Proceedings of International Collaboration on Advanced Neutron Sources (ICANS-VII), 1983 September 13-16
Atomic Energy of Canada Limited, Report AECL-8488

RADIATION-RESISTANT BEAMLINE COMPONENTS AT LAMPF*

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Summary

A variety of highly radiation-resistant beamline components have been successfully developed at LAMPF primarily for use in the target cells and beam stop area of the intense proton beamline. Design features and operating experience are reviewed for magnets, instrumentation, targets, vacuum seals, vacuum windows, collimators, and beam stops.

Introduction

Beamline components for the target cells and beam stop area of the 1 mA, 800 MeV main proton beam at LAMPF are exposed to very intense radiation fields. The requirements for reliable operation in this environment are formidable. The components must be highly resistant to radiation damage, be able to dissipate large beam-induced heat loads, be remotely serviceable, and be highly reliable. The development of components meeting these requirements has been a long-term challenge for the experimental areas staff.

In practice, radiation hardening has meant the exclusion of plastics and other organic materials from use in these components. Less familiar, substitute materials, such as ceramics, mica, mineral-insulated cable, etc., while very radiation resistant, have other properties which are not always desirable and have lead to modes of failure other than from radiation damage. For example, ceramics are highly radiation-resistant electrical insulators, but they are often porous or hygroscopic and lose their insulating properties in the presence of moisture. In addition, they are brittle and easily fractured during some handling operations.

The remote handling and servicing of highly radioactive components is a major, if not dominant, design consideration. As a first criterion, extraordinary reliability is desirable so that less frequent remote servicing is needed. Secondly, the procedures of remote handling in the confined space of a target cell are restrictive and time-consuming. Simplicity of design, of operation, and of installation cannot be over-emphasized.

Magnets

Three different types of mineral insulation have been used successfully at LAMPF to construct radiation-hardened magnets: 1) An inorganic, castable cement,[1] 2) Arc-sprayed alumina,[2] and 3) Mineral-insulated cable from Pyrotenax of Canada, Ltd.[3] The mineral-insulated quadrupole magnets of the drift-tube linac have had a very successful operating history for more than 10 years. They are insulated with a castable cement consisting of a calcium aluminate binder with 60-mesh aluminum oxide filler. It was developed at Los Alamos primarily to withstand the 1500° Fahrenheit temperatures encountered during the H_2 brazing furnace cycle used in the fabrication of the drift-tube bodies. This cement is hygroscopic and can pick up moisture from the air. However, for the drift-tube application, this is not a problem since the magnets operate in a soft vacuum of about 50×10^{-3} Torr.

Coils for magnets close to the meson production targets in the experimental area target cells are most commonly radiation hardened through the use of the mineral-insulated Pyrotenax cable. This cable consists of a water-cooled inner conductor, a layer of powdered MgO insulation, plus an outer copper sheath to contain the MgO. This insulating material is hygroscopic and will develop low electrical resistance when exposed to air for a period of time. Therefore, the ends of the cable are terminated with ceramic seals to keep out air and moisture and to insulate the sheath from the inner conductor. Ceramic water-carrying insulators with brazed-on metal ends are used to connect the water circuits of the conductors to the water piping.

Over 60 mineral-insulated magnets of this design have given generally satisfactory service at LAMPF since 1972.[4] Radiation damage has not been a major problem. Most failures have other causes which are usually related to water problems. One ceramic insulator failed by electrolytic corrosion in the early years of operation during a period when the water conductivity was not kept below 10^{-6} mho/cm, but rose to 10^{-4} mho/cm. High-pressure water leaks in the magnet or in nearby water-cooled components have caused several failures, such as ground faults and interrupted thermal interlock strings. A thoroughly wet magnet suffers from electrolytic corrosion of thermal switches and interlock wiring. Corroded copper wiring becomes brittle and breaks easily.

