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NEW APPLICATIONS OF PARTICLE ACCELERATORS IN MEDICINE, MATERIALS SCIENCE, AND INDUSTRY*

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Introduction

Recently, the application of particle accelerators to medicine, materials science, and other industrial uses has increased dramatically. A random sampling of some of these new programs is discussed here, primarily to give the scope of these new applications. This survey is certainly not meant to be exhaustive, and any omissions are regretted. The three areas, medicine, materials science or solid-state physics, and industrial applications, are chosen for their diversity and are representative of new accelerator applications for the future.

New Applications in Medicine

Historically, the application of accelerators to medicine occurred almost simultaneously with the invention of accelerators themselves, as Roentgen rays were used for medical x-ray purposes almost as soon as they were discovered. Recently, the application of accelerator technology to the generation of more exotic radiations for cancer therapy has been at the leading edge of radiotherapy research. Pi mesons, heavy ions, and neutrons are being applied to various tumor types with varying degrees of success. In general, it is still too early to predict success or failure for these research efforts. In pi-meson therapy, there have recently been two new facilities completed and therapy started, in addition to the one older ongoing therapy program at the Los Alamos Meson Physics Facility (LAMPF).

The first of these new programs is at the Swiss Institute for Nuclear Research (SIN) near Zurich, Switzerland. The SIN ring cyclotron operates at over 100-μA average proton current at a peak energy of 590 MeV. About 20-μA current can be diverted to a meson therapy treatment facility on a continuous basis so that, as in the case with LAMPF, a program of pi-meson radiation therapy can be carried on without severe interference with the ongoing physics research program. Figure 1 shows the beam layout at SIN, which allows this beam-sharing mode of operation. The pion delivery system at SIN uses a modified version of the superconducting "Orange Peel" spectrometer, first suggested and later constructed and tested by the Stanford University High Energy Physics Laboratory group for this purpose. In this system, a very large overall fraction of the produced pi mesons is accepted by forming 60 independent "beamlets," all with a common origin and a common focal point. Solid-angle acceptances of up to 1 sr with momentum acceptances of <3% are possible with such a system. Figure 2 shows the layout of the SIN "PIOTRON." Although the accurate delivery of 60 pion beams may seem a formidable task, SIN has made good progress on solving this problem. Initially, the pion channels will be tuned to the same momentum. The patient's tumor is scanned with the beam-stopping radiation peak by mechanically moving the patient within a water bolus to cover the treatment volume uniformly. Future development will see energy modulation within each beam and may remove the requirement for patient mechanical motion. An extremely important and difficult aspect of pion radiation therapy lies in the development of an adequate model of the radiation dose given the patient by the beams. The SIN group has developed a calculational model of the radiation produced by the 60 beams and has been successful in applying this model to the actual body cross section and density variations realized in practical radiotherapy.

This program is presently in the active start-up phase. Patients have been treated in the "PIOTRON," and an active referral network has been established in the Swiss hospital system. Performance, as reported by the SIN staff, indicates an ultimate dose rate of 40 rads/min/liter treatment volume, adequate to initiate trials for therapeutic treatment of a wide variety of tumors.

The second new pion therapy program has been initiated at the TRIUMF facility in Vancouver, British Columbia, Canada. The TRIUMF cyclotron is a negative-ion cyclotron with a proton current of approximately 100 μA at a peak energy of 480 MeV. In the case of the TRIUMF accelerator, the entire proton beam is used for pion generation, and as in the case of LAMPF, multiple-beam lines view the same target. Figure 3 shows the pion beam channel layout at the TRIUMF facility. The pion collection channel used for this facility is of conventional construction, with a chain of conventional bending and quadrupole magnets collecting and purifying the beam for direction to the tumor volume. The system performance allows a peak-dose rate of approximately 20 rads/min in a small volume, and a large field-dose rate of approximately 4 rads/min/liter with a 15-cm stopping width. Eight patients with multiple small skin-nodule tumors have been treated to date. The first treatments were undertaken in December 1979. Several facility improvements are planned in the next year or so, including an increased current capability and inclusion of a permanent magnet-quadrupole very near the target location. Adding a SIN-type superconducting collection system is being considered.

