R&D for MW Pion Production Targets for Next Generation Long Baseline Neutrino Facilities

Abstract

The Long Baseline Neutrino Facility (LBNF) in the US and T2K/HyperK in Japan are both competing and complementary next generation neutrino facilities. In order to realise the potential offered by multi-MW proton drivers, both facilities need to develop efficient, robust and reliable production targets and associated beam windows. This LoI introduces the overlapping international collaborations that are being developed between physicists, engineers and materials scientists at accelerator, nuclear and university laboratories in order to develop the materials and technologies required to deliver optimum physics performance for these next generation facilities.

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1. Introduction

The international LBNF/DUNE [1] and T2K/HyperK [2] collaborations are constructing/upgrading the next generation Long Baseline Neutrino Facilities utilising MW proton drivers and pion production targets. Those parts of the facility infrastructure which cannot be upgraded are designed for multi-MW operation, however significant R&D is still required to deliver efficient and reliable target systems for operation at such beam powers. Due to a combination of mechanical and physical properties, graphite, titanium, beryllium and potentially SiC-SiC composite are among the very few suitable materials for targets and the associated beam windows. It is known that radiation damage generated by the multi-GeV proton beams leads to severe degradation of material properties and decreases service lifetimes under intense thermal fatigue conditions. This is one of the most challenging factors in the design and operation of such facilities. To address this, the evolution of lifetime-defining properties of these materials needs to be investigated, understood and compared. Critical mechanical and physical properties are yield and fracture strength, toughness and fatigue limits, as well as specific heat and thermal conductivity. Despite some knowledge obtained by fission and fusion reactor communities, the database on radiation-assisted degradation effects in graphite, beryllium and titanium in prototypic conditions is sparse. The international RaDIATE (Radiation Damage In Accelerator Target Environments) collaboration [3] was formed to identify the most suitable material grades for targets, beam windows and beam dumps, as well as to measure and understand their lifetime properties so that the risk of failure during the operation of such facilities can be mitigated.

RAL (UK) leads the contribution of both the T2K(/HyperK) and LBNF targets for 1.2-1.3 MW operation. Collaborations with Fermilab, KEK, UK academia and the RaDIATE collaboration propose to carry out extensive physics, engineering and materials analyses to facilitate the future development of targets suitable for multi-MW operation. UK contributions will be carried out in concert with the international RaDIATE program with a collaboration between STFC/RAL, Culham, Birmingham, Warwick and Glasgow Universities exploiting and developing existing infrastructures in the UK. We will utilize the Diamond and ISIS facilities at RAL, with material irradiations conducted at an existing Birmingham University isotope production cyclotron and Post-Irradiation Examination at UKAEA Culham Laboratory.

2. Materials Science: Predicting and improving lifetimes and reliability of targets and beam windows

A DoE-supported project led by Fermilab involving international members of the RaDIATE collaboration has irradiated various material samples at the BLIP facility at BNL[4] with Post Irradiation Examination (PIE) conducted at PNNL [5]. A number of these samples (graphite, beryllium, titanium alloys) are also being sent to the Material Research Facility (MRF) at Culham for further PIE and advanced microscopy using a suite of advanced materials science equipment [6].

The size and shape of irradiated accelerator components usually does not allow fabrication of samples for standardized tests, therefore studying the evolution of yield/fracture strength and toughness will be done mainly at the microscale level using miniaturized samples and highly sensitive techniques such as nanoindentation hardness measurements. Correlation between properties at the micro-scale and standardized (macro) reference samples, such as those generated at PNNL, will be investigated in order to understand if results from micro-mechanical experiments can be used to make macro-scale predictions. A bespoke Ultrasonic Fatigue Rig is currently being commissioned at the Culham MRF to test Ti alloy meso-scale cantilever specimens irradiated at BLIP.

In order to understand the empirical relationships obtained between material properties and exposure doses, and for reliable predictions of material behavior under future working environments, extensive microstructural investigations of post-irradiated materials need to be performed. The goal is to determine the features of nucleation and evolution of point defect clusters (using TEM) and small angle scattering using Diamond and ISIS facilities, as well as to characterize the stability of matrix and grain-boundary chemistry (using APT/STEM) as a function of irradiation dose and temperature, information which is currently unavailable. Data on the evolution of size, number density and chemistry of irradiation-induced objects are needed in order to obtain models for analysis that can predict the evolution of material properties so that operational lifetime limits can be set.

We plan to perform an in-depth investigation of irradiation induced embrittlement of beryllium. Microcantilevers fracture tests and mapping of fractures in NuMI window will be carried out. In addition, complementary APT and TEM experiments will enable better understanding of embrittlement mechanisms as well as intra- to inter-granular fracture transitions in beryllium, which is the material chosen for the LBNF primary beam windows. Furthermore, micromechanical samples prepared from proton-irradiated graphite fins from the NuMI/NOvA neutrino experiments will allow us to explore the origins of target fractures and mitigate their causes in order to avoid potential failures in future LBNF targets.

We also intend to explore the use of laser-based additive manufacturing (3D printing) to produce titanium alloy components e.g.beam windows and develop new alloys with higher strength, lower modulus and improved irradiation damage resistance. Optimization of the alloy composition and evaluation of the thermal and irradiation properties of the 3D printed materials will enable the development of novel Ti-alloys for these accelerator components.

3. Material Irradiation Facilities

The BLIP facility at BNL is one of the very few suitable material irradiation facilities that are realistically available at a reasonable cost for irradiating material samples to the levels experienced in the world’s most intense particle accelerators. We propose to develop an existing cyclotron at Birmingham University into such a materials irradiation facility. The Scanditronix MC40 can supply up to 60 microamps of protons at energies below 9 MeV or between 11 to 39 MeV. This can generate in months the level of damage that would result from years of operation at the higher energy but lower current accelerator facilities of interest. An accelerator-based neutron source is also currently under development and the facility construction is expected to be completed by the end of 2021. The University also plans to develop a facility which will measure the mechanical and corrosion resistance properties of materials along with an in-situ irradiation capability in order to monitor real-time radiation damage. The sample environment (including vacuum and water) for the neutron source will be designed to be transferable to the proton irradiation facility. The irradiated samples can be seamlessly transported to the MRF at Culham for further preparation and characterisation.

References

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