Overheating of the target cell triplets (TCT) has occurred in recent years. Some of these magnets operate at 10-15% above design current and normally run close to a thermal trip point. A layer of CuO builds up in the water passages and apparently reduces the heat transfer from conductor to the cooling water sufficiently to raise the conductor temperature several degrees. Backflushing the magnets for several hours with a weak (4%) solution of phosphoric acid removes CuO and will restore the magnet to an operable condition. Backflushing is now a standard preventive maintenance procedure applied once or twice per year during down times and has essentially eliminated overheating problems.

The TCT's are shielded from scattered beam by water-cooled collimators. Even with this protection, the magnets become too radioactive for hands-on maintenance after any significant use at present intensities. Two TCT's suffering from ground faults and water leaks were removed this past year, but have not been repaired or disassembled for diagnosis because of the residual radioactivity. Radiation levels of several hundred R/hr are encountered which prevents hands-on work.

Operating experience to date has motivated several detailed improvements, some of which can be seen in the photograph of an improved TCT shown in figure 1. The water and electrical connections have been moved to the top of the triplet assembly where they can be more readily serviced with a remotely operated manipulator. The number of water insulators has been reduced by a factor of two while, at the same time, reducing the overall impedance to water flow. Thermal switches are mounted on the cable sheath instead of on the electrical conductor as before. Thermal protection is not compromised since the temperature drop from conductor to sheath is only a few degrees Fahrenheit. Electrolytic corrosion of wet thermal switches and interlock wiring is reduced by having the switches on the sheath at ground potential and using 6 volt ac instead of 24 volt dc excitation.

It is worth noting that the electrical impedance as a function of frequency for a magnet wound with the Pyrotenax cable is much different than that for the same magnet equipped with conventional epoxy-potted

*Work supported by the US Department of Energy.

coils.[5] This behavior can be explained by realizing that the mineral-insulated (MI) magnet can be pictured as a transformer whose secondary (the outer sheath) is a shorted turn. Measurements of LAMPF magnets show that below 500 Hz, the impedance is mainly resistive and at 60 and 360 Hz, it is an order of magnitude lower than the impedance of the same magnet equipped with conventional coils. As a result, the ripple current, for the same ripple voltage, is an order of magnitude larger for the MI magnet. Fortunately, the ripple flux is about the same in both.

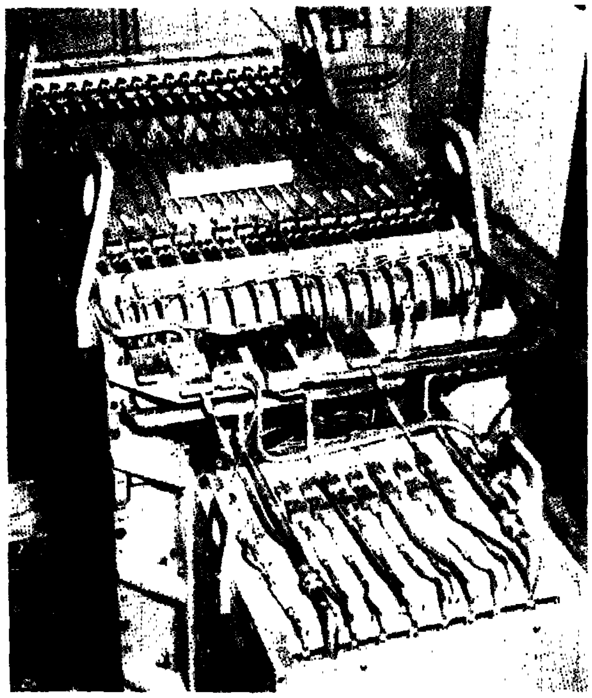

Figure 1. Improved target cell triplet.

Instrumentation

Several radiation-resistant instruments have been developed for beam diagnostics and beamline protection. For this paper we have chosen to discuss three of the most important devices, i.e., the harp profile monitors,[6] toroid current monitors,[7] and the secondary emission guard rings.[8]

Harps

These are secondary emission grids which sample the beam profile and are used to estimate beam centroid and spot size. The harps used in the experimental areas are not movable; they are always in the beam. This approach has the advantage that no radiation-hardened, moving mechanisms are required. However, it does require a thin, low Z filament that can survive the full intensity beam and produce negligible beam scattering. The filaments are radiation cooled and must operate below the temperature where thermionic emission becomes important.

