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# DESIGN FEATURES AND PERFORMANCE OF THE LAMPF HIGH INTENSITY BEAM AREA*

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## Summary

LAMPF is a multi-purpose high-intensity "meson factory" capable of producing a 1 mA beam of 800 MeV protons. The three target cells and the beam stop facilities in the high intensity area have many special design features that are required for operation in the presence of high heat loads and intense radiation fields where accessibility is extremely limited. Reliable targets, beam windows, beam stops, beam transport and diagnostic components, vacuum enclosures, and auxiliary systems have been developed. Sophisticated remote-handling systems are employed for maintenance. Complex protection systems have been developed to guard against damage caused by errant beam. Beam availability approaching 90% has been achieved at currents of 600-700 μA. A new facility for direct proton and neutron radiation effects studies will be installed in 1985. The new facility will provide an integrated spallation neutron flux of up to $5 \times 10^{17}\ \mathrm{m}^{-2}\mathrm{s}^{-1}$ and will enable proton irradiation studies in the primary beam.

## Overall Design Features

LAMPF is an 800 MeV proton linac capable of simultaneously accelerating $H^-$ ions to energies in the 200-800 MeV range. An overview of LAMPF was presented at the 1981 ICANS meeting in a paper entitled "Operating Experience with the Meson Factories," by R. J. Macek.[1] The principal design goal for LAMPF was to provide high-intensity (up to 1000 μA) proton beams for "meson factory" use for a number of non-interfering secondary beams of pions and muons, while also providing low-intensity variable-energy polarized and unpolarized primary beams, and additionally providing high-peak-intensity 800 MeV proton beams for a pulsed neutron facility at the Weapons Neutron Research (WNR) area.[2] Starting in 1985, LAMPF will also provide up to 100 μA of $H^-$ beam for injection into the 800 MeV Proton Storage Ring (PSR) now under construction.[2]

A layout drawing of the LAMPF experimental areas is given in Fig. 1. Low intensity beam from the accelerator is bent 45° to the left at the switchyard to serve the needs of experiments that utilize variable energy protons and neutrons at three target stations. High-peak-current beam is bent 90° to the right at the switchyard for delivery to the WNR and the PSR areas. The high-intensity main beam, currently operating at about 700 μA average current with a macroscopic duty factor of six percent, is transported through the switchyard to Beam Area A where it passes successively through three graphite production targets that serve six pion and muon beams. After passing through the three targets, the residual beam (reduced to about 745 MeV in energy and to about 2/3 of the incident current) is transported to the beam stop area for isotope production,[3] neutron and proton irradiation studies, and neutrino experiments.

The use of sequential targets mandates several design characteristics. Transport elements must be scaled to handle beams of large phase space. Quadrupole focusing elements must be placed as close as possible downstream of the targets to conserve useful beam. Collimators capable of accepting high power levels are needed to shield transport elements, diagnostic devices, and vacuum joints from intense heat loads.

Operation at very high intensity requires accurate knowledge of beam optics, precision in beam tuning, and the utilization of special radiation-hardened diagnostic devices (see "Radiation Resistant Beam Components at LAMPF," presented by R. J. Macek at this conference).[4] Fail-safe, fast-acting, redundant protection systems against faulty beam control must be provided, as a missteered high-intensity beam could cause severe component damage in times of the order of a second.

Target and beam stop areas must be heavily shielded, and, of course, become highly activated. Residual gamma ray levels up to $10^5$ R/h have been observed at LAMPF. Maintenance and replacement of targets and beam line components must be done by remote handling methods in order to avoid unacceptable radiation doses to personnel. At LAMPF, the "Monitor" system of special components, tools, and mobile manipulators is used for remote maintenance. Key elements of this system include highly maneuverable and flexible manipulators mounted on a remotely controlled hydraulic boom, remote-control television viewing systems, and remote crane controls. See another paper presented at this conference for more details: "Remote Handling at LAMPF," by D. Grisham and J. Lambert.[5]

Auxiliary systems require special attention at a high-intensity facility. Water-cooling systems must be designed for high levels of activation, including the generation of large quantities of tritium and $^{7}$Be. Maintaining high-purity low-conductivity water systems is particularly difficult in high radiation areas. Vacuum systems cannot be exhausted into personnel areas or experimental caves. Air activation (e.g., the production of $^{10}$C, $^{11}$C, $^{13}$N, $^{16}$N, $^{15}$O, and $^{41}$Ar) will occur where main beams or scattered beams pass through air. Waste products and trash from beam areas pose a hazard to personnel and precautions must be taken to protect the local environment.

