Proposal for J-PARC 30 GeV Proton Synchrotron

Measurement of displacement cross section of proton in energy region between 3 and 30 GeV for high-intensity proton accelerator facility

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Executive Summary

For estimation of damage such as beam window and target material used at the accelerator facility, displacement per atom (DPA) is widely employed as an index of the damage. The DPA is estimated by the particle flux multiplied displacement cross section, which is obtained by calculation based on intranuclear cascade model. Although the DPA is widely employed, the experimental data of displacement cross section are scarce for a proton in the energy region above 20 MeV. In the recent study of the displacement cross section, it was reported that the displacement cross section of tungsten has 8 times difference among the calculation models. To obtain experimental data, some of our group has measured the displacement cross section of Cu for 125-MeV proton at Kyoto University. The displacement cross section can be easily obtained by observing the change of resistivity of the sample cooled by a cryocooler to sustain the damage of the target.

In this study aiming to improve the calculation model, the displacement cross section will be measured. The sample will be irradiated by the proton with the kinetic energy range from 3 GeV to 30 GeV. The sample was contained in the vacuum chamber placed in front of the MR abort beam dump. Based on the previous experiment, the requirement of the accumulated intensity is found to be very low such as $5x10^{14}$ for each experiment, which used a thin sample. Therefore, the requirement beam time for the present experiment is very short and the residual radiation dose will be low.

The budget for the present proposed experiment was already obtained from Ministry of education, culture, sports science and technology Japan (MEXT). The similar experiment will be carried out by our group at the beam dump placed at exit channel of the 3-GeV synchrotron in J-PARC, to obtain the displacement cross section in the energy region from 0.4 GeV to 3 GeV. Also, the similar experiment will be carried out at RCNP to acuire the experimental data less than 400 MeV. Thus, in the huge energy range, the displacement cross section can be obtained for the proton, which will help to improve the damage estimation of the target material and superconducting magnet for the high power accelerator facilities.

1. Purpose and background

1.1 Introduction

As the power of accelerators is increasing, the prediction of the structural damage to materials under irradiation is essential for the design [1]. To decrease hazard of the radioactive waste produced in a nuclear reactor, Japan Atomic Energy Agency (JAEA) proposes the Accelerator Driven System (ADS) with extremely high power accelerator such as 30 MW with proton kinetic energy of 1.5 GeV. A lead-bismuth eutectic is one of a candidate of the target, which simultaneously plays the role of the coolant. In the design of the ADS, damage of the window material is one of a key issue. In J-PARC, transmutation experimental facility (TEF) is planned to build for the study of the target material for the ADS.

Beam windows play important roles in high-power proton accelerator facilities. At material life science experimental facility (MLF) in J-PARC, an aluminum alloy window is utilized. The T2K uses the titanium alloy is employed. To operate high power accelerator, the damage estimation of the target material is essential.

To specify the damage of the target material, displacement per atom (DPA) is employed in general, which is widely used for the estimation of damage nuclear reactor and fusion reactor. Normally, the characterization of the material is estimated by the post-irradiation examination (PIE). The DPA is estimated by the particle flux multiplied displacement cross section. In the lower energy region, say less than 20 MeV, the displacement cross section for charged particles can predict well because the displacement is mainly caused by Coulomb scattering. For the neutron in lower energy, the DPA can be estimated with good accuracy as well, based on elastic scattering and inelastic scattering, in which the cross section and outgoing energy of the second particle are well known, The calculation method of displacement cross section has been established for the low-energy regions where secondary particles are not produced by nuclear reactions.

However, for the particles in high energy region, the experimental data of displacement cross section are so scarce that the calculated displacement cross section has not been investigated for the high-energy regions, and the accuracy of the calculation method of displacement cross sections was unknown. For the neutron and charged particle in the energy region above 20 MeV, many reaction channels open to produce secondary particle. In order to obtain displacement cross section above 20 MeV, the intranuclear cascade model code such as PHITS, MARS, FLUKA, and MCNPX. Recent, cross sections obtained by MARS with several models [2] was compared with the experimental data as shown in Fig. 1. Mokov reported that the displacement cross section of tungsten has 8 times difference in various calculation models. It should be noted that 8 times of ambiguity for the displacement cross section makes 8 times ambiguity of lifetime estimation for target materials. For validation and improvement of the estimation of the DPA, the experimental data are crucial. However, the experimental data of the DPA are scarce, and there are five experimental data for displacement cross section in the proton energy region above 20 MeV. For improvement of the displacement cross section, the experimental data are required.