Coupled with the ongoing pion therapy program at Los Alamos, which has treated 150 patients so far and has started phase III clinical trials (randomized patient selection and tumor stages amenable to therapeutic treatment), these new facilities will soon give a clear picture of the efficacy of pion therapy in the control of malignant tumors. Many initial signs point to important contributions from these programs. At Los Alamos, the accelerator development required to make pion therapy possible in a hospital environment has progressed dramatically in the PIGMI program, funded by the National Cancer Institute. With the successful demonstration of the radio-frequency quadrupole accelerator system, a clear route to making a linear accelerator system both economically feasible and compatible in size with a hospital installation has been demonstrated. The accelerator community is prepared to satisfy the medical requirements to make widespread pion therapy a possibility, if the ongoing trials continue to be successful.

The application of heavy ions to cancer therapy is also progressing rapidly. Although no new programs have been initiated in the last few years, the heavy ion therapy program at the Berkeley Bevalac has been quite successful. The LBL accelerator community is actively studying the problems associated with a dedicated heavy ion synchrotron for hospital use.

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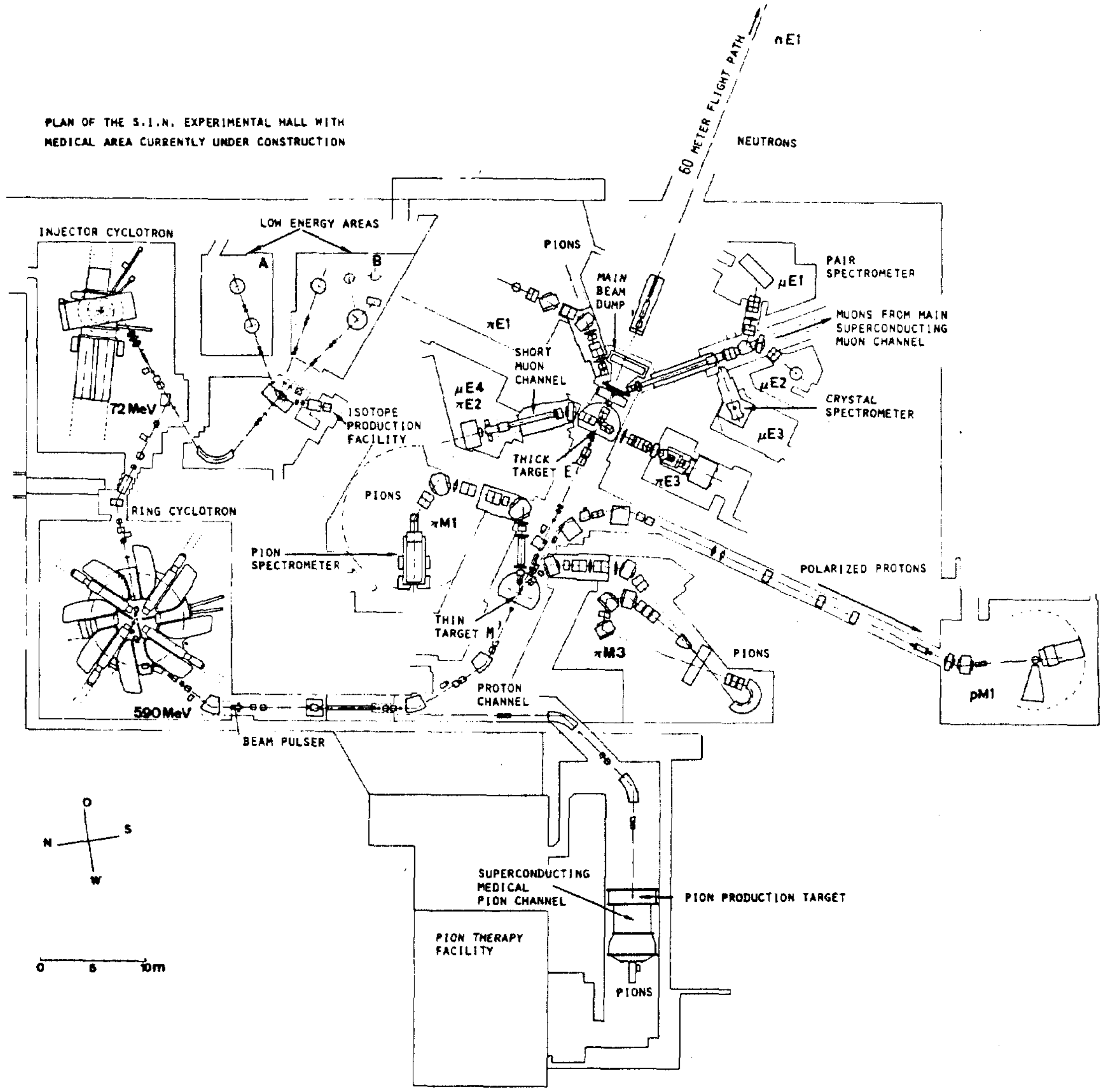