## Target Cell Features

LAMPF's intense beams place extreme operational requirements on pion-production targets, target cell components, and shielding. Targets and nearby components must operate at high temperatures in a vacuum and in intense radiation fields. During routine operation, the beam power is more than 500 kW, and nearly 1 MW of power was delivered during a recent 1200 μA test run. This power is distributed between three target cells and the beam stop area, with the latter absorbing about 2/3 of the total. Target cell enclosures and components are water cooled, as are the vacuum window and the beam stop. Materials of choice include stainless steel for enclosures and Inconel 718 for beam windows, with OFHC copper being used for collimators and the beam-absorbing plates of the beam stop. A drawing of the LAMPF beam stop design is shown in Fig. 2. No failures have been experienced with this design. Target box enclosures now employ a double-wall design with highly effective cooling provided by carefully directed water circulation between the two jackets. Regions of highest heat load have copper inserts that are welded directly to stainless steel. Fig. 3 shows the newest LAMPF target box, with collimated channels for two secondary beams ($P^3$ and SMC) and a radiatively-cooled rotating wheel target.

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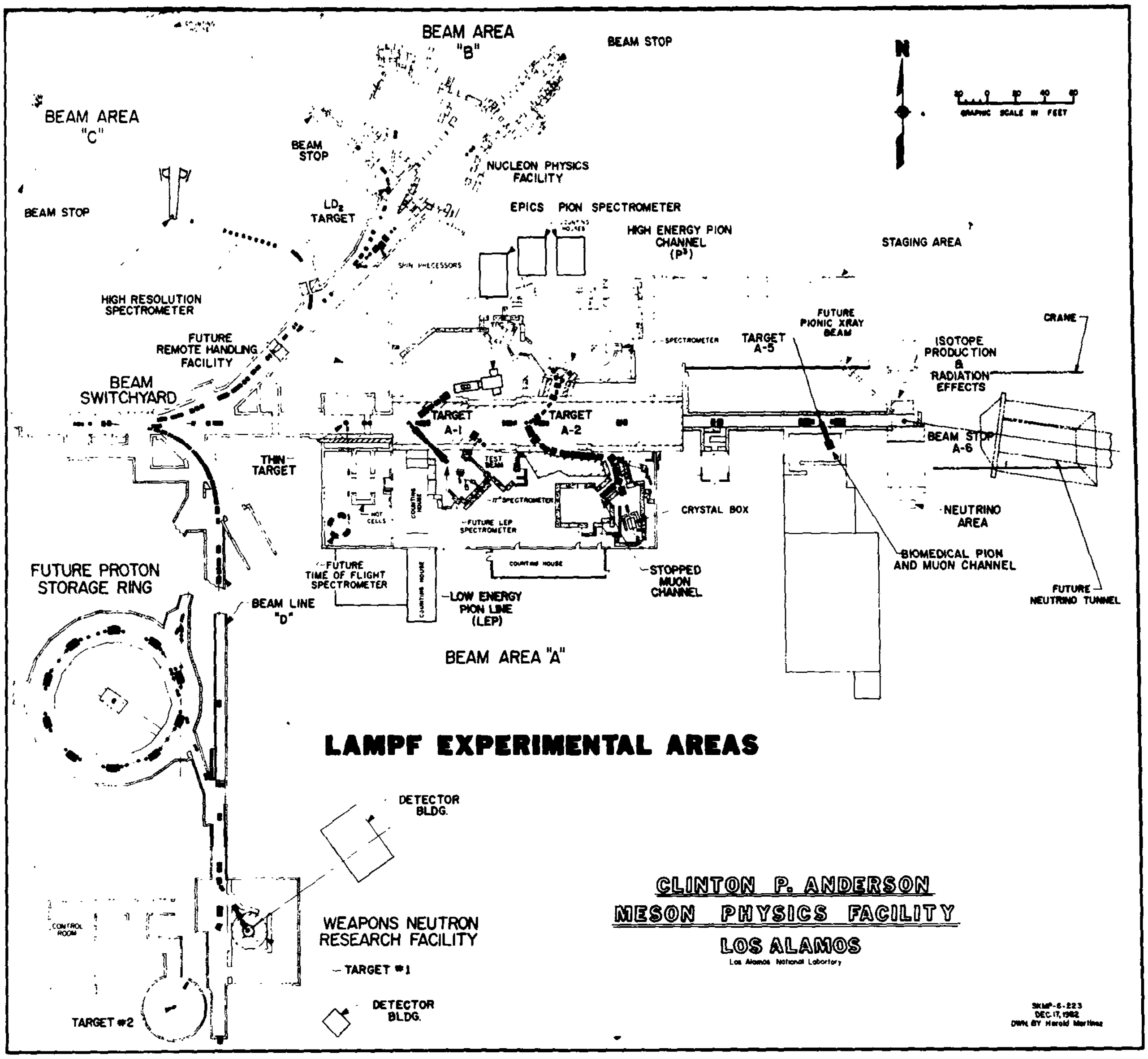

