-MW and two 20-MW klystrons. The second Linac is capable of producing a 35-MeV electron beam with an intensity of 2 A at pulse length less than 0.1 μs.

By rotating the injector of the second Linac it accepts the beam from the first machine, thereby creating a higher energy machine capable of delivering energies of up to 80 MeV.

Other features of the facility include six independent irradiated cells, 15 target positions, and a high power positron converter; as well as monoenergetic gamma ray sources, high intensity neutron targets, and a single particle per pulse capability. In addition, a special cell contains the APFA-III accelerator-pulsed fast burst reactor, which is operated at a multiplication of 1000 to obtain neutron fluences of 10^{12} - 10^{13} n/cm^2 in 5 μs.

Introduction

The linear accelerator facility was established at General Atomic in 1957 with the installation of a two-section S-band Linac and the construction of shielded housing. By 1960 research requirements were such that the S-band machine was replaced by a three-section L-band Linac using three 10-MW L-band klystrons. Since then a continuous program of improvement of the installation has been carried on. During this period no major shutdowns of the Linac facility have been experienced. Experimental research utilizes approximately 5000 hours of time during a calendar year. The accelerators are operated, maintained, and improved by a staff of three engineers and eight technicians on a 24-hr basis.

Accelerators

Three-Section Linac

Basically, the three-section Linac consists of an injector, accelerating waveguide sections, three klystron modulators, an RF driver system, and auxiliary equipment.

The injector provides a pulsed, high energy beam of electrons to the first section of the Linac at various pulse lengths and repetition rates. (See Fig. 1) The injector system consists of a 0-200 kV Cockroft-Walton power supply, a grid pulser, and an electron gun. The electron gun is operated with the anode at ground potential and the cathode at a high negative potential, typically 125 kV. The gun is biased off by a voltage of approximately 250 volts applied between the cathode and grid. The gun is keyed on by a pulse from the grid pulser, which consists of a distributed amplifier driven by a monostable pulse shaping circuit. The injector is capable of providing beam pulses that can be varied in width between 10 ns and 5 μs. The repetition rate can be varied to 720 pulses per second. Any klystron pulse repetition rate may be scaled by a factor of 4, 8, 16, or 32 at the injector, that over-all tuning can be done at a low average power, avoiding the risk of damaging the Linac while in the process of tuning and transporting the beam.

Two types of accelerating structures are used. Originally, constant impedance, $\pi/2$ structures were installed with input and output transition couplers that proved to be unreliable at powers in excess of 10 MW. At present the second and third accelerating structures have been replaced with constant gradient (no load), $2\pi/3$ structures having compensated iris couplers that use class "c" flat ceramic RF windows.

The microwave power (1300 Mc/s) required by the accelerating section is supplied by three L-band klystrons. The first section is powered by a 10-MW klystron and the other two sections are powered by 20-MW klystrons. The high voltage pulses required by the klystrons are supplied by a typical line type modulator in which a single ceramic thyratron is used to discharge multiple pulse lines in parallel. The pulse lines have individual coils for adjusting the pulse shape for the minimum droop and ripple required to obtain a tight energy spectrum from the accelerator.

The trigger generator supplies the timed pulses to all the various subsystems of the accelerator as well as to the experimental equipment. A solid state trigger generator has been developed[1] for reliability and ease of maintenance. Most of the electronic circuits are on plug-in printed circuit boards to minimize replacement time in case of failure. The trigger generator is capable of supplying continuously variable trigger pulses (from 1 to 720 pulses per s) to the entire four-section system. The injector trigger can be controlled remotely to allow the experimenter to gate the accelerator on and off or operate with single pulses or groups of pulses.

The three-section Linac is operated routinely in a large number of different modes. The electron energy spectrum may with care be optimized to a resolution from 1 to 3 percent full width at half maximum. Under present conditions the machines are available 80% of the time for experimentation. Tuning takes approximately a half-hour to change the mode of operation, and it is not uncommon to accommodate four different experiments in an eight-hour shift. The bulk of tuning time is often spent in piping the beam to satisfy specific experimental conditions. The critical Linac components are now reasonably reliable. The 10 and 20 MW klystrons operate for periods in excess of 7000 plate hours. Ceramic thyratrons have also increased the reliability of the modulators. Over-all modulator operation has been very satisfactory and has yielded the flexibility necessary for trouble-free (15 minute) changeover from short pulse to long pulse operation.

