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BEAM INSTRUMENTS FOR HIGH POWER SPALLATION NEUTRON SOURCE AND FACILITY FOR ADS

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Abstract

As increase of beam power, beam instruments play an essential role in the Hadron accelerator facility. In J-PARC, the pitting erosion on the mercury target vessel for the spallation neutron source is one of a pivotal issue to operate with the high power of the beam operation. Since the erosion is proportional to the 4th power of the beam current density, the minimization of the peak current density is required. To achieve low current density, the beam-flattening system by nonlinear beam optics using octupole magnets in J-PARC. By the present system, the peak density was successfully reduced by 30% compared to the conventional linear optics. Also in J-PARC, transmutation experimental facility is planned for the realization of the accelerator-driven system (ADS), which will employ powerful accelerator with the beam power of 30 MW. To achieve similar damage on the target as the ADS, the target will be received high current density. For the continuous observation of the beam status on the target, a robust beam profile monitor is required. Beam profile monitors have been developed with irradiation of the heavy-ion of Ar to give the damage efficiently.

INTRODUCTION

In the Japan Proton Accelerator Research Complex (J-PARC) [1], a MW-class pulsed neutron source, the Japan Spallation Neutron Source (JSNS) [2], and the Muon Science facility (MUSE) [3] will be installed in the Materials and Life Science Experimental Facility (MLF) shown in Fig. 1. Since 2008, this source has produced a high-power proton beam of 300 kW. In 2015, J-PARC successfully ramped up beam power to 500 kW and delivered the 1-MW beam to the targets. To produce a neutron source, a 3 GeV proton beam collides with a mercury target, and to produce a muon source, the 3 GeV proton beam collides with a 2-cm-thick carbon graphite target. To efficiently use the proton beam for particle production, both targets are aligned in a cascade scheme, with the graphite target placed 33 m upstream of the neutron target. For both sources, the 3 GeV proton beam is delivered from a rapid cycling synchrotron (RCS) to the targets by the 3NBT (3 GeV RCS to Neutron facility Beam Transport) [4–6]. Before injection into the RCS, the proton beam is accelerated up to 0.4 GeV by a LINAC. The beam is accumulated in two short bunches and accelerated up to 3 GeV in the RCS. The extracted 3 GeV proton beam, with a 150 ns bunch width and a spacing of 600 ns, is transferred to the muon production target and the spallation neutron source.

As the increase of beam power, beam profile monitoring plays an important role to avoid the damage to the targetetry at the MLF. Therefore it is imperative to watch continuously the status of the beam at the target at the JSNS especially for the peak current density. At the MLF, a reliable beam profile monitor has been developed with Multi-Wire Profile Monitor (MWPM). In order to watch the two-dimensional profile on the target, a beam profile monitor system has been developed base on the imaging of radiation of the target vessel after beam irradiation. For observation beam introduced to the target, MWPM was placed at the proton beam window. Furthermore, in J-PARC center, facilities for research and development for Accelerator Driven System (ADS) is planned. To satisfy the users' demand for neutron and muon, a new target facility called second target station is also planned. In those facilities, the beam will be more focused than the JSNS employs so that a robust beam profile monitor will be required [7], which will stand higher current density than the JSNS.

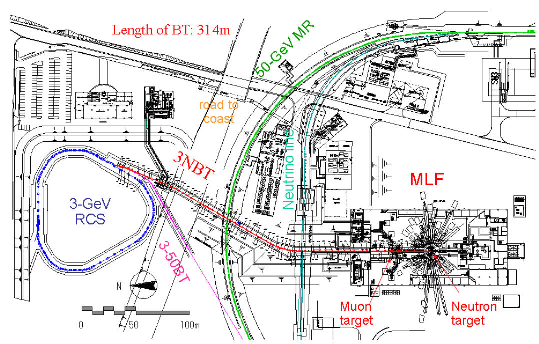

Figure 1: Plan of rapid cycling synchrotron (RCS) at the Materials and Life Science Experimental Facility (MLF) at J-PARC.

BEAM MONITOR SYSTEM AT THE BEAM TRANSPORT TO THE TARGET

Monitors Placed at Proton Beam Window

Continuously observing the characteristics of the proton beam introduced to the spallation target is very important. Due to the high activations caused by the neutron produced at the target, remote handling technique is necessary to exchange the beam monitor for the target. In order to decrease the radiation produced at the spallation neutron target, shielding above the monitor was required. To reduce the difficulties of the exchange work and decrease of the shielding, beam monitors were coupled with a Proton Beam Window (PBW) utilized as a physical separation between the vacuum region of the accelerator and the helium region around the neutron target. The PBW is better to be placed closer to the target where the distance between the target and the PBW is 1.8

