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ADVANCING MATERIALS STUDIES FOR HIGH-POWER PROTON ACCELERATORS IN J-PARC*

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Abstract

In modern proton accelerators, the survivability of beam-intercepting devices, such as targets, beam windows and beam dumps, under intense beam irradiation is a key factor limiting the achievement of higher beam power. This article introduces the challenges faced by the secondary particle production targets and beam windows at the Japan Proton Accelerator Research Complex (J-PARC), and the developments undertaken to overcome these challenges.

INTRODUCTION

In proton accelerators, secondary particles such as muons, pions, neutrons, neutrinos, and kaons are generated on the target by proton beam irradiation and are transported to experimental areas for research in various scientific fields. There is an increasing demand for high-power proton beams at accelerator facilities worldwide to enhance secondary particle yields. However, the achievable beam power is limited by the mechanical properties of beam-intercepting components such as targets and beam windows. High-intensity proton beams push these structural materials to their limits, reducing their survivability and service life. Therefore, it is important to conduct research to understand failure and material degradation mechanisms in accelerator environments and to develop novel materials that can withstand the harsh conditions of high-power accelerators.

Since the target is often cooled by gas or water, the beam window, which isolates the accelerator vacuum, is directly penetrated by the proton beam. Both target and beam window materials generate heat when exposed to the proton beam, necessitating efficient cooling. Additionally, exposure to the proton beam causes atomic-level damage to these materials, leading to reduced thermal conductivity, diminished mechanical strength, and dimensional changes. Furthermore, proton beam irradiation activates these components. When replacing failed targets or beam windows, the design must account for the maintenance of activated devices, often requiring remote operation capabilities. For targets and beam windows in high-intensity proton accelerators, design and development must proceed from a multifaceted perspective, encompassing secondary particle generation and transport, heat generation from the proton beam, degradation of material properties due to irradiation, and maintenance of activated components.

To transport secondary particles generated by proton beam irradiation of the target material, dense materials are preferred to minimize the spatial spread of secondary particles. However, increasing the density of the target material also increases the heat generation density. To disperse heat generation and irradiation-induced material damage over a wider area as proton beam intensities increase, practical approaches include rotating target systems and liquid metal target systems, where liquid metal circulates as the target material.

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Table 1: Overview of Current Targets and Current Beam Windows at J-PARC

	Neutron source	Muon target	Neutrino target	Hadron target	COMET target
Energy & Power of p+	3 GeV, 1 MW	3 GeV, 1 MW	30 GeV, 830 kW	30 GeV, 92 kW	8 GeV, 3.2kW(P1)
Time structure	25 Hz, < 1 μs	25 Hz < 1 μs	4 μsec. in 1.36 sec. cycle	2 sec. in 4.2 sec. cycle	0.5 sec. in 2.5 sec. cycle
Beam radius at target	σx: 35 mm σy: 10 mm	σx: 3.5 mm σy: 3.5 mm	σx: 4.2 mm σy: 4.2 mm	σx: 2.5 mm σy: 1 mm	σx: 2.3 mm σy: 2.3 mm
Target material	Mercury in SS316L	Graphite	Graphite	Gold	Graphite
Window material	A5083	-	Ti-6Al-4V	Be/Pure Ti	Ti-6Al-4V /SS304

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The beam window is used to isolate the beamline region, so it must withstand the differential pressure of the isolated atmosphere, which often exceeds 1 atm. At the same time, to minimize beam loss at the window, the density and thickness of the window material are kept as small as possible. Therefore, materials with low density that can be fabricated into thin windows are required. As a result, beam windows generate less total heat and are cooled over a large surface area, making their thermal endurance requirements less severe compared to targets. However, thin windows must still withstand the differential pressure, necessitating the selection of materials with high specific strength, strength per unit density.

