# TARGETRY CHALLENGES AT MEGAWATT PROTON ACCELERATOR FACILITIES *

P. Hurh†, K. Ammigan, B. Hartsell, R. Tschirhart, FNAL, Batavia, IL 60510, USA

*Abstract*

High intensity, multi-megawatt proton accelerator facilities, such as the proposed Project X at Fermilab, offer the opportunity to explore science in multiple experiments and programs simultaneously. The reliable operation of the associated target facilities is as critical to the success of the experimental program as the high intensity proton accelerator itself. The targetry requirements for the Project X experimental program range from 1 GeV, 1 MW, CW proton beam on a high-Z target (possibly liquid metal) to 120 GeV, 2.3 MW, pulsed proton beam on a low-Z target and include stringent, experiment-specific operating environments such as high magnetic fields from super-conducting magnets and/or moderator arrays for optimal neutronic production. Meeting the challenges presented by such wide-ranging and intertwined requirements calls for coordinated and cross-cutting R&D activities. Areas of interest applicable to many of the experimental facilities includes radiation damage, thermal shock, radiological protection, and target instrumentation. Descriptions of these challenges and Fermilab R&D activities to overcome these difficult challenges are presented.

## INTRODUCTION

Experimental facilities driven by the high intensity proton beam of the proposed Project X linac at Fermilab [1] are expected to include a high intensity neutrino source, a kaon experimental hall, a high intensity muon to electron conversion facility, and a spallation source for the study of particle physics and nuclear materials. Each of these facilities is expected to have to accept 1 megawatt or greater of primary proton beam power on target. Although each facility presents its own scientific and engineering challenges, many of the issues are similar, lending them to be more efficiently addressed by a broad-based program of coordinated R&D activities.

The Long Baseline Neutrino Experiment (LBNE) target facility conceptual design anticipates a proton beam power of up to 2.3 MW at 60-120 GeV (1.6e14 protons per pulse, 1.5-3.5 mm sigma, 9.8 μs pulse length) on a solid target (graphite or beryllium).

The current concept for the Project X Kaon facility is for two experimental areas (neutral and charged kaon experiments) to share a single graphite (or perhaps a liquid gallium waterfall) target irradiated by 1 MW proton beam at 1-3 GeV (CW).

Initial concepts for a next generation, high intensity Mu2e target facility driven by Project X include a rotating graphite drum target surrounded by a superconducting large aperture solenoid, subject to a 1 MW primary proton beam at 3 GeV (CW).

The notional concept for the Project X spallation source for nuclear materials irradiation and particle physics anticipates a 1 MW, 1 GeV proton beam (CW, 1-2 cm sigma) on a Pb-Bi liquid (or perhaps rotating solid tungsten) target surrounded by moderators, test sample modules, and channels for particle physics experiments.

## CRITICAL TARGET CHALLENGES

Although the facilities described are very different, they present many common challenges. These are radiation damage, high heat flux cooling, radiation protection and shielding, remote handling, and high intensity beam windows. At the 2012 Proton Accelerators for Science and Innovation workshop [2], target experts from US and UK institutions identified radiation damage as the leading cross-cutting target facility challenge. In addition it was noted that thermal shock was also a leading issue relevant for both pulsed beam facilities and CW facilities that utilize rotating or flowing targets. For the sake of brevity the other common challenges will not be specifically described here.

### *Thermal Shock*

Energy deposited in the target material by high intensity beam over a short time scale heats a volume of material surrounded by cooler material. The resulting sudden expansion generates stress waves radiating out from the beam spot. These stress waves reflect from free surfaces and can constructively interfere to create stress concentrations. Simulations have shown that dynamic stresses can be double that of static stresses alone depending upon the target material and characteristic length. LBNE studies predict temperature increases of over 200 K per pulse and dynamic stress beyond the yield strength (250 MPa) for a simple beryllium rod exposed to 2.3 MW of proton beam.

Methods to overcome thermal shock effects include material selection (high specific heat, low coefficient of thermal expansion, low modulus of elasticity, and high tensile/fatigue strength), segmenting target length (to avoid accumulation of expansion), avoidance of stress concentration shapes (such as sharp corners), compressive pre-loading to reduce tensile stresses, and manipulation of beam parameters (namely beam spot size and particles per pulse).

Thermal shock is detrimental to liquid targets due to cavitation and to cooling circuits positioned in the secondary shower near the target due to sudden heating. For example, sudden temperature increases of 5˚C have been estimated to cause pressure rises up to 350 psi in the NuMI low energy water cooling circuit.

