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High Power Targets: Challenges of next-generation high-intensity neutrino beams

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High power target systems are crucial elements in enabling future neutrino and other rare particle beams. These systems transform intense source of protons into secondary particles of interest to enable new scientific discoveries. As primary beam intensities increase in next-generation multi-megawatt accelerator facilities, high power target systems face key challenges. Thermal shock and radiation damage effects in beam-intercepting devices were identified as the leading cross-cutting challenges of high-power target facilities. Target materials R&D to address these challenges are therefore essential to enable and ensure reliable operation of future accelerator target facilities. This paper provides an overview of the R&D activities underway to help support high power target systems development for next-generation multi-MW facilities.

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1. Introduction

Recently, several major accelerator facilities have had to limit their beam powers because of the survivability of their targets and windows, rather than as a limitation of the accelerators themselves. The Neutrinos at the Main Injector (NuMI) beamline at Fermilab [1], the Spallation Neutron Source at Oak Ridge National Laboratory [2], and the Materials and Life Science Experimental Facility (MLF) at J-PARC [3] have all operated at reduced beam powers for extended periods due to target survivability concerns. These facilities achieved their maximum powers on target only through R&D of their targets and windows.

Next-generation multi-MW accelerator target facilities to support experiments such as the 2.4-MW DUNE at LBNF, muon-to-electron-conversion II experiment (Mu2e-II), the proposed Neutrino factory and Muon collider, are expected to operate at beam powers of up to 4 MW or higher. Timely research into robust high-power targets is therefore essential to fully reap the benefits of these experiments. Target materials R&D in particular will address the leading challenges of high-power high-intensity target facility operation. The goals of the research program are to maximize particle production efficiency, accurately predict component lifetimes and to reliably operate future accelerator target facilities.

2. Scope and challenges of high power targetry

The scope of high power targetry encompasses all the components, systems and infrastructure required to safely and reliably operate high-power and/or high-intensity accelerator target facilities. The scope includes beam intercepting devices such as particle-production targets, beam windows, collimators, beam dumps, collection optics (eg. neutrino horns or lithium lenses), beam monitors and instrumentation, and target facility systems such as remote handling, air handling, cooling systems and radiation protection.

Experts from several high-power accelerator facilities identified beam-induced radiation damage and thermal shock effects in beam-intercepting materials as the leading cross-cutting challenges facing high-power target facilities [4]. Beam-intercepting devices such as beam windows and particle production targets are critical accelerator target facility devices in delivering the particles of interest and maximizing uptime of physics experiments. The continuous bombardment of these components by high-energy high-intensity pulsed beams poses serious challenges to the operation and maintenance of target facilities.

Thermal shock phenomena arise in beam-intercepting materials as a result of localized energy deposition caused by very short pulsed-beams (1-10 μs). The typical peak temperature increase in a 1-MW neutrino target at Fermilab is approximately 250 K in 10 μs (2.5×10^7 K/s). The rapidly heated core volume of the material in the beam spot region expands but is constrained by the surrounding cooler target material. This condition creates a sudden localized region of compressive stress that propagates as stress waves through the material at sonic velocities. If the initial dynamic stress exceeds the yield strength of the material, it will permanently deform and eventually fail. In addition, the cyclic loading environment from the pulsed beam progressively damages the materials' microstructure such that it ultimately fails at stress levels that are actually lower than its failure strength (fatigue failure).

In addition, the bulk material properties change as a result of radiation damage in highly irradiated materials. Radiation damage disrupts the lattice structure of the material through the displacement of atoms, transmutation, and gas production after sustained particle beam bombardment. Irradiation-induced defects such as dislocation loops, point defect clusters, fine-scale precipitates and voids that accumulate at the microstructural level ultimately affect the bulk properties of the material. Typical bulk material effects include embrittlement, hardening, swelling, reduction of thermal conductivity, and an increase in diffusion-dependent phenomena such as segregation of impurities, and phase transformation [5], all of which are detrimental to the thermo-mechanical health and physics performance of the material.

