HIGH POWER TARGET R&D PROGRAM AT FERMILAB *

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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. Fermilab has some experience of these challenges from successful operation of high power neutrino beam sources. However, this experience has been limited to low density targets under short pulse high intensity proton beam. High density spallation type targets present new engineering and radiological challenges. 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 be designed for 1 megawatt or greater of primary proton beam 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 collaborative, and coordinated R&D activities. These activities would benefit the design, construction, and/or operational efforts of any planned megawatt-class target facility. Table 1 indicates the relevant target challenges associated with each proposed facility.

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 radius, 9.8 micro-sec pulse length) on a low density, 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 radius) on a Pb-Bi full-stopping liquid (or perhaps rotating solid tungsten) target surrounded by moderators, test sample modules, and channels for particle physics experiments.

CRITICAL TARGET CHALLENGES

As Table 1 indicates, many of the challenges associated with these target facilities are common across the various types. At the 2012 Proton Accelerators for Science and Innovation (PASI) workshop [2], target experts from US and UK institutions identified radiation damage as the leading cross-cutting target facility challenge. It was also noted that thermal shock was a leading issue relevant for both pulsed beam facilities as well as CW beam facilities that use rotating solid or flowing liquid targets. Although high heat flux cooling, radiation protection/shielding and remote handling are also of common relevance to almost all high power target facilities, for the sake of brevity they will not be specifically described here.

Table 1: Relevant Target Facility Challenges of Proposed Project X Experimental Facilities ("H": High, "M": Medium, "L": Low; *Depends on target technology chosen)

Project X Facility	Beam Energy (GeV)	Beam Power (MW)	Relevant Target Facility Challenges						
			Radiation Damage	Thermal Shock	Heat Removal	Radiation Protection	Remote Handling	Liquid Metal	Beam Windows
LBNE	60-120	2.3	H	H	M	H	M	-	H
Kaon	3	1	H	M*	M	H	M	M*	M
Muon	3	1	H	M*	M	H	H	M*	M
Spallation	1-3	1	H	M*	H	H	H	H*	M

*Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

Thermal Shock

Energy deposited in the target material by the high intensity primary beam over a short time scale creates a volume of heated material surrounded by cooler material. The resulting sudden compressive stress creates stress waves radiating out from the central 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) to reduce stresses to tolerable levels. Designs and simulations should consider the worst case accident conditions that include maximum beam intensity, minimum spot size, and mis-steered beam.

Thermal shock is detrimental to liquids as well. Not only for liquid targets in which cavitation from the incident beam can occur, but also for cooling media in pipes positioned in the secondary shower near the target. 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 (so-called "water hammer" effect).

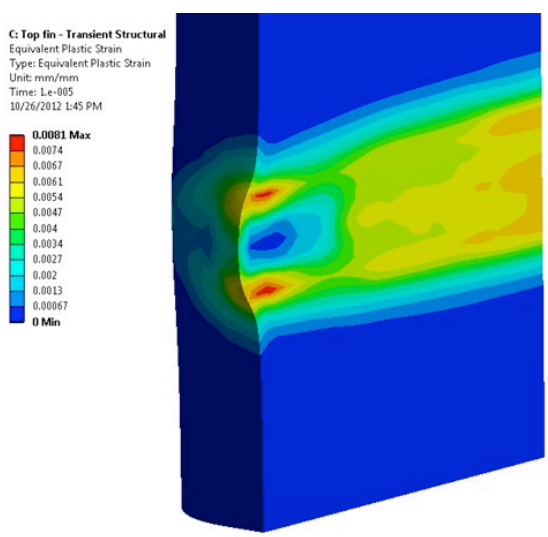

Figure 1: Simulation of 120 GeV protons (1.03e13 ppp, 0.16 x 0.22 mm sigma) on NuMI target test Be fin showing plastic strain.

Testing of prototypical target designs and materials with actual high intensity beam (or suitable analog) 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 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 (1.03e13 protons per pulse, 0.16 x 0.22 mm sigma radii, 10 μsec pulse length). Although plastic deformation occurs, the target is intact for the next pulse and, in fact, the elastic residual tensile strain left by the first pulse reduces the stress magnitude arising from subsequent pulses. Also note that the high temperature in the stressed region keeps the material in the ductile range. These results match anecdotal observations of Be components at Fermilab's anti-proton source facility, but need to be more rigorously tested in a controlled and instrumented beam test. Ideally, these beam tests would also be conducted on irradiated materials to account for radiation damage effects.