Fig. 1. SIN accelerator and experimental hall layout.

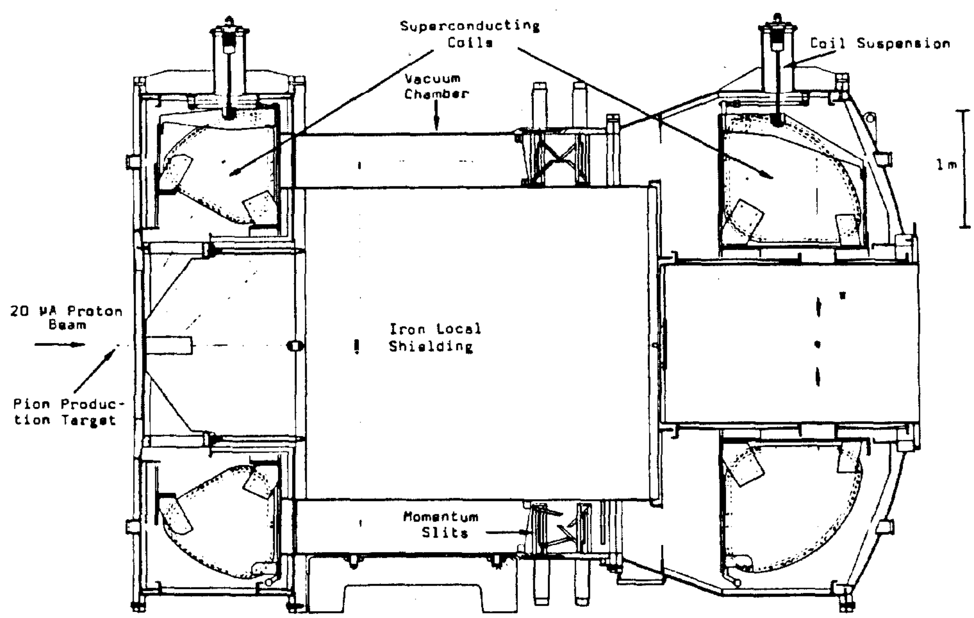

Fig. 2. SIN pion therapy applicator, "PIOTRON." Sixty beams are produced in a pie-shaped configuration about the beam axis.