Harps presently in use consist of two orthogonal planes of signal wires and three planes of clearing field wires at a potential of 57 volts. The signal wires are attached to alumina ceramic substrates via silver-based printed circuit inks. The ceramic boards and clearing field planes are mounted on a central stainless steel frame which hangs from a vacuum-sealing lid that contains an electrical feedthrough for each signal wire. A pair of ceramic p.c. edge connectors are mounted on the atmospheric side of the lid. A photograph of the harp assembly is shown in figure 2.

Both carbon and silicon carbide filaments are used for the wires that span the beamline aperture. Carbon filaments are easily pre-stressed and soldered to the printed circuit lands, but suffer from low strength since the maximum diameter commercially available is 0.05 mm. We are presently using 0.1-mm diameter silicon carbide filaments with a tensile strength of about 4×10^5 psi for the large harps. This wire is mounted by crimping a copper adapter to each end of the wire and using spring to maintain $1\text{-}2 \times 10^5$ dynes of tension. The springs were found to be necessary because the SiC elongates by about 1% when exposed to proton fluences of about 10^{20} cm^{-2}.

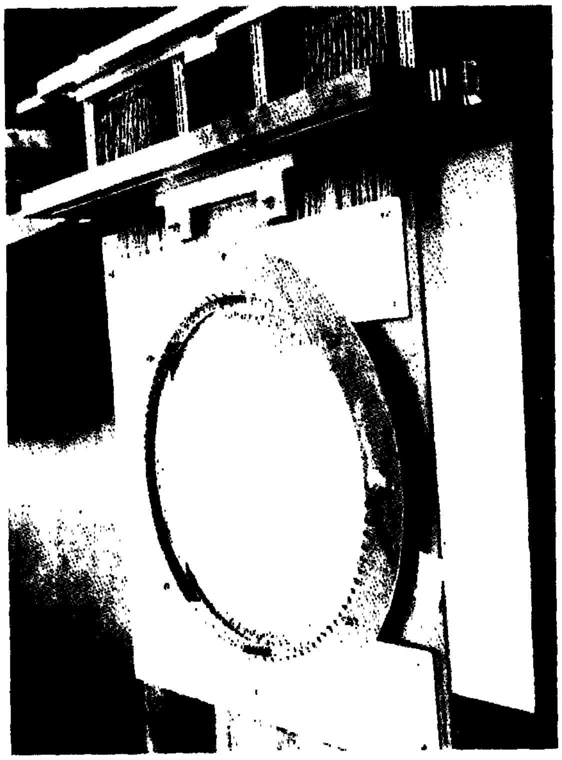

Figure 2. Harp assembly (33-cm inner diameter).

The harps are shielded from scattered beam, from secondary particle fluxes, and from errant beams by appropriately located collimators. They limit the thermal load to the massive outer parts of the harp and limit the flux of particles which can produce spurious signals by secondary emission from the relatively large area printed lands on the ceramic cards.

The harps perform as required for beams from 1 microamp to 1200 microamp average proton currents. Most difficulties are associated with thermal loads, gas flow forces, poor vacuum, water leaks, and mechanical connections. The ceramic insulated electrical feedthrough performs well when dry, but is prone to exhibit unacceptably low leakage resistance when damp. The reliability of ceramic edge connectors has been a continuing source of difficulty. Shrinkage during fabrication is difficult to control and breakage is a problem. They are also susceptible to the same moisture problems affecting the ceramic feedthroughs.

The signal cables that connect to the harp are either RG-174 or mineral-insulated coaxial cable. The MI bundle is very difficult to bend or flex and the cable itself is less reliable because of the difficulty of producing and maintaining a good hermetic seal at each end. Our experience to date indicates that the RG-174 is usable, with care, for a few years at two-thirds of the harp locations even though the insulation becomes brittle and develops cracks. We use the RG-174 cable whenever it is at all possible because the increased reliability and ease of installation outweigh the concern for long life, at least for the present.