Fig. 1. LAMPF Experimental Areas

Vacuum enclosures and collimators are subjected to heat-cycling to temperatures in the 300 C range, while temperatures of about 500 C have been observed on the main beam window. All-metal vacuum seals are located away from the high heating rates and are shielded for minimal thermal cycling. Water-cooled target boxes and beam line components at LAMPF are more fully described elswhere in these Proceedings[4] and in two previous publications.[6,7] Fabrication techniques are continually developed to increase operational reliability and lifetime, and schemes to ease installation, alignment, and removal by remote handling are steadily improved.

Graphite targets of two different types are used for pion production at LAMPF. At two target cells, rotating-wheel radiation-cooled polycrystalline graphite targets are used, while a water-cooled pyrolytic graphite target is used at the third target station. Both of these basic target designs have been successfully developed to the point of high reliability. The principal design concern for the rotating target has been with the bearings. Satisfactory performance is now obtained from bearings using a proprietary powder metallurgy product containing $MoS_2$. The principal concern for the stationary pyrolytic graphic target has been deterioration of strength and conductivity, accompanied by material swelling. This occurs in the small beam-spot area where thermal stresses and radiation damage are extreme. Target development at LAMPF and detailed descriptions of the target assemblies are given elsewhere in these Proceedings[4] and in three previous publications.[8-10]

Magnets and beam diagnostic instrumentation must be able to survive the extreme radiation and heat conditions in the target cells. These devices are described elsewhere in these Proceedings.[4]

Massive shielding and high activation levels combine to limit very severely the opportunity to carry out routine trouble-shooting efforts. Electrical faults, vacuum leaks, cooling water leaks, etc., can and do occur deep within the shielding. Beam components are generally inaccessible quickly, and are always unapproachable. This necessitates the adoption of special techniques for diagnosing hardware problems. These include the use of redundant interlock systems, special cabling, and the employment of numerous prepositioned tubes that penetrate the shielding to enable helium leak checking.