When the proton beam exhibits a pulsed temporal structure, there is concern that the target and beam window materials, whose performance has degraded due to beam irradiation, could be damaged by thermal shocks generated by instantaneous local heating. This beam pulse width, which is less than a microsecond, differs in timescale from rotation (ten to several hundred revolutions per minute) or liquid metal flow, meaning that simply increasing the speed of rotation or flow cannot resolve the issue. Thermal shock in proton accelerators differs from that in industrial equipment, which typically has a relatively gradual time structure; it cannot be mitigated by improving thermal conductivity. Furthermore, while industrial equipment often experiences surface stresses, thermal shock in proton accelerators is a phenomenon where compressive stresses propagate. This occurs because the volume of the beam path, instantaneously heated by beam irradiation, is confined by the cooler surrounding environment. When the target or window is solid, the propagation of instantaneous compressive stress alternates with tensile stress, causing failure if it exceeds the material's fatigue limit. For liquid metal targets, a major challenge is cavitation damage to the target vessel caused when stress waves propagating through the liquid reflect off the vessel walls.

It is recognized that the combination of proton irradiation damage and thermal shock in materials used in targets and beam windows is a common challenge at the world's leading high-intensity, high-energy accelerator facilities. To tackle these challenges, an internationally coordinated approach is considered the most efficient, as proton irradiation experiments and post-irradiation examinations (PIE) require enormous resources in terms of both budgets and manpower. The Radiation Damage In Accelerator Target Environments (RaDIATE) collaboration [1] enables cross-facility cooperation among engineers and researchers and facilitates the mutual use of irradiation test facilities at accelerator laboratories, as well as at nuclear fission and fusion materials research institutions in various countries. Established in 2013 by five institutions with Fermilab as the lead institution, the collaboration has gradually expanded, with J-PARC and CERN joining in 2017, and now comprises 19 participating institutions. A high-intensity proton beam irradiation experiments under the RaDIATE collaboration was conducted at the Brookhaven Linear Isotope Producer (BLIP) from 2017 to 2018 [2]. In this irradiation campaign, each participating accelerator institution brought materials for targets, win-dows, collimators, and beam dumps, such as beryllium, silicon, titanium alloys, TZM, iridium, and CuCrZr. An eight-week irradiation test was performed using a 181 MeV, 154 μA proton beam, and PIEs were conducted across multiple scales, from macro to micro.

This article introduces the challenges faced by the secondary particle production targets and beam windows at the Japan Proton Accelerator Research Complex (J-PARC), and the developments undertaken to overcome these challenges. Table 1 provides an overview of the current targets and beam windows at J-PARC, and Figure 1 shows a schematic view of these components.

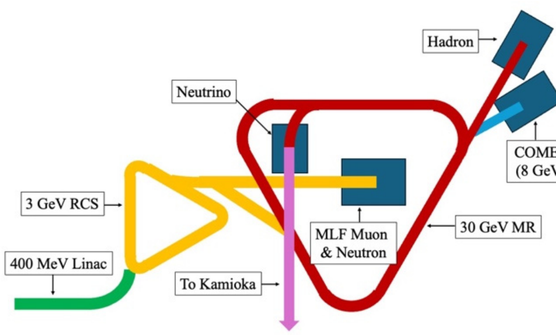

Figure 1: Schematic drawing of targets and beam windows at J-PARC.

TARGETS AND BEAM WINDOWS AT J-PARC

Muon Target and Neutron Source at MLF

The 3 GeV, 1 MW, 25 Hz proton beam accelerated by the Rapid-Cycling Synchrotron (RCS) is supplied to both the muon target and the spallation neutron source at the Materials and Life Science Experimental Facility (MLF). The muon target is installed upstream of the neutron source, and the proton beam passing through the muon target is subsequently delivered to the neutron source. This configuration enables simultaneous research using both muons and neutrons. At the start of operation in 2008, the muon target consisted of a fixed target made of 20 mm thick graphite bonded to a metal frame embedded with cooling water pipes. In 2014, a rotating target was introduced to distribute irradiation damage more evenly across the graphite. While the rotating target method addresses the issue of irradiation damage to the graphite, it introduces new challenges, such as wear on the bearings that support the rotating components in a high-temperature, high-vacuum, and high-radiation environment. To address this, J-PARC adopted bearings using bulk tungsten disulfide as a solid lubricant. The first rotating target achieved five years of continuous operation, and the second rotating target has been operating continuously for more than six years to date [3]. In 2011, the degradation of thermal conductivity in graphite materials from spent fixed targets was non-destructively measured using the laser spot heating method [4]. Currently, the release of tritium generated

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in graphite materials complicates maintenance. Therefore, research is being conducted on the tritium release behavior from graphite materials. Additionally, irradiation tests are being carried out on silicon carbide and graphite-based composite materials as next-generation muon production targets.

