PROCEEDINGS OF SCIENCE

Recent Progress on Radiation Damage Studies at RaDIATE

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Recent major accelerator facilities have been limited in beam power by production target and beam window survivability, where radiation damage to their constituent materials has been identified as the most cross-cutting challenge facing these high power target facilities. The RaDIATE collaboration, Radiation Damage In Accelerator Target Environments, was formed in 2012 to address this challenge by bringing together experts from the fields of nuclear materials and accelerator target facilities. The collaboration conducted high intensity proton beam irradiation of test specimens at the Brookhaven Linac Isotope Producer (BLIP) facility at BNL, where the specimens, including candidate materials for various beam intercepting device applications, were provided by participating accelerator facilities. Post-Irradiation Examination (PIE) of the irradiated specimens is being conducted at participating nuclear/fusion research institutions with appropriate "hot-cell" facilities, such as Pacific Northwest National Laboratory (PNNL). The recent collaboration work also includes efforts to provide the samples irradiated at BLIP to in-beam thermal shock test at CERN's HiRadMat facility. It will be the first examination to observe how the radiation-damaged material will behave when exposed to actual beam loading conditions. In this talk up-to-date status of these experiments, PIEs, and prospect for the works conducted by the RaDIATE collaboration are over-viewed [‡]

The 20th International Workshop on Neutrinos (NuFact2018)
12-18 August 2018
Blacksburg, Virginia

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[†] Readers can find more information at a collaboration meeting website: *https://indico.cern.ch/e/RaDIATE2018*

[‡] This work is financially supported by the U.S.-Japan Science and Technology Cooperation Program in High Energy Physics. This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

PoS(NuFACT2018)107

1. Introduction to RaDIATE Collaboration

In the recent past, major accelerator facilities have been limited in beam power by survivability of production target and beam window. Plans for future multi-MW target facilities will present even greater challenges. To maximize the benefit of high power accelerators, these challenges must be addressed in time, to provide critical input to design, construction and operation of LBNF, μ2e, J-PARC/Hyper-K, COMET, ESS, etc.. Radiation damage effect on materials has been identified as the most cross-cutting challenge facing these facilities. Especially for pulsed beam, understanding the response of highly irradiated materials to cyclic thermal shock loading conditions was deemed necessary for the robust operation of these beam intercepting devices. For example, J-PARC neutrino facility's beam window, made of Titanium alloy Ti-6Al-4V, experiences penetration of 3.3×10^{14} protons per pulse (ppp) in a few tens of mm^2 cross section, which causes localized energy deposition and periodic thermal stress wave of a few hundred MPa. When the facility is upgraded to proposed 1.3 MW beam operation, it will accumulate 2.4×10^{21} protons on target (pot) with about 8M pulses per operational year. The radiation damage, expressed in terms of Displacements Per Atom (dpa), *i.e.* number of displaced atoms in crystal lattice averaged over constituent atoms, is estimated to be about 2 dpa[1], whereas significant irradiation hardening and loss of ductility/embrittlement have been reported with 0.1 dpa. No datum higher than 0.3 dpa exists, and no known datum exists on high cycle fatigue ($> 10^3$ cycles) [1]. To replicate these extremely-severe HEP target environment and provide bulk samples for analysis, high energy, high fluence and large volume proton irradiations are needed. These runs, including Post-Irradiation Examination (PIE), are expensive and can take a very long time. To promote these studies, the RaDIATE collaboration, Radiation Damage In Accelerator Target Environments, was founded in 2012 by 5 institutions led by FNAL and STFC to bring together the HEP/BES accelerator target and nuclear fusion/fission materials communities. In 2017, 2nd MoU revision has counted J-PARC (KEK, JAEA) and CERN as official participants, and collaboration has now grown to about 70 members from 14 Institutions. The research program consists of determining the effect of high energy proton irradiation on the mechanical properties of potential target and beam window materials, and to understand the underlying changes by advanced micro-structural studies. The goal is to enable accurate targetry component lifetime prediction, to design robust multi-MW targetry components, and further, to develop new materials to extend lifetimes.