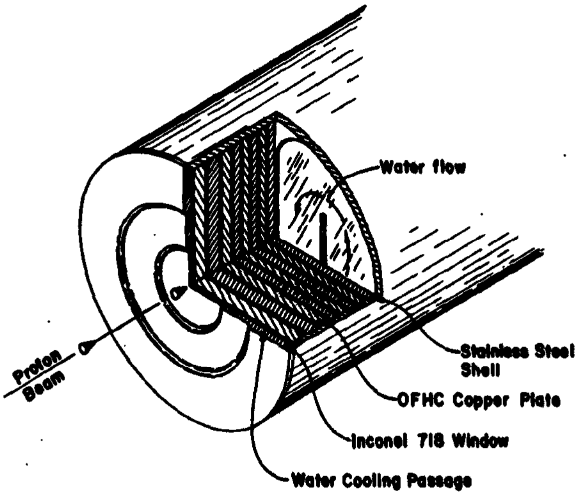

Fig. 2. LAMPF Beam Stop

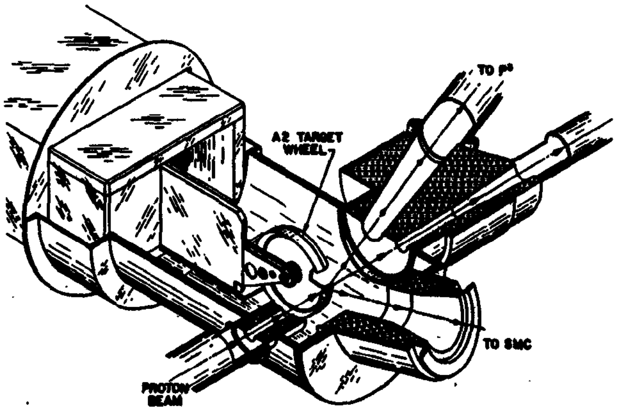

Fig. 3. A-2 Target Chamber

## Beam Diagnostics and Protection Systems

A comprehensive system of beam diagnostics and beamline protection devices and instrumentation is in place for the high intensity primary beamline. In a paper of this length, only selected points can be mentioned. Additional information is presented in two other papers at this conference,[4,5] and in prior documentation in the literature.[11,12]

In general, beam diagnostic instrumentation is used to obtain data, such as beam position, spot sizes and losses, which are useful for tuning and monitoring important beam parameters. The emphasis here is on accuracy, large dynamic range (0.1-1000 μA), completeness and flexibility. Computerized data acquisition, processing, logging, and display in the central control room are necessary features for effective control of the beam.

Protection devices and instrumentation, while often useful for diagnostic purposes, have as their main function the prevention of physical damage to beamline components from errant, high-powered beams. Fast, automatic response, redundancy, fail-safe, highly reliable operation, and credibility with operations personnel are important criteria for the protection system. Personnel protection is a related, but separate, issue not discussed here. In the meson area beyond the switchyard, components of both systems must be long-lived, radiation resistant, and remotely serviceable.

Beam profiles are obtained by sampling secondary emission signals from wire scanners or wire grids known as harps. Wire scanners are used in areas of hands-on maintenance, such as the beam switchyard, while radiation-hardened harps are in place in the primary beamline of the meson area. A schematic layout of the A-2 Target Cell is shown in Fig. 4.

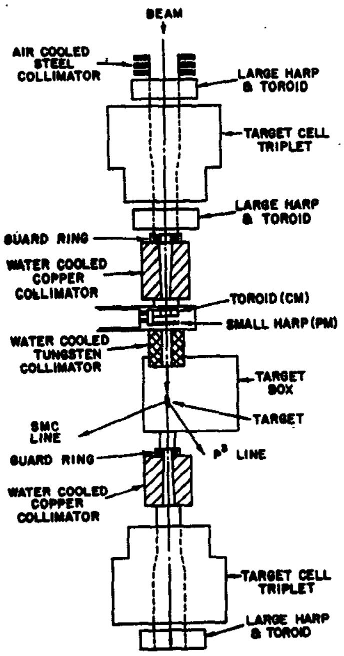

Fig. 4. Layout of the A-2 Target Cell

Harps are located at the entrance and exit of the target cell and at two interior points. The spot sizes obtained at these four locations are sufficient, in principle, for a complete determination of the beam envelope parameters including extrapolation to the production target. In practice, the uncertainties in the profile measurements and the magnet transport parameters combine to produce larger-than-desired, but still acceptable, uncertainties in the spot size estimate at the target. A profile measurement closer to the target would be desirable for greater accuracy; however, the difficulties of retrofitting and of operating close to the target are likely to prohibit any improvements in the near future.

Beam currents are accurately (~1 μA) measured with toroids configured as beam current transformers. Beam halos or spills are sensed in the secondary emission guard rings located in front of collimators. In the lower-spill areas, such as the beam switchyard, beam spills are detected by scintillator detectors.

The beamline protection system is composed of a number of fixed-aperture collimators for passive protection of components, plus hardwired instrumentation which detects unacceptable operating conditions and either shuts down the beam completely or automatically limits the current to acceptable levels. Typical locations for collimators are also shown in Fig. 4. Collimators are the limiting apertures of the beamline; they serve to shield components from excessive beam-induced heat loads and to reduce or limit spurious radiation-induced signals on instrumentation.

Anomalous overall beam losses which exceed preset tolerances are sensed by a hardwired transmission monitor based on beam current-sensing toroids. Beam spills are directly detected at specific locations by the system of secondary emission guard rings and scintillation detectors mentioned earlier. All of these instruments limit the average current through the so-called "fast protect" system. In this manner, the current is limited to a safe level, but enough beam is available for tuning or trouble-shooting.