Single Section Linac

The single section Linac is nearly identical in construction to the three-section Linac except that it is optimized for high peak current operation. The single section accelerating structure is a constant impedance, L-band structure with door knob type couplers. It operates in the $2\pi/3$ mode. Radio frequency power is supplied by a 20-MW klystron. The injector for the single section Linac is capable of 35 A at pulse widths between 7 ns and 50 ns. A combination of strong magnetic fields produced by a continuous solenoid and four thin focusing lenses confine the beam from the injector to the accelerating section. At the output of the accelerator, peak currents of 16 A at 12 MeV and 40 ns pulse width have been obtained at repetition rates up to 360 pulses per second. When operating in the long pulse mode, i. e., 0.1-4.5 μs, peak currents of 1.5 A at 8.4 MeV can be obtained (see Fig. 2).

Coupled Linacs

The single section and three-section Linacs have been constructed on the same axis so that they may be run in tandem. The machines are coupled by 17 ft of high vacuum tube. The beam is focused magnetically once between the machines. To accomplish the changeover to coupled operation the injector on the three-section Linac is rotated about thirty-five degrees and turned off. All controls for the single section are then transferred to the three-section Linac control room. This changeover takes about one half hour to execute. The coupled machine is tuned by first optimizing the single section machine using magnetic energy analysis. The beam is then piped into the second machine using nonintercept ferrite beam intensity monitors between Linacs. The two machines are phased properly for maximum beam loading in all sections to obtain the characteristics shown in Fig. 2.

Physical Facilities

At the outset, the facility was planned to permit beam usage with ease by a large number of researchers. As many as 15 beam exit ports have been set up at one time for the performance of research at the facility. The neutron experiments are generally all confined to one of two separate cells shown in Fig. 1. The high resolution port and photonuclear research areas are provided for the low background work. In addition to low residual background levels the high resolution port and photonuclear ports are arranged for measurements in which high energy resolution (0.1% to 2%) of either the electron or positron beams is important.

An important feature of the facility is that personnel may occupy certain areas while radiation experiments are being conducted in other areas. The experiments closest to the Linac generally run at the lowest power levels, thus the outlying cells have negligible radiation levels during operation in the adjacent cells. The cells that can be occupied during operation are carefully interlocked to prevent inadvertent exposures.

Years of experience have lead to the development of a beam output window that satisfies the beam power requirements of the Linac. The window is made of 0.001 in. thick titanium brazed to a standard copper flange gasket using a technique developed at General Atomic. A high velocity blast of air is used as the cooling medium.

The electron beam is diverted to the target locations by a variety of magnet arrangements. The most elaborate arrangement consists of two 36° sector wedge magnets with adjustable pole tips. For experiments in which energy resolution is not important, a simple system consisting of one bending magnet and two independent quadrupole lenses for refocusing the beam after the bend is used. Generally, ninety-percent beam transmission and a well-focused spot can be obtained with this arrangement at seven feet off the Linac beam axis. On the main beam axis a quadrupole pair is placed every 30 feet to refocus the beam.

In the design of high power accelerator facilities one must plan carefully to contend with a variety of specific hazards associated with this type of operation. At the General Atomic facility, these problems include the handling of highly radioactive uranium neutron sources and contaminated source coolants, induced activities in the target rooms and apparatus, short lived air activity, ozone generation, high radiation doses in facility electrical insulation, and possible airborne radioactive contamination from source failure.

Research Facilities

Fast Reactor Spectral Test Facility. During the last several years, facilities for performing precision time-of-flight spectral measurements using the pulsed source technique in fast multiplying assemblies have been constructed. The fast assemblies to be studied are either constructed in the neutron cell where the 70-m flight path is used or in the fast spectrum cell using the 220-m flight path. Two vertical assembly machines are used to position sections of spherical multiplying assemblies. A typical installation is shown in Fig. 3. The flat bed assembly machine is also located in the fast spectrum cell and uses a heterogeneous array of fast reactor fuel materials assembled in a honeycomb structure. The detectors for the fast spectral work are capable of high resolution in timing and energy discrimination. These are basically of two types, proton recoil liquid scintillators, and capture gamma-ray detectors.

Because of the magnitude of the data handling for the fast spectral test facility, an on-line data acquisition computer has been installed. The on-line system has the following features: 12-K word magnetic core memory size, 18 bits/word, including one parity and one memory protect bit, 1.1 μs memory cycle time, 14 interrupt data channels priority under program control, 1.25×10^6 word storage in a magnetic disc-pack.