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†hurh@fnal.gov

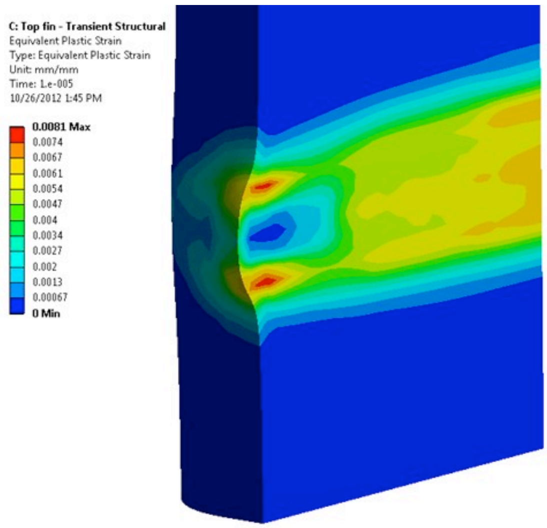


Figure 1: Simulation of 120 GeV protons (1.03e13 ppp, 0.16 x 0.22 mm sigma) on Be fin showing plastic strain.

Testing of prototypical target designs and materials with actual high intensity beam is necessary to validate modeling and simulation as well as material properties and failure criteria for the candidate materials. The latter is important because, at these load rates the material behavior is strain rate dependent and also because the compressive nature of the stress arising from the beam pulse may not "fail" the target material even if yielding occurs. Figure 1 shows simulation results for 120 GeV protons on beryllium. Although plastic deformation occurs, the target is intact for the next pulse and, in fact, the elastic residual tensile strain left after the first pulse reduces the peak stress from subsequent pulses. These results match anecdotal observations of Be components at Fermilab's anti-proton source, but need to be more rigorously tested in an instrumented beam test. Ideally, these beam tests would also be conducted on irradiated materials to account for radiation damage effects.

### *Radiation Damage*

As materials are irradiated, their material properties change due to displacements of atoms in the crystal structure. In addition, transmutation of target atoms generates hydrogen and helium gas which can be detrimental to the material structure. The manner in which the damage manifests in the material properties varies depending upon the material, the initial material structure, the type of radiation, the irradiation dose rate and the irradiation environment (especially irradiation temperature). Many common structural materials, such as stainless steel, can withstand 10 DPA (displacements per atom) or more before reaching end of useful life. However other materials, such as graphite, suffer significant damage at doses as low as 0.1-0.2 DPA [3]. Properties affected by radiation damage include tensile properties, ductility, He embrittlement, thermal and electrical properties, creep, oxidation, and dimensional changes (swelling). In addition, many of these effects are annealed above the irradiation temperature. Figure 2 shows the thermal expansion response of graphite irradiated at BLIP [4]. It can be seen that the sample length decreases as the temperature remains constant. This allows optimization of the operating temperature to reduce radiation damage effects. With overlapping parameters and effects, radiation damage is a complex issue that cannot be taken out of context and must be tested at conditions analogous to operating conditions.

Studies have been conducted over the past 60 years to determine irradiated properties and develop radiation damage tolerant materials for use in the nuclear power industry. Unfortunately such data is from lower energy neutron radiation and not high energy proton radiation. Table 1 compares the significant differences between the irradiation environments.

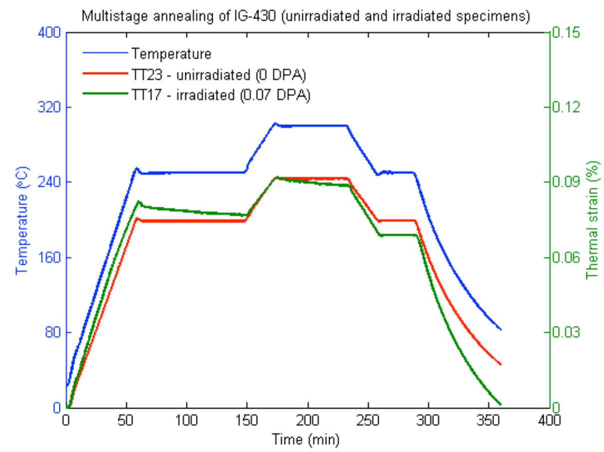


Figure 2: Multistage annealing of IG-430 graphite irradiated at BLIP to 0.07 DPA [4].