Temperature sensors are radiation-hardened thermocouples or thermal switches. Beam is automatically interrupted when excessive temperatures are sensed at critical locations, such as a vacuum flange or the vacuum window at the end of the beamline. Poor vacuum interferes with proper functioning of harps, guard rings, and current monitors. Poor vacuum results in more rapid oxidation of targets and is often a precursor of greater difficulties. For these reasons, beam is also interrupted when the primary beamline vacuum exceeds $10^{-2}$ Torr.

Sensor data and status information from the protection system are acquired by the central control computer for logging and monitoring purposes; however, we do not rely on computer processing for the decision to interrupt beam. Dedicated analog electronics and hardwired logic elements process signals and automatically interrupt the beam when pre-established conditions are detected. Operating experience for several years has shown this to be an effective system. If has prevented major damage from the effects of high-powered errant beams.

## Operating Experience

LAMPF has been operating at high intensity for more than five years, with average currents gradually climbing from 300 μA in early 1978 to periods of 700 μA operation in late 1982. A high intensity beam test was carried out successfully at 1200 μA in February 1983. Beam availability has been close to 90% during recent production runs. The yearly operating time, which is sharply dependent upon budgetary strength as well as major maintenance needs, will fall off to well below 3000 h of high-intensity research in 1983 after several years in the 3400 h range. In a typical year about 60 nuclear science experiments are carried out by about 450 scientists, most of whom are members of university research teams. The experimental areas can serve 10 to 12 simultaneous experiments, exclusive of pulsed neutron experiments at the WNR facility. The record of LAMPF's high intensity operation to date is presented in Fig. 5.

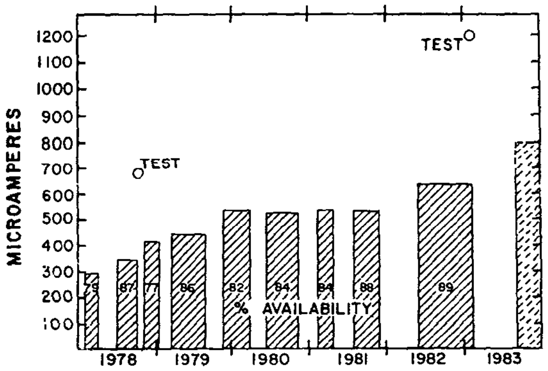

Fig. 5. LAMPF High Intensity Operation

After reaching production currents of 500 μA several years ago, LAMPF's management chose to emphasize high reliability and research output instead of increased intensity. Target cell and beam stop components that were marginal are being replaced or upgraded as beam schedules and resources permit. The normal production current for the near future is expected to be 700 to 900 μA.

Through the development of increasingly advanced remote handling techniques, and through the practice of good staff discipline, it has been possible to hold radiation exposures to maintenance personnel to limits that have not increased during the past six years--a period when hardware activation has increased an order of magnitude.

LAMPF's basic schedule has been changed to a format of long running periods (~6 months) alternating with long shutdowns during the 1982-1985 period. Such a schedule allows lengthy major improvements to be carried out, and also results in some economy of operation through the reduction of tune-up and checkout periods. In a major facility upgrade that required a full remote handling approach, LAMPF's A-2 target cell was completely rebuilt during the 1983 long shutdown. This will be followed by the replacement of the A-1 target cell in 1984 and a major revision of the beam stop facility in 1985.

## Neutron Facilities at LAMPF

Although a major research program utilizing spallation neutrons is based at the Weapons Neutron Research Facility (WNR), described elsewhere in these proceedings,[2] there exists at LAMPF additional opportunity for realizing a spallation neutron flux. At present, at the beam stop area (Target Station A-6), it is possible to emplace samples in a neutron flux of $\sim 1 \times 10^{17}\,\mathrm{m}^{-2}\mathrm{s}^{-1}$.[13] Line of sight apertures are available at 5° and 135° relative to the direct proton beam. Neutrons, as well as protons, pions, and other secondaries, are generated as the incident proton beam (~745 MeV at 500-700 μA) interacts with isotope production targets and finally with the beam stop. These facilities have been used for a limited number of radiation damage/effects studies, as well as for neutron flux and spectrum measurements.