Facilities for Resonance Cross Section Measurements. This cross section facility involves three intersecting flight paths; 18.6 m, 50 m and 220 m flight paths. The 220-m flight path is being set up at present for resonance capture cross section measurements in the neutron energy range to 2 MeV. Capture, self-indication, and total cross section measurements will comprise a part of the work done with this flight path. A 600-ℓ liquid scintillator detector is presently being installed. Figure 4 shows the detector, collimators, and vacuum system. The intense pulsed neutron source is now used in conjunction with the 18.6-m flight path and a 4000-ℓ liquid scintillator detector to obtain capture and self-indication data concurrently and is equipped with automatic sample-cycling apparatus in conjunction with fast magnetic core data acquisition instruments. The 4000-ℓ liquid scintillator has been modified to operate in a coincidence mode that effectively reduces the observed background count rates.

Thermal Cross Section Facility. A variety of thermal cross sections can be measured using pulsed thermal neutron beams produced by the linear accelerator. The facility consists of a high beam power fast neutron source adjacent to a water moderator designed to produce a pulse of thermal neutrons 50 μs wide. The neutrons from this moderator are timed to the scattering sample, which is located 12 m away. The sample may be polycrystalline or a single crystal with axes oriented in two planes by means of a precision goniometer. Both thermal elastic and inelastic scattering may be studied and the apparatus is especially well optimized for studying relaxation phenomena in neutron diffraction from single crystals.

Fast Cross Section Facility. A number of neutron and gamma-ray detectors and scattering arrangements may be installed at the 50 m flight path end station. Provisions exist for measurements of total and inelastic cross sections in the energy range up to 15 MeV by the time-of-flight technique.

Shield Test Facility (STF). The fundamental purpose for the STF is the differential measurement of neutron transport and of secondary gamma-ray production and transport in shields as a function of energy, angle, and position. Neutron spectra are measured within the shield assembly and on the surface by means of neutron time-of-flight or conventional activation and dosimetry methods. Secondary production is studied by measurements of gamma-ray spectra within the shield mass and by means of secondary production cross section measurements. Assemblies as large as 10 ft x 10 ft x 10 ft can be accommodated. Spectra have been measured at penetrations greater than 10 mean free paths for 10 MeV neutrons. Resolution varies from 5 to 10 percent at 10 MeV to a few tenths of a percent at thermal energy.

APFA-III Facility. The APFA-III (Accelerator Pulsed Fast Assembly) located in the fast spectrum cell is similar to the machine shown in Fig. 3. APFA is a bare spherical fast reactor fabricated of fully enriched (93% U-235) uranium with a total mass of ~60 kilograms. The APFA normally pulsed with the accelerator electron beam at the time the system is at a prompt multiplication of 1000 corresponding to an excess reactivity of 86 cents, which is 14 cents below prompt critical. This reactor is specifically designed to give a variable width high yield burst of radiation for transient radiation experiments. With projected Linac improvements it is expected that the General Atomic APFA-III will have the following characteristics for a maximum pulse: Peak Power - 1500 MW, Pulse Width - 7 μs, Fast Flux (internal) - 3×10^{17} n/cm^2/sec, Fast Flux (external) - 3×10^{16} n/cm^2/sec.

Electron Scattering Facility. The General Atomic Linear Accelerator provides a well collimated and energy analyzed beam of electron whose energy can be varied from 1 to 80 MeV. The experiments performed with this source are divided into dosimetric measurements and spectral measurements. The dosimetric measurements are performed to provide specific data regarding radiation dose at the exit side of a shield. The spectral measurements yield information regarding the energy and angular spectra of emergent electrons and bremsstrahlung as a function of incident electron energy and material. The facility is shown in Fig. 5.

Positron Production and Scattering. Four years ago a positron conversion system was installed in the three-section L-band Linac to provide research capabilities with positrons and monoenergetic gamma rays produced by the inflight annihilation of positrons. The positron system and the photonuclear beam port are shown in Fig. 1. Positrons are produced by electrons striking a high-Z converter target, which is located between the first and second section of the accelerator. Bremsstrahlung generated by the deceleration of the electrons causes pair production and some of the positrons escape from the converter. The secondary particles from the converter are then focused into the next section by means of a simple magnetic lens ($H_{peak} \simeq 3000$ G). The energy of the positron beam may be varied continuously from a few MeV to ~34 MeV, and the energy spread of the positron beam at the exit of the accelerator is ~1.3 MeV, almost independent of positron energy. Calculated and measured positron yields from this system have been published previously.[2] With 135 μA (time-averaged) of 12-MeV electrons incident on the converter, a positron current of a 6.5×10^{-10} A is obtained at the positron tuning port, which is located near the end of the accelerator.