2. High Power Proton Irradiation at BLIP & Post-Irradiation Examination (PIE)

One of major RaDIATE program activities is a high-intensity proton irradiation on mechanical /micro-structural test specimens at Brookhaven Linear Isotope Production (BLIP) facility [2]. Our radiation damage study capsule box is placed upstream of BLIP's medical isotope production target box. Multiple capsules contain different materials (Beryllium, Graphite, Silicon, Aluminum, Titanium and Heavy materials), where each capsule is made of stainless steel with thin beam windows. Each capsule is filled with numerous specimens (tensile, bend, fatigue, micro-structural studies) in inert gas or vacuum atmosphere, and the outer surface of the capsule is cooled by water. The

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[1] In this report dpa values are from Norgett-Robinson-Torrens (NRT) model. Although it is widely utilized for estimation of damage, displacement cross section has not been enough validated, especially for high energy protons.

total energy loss in all capsules is controlled to be 68 MeV out of 181 MeV beam energy. The irradiation was conducted in two periods, former was in 2017 and the latter was in 2018. Beam exposure was 55 days in total with up to 158μA proton beam current, and the integrated protons on target has reached to 4.6×10^{21}, which was enough comparable to a yearly operation of future MW facilities. For the titanium alloy, we have irradiated 3 capsules in different periods, where peak damage for each capsule was estimated to be 0.25, 0.96 and 1.5 dpa, respectively. The lowest dose capsule irradiated in 2017 has been shipped to PNNL to establish PIE procedures. It was opened in a hot-cell by newly-developed remote capsule opener, and a series of remote tensile tests has been started successfully on tensile specimens. As a result, we have observed increased hardness and rapid decrease of ductility on Ti-6Al-4V. The micro-structural studies like SEM, EBSD, and TEM will follow, and relevance to these macroscopic behaviors will be studied in detail. The capsule also contains bend-fatigue specimens and a thin foil with numerous meso-scale (a few mm) bend-fatigue cantilevers fabricated with laser machining. The former will be tested at Fermilab, and the latter will be tested at Culham Centre for Fusion Energy (CCFE, UK) in cooperation with STFC, to obtain the first-ever high-cycle fatigue data for the irradiated titanium alloys.

3. Thermal Shock Study at HiRadMat Facility

The collaboration also promotes thermal shock studies on targetry materials at CERN's HiRadMat facility. HiRadMat, High-Radiation to Materials, is a user facility designed to perform single to several beam impingements on materials or accelerator component assemblies to evaluate the effect of high-intensity pulsed beams in a controlled environment. Using existing fast extraction channel to LHC, a high-intensity proton beam from CERN SPS with 440 GeV beam energy is delivered to the facility to a maximum pulse intensity of 4.0×10^{13} with a pulse length of 7.2 μs, equivalent to 3.4 MJ total beam energy. The beam at the target is collimated with spot size around 1 mm^2, generating extremely high thermal stress which can potentially break even Graphite and Beryllium. The HRMT43-BeGrid2 experiment is a follow-up of a past experiment conducted by the collaboration[3], to expose Beryllium, a typical beam window material frequently used at Fermilab and other facilities, to even higher beam intensities than what was achieved. The main interest of the experiment is to expose material specimens irradiated at BLIP to compare thermal shock response with that for non-irradiated specimens. It is to be emphasized that testing highly irradiated samples with thermal shock from high intensity beam has never happened before, where irradiated specimens will include Beryllium, Graphite, Silicon, Titanium, SiC-coated Graphite and Glassy Carbon. The irradiated specimens have been shipped from BNL to PNNL, and will be assembled into an irradiation array at PNNL hot-cell. Irradiated boxes are then to be shipped from PNNL to CERN for final assembly to vertical base plate, to be ready for the thermal shock tests at HiRadMat facility, scheduled in early October, 2018.

References

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