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# GRAPHITE TARGETS FOR USE IN HIGH INTENSITY BEAMS AT LAMPF*

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## ABSTRACT

Graphite pion production targets are in use at the high intensity 800-MeV proton beam of the Clinton P. Anderson Meson Physics Facility (LAMPF). Radiatively cooled ATJ graphite targets have been used successfully at two target stations at proton currents of 500 μA. A water-cooled pyrolytic graphite target has been developed and put into service at the LAMPF Biomed target station at 400-μA proton current. Mechanical design features and performance data are presented.

## BACKGROUND

The LAMPF 800-MeV proton beam is focused to pass through three pion production targets in series. Typical average current in recent operation has been 400-500 μA at a macroscopic duty factor of 7.5%. There are 120 pulses per second, each 625 μs in duration. Target development effort is aimed toward the objective of providing low-Z targets that can perform reliably at high average power in a severe radiation environment in vacuum (about $10^{-3}$ mmHg). With beam spot sizes as small as 2 by 4 mm (FWHM), the targets have to survive instantaneous power depositions of ~350 kW/cm$^3$ and average power depositions of ~25 kW/cm$^3$. Successful targets must be able to withstand thermal shock and to transport large heat fluxes from the beam-target interaction region.

In a 1977 paper,[1] the evolution of the LAMPF pion production target mechanisms was traced up to a beam level of about 150 μA. Development efforts since that time have concentrated on graphite as a material, with general improvements in the basic design of the rotating wheel radiatively cooled target mechanisms, and with substantial changes in the water-cooled target design. The target systems presently in use are described in the following text.

## RADIATIVELY COOLED TARGETS

The pion production targets at Stations A-1 and A-2 are radiatively cooled, rotating wheels made of ATJ graphite (see Fig. 1). The size, relevant physical properties, and performance data for these targets are given in Table I, below. The wheels have a 3-cm hub and 5-mm disk web supporting a flanged rim, and are driven by a chain and sprocket mechanism. The proton beam passes through the rim of the wheel, which is about 1 cm wide (transverse to the beam). Target width is minimized to reduce electron contamination in pion and muon beams that view the production target in the horizontal plane. Target length in the beam is determined by the wheel's rim dimension.

Wheel rotation speeds are chosen to be relatively slow in order to minimize mechanical problems, but fast enough to prevent overlap of successive macropulses of the 120-pulses-per-second beam. During normal operation at 500-μA current, the wheel rim temperatures are estimated to be about 850-950°C, and the wheel hub temperatures about 550°C, with 8-16 kW of power (for A-1 and A-2, respectively) radiated to the walls of the vacuum enclosure. This radiant power load poses a heat removal problem for the enclosure, and the high hub temperatures pose a problem for ball bearings supporting the rotating spindle. Normal lubrication of the bearings is not feasible because of the vacuum, high temperatures, and intense radiation. Problems with bearing failure have arisen with the thicker target at A-2. Beam current is limited to about 300 μA when targets are stationary. Even so, cracks occur in the immediate beam spot area, so target rotation is interlocked to prevent damage to the graphite wheels. Examination of the failed stainless steel ball bearings showed evidence that annealing had occurred. Other bearing materials are being investigated for suitability in this use.

TABLE I

RADIATIVELY COOLED TARGETS AT LAMPF TARGET STATIONS A-1 AND A-2

| | |
|---|---|
| Material | ATJ Graphite |
| Density | 1.73 g/cm$^3$ |
| Wheel Diameter | 30 cm |
| Thermal Conductivity (1000 K) | 0.5 W-cm$^{-1}$-K$^{-1}$ |
| Emissivity | 0.8 |

| | Target Station A-1 | Target Station A-2 |
|---|---|---|
| Target Length in Beam | 3 cm | 6 cm |
| Beam Energy | 800 MeV | 788 MeV |
| Beam Current | 500 μA | 460 μA |
| Integrated Beam | 1.4 x $10^6$ μA-h | 1.8 x $10^6$ μA-h |
| Beam Spot (FWHM) | ~2 mm x 4 mm | ~3 mm x 6 mm |
| Power Absorbed (Estimate) | 8 kW | 16 kW |
| Calculated Maximum Temperature | 850°C | 950°C |
| Rotation Speed | 58 rpm | 28 rpm |

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## WATER-COOLED TARGET

The third pion production target, located at the Biomed target station, is a water-cooled stationary pyrolytic graphite target.