The thermal positron production facility consists of a converter target, energy analyzing magnet system, and electrostatic deceleration field. The positrons are slowed down and focused, resulting in a well collimated and energy analized beam whose energy can be varied from 1 to 1000 eV. This range of energies (with high enough intensity) permits scattering measurements from atoms and molecules. The first study performed at this facility was that of positron hydrogen scattering at energies below the threshold for inelastic processes.

Pulse Radiolysis Facility. The pulse radiolysis facility is used to detect radiation-produced reactive chemical species such as free radicals, positive and negative ions, solvated electrons, and electronically excited molecules. The equipment consists of an optical detection system which is used in conjunction with the 17 MeV accelerator. This combination, which provides, 7 ns pulse width, 16 A current, and transient time resolution in the tens of ns domain represents the most advanced system available in this country. Figure 6 is a schematic of the optical apparatus. The data obtained with this equipment can be related to both weapon effects and the effects of steady-state radiation. Two types of information are obtained. First, absorption spectra of radiation-produced transient species are determined. The spectra serve to identify the species, and intensity of the characteristic absorption may be used to determine the concentration, thus the yield, of both intermediate and final products. Second, the time dependence of the transient species may be analyzed. These data can be used to determine rates, rate constants, lifetimes, and mechanisms of reaction of the species.

References

1. P. R. Heid, Internal Report.
2. R. E. Sund, R. B. Walton, N. S. Norris, and M. H. MacGregor, Nucl. Instr. and Methods, 27, 109 (1964).