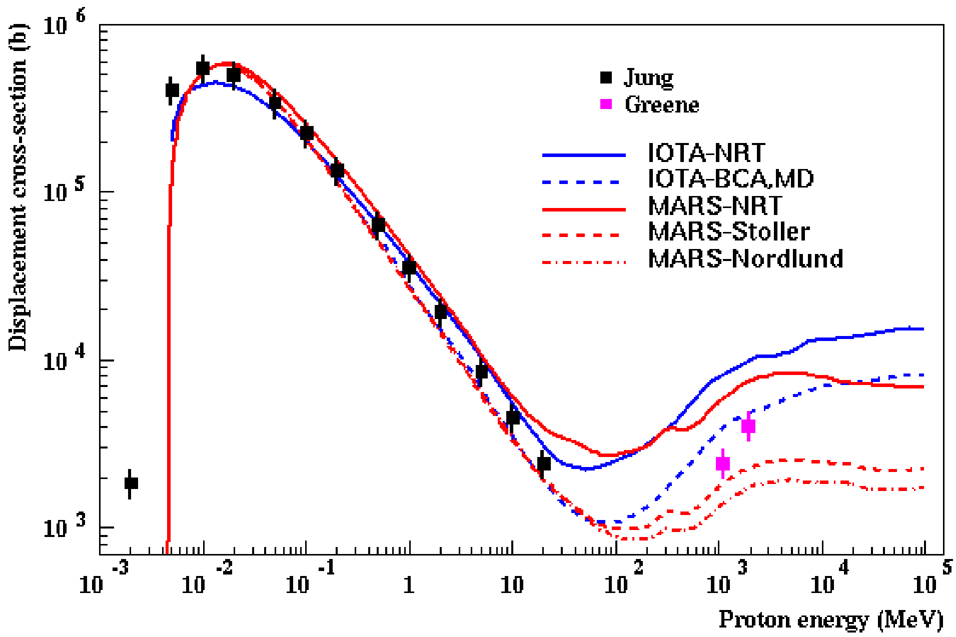

Fig. 1 : Comparison of displacement cross section between experiment and calculation with MARS by using various damage models [2].

As increase of the beam power, radiation damage of superconducting magnet is an issue. In J-PARC, the COMET experiment (J-PARC E21) is planned to search for the coherent neutrinoless transition of a muon to an electron in a muonic atom (μ−e conversion). The superconducting solenoid will be utilized to capture pion from the production target with high-efficiency. At LHC in CERN, superconducting magnets are utilized. Degradation of superconductors due to the radiation is one of the key issues of the superconducting magnet with increasing power of the beam. It is important to obtain the data of the degradation of superconductors.

1.2 Calculation of DPA

DPA is defined by the integral of displacement cross section $\sigma_{\mathrm{disp.}}$ and accumulated particle flux $\phi(E)$ as shown Eq. (1).

$$DPA = \int \sigma_{\mathrm{disp.}}(E)\phi(E)dE \qquad (1),$$

where E is the kinetic energy of irradiation particles. The displacement cross section is defined as following equations.

$$\sigma_{\mathrm{disp-cal.}} = \sum_i \int_{E_{\mathrm{d}}}^{T_i^{\max}} d\sigma/dT_i \times \eta N_{NRT}(T_i)dT_i \qquad (2),$$

where $d\sigma/dT_i$ is recoil atom kinetic energy distribution, T is the kinetic energy of recoil particle i, N_{NRT} is the number of defects (Frenkel pairs) which is defined as a vacancy and a self-interstitial atom in the irradiated material using the Norgertt–Robinson–Torrens (NRT) approximation [3], which has been widely used from that time. η is the defect production efficiency [4].