Now, a major upgrade of the beam stop area is in progress. This effort has practical application for LAMPF: improved environment for beamline diagnostics, improved shielding, the elimination of cracks to capture activated gas, remote handling and shielded transport of radioactive material, and rapid repair/replacement of components or experimental hardware.

A new facility for both direct proton and neutron radiation effects studies, improved facility for high-speed ("rabbit") and ultra-high-speed ("gas-jet") isotope identification, and access for additional experiment initiatives in nuclear and solid state physics, will be provided at the upgraded beamstop area.

All penetrations into the new target chamber are vertical shield plugs that support individual experiments or beam line components. A basic design criterion is that all services, including cooling water and controls needed for equipment and experiment, be carried with the shielded insertion plug for the component that they service. All connections will be made at the top of the shield plug. The line-of-sight capability has been retained.

The new design is shown in schematic form in Fig. 6. Handling and subsequent transport of radioactive material is accomplished by employing a remotely-operated bottom-entry shielded cask, shown schematically in Fig. 7.

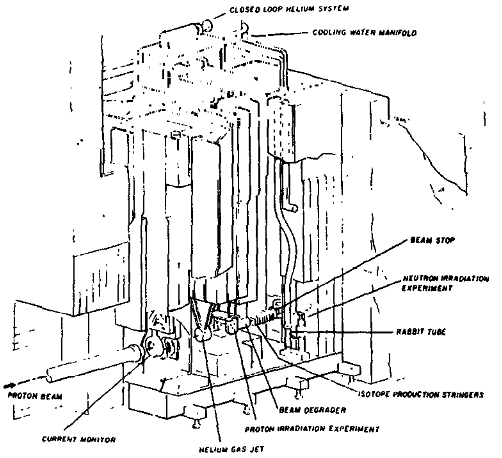

Fig. 6. Schematic layout of the new LAMPF Target Station A-6.

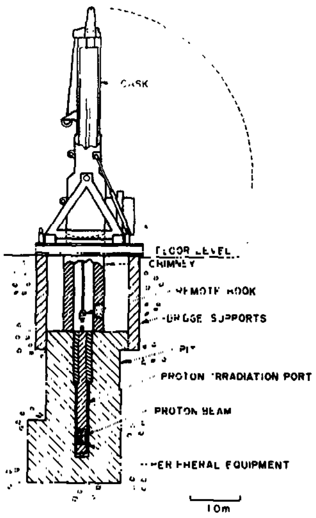

Fig. 7. Schematic showing the removal of a shield plug and experiment. Note the scale.

As an aid in the design of this facility, Monte Carlo calculations (2) using the Monte Carlo Code for the Transport of Neutrons and Protons (MCNP) and the High Energy Transport Code (HETC) were done to give an estimate of the expected neutron and secondary particle flux and spectrum at all locations in this facility. These results were used to design the placement of water-cooled shielding.

Fig. 8 shows an example of the results of the calculation. This histogram predicts the neutron flux and spectrum adjacent the second isotope production target. This location was found to have the maximum neutron flux in the facility, according to the calculation. Here, with LAMPF at 1000 $\mu$A, the integrated neutron flux was calculated to be $\sim 5 \times 10^{17}$ m$^{-2}$ s$^{-1}$.[14] Notice that substantial numbers of high energy (>20 MeV) neutrons will be available. Twelve independent penetrations into this neutron area will be available.

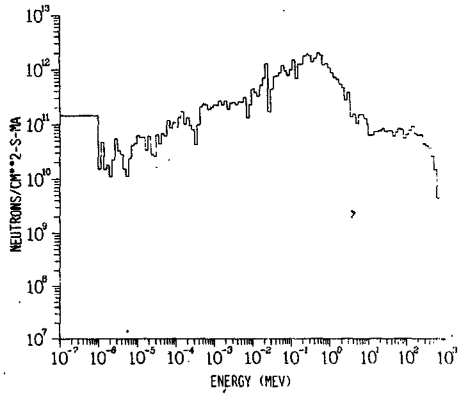

Fig. 8. Neutron flux and spectrum near the second Isotope Production Stringer calculated with MCNP and HETC.

Plans call for the completion of this facility in spring 1985. Several experiments have been identified, including a systematic study of materials intended for the German spallation neutron source (SNQ) target wheel.

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