Novel materials to improve High Power Target reliability

F. Pellemoine[1], K. Ammigan[1], S. Bidhar[1], A. Couet[2], T. Ishida[3], S. Makimura[3], M. Moorehead[2], K. Yonehara[1], B. Zwaska[1], RaDIATE collaboration
1 Fermilab, USA
2 University of Wisconsin-Madison, Engineering Physics, USA
3 High Energy Accelerator Research Organization (KEK) and J-PARC Center, Japan

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. 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 reduce drastically lifetime of targets and beam intercepting devices. The results of these defects include swelling, embrittlement and phase transformations.

One way to prevent and mitigate radiation damage in material is to create material with grain size as small as possible, where dislocation motion can be limited, which prevents the embrittlement and hardening that result in material failure [2]. Grain boundaries serve as defect sinks for absorbing and annihilating radiation-induced defects.

In order to keep reliable intercepting devices in the framework of energy and intensity increase project in the future, it is essential to develop new nanocrystalline materials which contain a high density of grain boundaries to mitigate radiation damage. To reduce thermal shock effect in devices, it is necessary to investigate new materials or new technology with improved thermo-mechanical properties. New coatings need to be explored to add a protective barrier from corrosion effect.

The RaDIATE collaboration (Radiation Damage In Accelerator Target Environment) [3] will coordinate the High Power Targetry R&D program between institutions who have expertise and common interest among the 14 international institution members.

Novel materials

Nanofiber

Nanofiber offers promising application in future multi-megawatt targets. Since the continuum is physically discretized at micro-scale, a lot of issues like thermal stress cycles and local heat accumulation can be mitigated.[4]. Electrospinning technique is selected for production of sinuous targets and with flexibility of imparting various physical properties.

It is also proposed to design the nanofiber as mixture of different materials such as CNT dispersed in ceramics materials to improve the protection against radiation damage, better thermal properties, high heat dissipation, high mechanical strength.

High Entropy Alloys (HEAs)

High entropy alloys are bringing significant attention due to their inherent excellent mechanical properties, good corrosion resistance, low activation and high radiation resistance making them potential candidates for high power Targetry applications.

High entropy alloys represent a new class of alloys that have the potential to replace conventional alloys in diverse applications, potentially offering superior irradiation resistance with lower density of dislocation loops and less radiation induced segregation compared to conventional alloys. Typically, they consist of four or five alloying elements in close to equiatomic concentrations. The original concept of HEAs was based on the idea that the high configurational entropy of the system would favor the formation of a disordered single-phase solid solution over ordered intermetallic compounds, resulting in simple microstructures with a disordered chemical landscape which could enhance material properties [5,6,7].

The current proton beam windows made of Be may be replaced in the future by regular Ti-6Al-4V alloys. A collaboration was initiated with the MADCOR group at the University of Wisconsin – Madison with the objective to design and manufacture low-activation, low density, high-entropy alloy materials based on the TiVCrMn system as a substitution of the Ti-alloys.

Additively manufactured materials also show finer microstructure than material produced by conventional metallurgical techniques due to the high local cooling rate. The combination of HEAs production with additive manufacturing methods may further improve the radiation resistance, the mechanical and thermal properties of such materials [8].

Other candidate materials

Other novel materials are also proposed within the RaDIATE collaboration R&D program to respond to thermo-mechanical challenges described above as proton accelerator target materials: glassy carbon, metal foams, Nano-powder Infiltration and Transient Eutectoid (NITE) SiC/SiC composite [9], Toughened Fine-Grained Recrystallized (TFGR) Tungsten [10] and dual-phase Ti-alloys [11] are some candidates that we would like to investigate. SiC-coated graphite is a new application to mitigate oxidation on graphite target.

Irradiation experiments

All the materials above (list non-exhaustive) were irradiated or will be irradiated with existing irradiation facilities such as BLIP facility at Brookhaven National Laboratory (BNL) [12], HiRadMat facility at CERN [13] with some Post Irradiation Examination (PIE) at BNL, at Pacific Northwest National Laboratory (PNNL) [14] or Material Research Facility (MRF) at Culham-UK [15].

Recommendation

Targets and beam interceptive devices made from conventional materials have their own limits and may not sustain the upgraded beam for future projects. Having high power targets with high reliability and longer lifetime may be possible with the development of novel materials such as the one presented above. This R&D will benefit both the existing and the future high-power targets worldwide and not only for HEP but also for heavy ion production and neutron production.

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