At MLF, operation of a mercury target as a spallation neutron source started in 2008. While mercury flow allows for the dispersion of heat density. Furthermore, since it is not inherently expected to function as a structural material, it does not suffer from radiation damage issues and can be reused, thereby reducing radioactive waste. However, the stainless steel (SS316L) container that houses and seals the mercury, while also functioning as the beam window, suffers from material degradation due to irradiation damage and is affected by cavitation. At the MLF, introducing helium microbubbles successfully reduced pressure waves to address this issue. Furthermore, a technique was developed to reduce container damage by forming a narrow flow channel at the beam entrance. This channel's narrow width and the steep velocity gradient and pressure distribution of the flowing mercury disrupt the growth and collapse process of cavitation bubbles. A wide range of developments are underway, including methods for measuring target vessel vibration during beam operation and establishing highly accurate methods for measuring the degree of damage inside the vessel after beam operation [5]. Figure 2 shows pictures of measurement process to evaluate the surface damage by cavitation. The specimens are cut from mercury vessel, and the damage is evaluated by tracing the surface damage on silicon rubber. In collaboration with Oak Ridge National Laboratory in the United States, research is being conducted on the degradation of mechanical properties of SS316L material and welded parts of SS316L due to proton irradiation. A reflector and moderators upstream of the neutron source are contained in Helium vessel. The partition between Helium vessel and the vacuum beamline is a water-cooled aluminium alloy beam window. J-PARC is investigating the performance degradation of the aluminium alloy due to irradiation. MLF achieved 1 MW operation, rated beam power of MLF, in April 2024. Continuing R&D for target and beam window aiming to achieve long-term stable operation and increase pulse energy.

Target and Beam Window at Neutrino Experimental Facility

At the neutrino experimental facility, a conventional neutrino beam is generated by fast extraction from the 30 GeV Main Ring (MR) and focused using an electromagnetic horn system. This beam is directed toward a near detector system at J-PARC and the Super-Kamiokande detector, a large underground detector located 295 km away, aiming to study neutrino oscillations. The target and beam window for the neutrino experimental facility were developed in collaboration between J-PARC and the Engineering Department of the UK Science and Technology Facilities Council (STFC). The target core, which is a graphite rod, is enclosed in a thin Ti-6Al-4V alloy sleeve and cooled by pressurized helium gas flowing in it [6]. The beam window, which separates the accelerator vacuum from the helium atmosphere surrounding the target, consists of two thin, partially spherical Ti-6Al-4V plates, each 0.4 mm thick, with a 2 mm concentric gap between them. Helium gas flows through this gap for cooling. The Hyper-Kamiokande project aims to increase the MR beam power from the current value of 830 kW to approximately 1.3 MW by increasing both the number of protons per pulse and the repetition rate. Consequently, upgrades of the target and beam window to accommodate higher beam power are in progress [7].

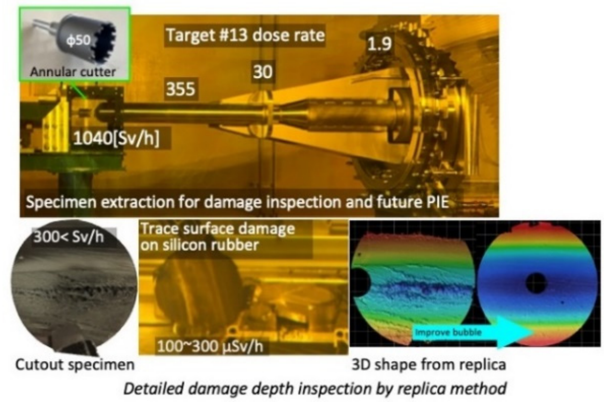

Figure 2: Pictures of measurement process to evaluate the surface damage by cavitation.