1.3 Measurement of displacement cross section at KURRI

Experimental displacement cross-sections are needed to validate DPA values calculated with Monte Carlo codes for lifetime estimation of devices at the ADS Target Test Facility (TEF-T) in J-PARC (400 MeV protons) [5], IFMIF (40 MeV deuteron) [6], and so on. However, there were no experimental displacement cross sections in the energy region lower than 20 MeV, except for data for 1.1 and 1.94 GeV proton irradiation of copper and tungsten obtained at the Brookhaven National Laboratory (BNL) [7]. The experimental displacement cross section is related to the defect-induced electrical resistivity changes as follows [8].

$$\sigma_{disp-\exp} = \frac{1}{\rho_{FP}} \frac{\Delta\rho_{metal}}{\phi} \quad (3).$$

Where $\Delta\rho_{metal}$ is the electrical resistivity increase (Ωm) which is the sum of resistivity per Frenkel pair and ϕ is the accumulated proton beam flux (/m^2). Damage rate (Ωm^3) is defined as $\Delta\rho_{metal}/\phi$. ρ_{FP} (Ωm) is the Frenkel-pair resistivity which was derived from damage rate measurements in single crystals under electron irradiation at low temperature and given by literature [4,9]. The number of defects is experimentally related to defect-induced changes in the electrical resistivity of metals at cryogenic temperature (around 10 K), where recombination of Frenkel pairs by thermal motion is well suppressed [6,9 and 10]. This means that a cryogenics facility is required to maintain the sample temperature at around 10 K to perform such irradiation experiments.

In the BNL experiments [7], the cryostat assembly for sample irradiation consisted of a complicated cryogenics system to deliver a metered flow of liquid cryogen (liquid nitrogen and liquid helium) for controlling the sample temperature. To measure the damage rate $\Delta\rho_{metal}/\phi$ using various beams without a complicated cryogenic system in accelerator facilities, we have developed a cryogen-free cooling system using a Gifford–McMahon (GM) cryocooler in the beam line of the Fixed-Field Alternating Gradient (FFAG) accelerator facility at Kyoto University Research Reactor Institute (KURRI) [12] as shown in Fig. 2 [13]. Note that beam energy and intensity (125 MeV and 1nA) are fixed at FFAG accelerator facility. The sample was a copper wire with a 250-μm diameter and 99.999 % purity sandwiched between two aluminum nitride ceramic sheets as shown in the right side of Fig. 3.

The electrical resistivity changes of the copper wire were measured using the four-probe technique. After 125 MeV proton irradiation with 1.45×10^{18} protons/m^2 (20 hours, 1 nA) at 12 K, the total resistivity increase was 4.94×10^{-13} Ωm (resistance increase: 1.53 μΩ). The resistivity increase did not change during annealing after irradiation below 15 K. Figure 4 shows the experimental displacement cross-section of copper in our work [13] and previous studies [7]. The experimental data at 125 MeV irradiation shows similar results to the experimental data for 1.1 and 1.94 GeV. Comparison with the PHITS and revised radiation damage model [14,15] gives a good quantitative description of the displacement cross-section in the energy region >100

MeV although the calculated results with SRIM code [16] (dashed line) are much smaller than the experimental data due to lack of the secondary particles produced by nuclear reactions.

The increase in electrical resistivity due to high-energy protons provides straightforward information such as degradation of the stabilizer of the superconductor, which compromises quench protection and increases magnetothermal instability [17], for the superconducting accelerator magnet in the High Luminosity Large Hadron Collider [18] and the Future Circular Collider [19].

Taking into consideration of these results, we have launched a comprehensive study of the radiation damage in metals (aluminum, copper, tungsten) under proton irradiation. Our final goal is to create data libraries of displacement cross sections using PHITS with an energy range from 0.1 to 30 GeV. It will be necessary to validate the model mentioned above based on measurements of damage rates using our cryogenic devices developed in KURRI.