The high-energy high-intensity beams in proton accelerators create an irradiation environment that is unlike nuclear reactor irradiation conditions. The damage accumulation rate (DPA/s), DPA dose concentration/gradients and helium gas production (He appm/DPA) are orders of magnitude higher in accelerator beam-intercepting materials than in neutron-irradiated nuclear reactor materials [6]. The pulsed beam structure and small beam spot size (~1 mm) in accelerators also induce more severe thermal shock effects. As a result, materials radiation damage data that cover the accelerator irradiation parameter space are lacking in the literature. It is therefore imperative to understand the behavior of materials under irradiation conditions analogous to future accelerator target facilities.

Since 2013, the Radiation Damage In Accelerator Target Environments (RaDIATE) collaboration [7] is addressing these material challenges by involving experts from the nuclear materials and accelerator target communities to perform mutually beneficial research [8]. The collaboration now consists of over 70 participants from 14 national and international institutions working together on various accelerator materials R&D projects. This highlights the importance and concerns in meeting the demands of future accelerator target facilities.

3. High-power target materials R&D

R&D of high-power target materials primarily entails examining targets and beam window materials behavior under prototypic multi-MW proton beam conditions. The benefits of the R&D program will help inform the material choice, cooling system design, optimal operating temperature, tolerable beam intensities, and expected component lifetimes. The R&D program also aims to push the current state-of-the-art by exploring and developing novel beam-intercepting materials that are more resistant to thermal shock and radiation damage. Conventional targetry materials that are currently being investigated include graphite, titanium alloys and beryllium. The next sections provide an overview of the ongoing and future R&D activities within the scope of the Fermilab High Power Targetry R&D program and the RaDIATE collaboration.

3.1 NuMI graphite target fin analysis

The NT-02 neutrino production target in the NuMI beamline at Fermilab showed a gradual decline in neutrino yield (10-15%) over the last half of its lifetime [9]. The graphite fins were exposed to a total of 6.1×10^{20} protons (120 GeV) generating approximately 0.6 displacement per atom (DPA) over the service period of ~3.5 years. Target autopsy and post-irradiation examination (PIE) at Pacific Northwest National Lab revealed through-thickness cracks along the beam path and bulk swelling of up to 4% across the fin width [10]. Figure 1 shows the cracks along the beam path of the NT-02 target fins and post-irradiation dimensional measurements of the fin width.

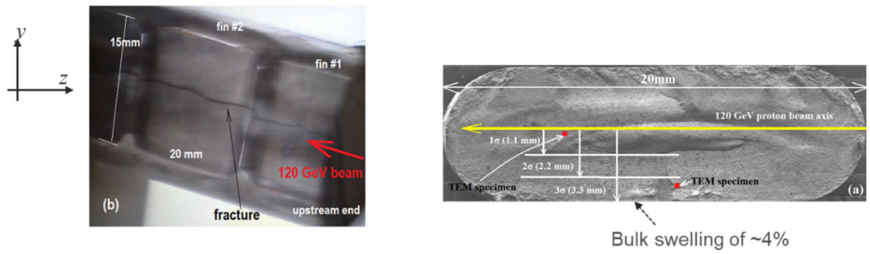

Figure 1. NT-02 target graphite fins cracked along 120-GeV proton beam path and dimensional measurements indicated bulk swelling.

Further X-ray diffraction PIE work at NSLS-II at Brookhaven National Laboratory (BNL) showed lattice swelling and evidence of amorphization near the beam spot region of the graphite fins [11]. The latter indicates that the material has lost its crystallinity and associated thermomechanical properties. The observed radiation-induced swelling reduces the effective density of the material and contributes to the build up of internal stresses in the graphite. Advanced numerical simulations indeed confirmed that that the radiation-induced swelling aggravated the thermal shock effects and led to the failure of the NT-02 target [12].

3.2 NuMI beryllium window analysis

An irradiated disc of PF-60 grade beryllium was recovered from the Fermilab NuMI primary beam window assembly and sent to the University of Oxford for PIE activities [13]. The beryllium disc was exposed to a total of 1.6×10^{21} protons (120 GeV), equivalent to about 0.5 peak DPA, with an irradiation temperature of about 50 °C. PIE analyses revealed that the crack morphology at high doses transitioned from transgranular to grain boundary fracture, indicating a weakening of the grain boundary and/or strengthening of the crystal matrix.