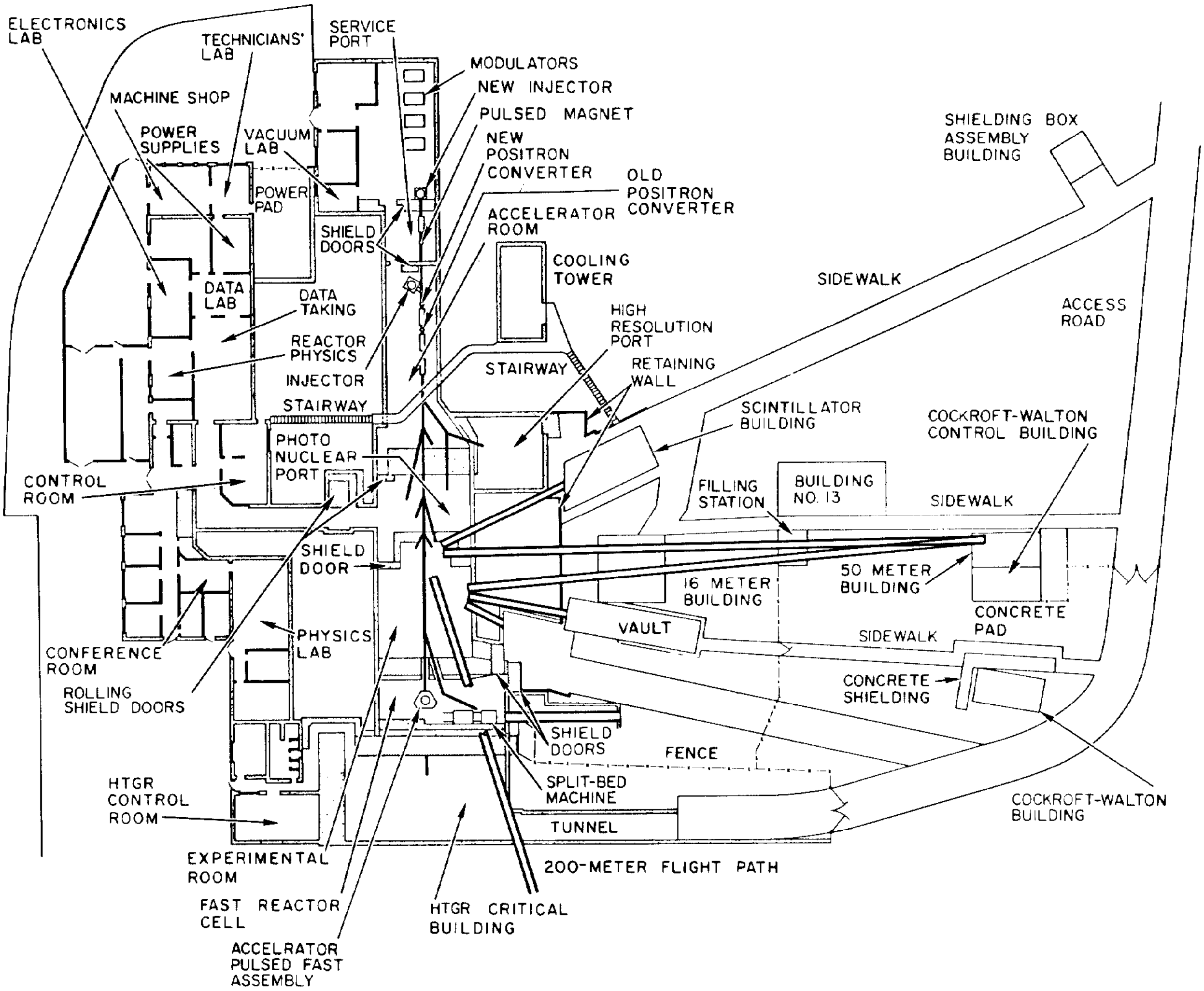

Fig. 1. Layout of Linear Accelerator Facility.

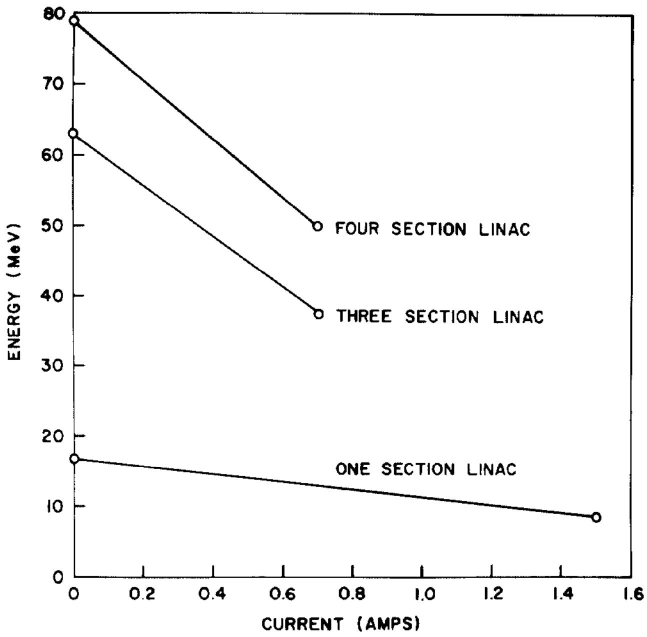

Fig. 2. Beam loading curves.

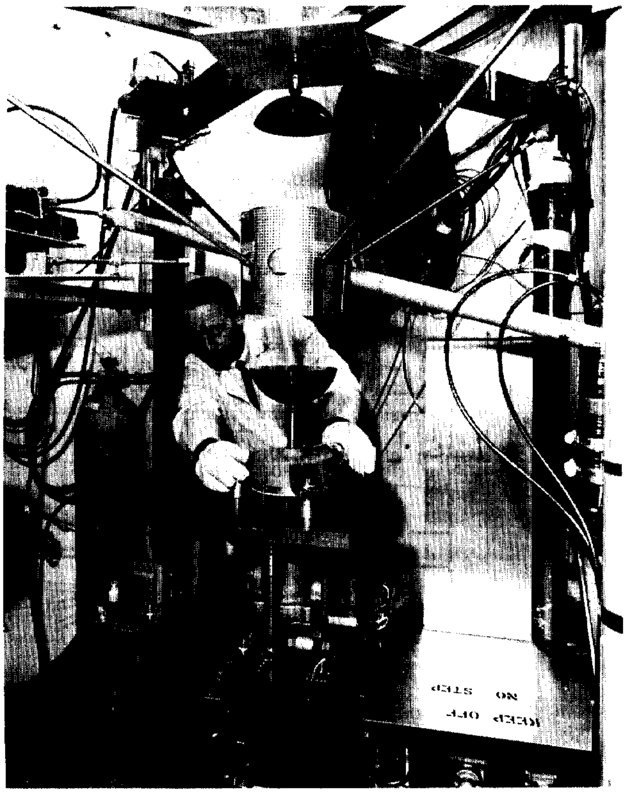

Fig. 3. View of Accelerator Pulsed Fast Assembly.