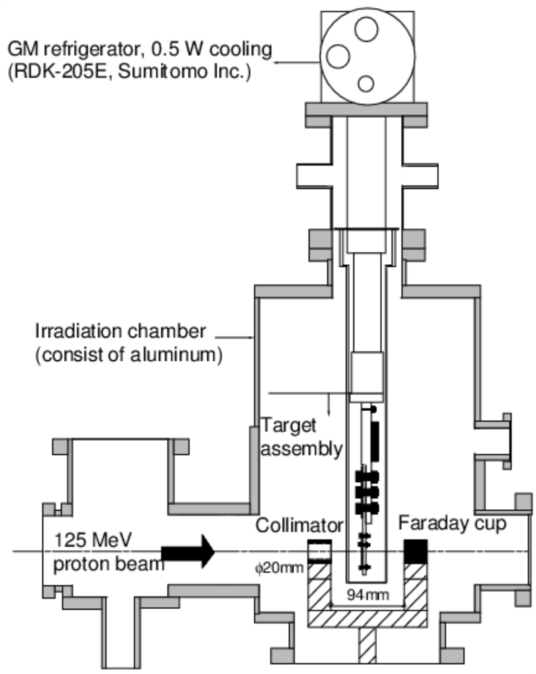

Fig. 2: Schematic of the irradiation chamber developed in the beam line at FFAG accelerator facility in Kyoto University Research Reactor Institute (KURRI) [13].

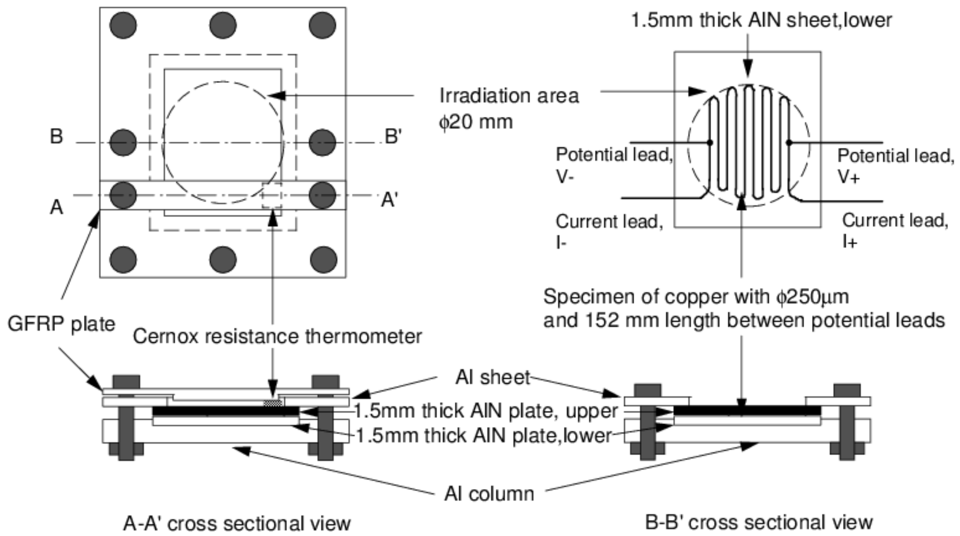

Fig. 3: Drawing of the sample and its retention developed in the beam line at FFAG accelerator facility in KURRI [13].

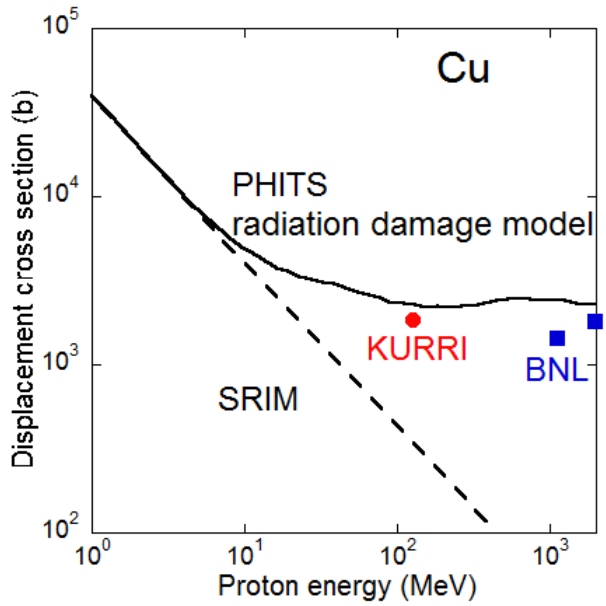

Fig. 4: Displacement cross-sections for proton irradiation of copper: our group work [13] (red circle), from the BNL data [7] (blue squares), the cross-section calculated using the PHITS-radiation damage model [15] (solid line), and SRIM code [16] (solid dashed line).