Current Monitors

Radiation resistant toroids configured as beam current transformers are the principal current monitors for both beam diagnostic and beamline protection purposes. They are key elements of the beamline protection system where they function as transmission monitors. For this application, the current monitor signals are processed electronically to give an accurate determination of transmission or loss between two monitoring locations.

Construction of the latest version of the toroids is shown in figure 3. The toroid core is wound of mu-metal tape insulated with a thin coating of MgO. The core is enclosed in an anodized aluminum casing packed with MgO. The anodized aluminum enclosure is fabricated with an insulated circumferential break which prevents the transformer from having, in effect, a shorted secondary turn. The actual secondary is wound on the ceramic spacer ring which is slotted to immobilize the windings. Finally, the wound core assembly is placed in a steel container, filled with an inorganic potting material known by the commercial name of Saureisen, and then baked and evacuated. The steel container also has a circumferential break to prevent a shorted secondary turn.

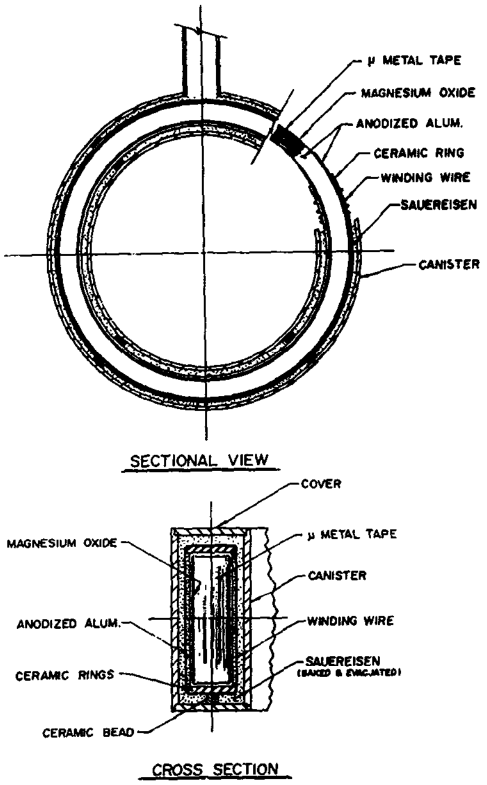

Figure 3. Toroid current monitor assembly.

Collimators are also used to shield the toroids from scattered beam, secondary particle fluxes, and errant beams. This is necessary to limit the thermal load on the toroid and to suppress spurious signals induced by charged particles striking the toroid.

Since the toroid is constructed from purely inorganic materials, it is very resistant to radiation damage to its mechanical structure. However, it is susceptible to a more subtle degradation of its electrical performance. The initial permeability, hence inductance, drops as a function of integrated radiation dose.[9] The toroids at the beam stop are the most affected. A plot of inductance of a beam stop toroid as a function of total integrated beam current is shown in figure 4. This toroid has suffered a drop in inductance by a factor of 25 in less than 6 months of operation. The current monitor electronics system has been improved to the point where it can just handle a change of this magnitude without serious error. The neutron fluence at the toroid for this same period of time has been estimated at about 2×10^{17} n/cm^2 (neutrons below 20 MeV) from Monte Carlo simulation using the nucleon-meson cascade code, HETC, and the neutron transport code, MCNP.[10]

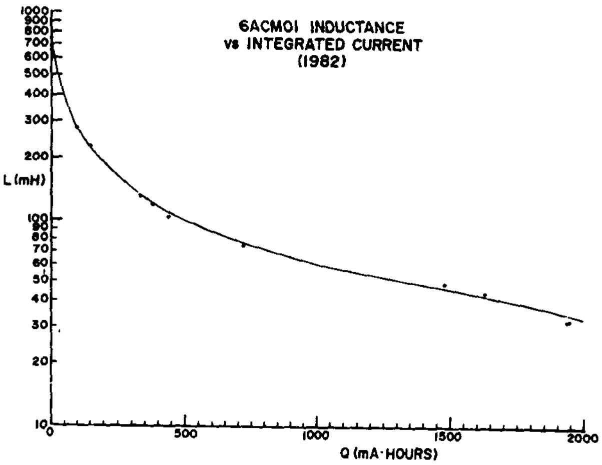

Figure 4. Toroid inductance degradation.

