MEASUREMENT OF DISPLACEMENT CROSS SECTION USING 440-GEV PROTONS AT CERN HiRadMat

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Abstract

The displacement per atom (dpa) is a damage index for beam-interaction materials and accelerator components, calculated by integrating the particle flux and the displacement cross section. Although the dpa is used as the standard, the experimental data are insufficient to validate the displacement model for the high-energy projectiles. To obtain data for the high-energy region, the displacement cross sections of Al, Cu, and W for proton irradiation at 440 GeV/c were measured at CERN HiRadMat. The preliminary experimental results were compared with PHITS and FLUKA calculations using both the Norgertt-Robinson-Torrens (NRT) and athermal recombination-corrected dpa (arc-dpa) models. Consistent with the existing data at energies below 120 GeV, the preliminary experiment showed that the widely used NRT model overestimates the cross section by a factor of 4 ~ 5, whereas the arc-dpa model shows remarkably good agreement with the present data.

INTRODUCTION

To reduce the hazard of radioactive waste generated by nuclear reactors [1], Japan Atomic Energy Agency (JAEA) has proposed an Accelerator Driven System (ADS) consisting of a very high-power accelerator (30 MW) with a proton kinetic energy of 1.5 GeV. Lead-bismuth eutectic (LBE) is used as both the target material and the coolant. In ADS design, damage to the beam-intercepting material is a critical issue. The beam interceptor also plays an essential role in other high-intensity accelerator facilities, such as neutron source facilities. In the Materials and Life Science Experimental Facility (MLF) [2, 3] of the Japan Proton Accelerator Research Complex (J-PARC) [4], an aluminum alloy beam window (A5083) is employed [5]. The T2K collaboration [6] at J-PARC also uses a titanium alloy [7] for the beam window. The fixed tungsten target is also one of the candidates for the COMET [8] experiment, which will be used to produce muons in the plan of J-PARC. To operate the high-power accelerator safely, it is essential to assess damage to the metallic materials. To quantitatively estimate damage to the target materials, the displacement per atom (dpa) is commonly employed.

The dpa is widely used to quantify damage in nuclear and fusion reactors, which is estimated by multiplying the particle fluence by the displacement cross section, typically obtained from the Norgertt–Robinson–Torrens (NRT) model [9]. In the low-energy region below 20 MeV, the displacement by protons is mainly done by the Coulomb force, so that the displacement cross section can be reliably predicted.

Since experimental data were scarce in the energy range above 20 MeV, our group conducted displacement cross section measurements at accelerator facilities both domestically and internationally for proton incident energies ranging from 0.1 to 120 GeV [10–16]. In the high-energy region, the energy deposition density in materials is expected to increase with incident energy due to relativistic effects in the electronic magnetic force and hadron interaction, which may enhance the displacement cross section. Conversely, the classical Lindhard model [17] predicts that the number of displaced atoms saturates, so the calculated displacement cross section does not increase at high energies. This study aims to verify the applicability of the spallation model in the high-energy region. Using the highest-energy proton beam (kinetic energy ~440 GeV, exactly momentum 440 GeV/c) available for fixed-target experiments at CERN HiRadMat, the displacement cross sections were measured.

EXPERIMENT AT HiRadMat

The number of displaced atoms can be determined from the change in electrical resistivity upon irradiating samples cooled to cryogenic temperatures, using the Matthiessen rule. Although HiRadMat produces a fast extraction beam, a weak beam of 1×10^{11} protons per shot, with a single bunch for every 30 seconds, was used, which kept the sample temperature below 30 K during beam irradiation. The Al, Cu, and W sample wires, each with a diameter of 0.25 mm and approximately 60 mm long, were used. The sample wires were horizontally supported by the holder using insulating material with a 30 mm hole, as shown in Fig. 1. A DC current source (Keithley 6221) and a nano-voltmeter (Keithley 2182A) with a multiplexer (Keithley 2700) were employed to measure the resistance of sample wires. All sample wires with a diameter of 0.25 mm and a purity of 99.9% were used in the experiment. Before installing the wires, they were annealed to eliminate lattice defects, about 20% below the melting point of each wire. The four-terminal method was applied to obtain the precise resistance of the samples. The sample holders were placed on the copper base plate, which

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was cooled by a cryogenic cooler (Sumitomo RP-082B2). Before irradiation, the samples were confirmed to be cooled to ~ 8 K.