Nano-hardness measurements were performed to estimate the irradiation effect and showed significant hardening even at 0.1 DPA. The hardness of the irradiated beryllium was also observed to be less anisotropic. This radiation-induced hardening means that the material is less ductile and that there is a higher chance of the material failing suddenly with the rapid growth of cracks.

3.3 High-energy proton irradiation and Post-Irradiation Examination (PIE)

Another approach of the research program is to expose candidate material specimens to prototypic high-energy (HE) proton beams. In 2018, the RaDIATE collaboration completed a multi-material irradiation experiment at the Brookhaven Linac Isotope Producer Facility (BLIP) at BNL. High-energy protons (180 MeV) irradiated several material capsules containing over 200 miniature specimens (tensile, bend, fatigue, microstructural) for a period of 8 weeks. A total fluence of 4.5×10^{21} protons with a peak DPA of 0.95 in titanium alloy specimens were accumulated. The irradiated materials included beryllium, graphite, aluminum alloys, titanium alloys, silicon, TZM, CuCrZr and iridium, each relevant to the participating institutions' future programs and specific applications [14].

Following the irradiation campaign, the activated material specimens were allowed to cool down before transportation to PNNL for PIE work in hot cells. PIE results revealed important radiation-induced changes in the properties of the materials. For instance, Ti-6Al-4V alloy showed increased hardness and decrease in ductility upon irradiation [15]. Similarly, Be specimens showed reduced ductility at very low DPA levels (~0.05). High-cycle fatigue testing of irradiated Ti alloys at Fermilab showed reduced fatigue strength. Mechanical bend testing of several beryllium grades and mesoscale fatigue testing of Ti foils will be performed over the coming year. Results from the BLIP experiment provide valuable insight into materials behavior under proton irradiation and will help evaluate the performance and lifetimes of beam-intercepting devices.

3.4 Low-energy ion irradiation studies

An alternative method to mimic high-energy proton-induced radiation damage is to use low-energy (LE) ion irradiation, which has been used extensively in the nuclear materials community to emulate radiation damage effects in reactor materials [16]. LE ion irradiations enable high damage (DPA) accumulation very quickly without activating the material. Dual or triple ion beams irradiation can be used to reproduce transmutation gas production in the material. One drawback is the shallow damage depth (between 1 to a few micrometers depending on ion energy and material) from LE ions. However, micromechanical testing techniques can effectively probe the shallow damage region to measure relative changes in thermal and mechanical properties before and after irradiation. LE ion irradiation is a more cost- and time-efficient method for screening materials, in contrast to the more costly and time demanding HE proton irradiations.

LE ion irradiation of different grades of beryllium was recently carried out to study the microstructure evolution and hardening of the material. With an average damage level of 0.1 DPA and He content of 2000 appm, nanoindentation experiments showed a 60% and 100% increase in the hardness of beryllium when irradiated at 200 °C and 50 °C, respectively [17]. Similar experiments are being carried out on graphite and titanium alloys to explore radiation damage effects at higher DPAs and to evaluate and screen several candidate alloys/grades.

3.5 Thermal shock studies at CERN's HiRadMat facility

In-beam thermal shock experiments have been carried at CERN's HiRadMat facility [18]. In 2015, several grades of beryllium specimens of varying thicknesses were exposed to very high intensity beams – up to 2.8×10^{13} protons (440 GeV) per 7.2 μs pulses with beam spot sizes of less than 0.3 mm (Gaussian beam sigma). These beams parameters were chosen to push the beryllium to their failure limit through plastic deformation at high temperatures. PIE work was then carried out at the University of Oxford where distinct thermal shock response of the various beryllium grades was observed via profilometry. The PIE results were successfully validated a Johnson-Cook strength model for beryllium S200-FH grade [19].

A follow-up experiment was carried out in 2018 where pre-irradiated specimens in parallel with their non-irradiated counterparts (beryllium, graphite, silicon, titanium alloys) were tested to explore radiation damage effects on the materials' thermal shock response [20]. Dynamic online measurements (strain, temperature and vibration) of the thermal shock response of graphite slugs were also acquired. PIE work at the UK Atomic Energy Authority Materials Research Facility is nearly complete. Another experiment that will include several novel materials is planned in 2022.