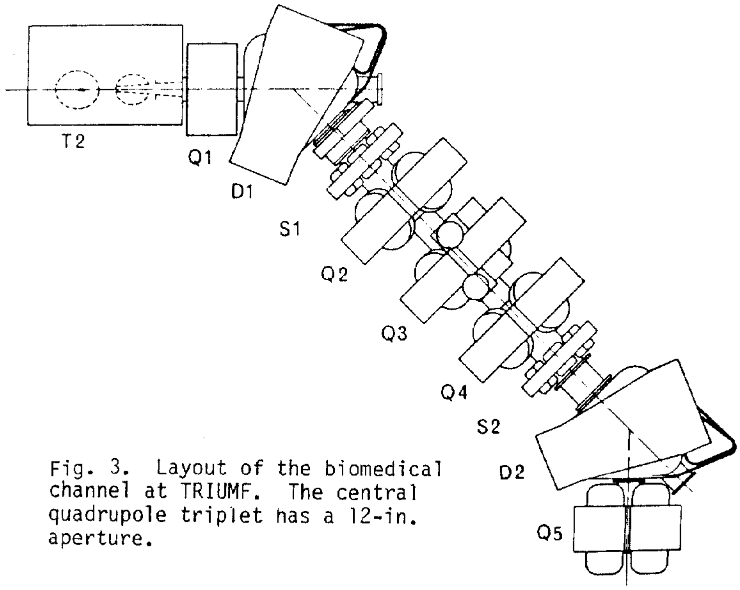

Fig. 3. Layout of the biomedical channel at TRIUMF. The central quadrupole triplet has a 12-in. aperture.

Neutron diffraction can be used to examine structural questions in a fashion similar to x-ray diffraction. However, the neutron interacts most strongly with the nucleus rather than the electron, so that its scattering cross section is such that neutron diffraction often provides unique information regarding crystal or molecular structure. Neutrons are a particularly powerful probe for investigating light atoms such as hydrogen, because of the sizable interaction of neutrons with these atoms (compared to x rays). Neutrons are also essential in studies of the hydrogen bonds that underlie the microscopic properties of broad classes of materials, ranging from soft ferroelectrics to biomolecules.

The determination of complex magnetic structures is almost entirely based on neutron diffraction. The nature of the magnetic order in chromium, rare earth metals, and numerous insulating compounds has been established. In addition, the magnetic excitations of these materials are uniquely probed by inelastic neutron scattering.

Also, the PIGMI technology at Los Alamos, coupled with a high-charge-state ion source, such as the EBIS, makes a very interesting and compact heavy ion therapy radiation source. This combination is being considered at Los Alamos.

New Accelerator Applications in Material Science

Two areas of accelerator application in materials science are the generation of thermal neutron beams by spallation neutron sources for basic materials science research, and the generation of fast neutron beams for radiation damage studies relating to thermonuclear reactors.

Spallation Neutron Sources

Spallation neutron sources for materials science are in operation, under construction, or under consideration in the United States, Great Britain, Germany, and Japan. Operating facilities at present include the IPNS-I, at the Argonne National Laboratory, described in detail by the previous speaker; the WNR facility attached to the LAMPF accelerator; and the pulsed-neutron facility associated with the booster synchrotron at KEK in Japan. The most powerful of these facilities is the IPNS-I at Argonne, where an active program of materials science is under way.

Research using neutron scattering provides essential and unique information about the microscopic nature of a broad spectrum of phenomena occurring in fields as diverse as materials science and biology. The neutron is an excellent probe of condensed matter because it has no charge and, when thermalized, has a wavelength approximately the same as the atomic separations. In addition, its magnetic moment couples it to the magnetic structure of bulk-condensed matter. The neutron acts effectively as a passive probe, causing little perturbation of the system under investigation. Because of the thermal neutron's rather low energy and short wavelength, inelastic neutron scattering can be used to measure low-energy (milli-electron volt) excitations of condensed matter at short wavelengths, a regime that is not accessible by any other modern spectroscopic technique.