Targets and Beam Windows at Hadron Experimental Facility

At the Hadron Experiment Facility, a 30 GeV, 92 kW proton beam is supplied to the target via slow extraction with a time structure of 2 seconds in a 4.2-second cycle, producing secondary particles such as kaons and pions. An indirectly cooled gold target is currently employed, with the gold bonded to a water-cooled copper block. Development of a rotating tungsten target is underway to increase the acceptable beam intensity to 150 kW. The Hadron Experiment Facility utilizes beryllium beam windows and pure titanium beam windows [8].

Additionally, the COMET experiment, which branches off the beamline to the Hadron Facility to explore muon-electron conversion processes, receives an 8 GeV proton beam. The pion production target is positioned at the center of a superconducting solenoid, enabling experiments using high-intensity muons over a large solid angle. Development of a graphite target is underway for Phase 1, and a tungsten target for Phase 2. For the COMET experiment, progress is being made in manufacturing high-pressure-resistant spherical-shell beam windows using additive manufacturing to withstand pressure increases caused by helium leakage from the superconducting solenoid during quench events [9].

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RADIATION DAMAGE STUDIES AT J-PARC

Proton Irradiation Test of Ti-Alloys and SiC Coated Graphite at BLIP Facility

At the J-PARC neutrino facility, a high-strength titanium alloy, Ti-6Al-4V(Ti-64), is used as beam window material. Pure titanium undergoes a transformation in its crystal structure depending on temperature, changing from the low-temperature α(HCP)-phase to the high-temperature β(BCC)-phase. Ti-64 is an α+β phase alloy, *i.e.*, both phases coexist due to phase stabilizing alloying elements, offering both high strength and excellent ductility. Proton irradiation studies at the BLIP facility revealed that when Ti-64 is exposed to a proton beam, high-density defect clusters several nano-meters in size form in the α phase, and a crystalline structure called the "ω phase," which causes embrittlement, is irradiation-induced in the β phase. These effects result in significant hardening and loss of ductility even under minimal beam irradiation [10]. Systematic investigations into the radiation damage tolerance of various titanium alloy grades are ongoing.

At the graphite muon target in the J-PARC MLF Facility, tritium generated by proton irradiation is released into the beamline vacuum, complicating maintenance. In addition, during operation, unexpected air ingress can cause rapid oxidation of the heated graphite, potentially releasing tritium. To enhance oxidation resistance and suppress tritium release, research on graphite coated with silicon carbide (SiC) is being conducted, and test specimens were irradiated at BLIP facility.

Thermal Shock Experiment at CERN HiRadMat

Figure 3: A picture of the beamline in HiRadMat facility.

As mentioned earlier, thermal shock occurs with pulsed proton beams. CERN's HiRadMat facility aims to elucidate the effects of the world's most intense thermal shock by directly irradiating materials and accelerator equipment with 440 GeV high-intensity, highly focused proton beam pulses from the Super Proton Synchrotron (SPS) accelerator [11]. While BLIP can provide beam exposure, its DC beam cannot simulate thermal shock. HiRadMat can simulate thermal shock but cannot deliver high exposure doses. Therefore, materials irradiated with the proton beam at BLIP were assembled into irradiation vessels at the remote handling facility (hot cell) of the Pacific Northwest National Laboratory (PNNL) in the United States, transported to CERN, and subjected to beam thermal shock testing at HiRadMat within the framework of RaDIATE collaboration. Specimens irradiated in HiRadMat were returned to PNNL to evaluate the response to thermal shock of materials hardened and embrittled by irradiation damage. Additionally, irradiation tests on next-generation target candidate materials, such as silicon carbide composites, were also conducted. Figure 3 shows a picture of the beamline in HiRadMat facility.

Radiation Damage Studies by Heavy Ion Irradiation

The effect of irradiation on mechanical properties is ideally confirmed by measuring fracture strength and other properties using tensile tests on dumbbell-shaped specimens. However, the irradiation area of a proton beam is small, making it difficult to comprehensively investigate many conditions using tensile specimens. Therefore, instead of a proton beam, we evaluate irradiation effects using irradiation with a few MeV ion beams, controlling both temperature and the amount of irradiation damage at High Fluence Irradiation Facility (HIT) in Tokyo University [12]. Ion beam irradiation concentrates the damaged region to a depth of 1 to several micrometers. This allows imparting irradiation damage equivalent to several years of high-intensity proton beam irradiation in about half a day, with the added advantage that the sample does not become activated. For analysing such micro-materials, we comprehensively evaluate irradiation damage trends using hardness changes in the irradiated region measured by a nano-indenter, and transmission electron microscopy (TEM) observations of samples processed with a focused ion beam (FIB) in the irradiated region. Figure 4 shows a picture of sample holder in HIT facility.