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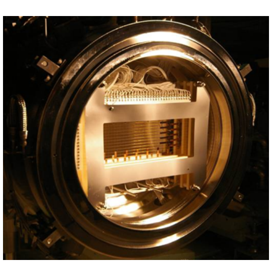
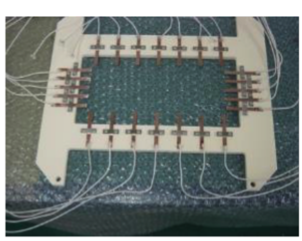
m, which gives reliable profile at the target. In Fig. 2, the MWPM placed at the center of a vacuum chamber of the PBW is shown. To avoid excessive heat at target vicinities, beam halo monitors are placed as well. The chamber of the PBW has inflatable vacuum seal called pillow seal. Due to the pillow seal, the monitors can be changed by the remote handling. To calibrate the sensitivity of each wire, the signal was observed by the scanning the position with narrow width beam. It was found that the difference of individual sensitivity was 6% at most.

In an actual beam operation, the heat at the target vicinities such as shielding, which mainly does not have water cooling channel, is necessary for reducing the peak density. Beam halo monitors attached at the PBW to observe the heat deposition at the target vicinities such as reflector and shielding, which is not allowed to exceed 1 W/cm^3. A close-up view of the beam halo monitor is also shown in Fig. 2. Two types of beam halo monitors were utilized to obtain the thermal information by thermocouples and the emission of an electron by the electrode. Since the emission of electron indicates relative intensity of the beam halo, the beam halo relative strength, which can be normalized by the following thermal observation, can be obtained by several shots of the beam. To observe the absolute intensity of the halo, the thermocouple type was implemented, which consists of copper strips coupled with the thermocouple. With 5 minutes of 25 Hz beam operation, the absolute intensity of the beam halo can be determined by the differential of temperature by time. These procedures were typically performed in actual beam operation.

The temperature observed by the thermocouples gives essential information to the operator, which are included in the machine protection system (MPS). On May 27 in 2018, a quadrupole magnet had a malfunction of layer short, which lost field about 30% at a pole. Due to the magnetic center shift, the beam center at the target was offset about 20 mm at the target for both horizontal and vertical directions. In such abnormal condition, the beam halo monitors detected anomaly by the temperature of thermocouples, which immediately halted the beam and noticed operators the anomaly.



(a) Beam monitors placed at the PBW



(b) Halo monitor

Figure 2: Mulit-Wire Profile Monitor (MWPM) and beam halo monitors placed at the Proton Beam Window (PBW). (a) Whole view of the MWPM and halo monitors. (b) Close up of the thermocouple type of beam halo monitors.

Since wires at the MWPM placed at the PBW are fixed type and continuously irradiated with the beam, long lifetime wire is required. The profile monitor at the PBW is essential so that a redundant system using SiC and tungsten wires was applied. In summer of 2013, some spots were observed at the surface of helium side of the PBW, which were thought to be produced by the erosion with the nitric acid produced by the radiolysis around the target. The 1st PBW has already received the integration beam power of 2 GWh to the new one. After exchange 1st PBW, because of stability of signal, only SiC wires were employed, which were deployed 2nd PBW. After 4 years operation, the 2nd PBW was changed in summer of 2017.

Lifetime of SiC Wires

As a material of sensitive wire, usually, tungsten wire is selected due to the large emission amount of the electron and having a high-temperature melting point. In the present system, silicon carbide (SiC) was chosen due to the high resistance of the radiation, which is thought to survive up to 80 DPA [8]. To obtain accurate displacement on the wire, a measurement of the displacement cross section has started for 0.4 to 3 GeV protons [9, 10].

Due to the interaction, the beam loss is caused, which is one of the issues of the high-intensity proton accelerator and the optimization of the beam loss is essential. The angular differential cross-section of Coulomb scattering is proportional to a square of an atomic number of the wire material. Since the average atomic number of the SiC is about 10, the cross-section of the SiC becomes 2% of tungsten. Therefore, a material of low atomic number has an advantage for the loss and distortion of the beam.

Until receiving 2 GWh, the wires still gave standard signals and, it was not found severe damage by inspection after irradiation. However, slight elongation of the SiC wires was observed as shown in Fig. 3. This elongation could be caused by the periodical thermal expansion of wire. By revision fixing of the wire, the elongation can be thought to be mitigated, which will be applied next generation of the monitor.

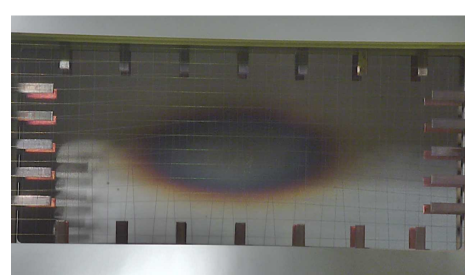


Figure 3: Elongated SiC wire utilized as the MWPM on the 1st PBW.

