September 5, 2014

Research Proposal

Study of the Performance Envelope for Carbon-Based Targets

in High Power Beams

H.G. Kirk, N. Simos, Brookhaven National Laboratory

K.T. McDonald, Princeton University

Introduction

The DOE-HEPAP Particle Physics Project Prioritization Panel (P5) report has given clear directions for the establishment of a robust Intensity Frontier capability in the U.S. Specifically:

Redirect specific activities and efforts at Fermilab to the PIP-II program of improvements to the accelerator complex, which will provide proton beams with power greater than one megawatt by the time of first operation of the new long-baseline neutrino facility.

The rational for establishing this capability is to respond to two foreseen physics drivers: *i) Pursue the physics associated with neutrino mass,* and *ii) Explore the unknown: new particles, interactions, and physical principles.*

This scenario will require supporting R&D for the development of target systems capable of receiving the multi-MW protons beams and generating intense secondary and tertiary beams useful for the desired physics programs. Key technical issues include: i) an understanding of the influence of radiation on the physical properties of the targets as well as the surrounding supporting infrastructure, ii) management of the steady state heat load in the target, and iii) an understanding of the physical limits of the target material to disruption resulting from thermal shock.

Fixed-Target Requirements for the Intensity Frontier

Depending on the desired secondary beam to be produced, low-, mid-, and high-*Z* target materials need to be considered. As the beam power transcends 1 MW, solid targets, preferred for their simplicity and ease of handling, become less viable and liquid targets may be preferable despite the additional complexity of a liquid-target systems. In this context, it is desirable to have an understanding of the limitations of solid targets as the incident proton beams increase in power, particularly in case of low duty factor (short pulse) operation.

R&D will be necessary to determine the limitations of various target materials as well as providing an understanding of the impact of severe radiation on the physical properties of potential target materials and in particular on the lowering of material fracture toughness. The resistance to thermal shock in the target is sensitive to various physical parameters such as heat capacity, tensile strength, coefficient of thermal expansion, and Young's modulus. Knowledge of these parameters for materials which have been exposed to various degress of irradiation is essential and a program to measure these parameters for irradiated and non-irradiated target material should be employed. Beam tests with high-power, focused beams will be required to validate models for target disruption.

R&D Objectives

This proposal is structured to address to the challenges of physical limitations posed by fixed targets for the intense proton drive beams envisioned for a future LBNF and the extremely short pulses associated with initiatives such as the Neutrino Factory. The primary objective is the establishment of realistic and verified limitations of materials in the role of production targets linked to the intensity frontier and in particular to beam/target interaction scenarios where intense, short pulses are sought to produce unique secondary spectra. This objective is to be achieved through a systematic approach that combines an integrated set of novel experiments specifically designed to push the intensity envelope with state-of-the-art characterization of the interaction process and augmented by high fidelity simulations and modeling that will aid in the establishing specific limitations and operating envelopes for the intensity frontier initiatives.

A limiting factor and a significant challenge in next generation accelerators is the survivability of the production target subjected to a number of extreme conditions that occur simultaneously, namely radiation damage due to the prolonged exposure of the target material to the beam resulting in displaced atoms and accumulation as well as evolution of defects detrimental to the thermo-mechanical properties of the material, fatigue-induced degradation resulting from pulsed beams, phase transformations due to deposited energy, chemistry effects from interaction with the environment (oxidation and/or corrosion). In an effort to extend the life of the targets, all of these effects are continuously being addressed through research and by safe design either individually and/or in combination.

This three-year study, however, aims at a very specific but dominant part of the overall target problem which stems from the interaction of the intense beam with the microstructure and the changes that it induces to the lattice of the materials as the boundary that separates extreme thermal shock from acoustic shock is being approached with ever increased intensity and reduced pulse length, both parameters desired by experiments such as the Neutrino Factory. The interception of such intense, fast beams by the production target will lead to microstructural changes, lattice disturbances and phase transformations which in turn alter the macro-structural properties and the ability of the beam intercepting volume to produce the desired spectrum. In extreme cases that could lead to target fragmentation through a violent process whose onset may be a single intense beam pulse. How the long-term degradation due to continuous irradiation, themo-mechanical fatigue as well as chemistry effects such as oxidation or corrosion affect both the pulse intensity/pulse length threshold as compared to a virgin material lattice, is a key aspect and thrust of the proposed research.