The smaller physical dimensions of the vacuum enclosure at this target station, together with a rather different situation with regard to access through shielding, make it impossible to use rotating disk targets similar to those used at Target Stations A-1 and A-2.

Thermal shock resistance, high melting point, and high conductivity are primary requirements for a stationary target. Pyrolytic graphite has a number of properties that make it a suitable material. It has high thermal conductivity, good strength, a high melting point, and relatively high density (2.2 g/cm$^3$, compared with 1.73 g/cm$^3$ for ATJ graphite).

Radiatively cooled stationary targets in a slab geometry were used for about two years, but were dropped in favor of a water-cooled target for several reasons: (1) As the LAMPF beam current increased to the 400-500 μA level, the graphite temperature in the beam spot area climbed to about 2200 K, approaching the level where excessive graphite evaporation rates occur; (2) in order to prevent target fractures at high thermal gradients, it was necessary to use thicker slabs, which presented problems in designing for minimum electron contamination in the pion treatment beam; and (3) the large heat load on the vacuum enclosure due to cooling by radiation was troublesome.

A successful water-cooled target depends on a physical bond between pyrographite and copper. This was achieved after development of graphite-to-metal brazing techniques by Lindquist and Mah.[2] The brazed bond has mechanical strength, long life under thermal cycling, and permits large heat fluxes. Figure 2 shows the nature of the bond attained between the pyrographite and the copper-cooling tube. The braze, shown in the center of the photomicrograph, is a copper/nickel/titanium alloy that bonds to the pyrographite as the result of the formation of titanium carbide at the interface.

The water-cooled pyrographite target now in use is shown in Fig. 3. Dimensions and other relevant data are given in Table II. The target is cooled by conduction of heat to five 8-mm copper tubes that are brazed to the pyrographite. Deionized water at a flow velocity of 4 m/s and a pressure of 125 psi flows through the copper tubes. The heat transfer at the copper/water interface is 450 W/cm$^2$ at 400 μA, which corresponds to a total power removal of 22 kW.

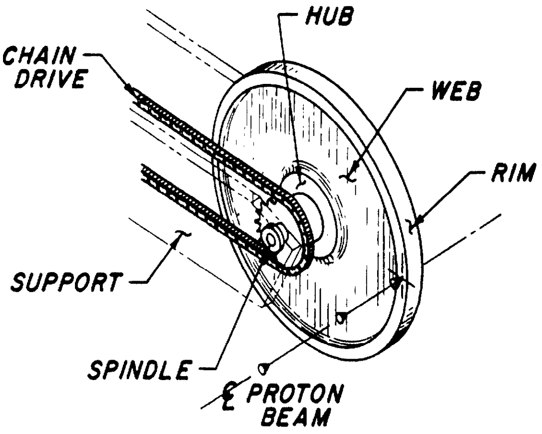

Fig. 1. A-1 disk target.

Pyrolytic graphite, which sublimes at 3652-3697°C, has the highest temperature limit of any elemental material. A high degree of heat transfer anisotropy exists because of its ordered layered structure. In the "a-b" plane, pyrographite has a higher conductivity than copper, while between the planes it is a factor of 100 lower. In order to maximize the use of the thermal conductivity of the a-b plane for the target, the proton beam direction is perpendicular to the plane. The heat generated by the beam is rapidly conducted away from the heated volume. Pyrographite is also strongest in the a-b plane. The orientation of the plane provides maximum strength for thermal stress considerations.

TABLE II

WATER-COOLED TARGET AT LAMPF BIOMED TARGET STATION

| | |
|---|---|
| Material | Pyrolytic Graphite |
| Density | 2.2 g/cm$^3$ |
| Thermal Conductivity (300 K) | 20 W-cm$^{-1}$-K$^{-1}$ |
| Target Length in Beam | 6.5 cm |
| Beam Energy | 765 MeV |
| Beam Current | 380 μA |
| Integrated Beam | 1.4 x 10$^5$ μA-h |
| Beam Spot (FWHM) | ~8 mm x 8 mm |
| Water Flow | 0.4 ℓ/s |
| Water ΔT | 13°C |
| Power Removed | 22 kW |
| Maximum Temperature (Calculated) | 860°C |
| Upstream Measured Graphite Temperatures Near Cooling Tubes | 265°C |
| Downstream Measured Graphite Temperatures Near Cooling Tubes | 305°C |