Table 1: Comparison of typical irradiation parameters

| Irradiation Source | DPA rate (dpa/s) | He gas production (appm/DPA) | Irradiation Temperature (ºC) |
|---|---|---|---|
| Mixed spectrum fission reactor | 3e-7 | 0.1 | 200-600 |
| Fusion reactor | 1e-6 | 10 | 400-1000 |
| High energy proton beam | 6e-3 | 100 | 100-800 |

## FERMILAB HIGH POWER TARGET R&D ACTIVITIES

To address the critical challenges presented by megawatt class target facilities, Fermilab has embarked on several R&D activities, including prototyping and conceptual design efforts for near future facilities, autopsy of failed targets, lessons learned meetings and more. However, the 2 cross-cutting issues of thermal shock and radiation damage have been focused on.

### *Thermal Shock R&D Activities*

In order to validate and refine analysis tools for pushing target materials to their limits, it is necessary to test target materials in very intense particle beam. It is important to characterize the failure modes as well as the material properties through these tests. As was mentioned earlier,




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traditional "failure" limits of plastic yielding may be too conservative for this type of loading. Therefore it is important to detect onset of yield as well as actual failure to ensure simulation tools accurately capture the high strain rate behavior (strain rate is typically 100-1,000 $s^{-1}$). Note that these loading rates are not fast enough to create actual shockwaves in the target material, but will create significant elastic/plastic stress waves.

Currently it is planned to use the HiRadMat facility at CERN [5] to test beryllium's response to beam. Beryllium has been chosen because of its usefulness as a neutrino target material and wide-spread use for beam windows. Proton beam capabilities at HiRadMat are up to 4.9e13 ppp at 440 GeV with a spot size varying from 0.1 mm – 2.0 mm sigma radius [6]. Current simulations indicate that at the most intense conditions the beryllium will melt before fracture. The experiment will be designed to detect the onset of plastic deformation, detect fracture or other window failure as the melting temperature is approached, examine thermal shock effects on previously irradiated beryllium, and explore the effect of mis-steered beam. Additionally, other promising beam window candidate materials may be tested (such as Albemet and diamond).

### *Radiation Damage R&D Activities*

Fermilab has initiated the RaDIATE collaboration (Radiation Damage In Accelerator Target Environments) to explore radiation damage issues relevant to high power target facilities [7]. The RaDIATE Collaboration will draw on existing expertise in related fields in fission and fusion research to formulate and implement a research program that will apply the unique combination of facilities and expertise at participating institutions to a broad range of high power accelerator projects of interest to the collaboration. The broad aims are threefold:

- to generate new and useful materials data for the accelerator and fission/fusion communities;
- to recruit and develop new experts who can cross the boundaries between these communities;
- to initiate and coordinate a continuing synergy between these communities.

Initial participating institutions include Fermilab, Pacific Northwest National Laboratory, the Materials for Fusion and Fission Power group at University of Oxford, the Science and Technology Facilities Council, and Brookhaven National Laboratory. The research and development program currently consists of a research program centered at Oxford into radiation damage effects in beryllium (motivated by the use in high power beam windows), a research activity centered at BNL into radiation damage effects in graphite (motivated by the use as neutrino and ion beam targets), and a study on radiation damage effects in tungsten (motivated by the use in spallation sources). The work at BNL on graphite has been ongoing for the past several years and some of the results are described in the IPAC13 proceedings [8,9]. It is expected that the research program incorporate both bulk sample irradiations for traditional tensile testing as well as lower energy ion shallow irradiations to take advantage of recent developments in micro-mechanics testing. Figure 3 shows an example of these micro-mechanics test cantilevers produced at Oxford.

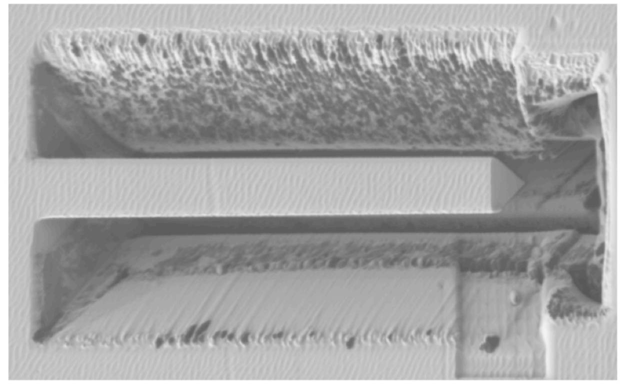

Figure 3: Micro-cantilever (17µm x 3µm) machined in tungsten (image courtesy of D. Armstrong, Oxford).

## FUTURE WORK

Future high power target R&D efforts will focus on continuing and expanding the RaDIATE collaboration activities with results for graphite, beryllium, and tungsten expected in 2015-2016. Expanding RaDIATE to include other materials (such as titanium alloys and superconductors) is being considered. In addition, thermal shock effects in solids will be addressed with testing of beryllium and other beam window materials at HiRadMat expected in early 2015.

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