Radiation Damage

Although it may be fairly straightforward to design target components to stay within the known design limits of materials, it is much more difficult to confidently design for target survival in the irradiated state. 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 irradiation particle, 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 2 compares the significant differences between the irradiation environments.

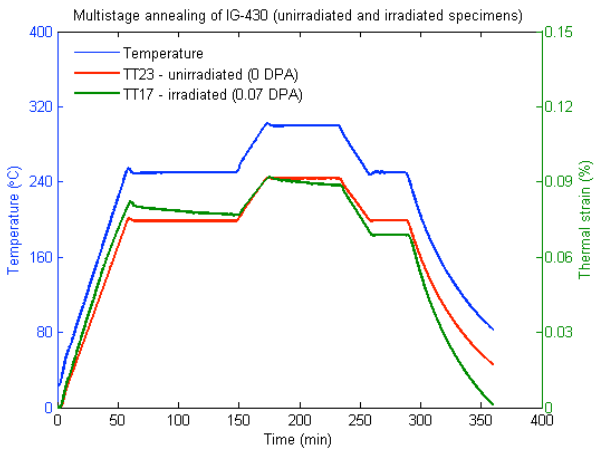

Figure 2: Multistage annealing of IG-430 graphite irradiated at BLIP to 0.07 DPA [4].

Table 2: 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 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, and more. However, the two cross-cutting issues of radiation damage and thermal shock are focused on here.

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 [5]. 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.

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 [6]. Table 3 lists materials tested at BNL in the BLIP facility along with the primary motivating reasons. The samples received a peak integrated flux of about 5.9e20 protons/cm^2.

Table 3: BLIP Test Materials

Material	Motivation
C-C Composite (3D)	2006 BLIP failure
POCO ZXF-5Q	NuMI/NOvA target material
Toyo-Tanso IG-430	Nuclear grade for T2K
Carbone-Lorraine 2020	CNGS target material
SGL R7650	NuMI/NOvA baffle material
St.-Gobain AX05 h-BN	Hexagonal Boron Nitride

Figure 3 shows a summary of measured coefficient of thermal expansion (CTE) results compared to a controls sample. Upon the first thermal cycle, the apparent CTE is much lower than the control due to the annealing effect at test temperatures above the irradiation temperature (120 – 150 C). However, on the second thermal cycle, the measured CTE of the now annealed sample is actually higher than the un-irradiated sample.

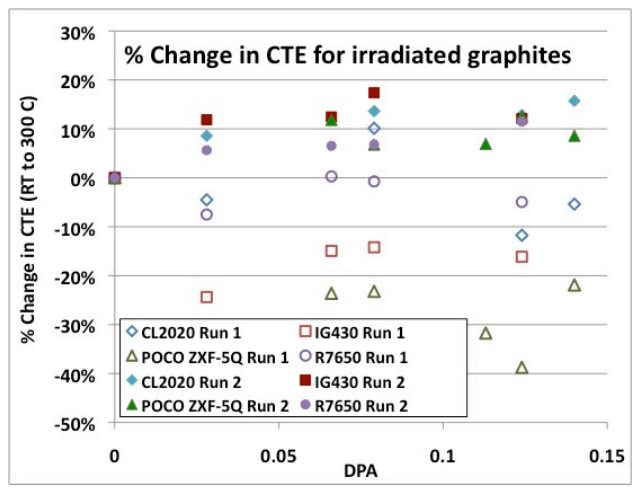

Figure 3: Comparison of change in CTE (20-300˚C) for graphite samples during two consecutive thermal cycles after irradiating at BLIP (Open symbols: First cycle; Filled symbols: Second cycle).

It is expected that the RaDIATE research program incorporate both bulk sample irradiations for traditional tensile testing as well as lower energy ion irradiations to take advantage of developments in micro-mechanics testing. More description of the RaDIATE R&D Program are included elsewhere in these proceedings [7].

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, traditional "failure" limits of plastic yielding may be too

conservative for this type of loading. Therefore it is important to detect onset of yield or other damage 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 typically not fast enough to create actual shockwaves in the target material, but may create significant elastic/plastic stress waves.