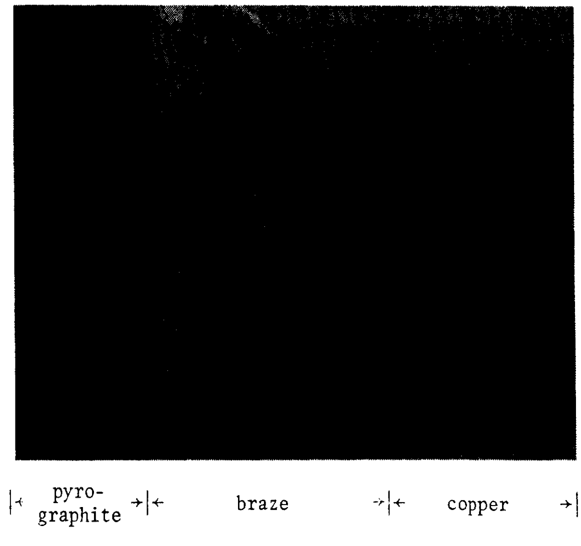

Fig. 2. Photomicrograph of copper-to-pyrographite braze joint.

Chromel-Alumel thermocouples are mounted on the graphite target at a position 4 cm from the normal beam centroid and about 0.5 cm from the nearest copper tubes. Temperatures are monitored during beam operation; the observed values are consistent with the expected heat transport and calculated temperature distributions.

The downstream graphite temperatures run slightly higher than the upstream temperatures, as expected due to the production of secondary particles. The total power removed in the Biomed target is nearly twice the power deposited by dE/dx energy losses in the primary beam.

The five-tube target design (Fig. 3) is straightforward to fabricate. The copper tubes are welded to the copper manifolds by electron beam techniques before the braze is made in a vacuum furnace. The use of relatively long tubes between the manifolds and braze prevents excessive stresses on the graphite, as well as the tubes.

The target is shaped with the side facing the Biomed beam cut at a 30° angle with the vertical. The target support mechanism has a vertical-insertion drive system with precision control for target scanning. This arrangement enables the target to be adjusted to an optimum position that balances interception of the full beam against a minimum amount of target material between the pion production region and the beam line. This allows the Biomed channel users to minimize the $e^-/\pi^-$ ratio in the beam.[3]

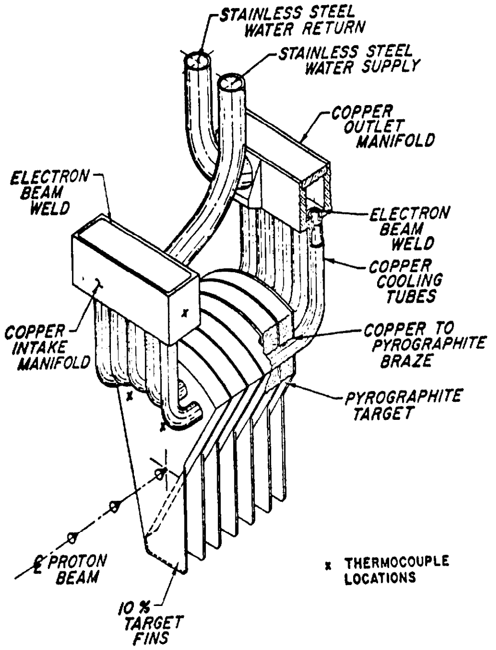

Fig. 3. Five-tube water-cooled A-5 target.

The bottom of the target is extended by the addition of thin fins that are about 10% of the main target thickness. This arrangement allows Biomed beam-line development studies to be carried out at reduced particle fluxes with approximately the same source geometry as given by the full target.

Temperature and stress calculations have been performed by Lindquist and Scarbrough[4,5] for a model of a water-cooled target that is similar to the Biomed target. At a beam current of 1 mA, it was found that expected peak temperatures could be maintained well below the level (~2300 K) where free vaporization of carbon becomes a problem. They also found that the stresses induced in the target due to beam heating are less than the ultimate tensile strength of graphite.

Design and fabrication efforts are under way to implement the water-cooled graphite concept in the two target locations where radiatively cooled rotating disk mechanisms are presently in use.

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