1.4 Expected results and their significance

Expected result is to produce the experimental displacement cross sections of materials for validation of radiation damage models in PHITS which will be used for the design of J-PARC TEF (400 MeV) and ADS design (above several hundred MeV). The experimental data will also be utilized for the coordinated research project (CRP) in International Atomic Energy Agency (IAEA) titled with “Primary Radiation Damage Cross Sections” [20]. One of expected CRP outputs is to produce a digital database for displacement cross sections of materials in the accelerator facilities. In the 2nd CRP meeting in June 2015, the CRP members suggested that our measurement data are essential to evaluate the displacement cross sections because of no experimental data from 1 MeV to 1 GeV and no activity of this measurement except for us all over the world. They highly recommended us to continue the measurements.

After proton irradiations, the cryogenic device can also measure the thermal recovery of the radiation-induced resistivity increase using an electric heater. This data is required for the design of the superconducting magnet used in accelerator facilities. We found that the behavior of the resistivity recovery for 125 MeV protons is similar to that for 0.54 MeV protons, while 20% of the defects remain at an annealing temperature of 290 K. As there are no data on thermal recovery of radiation defects, our experimental data are also valuable for the design of superconducting magnet in accelerator facilities. In summary of the workshop of radiation effects in superconducting magnet materials held in FRIB Michigan State University in 2015 [21], we were also strongly recommended to carry out cryogenic irradiation measurements on metals employed as a superconducting magnet.

2. Experimental Method

2.1 Experiment at MR tunnel

A schematic drawing of experimental arrangement is illustrated in Fig. 5, which is utilized similar experiment carried out 3-GeV synchrotron in J-PARC. The proton beam extracted from the Main Ring (MR) will be transported to the abort dump and irradiated a sample with a 4 mm thick aluminum folder placed in the irradiation chamber in front of the MR abort beam dump. The experimental setup of the irradiation chamber will be similar as used in the previous measurements at KURRI [12] except movable stage for samples, which is required to evacuate the beam position when the experiment is not performed. As shown in Fig. 5, the sample is placed at the movable stage so as to evacuate unused time.

Before the cryogenic irradiation on the sample, characteristic of the beam will be measured by beam monitors placed at MR to obtain the beam profile at the sample, which will be carried out following to beam study at MR. It is assumed that damage rate, $\Delta\rho_{metal}/\phi$ (resistivity change per beam intensity), is not so changed within beam area with the 20 mm diameter on the sample in BNL and KURRI experiments because the BNL experiment indicated that resistivity increase of sample is proportional to beam intensity [6].

For measurement of the electric resistivity increase under cryogenic irradiation, we will use the same manner with our previous experiment using 125 MeV protons at KURRI as described in Section 1. Table 1 shows the estimated resistance increase of Al, W and Cu wires with Eq. (3), displacement cross section calculated with PHITS. The sample wire will have a dimension of 13-cm length and 0.2-mm diameter. Our experiments will be successful under proton irradiation with 5×10^{14} protons on the sample, which has beam power of 0.7 kW with duration of 1 h for proton having the kinetic energy of 30 GeV. Since the allowable intensity of abort beam dump is 7.5 kW, the requirement beam power of 0.7 kW is 10 times smaller than the allowable intensity at the beam dump. In this experiment, it is important to sustain the sample in low temperature to remain the damage caused by proton. Beam current will be chosen in the intensity range lower than 1×10^{13} protons per shot, which will be adjusted so as to keep the low temperature at the sample. For each run of the experiment, the amount of the proton is required to 5×10^{14}. The duration of each run is expected less than 1h, which allows us the flexibility of beam time coupled with accelerator study of MR. Samples of aluminum, tungsten, and copper will be utilized in this experiment. The samples will be changed during outage period so as not to disturb another experiment carried out at neutrino and hadron facilities. In this experiment 8 and 30 GeV proton will be introduced to the target. COMET experiment uses the 8 GeV protons so that 8 GeV proton is essential for the present experiment. By changing the timing for extraction kicker magnet, proton beam with 8 GeV can be delivered to the sample. The GM cryocooler is placed at the top of the chamber as shown in Fig. 5. Compressor for the GM cryocooler will be located at the MR beam tunnel due to the length of helium supply.