The experiment was conducted at the beam tunnel TNC in HiRadMat, which used the proton beam extracted at SPS (Super Proton Synchrotron) at CERN. The beam profile required to determine the cross section was obtained using two beam monitors, BTV1 and BTV2, as shown in Fig. 2. The experimental apparatus was mounted on a remotely controlled, vertically movable stage. The beam position and width were determined from the W-wire resistance changes at various positions, which are sensitive to proton-induced changes in resistance. The results showed good agreement between the beam center position and width derived from these measurements and those obtained from the survey, metrology, and BTV. To minimize errors in the beam central position, a relatively larger beam width of 2 mm was employed, compared with the normally used about 1 mm at HiRadMat. We used a beam width of ~2 mm at 1σ in both the horizontal and vertical directions. In the horizontal direction, the aperture of the sample holder of 30 mm in diameter is sufficiently large to avoid unnecessary beam interaction at the sample holders.

The experimental displacement cross section $\sigma_{exp}(E)$ for the projectile proton energy of E can be obtained by observing the change of the electrical resistivity $\Delta\rho$ due to irradiation at cryogenic temperature, given as follows,

$$\sigma_{exp}(E) == \pi \Delta R D^2 / (4 L \rho_{FP} \, \overline{\phi(E)}), \tag{1}$$

where ρ_{FP} is the electrical resistivity change per Frenkel pair of the sample [16] , Δ R is the resistance change of the sample wire, L is the distance between electrodes, and D is the wire diameter. The intensity of the proton beam incident on the sample was measured using a well-calibrated current monitor placed at HiRadMat. The average proton fluence over the sample $\overline{\phi(E)}$ shown in Eq. (1) is given by the following for the case where the wire length of L is sufficiently larger than the horizontal beam width,

$$\overline{\phi(E)} = \frac{N_p(E)}{\sqrt{2\pi}\sigma_y L D} \int_{-D/2}^{D/2} \exp(-\frac{y^2}{2\sigma_y^2}) dy, \tag{2}$$

where y denotes the vertical positions, σ_y is the vertical beam width, and $N_p(E)$ is the integrated number of the projectile protons.

CALCULATION OF DISPLACEMENT CROSS SECTION

The displacement cross section is defined by the following equation, based on intranuclear-cascade model calculations.

$$\sigma_{disp-calc}(E) = \sum_i \int_{E_d}^{T_i^{max}} N_d(T_i) \frac{d\sigma}{dT_i} dT_i, \tag{3}$$

where E is the kinetic energy of the projectile, $d\sigma/dT_i$ is the recoil atom kinetic energy distribution, T_i is the kinetic energy of the recoil particle i effective up to a maximum of T_i^{max}, and E_d is the effective threshold displacement energy. In addition, $N_d(T_i)$ is the number of Frenkel pairs representing the efficiency of defect formation defined by vacancies and interstitial atoms in the irradiated material, which is widely used in the NRT model [9]. The number of atomic displacements as a function of cascade energy and damage function (N_d) is given by the NRT model, given as the following equation:

$$N_d(T_d) = \begin{cases} 0, & (T_d < E_d) \\ 1, & (E_d \leq T_d < 2E_d/0.8) \\ \xi(T_d) \cdot 0.8 T_d / 2E_d, & (2E_d/0.8 \leq T_d) \end{cases}, \tag{4}$$

where T_d is the damage energy, i.e., the kinetic energy available to produce the atomic displacement. The NRT model sets the defect efficiency ξ as 1, regardless of T_d, which applies an approximation with a simple linear collision cascade in the lattice.