Research Profile

To identify the limit states for carbon-based targets associated with the intensity frontier we propose a suite of studies consisting of: intense beam-target interaction experiments, microscopic characterization experiments and augmenting numerical simulations.

The generation of disorder in the target lattice with beams that mimic the deposited energy density anticipated in the future intensity frontier experiments will be facilitated by the following:

- Intense, short 440-GeV proton pulses on carbon-based targets (graphite, carbon-fiber composites, *etc.*) using the CERN SPS at the HiRadMat facility[i].[1][2] This facility features up to 4.9 x 10^{13} protons per spill with rms beam radius as small as 0.1 mm.

The uniqueness of this experimental effort lies in the fact that both non-irradiated and previously irradiated carbon-based target materials will be used to intercept the SPS beam as a function of pulse intensity and pulse length. The proposing team has successfully (a) conducted irradiation damage studies on carbon-based materials using the 200 MeV protons of the BNL Linac which in turn has made available an array of already irradiated specimens to be used and (b) completed an experiment of similar nature but at lower energies and intensities using the 24 GeV of the BNL AGS (AGS E-951) on graphite and carbon fiber composite in an effort to delineate the response of the two micro-structures.

- Intense electron and focused laser beams offered by the BNL Accelerator Test Facility (ATF) as well as available high power lasers which are capable of inducing extreme thermal shock and potentially acoustic shock under extreme focusing and pulse length.

- To unravel the microstructural damage and the phase transformations that are triggered by the pulse intensity which in turn is strongly correlated with the limit-state or threshold in beam intensity that the target material microstructure (for both states, unirradiated and previously irradiated and fatigued) a revolutionary process of x-ray diffraction will be utilized enabling the study in the bulk state. Specifically, an experimental post-irradiation characterization of phase mapping and crystalline-to-amorphous transition recently developed by the team using hard X-rays and in-situ 3D Energy Dispersive Diffraction (EDXRD) will enable the study of the microstructure and its evolution along the intense beam path and help reveal the onset of transitions induced by the beam/target interaction manifested as phase and crystalline-to-amorphous transitions. Transmission and scanning electron microscopy performed at the Center of Functional Nanomaterials will complement the micro-structural evolution of the affected volume in the beam path.

- The experimental study will be coupled of a series of numerical simulations and modeling that will not only guide the design of the unique experiments but also help in the understanding of the

---

[1] HighRadMat home page: https://espace.cern.ch/hiradmat-sps/Wiki%20Pages/Home.aspx
[2] I. Efthymiopoulos, *HighRadMat, A Facility at CERN for Material & Component Testing*, https://indico.cern.ch/event/259596/session/3/contribution/10/material/slides/0.pdf

interaction process and the transformation of experimental observations into target-relevant safe operation envelope and parameter space that can in turn be used in the design of intensity frontier experiments. Specifically, particle transport and interaction with matter codes including photon-matter interaction, first-principle and molecular dynamics codes will be integrated to form a coupled suite of tools that will help understand the interaction in the length scale from the atomic to micro-scale while special non-linear numerical processes based on finite element discretization will be incorporated to correlate experimental observations with the meso-scale and continuum.

Budget for the proposed work

Year 1		FTEs	$K
	Effort	1.2	
	M&S		160
	Travel		20
Year 2			
	Effort	1.4	
	M&S		140
	Travel		40
Year 3			
	Effort	0.8	
	M&S		40
	Travel		20
Total		3.4	420

[iii] HighRadMat home page: https://espace.cern.ch/hiradmat-sps/Wiki%20Pages/Home.aspx