After irradiation, the resistivity of the sample will be measured for thermal recovery of defects for samples. In order to avoid disturbance of the beam turning at the MR, the sample is placed on movable stage shown in Fig. 5. After irradiation, the sample will be retracted from beam irradiation position. The thermal recovery of defects will be measured at the evacuation position. In order to perform irradiation efficiently, the status of beam irradiation such as proton amount per shot and accumulated proton power will be controlled by the machine protection system (MPS) of the accelerator control system. Also, the MPS will control irradiation condition according to the sample position.

After the present proposal granted, the detail design of the chamber will be performed with the association of the MR group. The chamber will be installed by our group with the association of the MR group. In the experiment, after beam tuning by the MR group, the electro-resistance and temperature will be measured by our team.

It should be noted that the similar experiment is planned at the 3-GeV synchrotron in J-PARC using the target chamber shown in Fig. 5 for the proton energy from 0.4 to 3 GeV. During summer outage in 2017, the chamber will be installed at the exit channel of the 3-GeV synchrotron. Furthermore, the similar experiment for the proton energy less than 0.4 GeV will be performed at RCNP in Osaka University. With gathering all experimental results, the experimental displacement cross section will be covered with an extended the kinetic energy range.

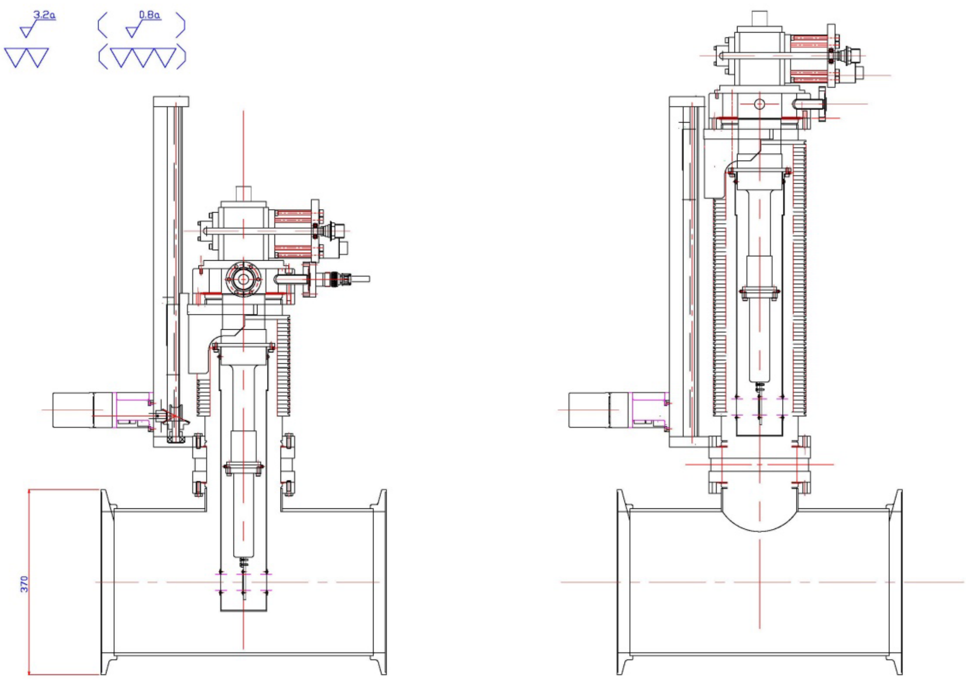

Fig. 5: Schematic of target chamber placed at beam transport line at 3-GeV synchrotron. Left and right-hand side show irradiation and evacuation position of the sample, respectively. The similar structural chamber will be employed with placing at the beam transport line to the MR abort beam dump.

Table 1: Estimated resistance increase of Al, W and Cu target using Eq. (3) and displacement cross section calculated with PHITS.

