Irradiation facilities and irradiation methods for High Power Targetry

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Background

A high-power target system is a key beam element to complete future High Energy Physics (HEP) experiments. The current target technology tolerates a beam power up to 1 Mega Watt (MW). Future neutrino facilities, like LBNF [1] and J-PARC, propose 1-3 MW proton beams delivering to a neutrino target. The beam power range is comparable with a muon collider and neutrino factory, which propose 2-5 MW proton beams.

In the recent past, major accelerator facilities have been limited in beam power not by their accelerators, but by the beam intercepting device survivability. The target must then endure high power pulsed beam, leading to high cycle thermal stresses/ pressures and thermal shocks. Repeated pulses create a cyclic loading environment that can be damaging to the material even at stress levels well below the failure strength of the material (fatigue failure). The increase beam power will create also significant challenges such as corrosion and radiation damage. The targets must be capable to efficiently remove the heat deposition from the primary beam while they need to be optimized for the secondary particle production. The radiation-induced defects can cause harmful effect on material and degrade their mechanical and thermal properties during irradiation, that can lead the failure of material and drastically reduce the lifetime of targets and beam intercepting devices.

Fermilab has limited capabilities in the areas of irradiation and post-irradiation examination (PIE) facilities and Targetry Applications technologies (e.g. remote handling, high heat-flux cooling, etc.). These under-developed capabilities, relative to those of the global HPT and nuclear materials communities, create vulnerabilities that must be addressed to ensure continued Fermilab leadership in High Power Targetry and the successful operation of multi-MW target facilities in the future. The goal of the High Power Targetry program is to develop the knowledge and the infrastructure necessary to support multi-MW target facility operations as a core of competency at Fermilab.

The RaDIATE collaboration (Radiation Damage In Accelerator Target Environment) [2] led by Fermilab will coordinate the HPT R&D program between institutions who have expertise and common interest among the 14 international institution members.

High intensity proton irradiation station

Fermilab already proposes several test areas on-site such as Fermilab Test Beam Facility (FTBF), Irradiation Test Area (ITA), High Rate Tracking Area, MINOS underground areas; but none of them are suitable for material irradiation where lower proton energy combined with higher intensity beams are desired.

An upgrade of its accelerator infrastructure is planned to deliver 2.4 MW 120 GeV proton beam for LBNF/DUNE. Technology options for this upgrade include an extension of the PIP-II superconducting Linac, a modification or replacement of the Booster, and modifications of the cycling ring and the Main Injector. The Booster Replacement (BR) will replace the current 8 GeV booster with a new accelerating facility. PIP-II is a CW compatible machine capable to deliver

1.6 MW of beam power at the end of the Linac. LBNF with the Booster takes only ~1% of the total intensity, leaving several options for multi-user operations.

We would like to use this opportunity to investigate the possibility to include an irradiation station along the facility at PIP-II or at the Booster Replacement where higher intensity protons beams will be available. The goal is to create an irradiation station with continuous beam dedicated to radiation-induced defect studies in High Power Targetry materials or with pulsed beam devoted to thermal shock and fatigue studies.

The BLIP [3] facility at BNL is a unique facility in US that offers a suitable material irradiation station. In the past, we irradiated numerous candidate materials at a reasonable cost and irradiation time. But with scientific goal changes, this facility may not be available anymore in the future at an effective cost. The HiRadMat beamline [4] at CERN is the only user facility that provide pulsed beam at high proton intensity but has limitations in the number of consecutive pulses per experiment (~100 pulses maximum) dependent upon the LHC beam operation schedule, and residual activity of the specimens. While BLIP facility is suitable for long-term-radiation damage studies, HiRadMat is a “single-shot” thermal shock test facility.

Electron beam station as an alternative for thermal shock and high cycle fatigue studies

An alternative solution to thermal shock and high-cycle fatigue studies and at certain level irradiation damage is to use intense electron source or laser sources (> 1×10^7 loading cycles). Fermilab has explored using the Accelerator Application Development and Demonstration (A2D2) electron linac at the Illinois Accelerator Research Center (IARC) [5] for thermal shock testing. The linac has a capability to provide an electron beam of up to 1.2 kW at 9 MeV with a beam sigma of 8.8 cm. We are investigating the possibility to narrow the beam size to the order of a millimeter to fit with power density requirement at a level adequate for target testing. This study is part of a PhD program in collaboration with University of Iowa on “Optimizing beam parameters of a medical electron accelerator for simultaneous evaluation of radiation damage, thermal shock and fatigue in accelerator components”.

Heavy Ion irradiation as alternative to proton irradiation-induced defect studies

Low energy ion irradiations have been explored extensively in the nuclear materials community as an alternative to nuclear test reactor irradiations in order to lower the costs of irradiation and Post Irradiation Examination (PIE) as well as significantly decreasing the irradiation time. These low energy ion irradiation methods have also been used to mimic the irradiation conditions of high-energy proton irradiations and can reach the equivalent proton fluence range desired in the matter of a few days or weeks, rather than years, and without activating the specimens. Disadvantages of this method include generating only atomic displacement damage (no transmutation) and very shallow penetration (typically under 10 microns). There are developing techniques to address these drawbacks (micro-mechanics and gas implantation), but the results are not consistent and must still be validated/correlated with results from high energy proton irradiation studies.

A PhD has been initiated in collaboration with the Illinois Institute of Technology (IIT) about “Characterization of radiation damage effects in high-energy neutrino target graphite using low-energy ions”. The goal is to determine low-energy ion irradiation conditions that will induce the same level of damage observed in previously failed Fermilab graphite targets and those expected in future targets of higher energy and intensity accelerators. Relevant property changes to be observed during PIE work on the irradiated graphite (microstructural defects such as dislocation lines and loops, swelling and lattice spacing changes, as well as changes in mechanical stress, strain and embrittlement) will be compared to those obtained from proton irradiation.

Recommendation

The addition of irradiation stations at Fermilab (proton beam and electron beam) for radiation will be unique and beneficial HPT R&D capabilities and will reinforce the leadership role of Fermilab in the global community for radiation damage effects in accelerator target materials. If successfully validated, the new method to mimic proton irradiation by using heavy ions will be a great and cost-effective tool to support HPT R&D program.

References

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