Currently it is planned to use the HiRadMat facility at CERN [8] 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 [9]. Current simulations with non-strain rate dependent properties indicate that the beryllium will yield during the end of the beam pulse, but not fracture due to the ductility of the beryllium at high temperature. However, during subsequent cool down, simulations predict the fracture of the beryllium window due to residual stress exceeding ultimate tensile stress limit of the now cooler material. Figure 4 shows elastic-plastic simulation results for HiRadMat beam on beryllium windows of various thicknesses. Note that the maximum principal stress exceeds the ultimate tensile strength (~ 435 MPa for S65 HIP grade [10]) for beryllium at a temperature of 30 °C, about 0.15 sec after the beam pulse for a window thickness of 3 mm. Figure 5 shows a contour plot indicating the location of limiting stress in the window after cool down. The maximum principal stress of about 700 MPa is aligned in the axial direction of the window, with similar stress values in the radial and circumferential directions.

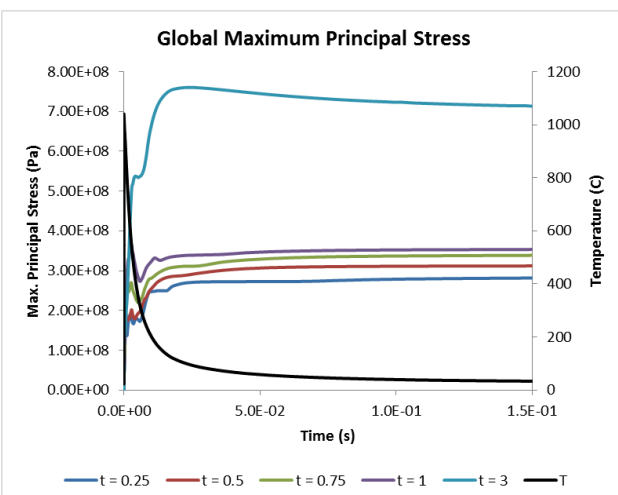

Figure 4: Plot of global maximum principal stress versus time after pulse for various window thicknesses with diameter of 40 mm.

The above results were obtained with assuming the beam heating was averaged over the length of the pulse (7.2 µsec). However, more recent simulations have modeled the beam heating as individual short bunches (288 x 0.375 nsec with 25 nsec bunch spacing). The dynamic (inertial effects) are quite enhanced due to the increase in instantaneous strain rate, as seen in Fig. 6. However, it should be noted that these effects do not result in increased plastic deformation. If the timing of the bunch structure of the beam coincides with the characteristic length of the window, resonance effects may be dramatic. This resonance effect may be explored in the HiRadMat experiment with beryllium.

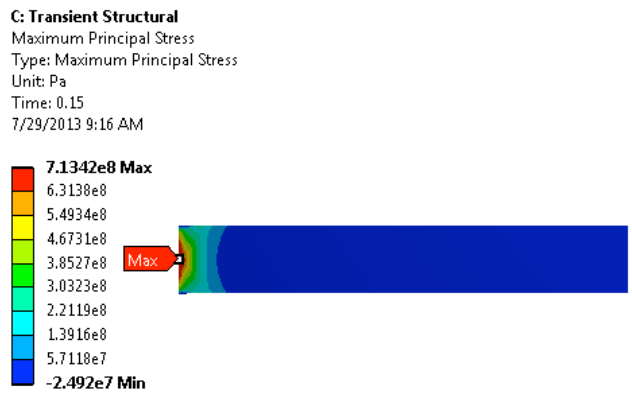

Figure 5: Contour plot of axisymmetric window (40 mm diameter, 3 mm thick) after beam pulse showing location of high stress and/or plastic strain

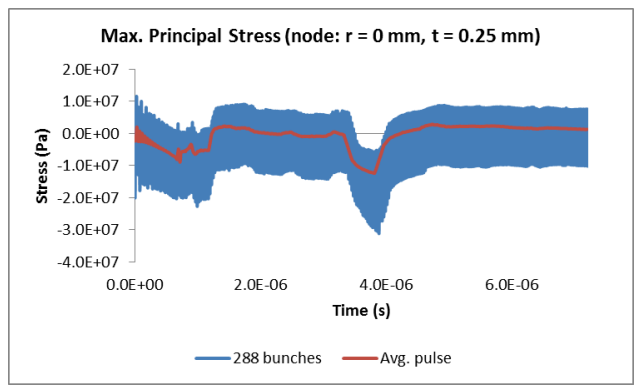

Figure 6: Plot of maximum principal stress as a function of time for 288 bunches versus 7.2 µsec pulse (40 mm diameter and 0.25 mm thick window).

The HiRadMat 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. Leak detection methods and strain gauges will be utilized for online monitoring of window failure. Digital Image Correlation (DIC) is being explored to map plastic strain and identify fracture features offline (before and after digital image correlation with sub-pixel resolution). DIC has been shown capable of obtaining full field strain data not observable by optical microscopy [11].