Secondary Emission Guard Rings

These are fast, radiation-hardened beam spill monitors that are placed in the vacuum envelope in front of collimators in the target cells and near the beam stop. They are used both for protection and diagnostic purposes. The detector shown in figure 5 consists of two signal planes each divided into quadrants and three high voltage planes surrounded by an isolated ground casing. The spacers between planes are ceramic insulators. The vacuum feedthrough is a Gulton Durock Hermetic TI-12-10 connector with a radiation hard (about 10^{15} rads) silico-ceramic insulation. Nickel wire, sleeved with alumina beads, is used to make connections that are spot welded rather than soldered.

Except for failures due to water damage, the operating experience with the guard ring system has been quite satisfactory. The devices are radiation hard, have a fast response time, low false alarm rate, good sensitivity (<100 nA) for protection, and even better for diagnostic uses. They are very specific in the sense that they directly measure beam spill in a geometrically well-defined region. Water leaks in the target cell short out the connectors and fiberglass-insulated cables. Electrolytic corrosion of wet conductors under the influence of the clearing field potential leads to permanent damage.

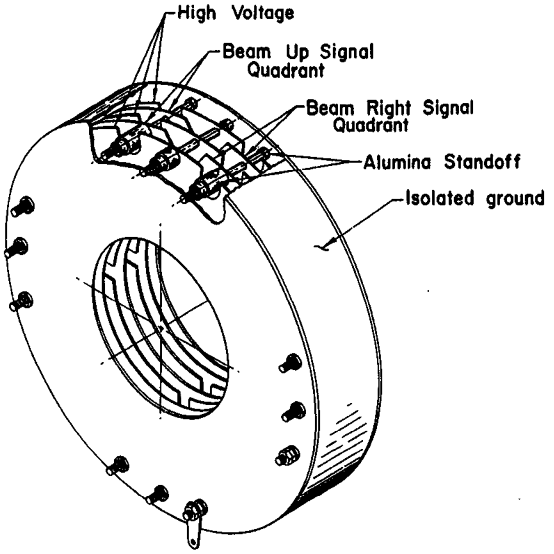

Figure 5. Guard ring detector assembly.

Targets[11,12,13]

Two types of pion production targets are used in the main proton beamline at LAMPF. The first two target cells use rotating wheels of normal graphite (ATJ) with a density of 1.73 gm/cm^3. They are 3 cm and 6 cm in length, respectively. As shown in figure 6, the machined wheel is mounted on a spindle and rotated by a roller chain which is driven from outside the shielding. The wheels rotate at approximately 1 revolution per second to prevent two consecutive beam pulses from hitting the same spot and to rotate the hot spot to a cooler area. Since all cooling is radiative, the wheel operates at a high temperature. Calculations indicate that the maximum temperature at 1 mA is approximately 1900^{o}K, but varies only 10-20^{o}K per revolution.

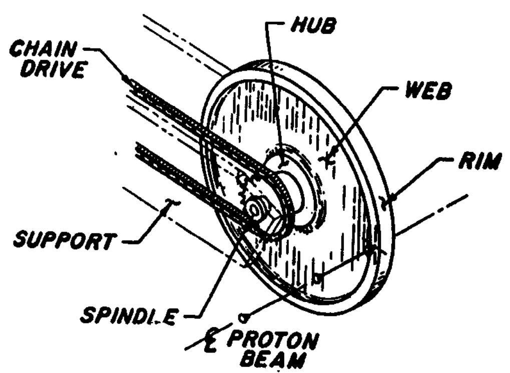

Figure 6. Radiation-cooled rotating graphite target.