3.6 Novel targetry materials

Investigation of novel materials is also underway to push the current state-of-the-art of target materials to improve the performance, reliability and operation lifetimes of next generation multi-megawatt accelerator target facilities. Novel materials with increased tolerance to thermal shock

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and radiation damage are essential to sustain the expected order of magnitude increase in beam intensities of future facilities.

Electrospun nanofiber materials are currently being developed at Fermilab as a potential particle-producing target material. Figure 2 shows SEM images of Zirconia nanofibers that were fabricated using a unique nanofiber electrospinning unit developed at Fermilab [21]. The nanofiber material continuum is physically discretized at the microscale and allows the fibers to absorb and dampen beam-induced stress waves, thus making it more thermal shock tolerant. The nanopolycrystalline structure of nanofibers also helps to resist radiation damage effects as the associated large number of grain boundaries acts as defect sinks to limit lattice defect growth and mobility. Results from in-beam tests at CERN's HiRadMat facility and in-situ ion irradiation Transmission Electron Microscopy (TEM) at the Argonne National Laboratory – Intermediate Voltage Electron Microscopy (IVEM) facility show promising evidence of thermal shock and radiation damage tolerance of nanofiber mats [22].

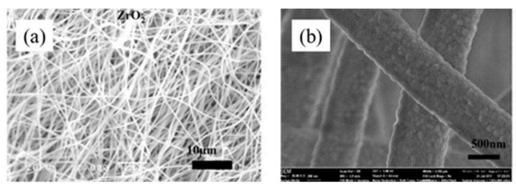

Figure 2. SEM images of Zirconia nanofibers produced at Fermilab, (a) bulk nanofiber mat, (b) single nanofibers revealing polycrystalline grains.

High-Entropy Alloys (HEAs) are also being explored as potential beam-intercepting materials in collaboration with the University of Wisconsin-Madison. HEAs are a relatively novel class of alloy with a focus on multi-element single-phase materials. HEAs consist of three or more principal elements in close to equiatomic concentrations, fundamentally different from conventional alloys. The compositionally complex matrix of HEAs provides a new design pathway for improving radiation damage resistance of materials. They offer an opportunity to explore a broader range of novel alloy systems with functional properties specific to accelerator applications. Besides enhanced radiation damage tolerance [23, 24], HEAs have shown high-temperature strength, good structural stability, high thermal stability, good corrosion and oxidation resistance, all attractive properties for accelerator applications.

3.7 Future target R&D activities

Ongoing and future activities of the high-power target R&D program at Fermilab and within the RaDIATE collaboration include the completion of the PIE work of irradiated materials from the 2018 BLIP and HiRadMat experiments. The RaDIATE collaboration is currently preparing for the next thermal shock experiment at the HiRadMat facility scheduled in late 2022, and also planning the next multi-material high-energy proton irradiation at BLIP in the 2024 timeframe.

Low-energy ion irradiation studies will continue in an effort to correlate damage effects with high-energy proton irradiations at higher doses and elevated temperatures, and for candidate material down-selection. Efforts to develop more effective alternative testing methods to reduce the cost and duration of R&D cycles are also underway. This includes using low-energy ion and/or electron beams for radiation damage, fatigue and thermal shock studies.

Radiation damage modeling work at the atomistic level recently begun in collaboration with the University of Wisconsin-Madison and Pacific Northwest National Laboratory. Radiation damage effects in beryllium and titanium alloys are being modeled and will be validated with experimental data. The work to develop and qualify novel materials for next-generation target facilities will also continue over the coming years.

4. Conclusions

Materials R&D activities by the global accelerator targets community and within the framework of the RaDIATE collaboration are advancing at a fast past to help meet future challenges. Useful materials data are being generated and will help guide the design and select suitable materials for next-generation multi-MW beam-intercepting devices. In addition, several promising novel materials are being explored to push the current state-of-the-art. The ongoing and planned high-power targetry R&D program is crucial in enabling future accelerator facilities and maximizing the physics benefits of the experiments.

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