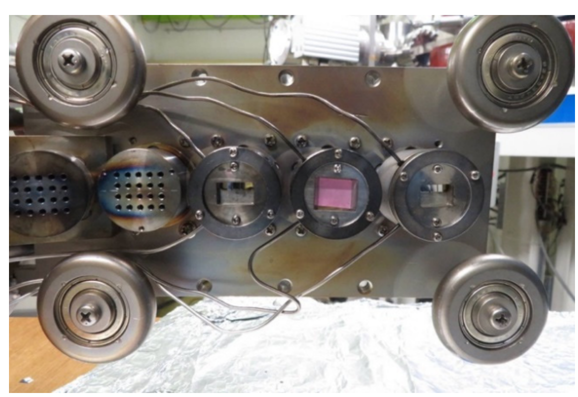

Figure 4: A picture of sample holder in HIT facility.

Tungsten Material Development

Tungsten (hereinafter, W) possesses excellent properties such as high density, high thermal conductivity, low

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thermal expansion coefficient, and low vapor pressure, making it a promising target material for proton accelerators worldwide. However, W inherently has a critical disadvantage: brittleness at around room temperature (low-temperature brittleness). This brittleness can be mitigated by heavy plastic working. Nevertheless, even if the brittleness is alleviated, W exhibits significant embrittlement due to recrystallization that occurs when it is heated at or above the recrystallization temperature, which is almost one-third of its melting point (recrystallization embrittlement). Moreover, W also exhibits significant embrittlement due to proton irradiation (irradiation embrittlement). Extensive efforts have been made worldwide to develop W materials with enhanced resistance to these types of embrittlement.

Possessing a fine-grained microstructure with a high density of grain boundaries and precipitates, which act as sink sites for irradiation defects, is effective in suppressing embrittlement. J-PARC has successfully manufactured a toughened, fine-grained, recrystallized W alloy with an isotropic, fine microstructure through an academia-industry collaboration with Metal Technology Co., LTD. This alloy exhibits ductility at room temperature while maintaining its recrystallized structure. The alloy was produced using a powder metallurgy method that utilizes the segregation of titanium carbide to grain boundaries through superplastic deformation (a process involving large deformation at low speed under high temperatures). J-PARC plans to continue development toward further performance enhancement, mass production, and verification of irradiation effects.

Radiation Damage Studies in SS316L for Mercury Vessel

It is known that the helium and hydrogen production in the material by proton irradiation is depending on the incident proton beam energy. 3 GeV for the J-PARC is higher than that of the proceed facilities of 1 GeV for Spallation Neutron Source (SNS) in Oak Ridge National Laboratory (ORNL) in the United States and 570 MeV for the Swiss Spallation Neutron Source (SINQ) in the Paul Scherrer Institute. It is concerned that the ductility after irradiation tends to be dependent on the amount of helium production and required that the PIE by using 3 GeV irradiated materials. Due to the difficulties of PIE tests such as tensile test in J-PARC, development of evaluation of stress-strain relation conveniently from nano/micro indentation technique is proposed and its validity is evaluating under the collaboration with the ORNL by using actually tensile-tested specimens. Prior to the actual PIE tests, we are now accumulating the experimental data for dual and triple ion irradiation tests by parametrically changing the amount of helium and hydrogen implantation in order to investigate the effect of gas production rate on mechanical properties by nano indentation.

CONCLUSION

At J-PARC, targets are employed to produce secondary particles such as muons, pions, neutrons, neutrinos, and kaons. Simultaneously, beam windows are used to isolate the beamline region. Research on proton irradiation damage is being advanced by subjecting materials, such as titanium alloys, aluminum alloys, tungsten alloys, stainless steel, graphite, and silicon carbide, to both proton and heavy ion beams, followed by post-irradiation testing.

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