Research using neutron scattering typically has been done at large research reactors, such as the ILL reactor in Grenoble, France. Recently, however, the value of the spallation source in the thermal neutron research area has been more widely appreciated. Accelerator-driven pulsed neutron sources are ideal where the source must be pulsed for a short time, be very high in intensity, have a low gamma background, and allow a versatile moderator geometry for tailoring beams precisely to the particular experiment. To gain an order of magnitude in peak thermal neutron flux, the spallation source is the only route available, since reactor power densities become impractical.

I will briefly discuss the two large spallation neutron sources under construction, one at Los Alamos and the other at the Rutherford Lab in England. They illustrate the parameters required for these sources and also two ways of approaching the accelerator problem, one with a rapid cycling synchrotron, the other with a fixed-energy storage ring.

SNS, The Rutherford Spallation Neutron Source. The SNS is a rapid-cycling synchrotron specifically designed for thermal neutron production. The system parameters include the following.

Proton design intensity	2.5×10^{13}ppp
Proton kinetic energy	800 MeV
Injection energy	70 MeV
Repetition rate	53 Hz
Injection scheme	H^- charge exchange
Mean radius of synchrotron	26.0 m
Duration of proton pulse	0.22 μs
Target power	350 kW (160-kW beam)
Average proton current	200 μA

The main technical problem associated with this source is particle loss and the resultant activation of the accelerator components. The intensity of 2.5×10^{13} protons per pulse is essentially the space-charge limit for the ring at injection energy; very careful tailoring of emittance on injection will be required to limit beam spill.

Construction is well under way at Rutherford. The injector linac is the old PLA rebuilt for this repetition rate. Figure 4 shows the layout of the SNS. The entire facility is located in the building complex that housed the NIMROD accelerator, which was decommissioned in 1976. It is now expected that the SNS