The primary problems with with wheels have been with bearing wear or seizure with a lessr problem of chain stretch and wear during continued rotation under the severe conditions of high radiation fields, high temperature, and being in a vacuum. The radiation level has not been measured, but the use of melt wires in the spindle indicates that the bearing temperatures exceed 900K at approximately 700 μA beam current. The bearings have progressed from standard commercial stainless steel ball bearings to special high temperature stainless ball bearings, then special high temperature graphite sleeve bearings, finally to the present powder metallurgy molybdenum sleeve bearings impregnated with molybdenum disulfide. Table I gives the estimated running times for the various bearings at a beam current of 1 mA.

Table I

Bearing	Estimated running time months
standard SS	.0001
special SS	.01
graphite	2-3
molybdenum	9-12

The remaining target is a water-cooled pyrographite target at a density of 2.2 gm/cm^3. As shown in figure 7, it consists of pyrographite plates brazed to five copper cooling tubes which, in turn, combine in common inlet and outlet manifolds. The critical technique of the brazing of the pyrographite to the cooling tubes is the key to the success of this target, and has now become routine.

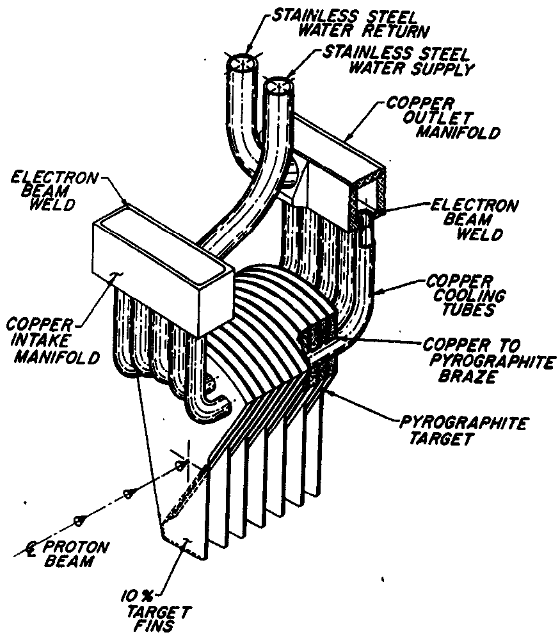

Figure 7. Water-cooled pryographite target.

The difficulties with this target have been caused by the swelling of the pyrographite due to radiation damage and accentuated by having a stationary target. The condition can be helped by occasionally moving the beam spot, but is only partially successful since the swelling extends beyond the actual beam spot. The estimated life of this design at a beam current of 1 mA is about 6 months.

Vacuum Seals

Figure 8 is an isometric sketch of a typical radiation-hardened vacuum joint used in the LAMPF main beamline. The seal consists of a stiff annulor body with integral sealing lips. The seal is machined from heat-treated AISI-4340 steel, and plated with a soft metal, such as lead, silver or gold, depending upon the operating temperature of the particular joint. Compression of the sealing lips is controlled by the thickness of the seal body. When compressed, the seal lips are not stressed beyond the elastic limit, thereby retaining relatively constant sealing forces during thermal cycling of the joint. Elastic metal seals of this type require relatively low sealing forces (~100 newton/cm), while other metal seals which require crushing beyond the elastic limit require sealing forces up to 5000 newton/cm.

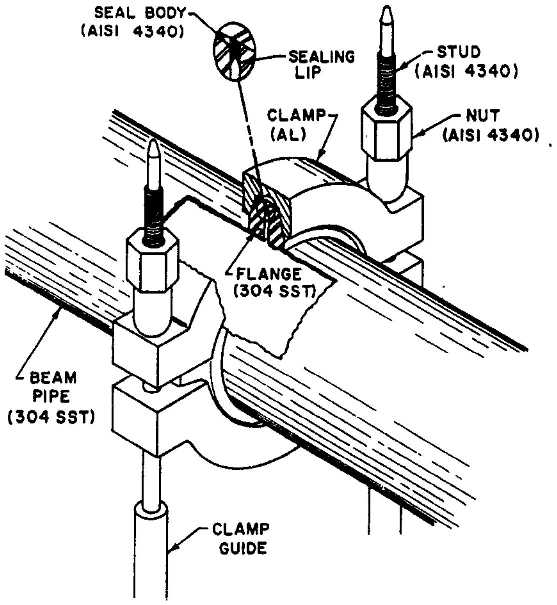

Figure 8. Radiation-hardened vacuum joint.