Recently, the damage model has advanced through Molecular Dynamics (MD) simulations, which suggest using an athermal-recombination-corrected dpa (arc-dpa) model [18, 19] for accurate displacement estimation. When atoms are highly excited due to receiving recoil energy, called the Primary Knock-on Atom (PKA), many of them are displaced from their initial lattice. When the cascade equilibrates with its surroundings, the MD results show that nearly all atoms return to their full lattice positions. The final number of

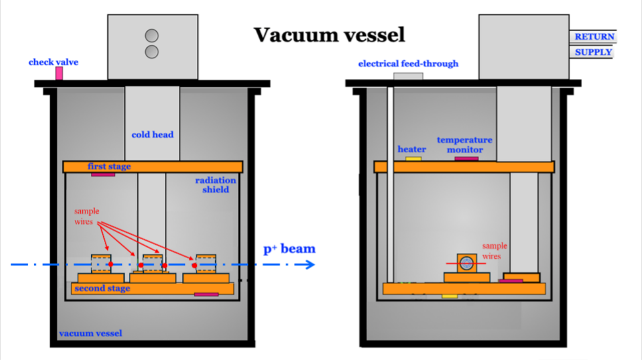

Figure 1: Schematic of the sample wires, cryochamber, and cryocooler used for the present experiment.

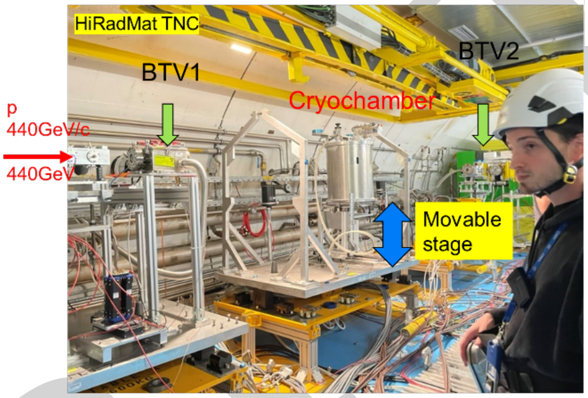

Figure 2: Experimental setup for the present study at HiRadMat.

defects is much smaller, and the number of atoms replaced by other atoms (atom mixing) is much larger than that predicted by the NRT model. In the arc-dpa model, when T_d is greater than $2E_d/0.8$, the defect production efficiency ξ is expressed by the following:

$$\xi(T_d) = (1-c)(2E_d/0.8)^{-b}T_d^b + c, \qquad (5)$$

where the parameters b and c are derived from the MD [19], which were determined to be -1 and 0.63, respectively. Using PHITS and FLUKA codes, the displacement cross section with the NRT and arc-dpa models was calculated.

RESULTS AND DISCUSSION OF DISPLACEMENT CROSS-SECTION

The trend in resistance of the W sample during beam irradiation is shown in Fig. 3, which used 1,898 shots of proton beams. The resistance rapidly increases with increasing temperature due to the beam irradiation. It can be seen that the resistance increased by 13.99 $\mu\Omega$ due to the displacement of atoms, and this effect was clearly observed after sufficient cooling following the finished beam irradiation. During irradiation, the beam was stopped several times, including the beam injection for the Large Hadron Collider (LHC), which had priority over HiRadMat. In Fig. 4, the preliminary present results of the displacement cross sections for W is compared with previous experimental data. Since the cross sections of Jung [20] are not explicitly given, the experimental cross sections were calculated by dividing the damage rate [20] given in the literature by the value of ρ_{FP}, which is the same as the present experimental data. The experimental data indicate that the displacement cross section is dominated by the Coulomb force at low energies and decreases rapidly with increasing proton energy. Meanwhile, in the high-energy region, nuclear reactions dominate the cross sections.

Also, PHITS and FLUKA calculations for W sample are shown in Fig. 4 using both the NRT and arc-dpa models. The present preliminary data for Al, Cu and W indicate an overestimation of the NRT model by a factor of 4 ~ 5 using PHITS and FLUKA. Applying the arc-dpa model, PHITS and FLUKA calculations show good agreement with the present experimental data.

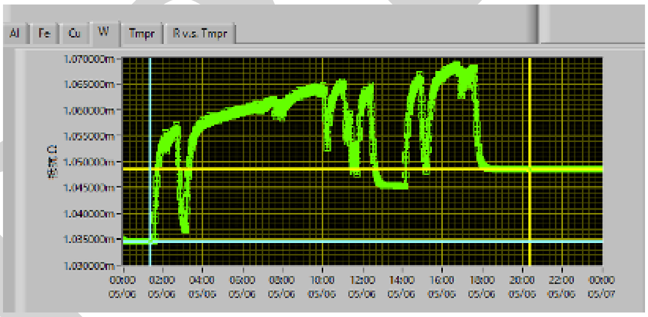

Figure 3: Resistance trend of W during beam irradiation.