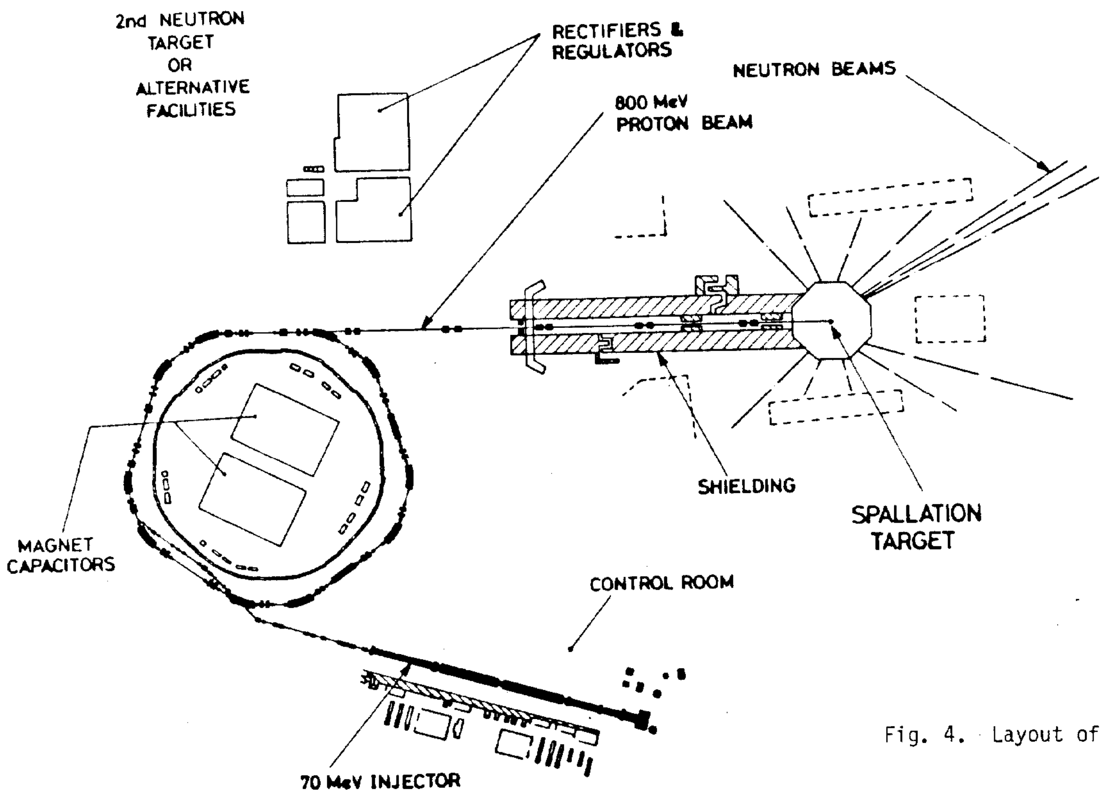

Fig. 4. Layout of SNS facility.

source will turn on in 1985 and that an active research program will follow.

PSR, the Los Alamos Proton Storage Ring. The Proton Storage Ring (PSR) at Los Alamos is a static storage ring using H^- injection of a full-energy beam from the LAMPF 800-MeV linear accelerator. The system parameters include the following.

Proton design intensity	5×10^{13} ppp
Proton kinetic energy	797 MeV
Injection energy	797 MeV
Repetition rate	12 Hz
Injection scheme	H^- charge exchange
Mean radius of storage ring	14.4 m
Duration of proton pulse	0.270 μs
Average proton current	100 μA
Space-charge limit	4×10^{14} ppp

As with the SNS synchrotron, beam loss is a major technical problem to be considered in the design of this source. Special attention has been paid to beam loss in the beam-extraction system to minimize activation. The PSR also operates in a short-pulse mode for fast neutron time-of-flight measurements, and will be used for both materials science and fast-neutron physics. Figure 5 shows the plan view of the PSR.

Construction of the PSR has been started, and completion is projected for 1985. The overall project involves modifying LAMPF for a high-current H^- beam, building the storage ring, and upgrading the neutron-source target for high-average power.

Fast Neutron Source for Materials Damage Studies

The Fusion Materials Irradiation Test Facility (FMIT) is a very high-power deuteron linear accelerator designed to produce fast (14 MeV) neutron fluxes to test material candidates for first-wall application

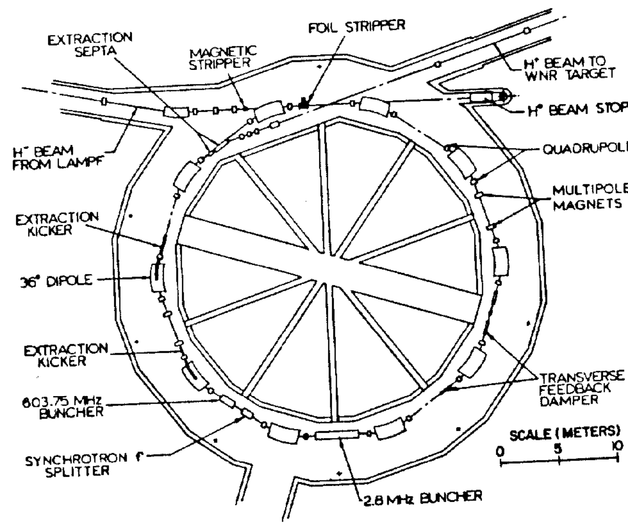

Fig. 5. PSR layout.

in future fusion reactors. FMIT will be, when completed, the highest current ion linear accelerator ever built. Some parameters of the FMIT accelerator are listed below.

Deuteron intensity	100 mA
Deuteron energy	35 MeV
Beam power	3.5 MW
Injection energy	75 kV
Radio-frequency quadrupole	75 kV → 2 MeV
Drift-tube linac	2 MeV → 35 MeV
Total RF power	7.5 MW
Neutron target	liquid lithium
Sample volume 10^{15} n/cm^2/s	7 cc

The FMIT accelerator is to be built and operated in Hanford, Washington, by the Westinghouse Hanford Company. Design of the accelerator portions of the project and the operation of a 5-MeV prototype are the responsibility of the Los Alamos National Laboratory. The prototype is more than half complete, and operation is expected in 1982. Completion of the FMIT facility is expected in 1985.