Crush-type metal seals are also not satisfactory for joints subject to thermal cycling as they do not have sufficient elasticity to accommodate even small dimensional changes in the joint. Other disadvantages include the requirement for larger, more complicated clamping devices which are not suited for remote handling.

Operating experience at LAMPF has shown that simple two-piece clamps as illustrated in figure 9 provide adequate sealing forces for flanges up to 60-cm diameter. The simplicity of this design is well suited to remote handling. The studs and nuts used in this design are made from heat-treated high alloy steel to minimize possible thread damage during remote assembly operations. The clamping angle of 20° (40° included) represents the best compromise between mechanical advantages and ease of removal. Prior to assembly of a joint, all threads and clamping surfaces are lubricated with dry molybdenum disulfide. Organic lubricants should be avoided, as the residue from decomposition may create problems in later disassembly of the joint. The use of any organic materials in joints subject to high radiation would not be worthwhile due to short useful service life.

Beamline Window[14]

At the end of Line A, a window is required since isotope production stringers as well as the beam stop are not under vacuum. During the first few months of operation, an air-cooled foil window was used. Although the allowable power level could have been increased by using helium as a coolant, it was decided to convert to a water-cooled window in late 1976. After the water flow for the first window failed due to a manufacturing defect, the design shown in figure 10 was placed in operation and has been in continuous service since. Another new window of this design was just recently installed. It consists of two stepped flat plates that are cooled by water flowing transversely at high velocity between the plates. The inherent disadvantage of this design is the high stress due to internal water pressure. The hardened Inconel window has allowable strengths sufficient for this application, but manufacturing tolerances, surface finishes, and elimination of stress risers become very critical. Table II gives the maximum stresses for two conditions and the yield stress of Inconel 718 for comparison.

Table II

Condition	Stress/strength-MPa
water pressure only	895
water + 1.05 mA	1020
yield strength	1100

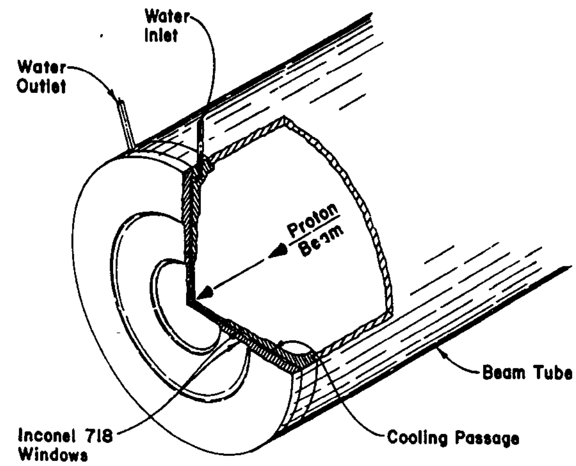

Figure 9. Water-cooled beamline window.

To reduce the high stresses, a new design was developed and is now in the fabrication stage. It consists of a pair of spherical windows with water flowing between them. The main advantage is that the total stress is reduced to ~240 MPa for the same beam conditions. Further cold testing will take place soon and it is expected that the spherical window will be installed in the spring of 1984.

Beam Stop[14]

The original (and the present) beam stop design for the high intensity primary beam at LAMPF is shown in figure 10. It consists of a stainless steel shell with an Inconel 718 stepped flat plate window with 29 OHFC copper plates of varying thickness as the stopping material. The plates, as well as the window, are cooled by high velocity water flowing transversely between the plates. The copper plate thickness was determined by its heat deposition so as to limit the maximum temperature in the copper. The copper plates are plated electroless nickel followed by a flash of gold to reduce the corrosion of the copper accelerated by the decomposition of the water as it passes through the beam.