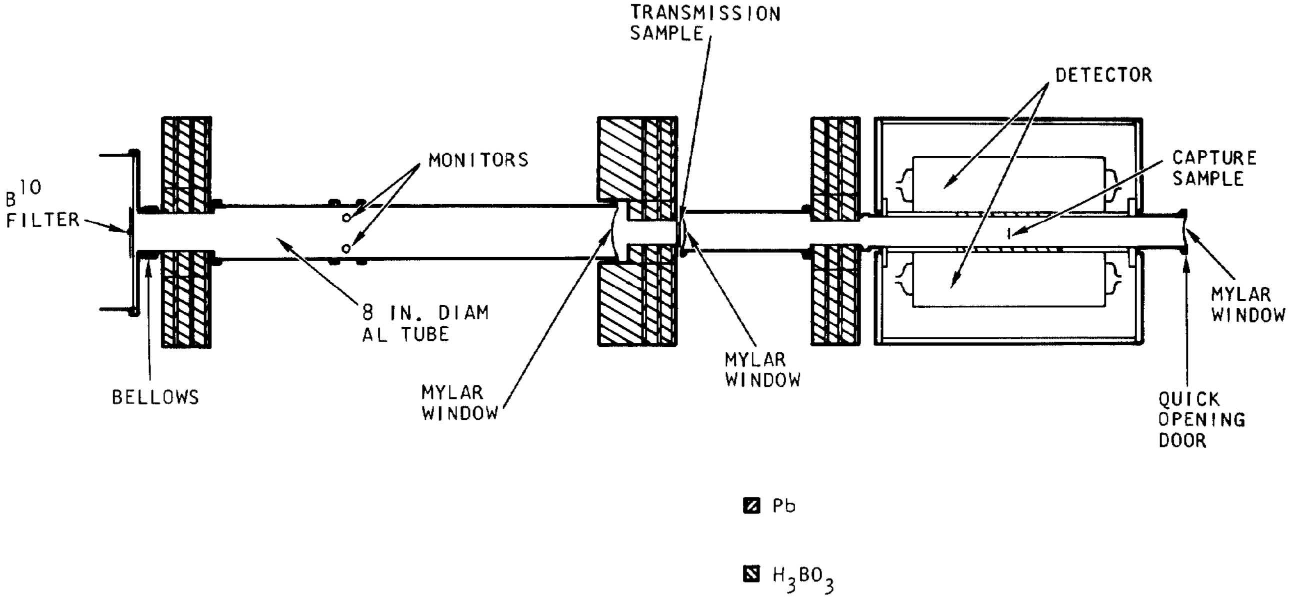

Fig. 4. Plan view of collimators and vacuum system used with 600-liter liquid scintillator at the 220-meter flight path.