An interesting feature of the accelerator combines a low-voltage injector and a radio-frequency quadrupole accelerator system to provide injection into the drift-tube linac. The radio-frequency quadrupole design tube captures 95% of a direct-current 75-kV ion beam, bunches this beam, and accelerates it to the required 2 MeV. The beam's target is unique; it must dissipate 3.5 MW of beam power while providing a very high conversion from deuterons to fast neutrons. The liquid-metal coolant technology developed for fast-reactor systems will be adapted to provide a windowless flowing lithium target for this neutron production. Figure 6 shows a layout of the FMIT accelerator system with beam transport to two target stations.

New Applications in Industry

The New England Nuclear Company has undertaken the construction of a very large proton linear accelerator for the commercial production of radioactive isotopes for its customers. Some parameters for this accelerator include the following.

Proton energy	45 MeV
Proton intensity	5 ma avg
Injection energy	750 keV
Beam power	225 kW
RF duty factor	12%
Cavity length	27.65 m
Number of drift tubes	108
Focusing system	permanent magnet

The design of this accelerator is conventional except for the focusing system, which uses for the first time, in a linear ion accelerator, permanent magnets located inside the drift tubes of the resonant radio-frequency cavity. This is a significant advance in accelerator technology and should result in a reliable and elegant system for this industrial use. First operation of the NEN linac is expected in about one year. The energy is chosen to optimize the production of ^{201}Tl, an isotope now in very great demand for medical applications.

In conclusion, I can only point out that I have barely scratched the surface of new applications of particle accelerators. Many lower energy machines are being used for medical diagnosis and therapy, in solid-state physics, and in industrial applications, and are now making a significant contribution to our gross industrial output. I believe the next decade will see further substantial use of accelerator technology in fields far from those where this technology was first developed.

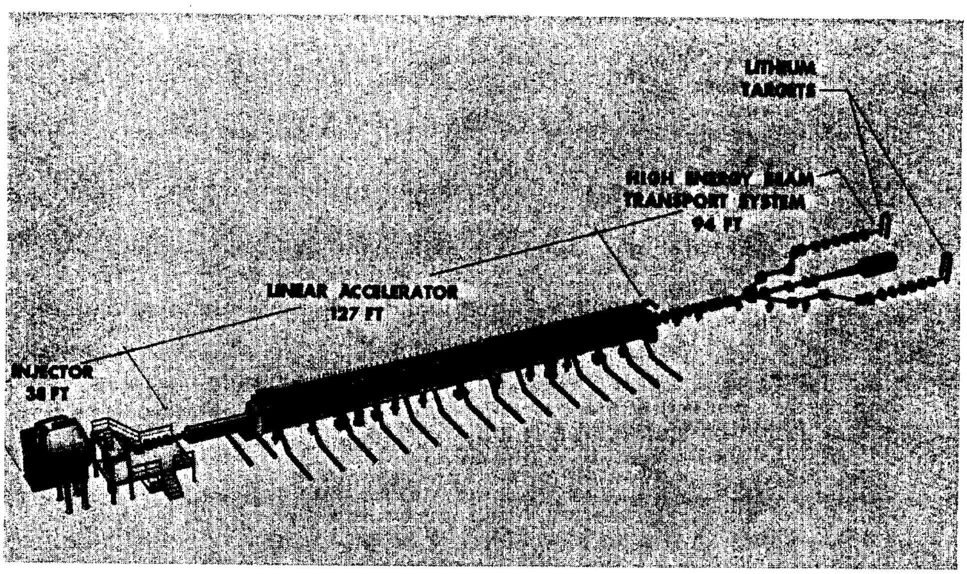

Fig. 6. Layout of the FMIT accelerator system.