The first beam stop operated from early 1976 to late 1980 at which time it was replaced by the present one. The first beam stop received ~4.7×10^6 µA-h without obvious damage or functional degredation. A detailed post mortem examination of the copper plates will be completed in the next few months. At that point we will better understand the actual damage, possibly can infer the cause, and, hopefully, can determine future improvements. The present stop is scheduled to be replaced next year at which point it will have received more protons than the original. This will give us another chance to assess our design.

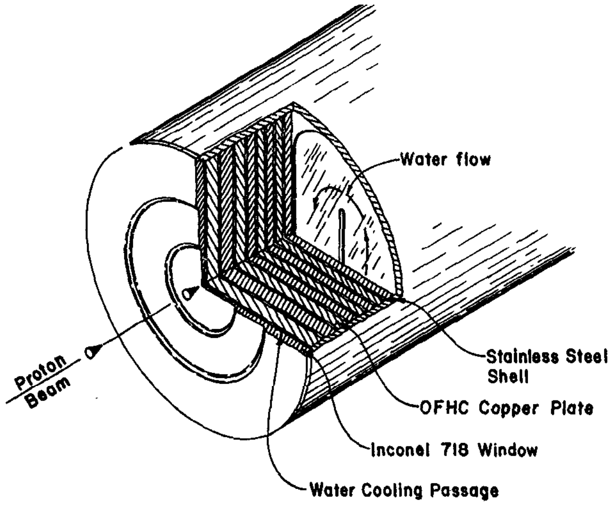

Figure 10. Water-cooled beam stop.

Collimators[14]

Because of the high beam current and subsequently high heat depositions in the components around the pion production target, water-cooled collimators have been placed between the target and such components. An illustration of this arrangement is shown in Reference 10.

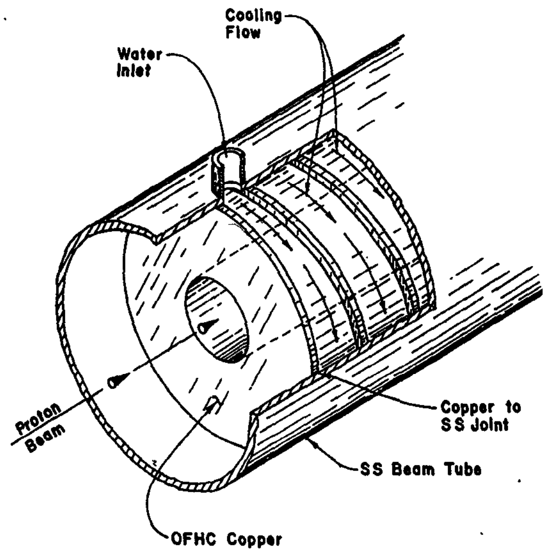

Figure 11. Water-cooled collimator.

Some of the original collimators were made of tungsten brazed inside a stainless steel tube that had cooling water tubing brazed to the outside. These are primarily placed to reduce backscattering from the target to upstream diagnostic instrumentation and are not suitable for areas of high heat deposition.

The collimators for high heat deposition areas consist of an OHFC copper cylinder directly water cooled on the outside and welded to the inside of a stainless steel tube as shown in figure 12. The secret to the success of this design is the copper to stainless steel joint which is the barrier between the cooling water system (2.07 MPa) and the beamline vacuum. The joint is made with a tungsten inert gas welding torch using RTSN brazing material as a filler. Although the technique is critical, trained welders can learn it in a few hours.

A number of collimators of this design have been in service since early 1976 with no leaks across the joints. The new collimators recently installed in the new A-2 target cell are of the identical design and just differ in size and flow passage arrangement. The collimators for the upcoming A-1 target cell rebuild will, again, be of the same design.

Acknowledgments

Space does not permit individual acknowledgment of all of the many colleagues who have contributed over the years to the work reported here. However, we wish to make special mention of the leading contributions by A. Harvey and E.D. Bush, Jr., to magnet development and by Earl Hoffman, David Lee, and Calvin Hansen to the instrumentation progress reported here.

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