Combining Thermal Shock and Radiation Damage R&D

Currently the effects of radiation damage and thermal shock are being considered separately due to the

complexities of untangling the intertwined effects from each other. Once they are better understood separately, it is planned to combine these effects through simulation to enable target and window design for a variety of beam and irradiation environments. However, the unique nature of beam irradiation can make the modeling of both effects difficult.

High intensity proton beam profiles are typically Gaussian with beam radii of between 1 mm and a few cm. This gradient of flux from the peak in the center to zero at the edge must be modeled accurately to completely understand the long-term response to beam exposure. After a significant exposure, the peak damage at the center of the beam may be several DPA with high gas production, while at the edge of the beam damage and gas production will be very low. Likewise, during the pulse, material at the center of the beam spot will experience much higher temperatures than the cooler material surrounding the beam spot (this has a significant effect on radiation effects due to self-annealing). One can imagine the case where, after running beam on a window in one spot for a long time, the beam position is changed resulting in the epicenter of the thermal shock occurring in an asymmetric location relative to the previously induced damage.

To simulate these gradient effects, it is anticipated to use two different approaches. In the near-term, it is planned to model the target/window material as several materials defined with properties corresponding to different radiation damage states. This zoning technique has the advantages that commercially provided element formulations can be utilized that have been well validated by industry. A drawback is that it can introduce discontinuities between zones that complicate interpretation of results and/or give anomalous results. In the longer term, it is planned to develop user-defined material models that provide the equations of state developed from radiation damage and strain-dependent testing data. This more ambitious method has the advantage of being a more comprehensive and continuous representation of radiation damage and thermal shock effects. However, because it is essentially the development of a new material model, it will entail a great deal of dedicated effort and validation.

Multiple time dependent effects create additional complications to combining effects. Due to the bunch structure of the beam, dynamic effects can be significant at the short time scale, while irradiation creep effects will be significant only at the long time scale. Simulating multiple time dependent effects using commercial FEA software is currently very difficult (creep and visco-elasticity/plasticity models simultaneously).

Simulations of this complex nature must be validated to be useful as design and analysis tools. One such test is to replace 3 graphite fins in the NOvA medium energy neutrino production target (out of 40) with 3 beryllium fins for an upcoming irradiation. The NOvA beam parameters are aggressive enough to effect change in the material properties due to radiation damage and challenge the strength of the material due to thermal shock. Positions in the ~2 interaction length target will be chosen so that three different data points can be generated. Monitoring of the fins is accomplished only in the aggregate by monitoring secondary particle yields in downstream detectors. However, disassembly for inspection of the fins is possible in Fermilab's Remote Handling Facility at C-0. Simulation of the beryllium fin response to these conditions is currently underway (see Fig. 1) and will be compared to actual performance in beam when the NOvA beam run with this experimental target is completed.

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 further addressed with continued simulation and eventual testing of beryllium and other beam window materials at HiRadMat expected in early 2015.

REFERENCES

[1] R. Tschirhart, "The High Intensity Horizon at Fermilab," IPAC'12, New Orleans, July 2012, WEXA01, http://www.JACoW.org.

[2] PASI web-site, http://pasi.org.uk/Meetings

[3] R.L. Sindelar, et al., "Corrosion of metals and alloys in high radiation fields," Materials Characterization 43:147-157 (1999).

[4] N. Simos, et al., "LBNE target material radiation damage from energetic protons of the BLIP facility," Final Report, Fermilab (2013).

[5] RaDIATE web-site, http://www-radiate.fnal.gov/

[6] Hurh, et al., "Radiation Damage Study of Graphite and Carbon-Carbon Composite Target Materials," IPAC'13, Shanghai, June 2013, THPFI083, http://www.JACoW.org.

[7] K. Ammigan, et al., "The RaDIATE Collaboration R&D Program: Status and Update", these proceedings, THOTA03, 2013.

[8] A. Fabich, et al., "First Year of Operations in the HiRadMat Irradiation Facility at CERN," IPAC'13, Shanghai, June 2013, THPFI055, http://www.JACoW.org.

[9] C. Hessler, et al., "HiRadMat Beam Parameters," CERN EDMS #1054880, (2010).

[10] R. Chaouadi, et al., "Tensile and Fracture Toughness Test Results of Neutron Irradiated Beryllium", European Fusion Programme, TEC97/51.F040010/15 Rev.1, 1997.

[11] J. Quinta da Fonseca, P. M. Mummery and P. J. Withers, Journal of Microscopy, 218, 9 (2005).