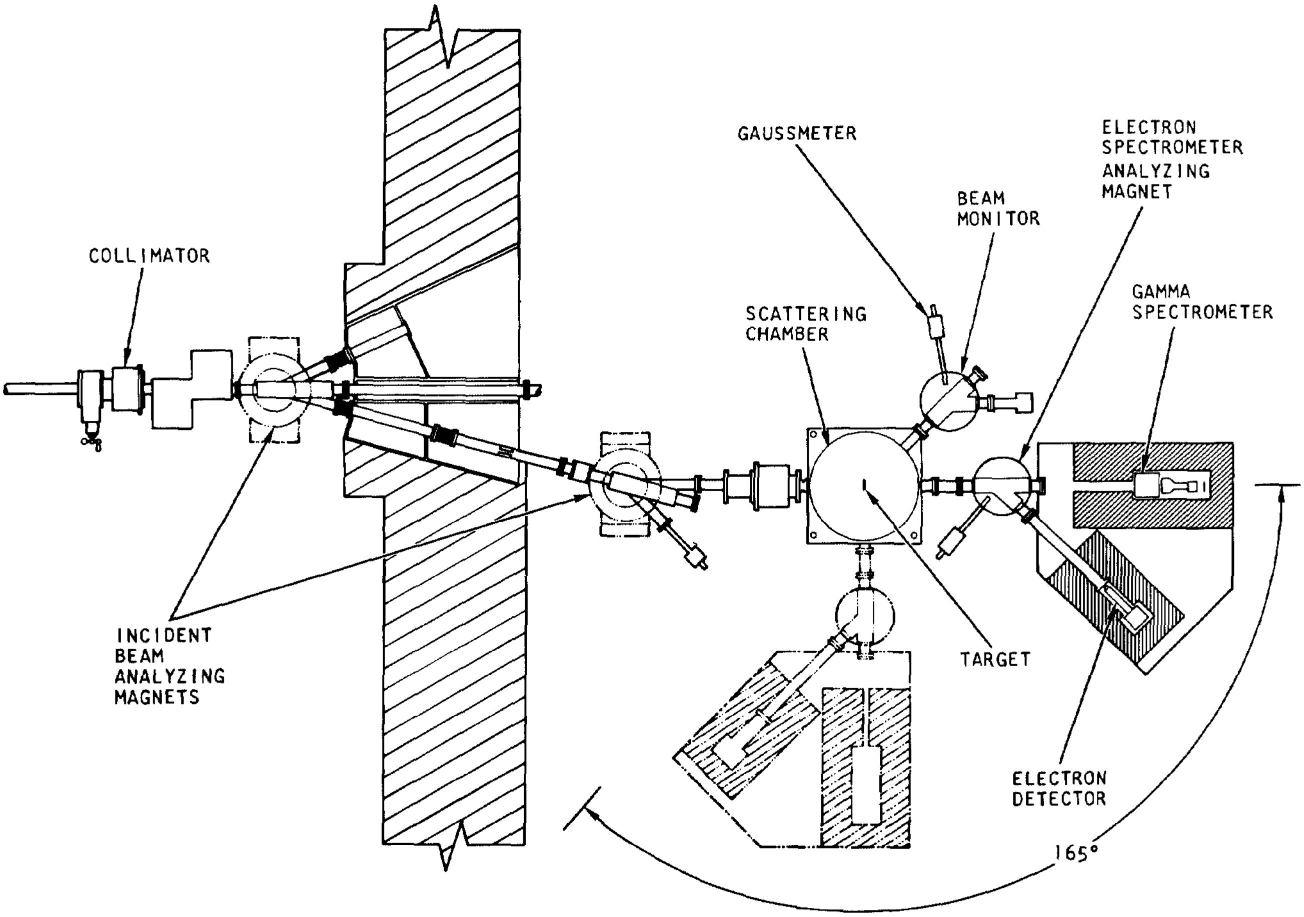

Fig. 5. Experimental arrangement for electron penetration experiments.

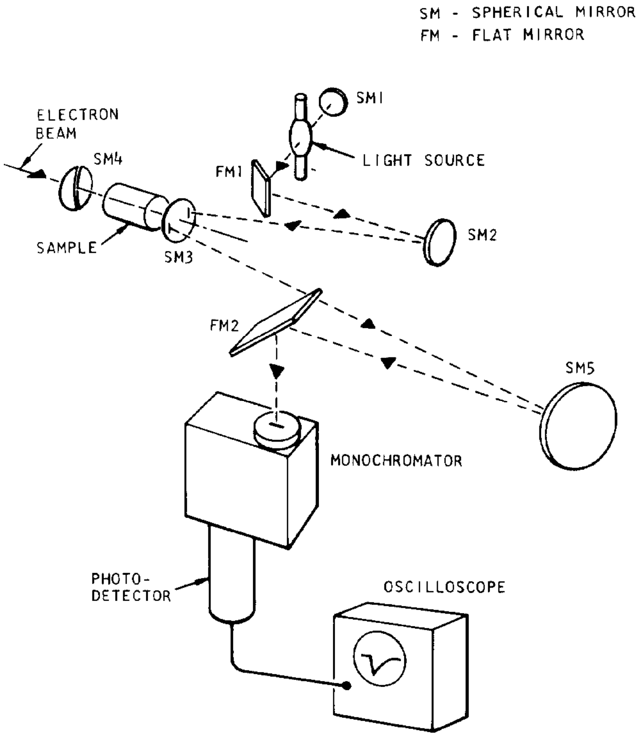

Fig. 6. Schematic of General Atomic pulse radiolysis apparatus.