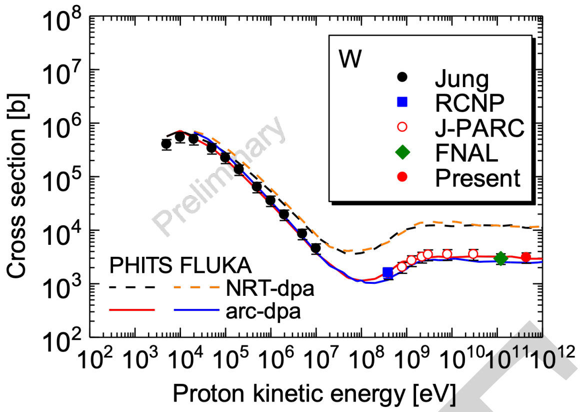

Figure 4: Comparison of the present preliminary data of W with previous experimen- tal data, calculated data by PHITS and FLUKA using the NRT-dpa and arc-dpa models

CONCLUSION

Displacement cross-section experiments were conducted at HiRadMat to evaluate the accelerator components used in a high-intensity proton accelerator. We successfully obtained displacement cross sections of Al, Cu, and W irradiated with protons having a kinetic momentum of 440 GeV/c. The data were obtained by observing the change in the electrical resistance of the irradiated specimens at low temperatures (< 30 K). The present data constitute the first experimental measurements of energy at 440 GeV, and show the applicability of the Lindhard model to the extremely relativistic kinetic-energy regime.

The present experimental displacement cross-section data were compared with calculations using PHITS and FLUKA, applying both the NRT and arc-dpa models. The widely adopted NRT model overestimated the experimental data by a factor of 4 ~ 5, whereas it agreed well with the data for low-energy proton projectiles below 10 MeV. In contrast, the arc-dpa model agrees remarkably well with the present experimental results across the entire energy range. Therefore, the arc-dpa model should be adopted for dpa calculations to evaluate damage from Al to W elements, consistent with previous studies at lower energies.

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REFERENCES

[1] K Tsujimoto, *et al.*, J. Nucl. Sci. and Technol. **44**, 483 (2007).

[2] Y Ikeda, Nucl. Instr. Meth. A **600**, 1 (2009).

[3] Y Miyake, *et al.*, Physica B **404**, 957 (2009).

[4] JAERI-Tech 99-56, JHF-99-3, and KEK Report (1999).

[5] S Meigo, *et al.*, J. Nucl. Mater. **450**, 141 (2014).

[6] K Abe, *et al.*, Nucl. Instr. Meth. A **659**, 106 (2011).

[7] T Ishida, *et al.*, J. Nucl. Mater. **541**, 152413 (2020).

[8] KEK/J-PARC-PAC 2012, KEK (2012).

[9] M Norgett, M Robinson, I Torrens, Nuclear Engineering and Design **33**, 50 (1975).

[10] Y Iwamoto, *et al.*, J. Nucl. Mater. **458**, 369 (2015).

[11] Y Iwamoto, *et al.*, J. Nucl. Mater. **508**, 195 (2018).

[12] H. Matsuda, *et al.*, J. Nucl. Sci. Technol. **57**, 1141 (2020).

[13] S Meigo, *et al.*, EPJ Web of Conf. **33**, 011050 (2021).

[14] Y Iwamoto, *et al.*, Mater. Sci. Forum **1024**, 95 (2021).

[15] S Meigo, *et al.*, EPJ Web of Conf. **284**, 05001 (2023).

[16] Y Iwamoto, *et al.*, Nucl. Instr. Meth. B **557**, 165543 (2024).

[17] J Lindhard, *et al.*, Mat. Fys. Medd. Dan. Vid. Selsk. **36**, 31 (1963).

[18] K Nordlund, *et al.*,Nature Communications **9**, 1084 (2018).

[19] A Konobeyev, *et al.*, Nucl. Energy and Technol. **3**, 169 (2017).

[20] P Jung, J. Nucl. Mater. **117**, 70 (1983).