# HIGH POWER (MW-CLASS) TARGETS FOR PARTICLE BEAMS

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*Abstract*

Many applications that use accelerators are demanding ever-higher beam powers, which place greater demands on accelerator design and operation. Equally demanding is the design of targets that can operate safely and optimally at these power levels. High-power target design considerations include performance optimization, heat load, radiation damage and lifetime, safety, operability, reliability, and for pulsed beams, dynamic stresses from thermal cycling. The design and operation of these targets draws upon the experience gained in operating lower power targets.

## HEAT LOAD

Heat load in high-power targets can be a major driver in target design. For traditional targets made of solid metal, heat load is normally limited by heat flux at the target-coolant interface. Deposited power density goes linearly with beam power and inversely proportional to beam spot area on target. One way to address higher beam power is by increasing the size of the beam spot on target.

As beam power on target increases, so does the engineering complexity of the target. Solutions that are viable at low power, such as cooling at the periphery, are no longer viable. Figure 1 shows a spent tungsten target from the Manuel Lujan Neutron Scattering Center at Los Alamos National Laboratory [1]. This target is a solid cylinder of tungsten, 10 cm in diameter by 7.5 cm long, encased in an Alloy 718 shell that served to contain the water which passed over the tungsten surface to carry away the 60 kW of heat deposited by the 800-MeV proton beam. Two features are clearly evident. First, the target is broken into four quadrants, most likely caused by unacceptably high thermal stresses in the target. Second, substantial corrosion of the tungsten has occurred, which is due to the creation of short-lived highly oxidizing radicals in the cooling water. These radicals have been shown to be highly corrosive to tungsten [2]. Radioactive spallation products within the tungsten enter the coolant stream as the tungsten corrodes, leaving the cooling components, such as filters, ion exchange columns, highly radioactive.

At the megawatt level and higher, innovative solutions to the problem of target cooling have been proposed, such as flowing liquid metal [3,4,5,6] and rotating solid targets [SNQ, SNS TS2, Bilbao, ESS]. A liquid metal target, such as that shown in Fig. 2, has the potential to handle very high power densities due to its high heat capacity. Two liquid metals that have been successfully demonstrated as spallation targets are mercury [4,5] and lead-bismuth eutectic [6]. Lithium is proposed as the target material for the International Fusion Materials Irradiation Facility, (IFMIF) with a baseline 10 MW, 40-MeV deuteron beam. This project is now completing its engineering development and demonstration phase, including development of the lithium target [7].

At the megawatt level, full-scale thermal testing of the target prior to putting it into service is difficult and normally cost prohibitive. This is compounded by the complexity of trying to simulate the power deposition profile of the accelerator beam. As a consequence, normally small-scale tests are conducted instead. These tests are normally designed to validate uncertainties that may exist in the data or models in the simulations used in the thermo-mechanical design of the target.

## SAFETY

Targets for high-power accelerators become radioactive as a consequence of beam-induced nuclear reactions within the target. For >100-MeV beams, a good rule of thumb is that the radioactive inventory within an accelerator target is on par with a nuclear fission reactor with one order of magnitude less power, e.g., a 1-MW proton beam on a spallation target will have a radionuclide inventory, as measured in becquerels, on par with that of a 100-kW fission reactor. This inventory will generate decay heat, or afterheat, following beam shutdown that must be removed in a robust and reliable manner.

Because of the risk to workers and the public presented by this radioactive material, designers of high-power targets do well to adopt a “safety by design” philosophy, whereby safety is an omnipresent consideration in the design optimization process. A number of recently designed high-power targets [APT, SNS, MTS] draw from the safety philosophy developed for the nuclear

Figure 1: Broken and corroded Lujan Center tungsten target (from [1]).

industry. First, hazards are identified, and initiating events that may produce these hazards are postulated. Those events with high frequency of occurrence and potentially high consequences are then selected as "design basis accidents." These postulated accidents undergo quantitative analyses to assess potential radiation doses to workers and the public. If needed to keep such doses within acceptable limits, mitigations are identified and incorporated into the design. These mitigations are credited safety controls that normally require a higher pedigree of design, procurement, installation, testing, and maintenance. Wherever possible, incorporation of passive safety features into the design is preferred over reliance on credited controls, as passively safe features are usually simpler to analyze (and therefore defend to regulators), more reliable, and lower cost.

## PERFORMANCE

With respect to targets, beam power increases are normally addressed through the introduction of greater coolant volume fraction within the target, more structural material to accommodate larger thermal and mechanical stresses, larger gaps between components for ease of servicing, and similar features, which normally contribute to a degradation in target performance, for instance neutron production or neutrino production. A general rule of thumb is that an increase in beam power will not result in a proportional increase in performance, but rather will be proportional to (beam power)$^{0.8}$.

## OPERATIONS

High-power targets operate in intense radiation environments. If the beam passes through water that is used to cool the target

As the radioactive inventory increases, the infrastructure required to operate accelerator targets becomes more substantial. Normally hot cells are located near the target operating position, and target maintenance or replacement requires a means to transfer the activated target from its operating position to the hot cell or other appropriate facility where the target can be prepared for disposal.

Transport of spent targets can require substantial infrastructure. This process normally requires shielded casks approved for the transport of radioactive material on public roads or railways. One example, shown in Fig. 2, is the cask used to transport the spent MEGAPIE target to less than 1 km, from the SINQ facility at the Paul Scherrer Institute to the Zwilag facility, where it was cut up for post-irradiation examination [MEAPIE PIE].

## RADIATION DAMAGE AND LIFETIME

The structural material of high power targets is subjected to the most severe radiation damage of any application, more than fusion reactor first walls and fuel cladding in fast reactors (the fuel itself, a non-structural material, sees greater radiation damage). The damage is due both to displacements of atoms from their lattice sites and from the production of helium atoms that can cause embrittlement. Figure 4 shows the cross sections for proton-induced atomic displacements and helium production in iron. The displacement cross section is somewhat insensitive to the proton energy, while helium production increases steadily with increasing energy.

## RELIABILITY

Target systems generally exhibit greater reliability and availability than high-power accelerators that drive them. This is due to the far fewer number of components in a target station as compared to a modern accelerator. However, the significant cost associated with some of the major systems of a target station usually preclude the ability to keep one or more spares in inventory. Further, many of the components must be handled and replaced remotely, which is labor- and time-intensive. The result is that, while target station component failures are usually rare, when they happen they have the potential to bring the facility down for weeks, or in the worse case, months.

## CONCLUSIONS

Target designers are meeting the challenge of building targets that handle the ever-increasing beam power that today's modern accelerators are capable of delivering.

Figure 2: Transfer cask and custom trailer for the MEGAPIE target at the Paul Scherrer Institute.

## REFERENCES

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