Sample	Electric resistance at 6 K ($\mu\Omega$)	Frenkel pair resistivity ρ_{FP} ($\mu\Omega$m)	Expected displacement cross section ($\times 10^{-25}$ m^2)	Accumulated beam flux at sample ($\times 10^{19}$/m^2)	Estimated increase of resistance ($\mu\Omega$)
Al	137	3.7	0.2	1.78	4
W	9700	27.5	2	1.78	292
Cu	29.4	2	1	1.78	11

2.2 Residual dose

The residual dose after beam irradiation was estimated by PHITS code with the total amount of protons of 5×10^{14}. By using the geometrical model shown in Fig. 6, the residual dose was estimated. The calculation result of the residual dose is shown in Table 2. Due to the small amount of the proton and thin samples, the residual dose is insignificantly small. Therefore, the sample can be handled by a human after irradiation.

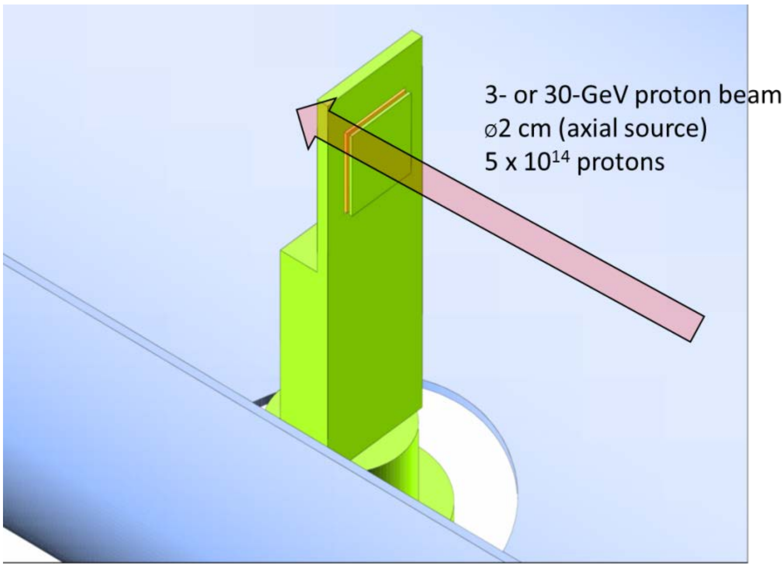

Fig. 6: Geometry employed for residual dose calculation with PHITS.

Table 2: Estimated residual dose [μSv/h] of the sample for each decay time after irradiation.

Distance from sample	1h	4h	24h	7days
10 cm	715	275	80.3	0.175
30 cm	75.0	29.0	8.57	0.0185
1 m	6.80	2.62	0.771	0.00167

3. Beam request and schedule

3.1 Beam request

Requested beam time is shown in Table 3. As the kinetic energy of the proton, 8 and

30 GeV will be utilized. In JFY 2018 after summer outage, the chamber will be installed, and a test examination will be performed. In JFY 2019, the displacement cross section will be obtained.

Table 3: Beam time for the present experiment.

Sample	Proton kinetic energy [GeV]	Requirement beam time each run [hour/run]	Run number each fiscal year [times/year]	
			2018	2019
Al	8	1	0	2
	30	1	1	3
W	8	1	0	2
	30	1	1	3
Cu	8	1	0	2
	30	1	1	3

3.2 Readiness

The budget of the present proposal has been already funded in the research program of 'Measurement of displacement cross section using J-PARC of structural material for Accelerator Driven System (ADS)' entrusted to Japan Atomic Energy Agency (JAEA) by the Ministry of education, culture, sports science, and technology Japan (MEXT). All the equipment for the present experiment is procured by KEK, whose budget is given by JAEA as entrusted research. Already, procurements of the GM cryocooler, DC power supplies and voltage meter for resistivity measurement, and the thermometer had finished in last Japanese fiscal year.

3.3 Schedule

In Japanese fiscal year (JFY) 2017, the beam chamber will be fabricated to carry out sample cooling test. After the present proposal approved by the PAC, the target chamber with revision by the result of the cooling test will be installed during summer outage in 2018 from July to September 2018. The experiment will be prospectively carried out in JFY2018 and JFY2019. Following the research plan granted by MEXT, the present experiment will run up to the end of JFY2019 March 2020.

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