Beam Profile with Nonlinear Optics

To obtain the beam profile at the neutron source, the SAD code is utilized, which provide beam information by fitting

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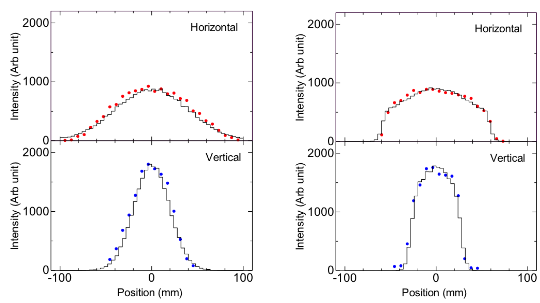
the result given by the MWPM placed at upstream of the octupole magnet. Also revised DECAY-TURTLE [11] by Paul Scherrer Institute (PSI) [12] is utilized to simulate multiple scattering at the muon target. Figure 4 shows results of beam profile for 800 kW beam with and without excitation of the octupole magnets. The beam profile is shown in Fig. 4, which was observed by the MWPM placed at the PBW. It can be found that considerable flat distribution can be obtained by the nonlinear optics. The calculation results with and without excitation are also shown in Fig 4. The calculation shows good agreement with the experiment for the cases with and without octupole magnetic field. It is also confirmed that the calculated beam profile by using the muon target showed good agreement with the experiment for both cases with and without octupole magnetic field. By the calculation result, the peak density can be thought to be reduced by 30% compared with the linear optics.



(a) with OCT 0A (b) with OCT 698A

Figure 4: Beam profile obtained with calculations (line) compared with result by the MWPM (dots) supplying current of (a) 0 A and (b) 698 A to octupole magnet . Upper and bottom figure represents for horizontal and vertical directions, respectively.

DEVELOPMENT OF NEW PROFILE MONITOR

Until now the wire of the monitor survived up to 2 GWh, which was at attached the first and the second generation of the PBW, however, it is not clear that the MWPM will survive for the long duration of 1 MW beam. The lifetime of the PBW is expected as 2 years for 1 MW beam [13], which has proton fluence 2×10^{21} cm^{-2} and the integral beam power of 10 GWh. To observe beam profile in 2D, an online type profile monitor is desired because the present 2D beam profile by IP can be obtained after the irradiation. Therefore a new beam profile monitor based on luminescence due to the beam was started to develop.

Beam Imaging Test Using Ar Beam

In order to obtain a 2D profile on the target, luminescence monitor is planned which is painted on the vessel of the mercury target. It was reported that degradation of luminescence was observed by the profile monitor used at the SNS in ORNL so that the intensity of light was observed by using $^{40}Ar^{+15}$ with total kinematic energy of 150 MeV, providing 10^6 times displacement on the sample than 3-GeV protons at Takasaki Advanced Radiation Research Institute (TIARA) of Quantum Beam Science Research Directorate (QST). To simplify the damage on the light emission, flat-shaped beam distribution was employed with nonlinear focus made by octupole field [14]. In the experiment, AF995R (Al_2O_3 99.5% and CrO_3 0.5%, Demarquest) with a thickness of 5 mm and DRZ-High (Gd_2O_2S:Tb) with a thickness of 5 mm were irradiated with Ar beam. The spectrum of the photon emitted from the sample was observed with the spectrometer (Flame-NIR: Ocean Photonics).

For the development of profile monitor system, the image of the luminescence from the AF995R and DRZ-High (Gd_2O_2S:Tb) was observed with the ordinary CCD camera through imaging fiber (Fujikura FISR-20) having 20,000 pixels and length of 5 m having high radiation hardening.

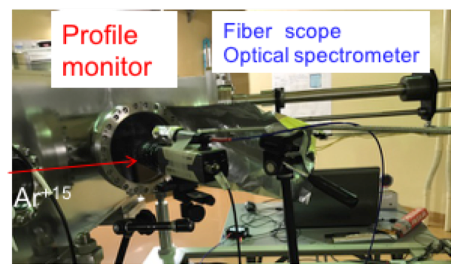


Figure 5: Experimental setup of beam profile imaging system for Ar beam irradiation.

Result of Beam Imaging

The 2D image of the beam obtained by the AF995R and DRZ-High is shown in Fig. 6, which is utilized square flat beam by nonlinear optics. Since the ordinary CCD camera was utilized being insensitive to the light in the long wavelength, the red light emitted from the AF995R was observed to be low intensity. Using 3 CCD camera being less dependence on wavelength, a clear image will be obtained. The DRZ-High has high photon emission rate in short wavelength, so that the image was clear and high intensity. However, the degradation of light yield was found to be more rapid than AF995R. By the present system, it was demonstrated that a clear image of the beam profile can be obtained.

Result of Luminescence Spectrum and Intensity

The spectrum is shown in solid line in Fig. 5 for the first shot of beam. The spectrum has a prominent peak at 694 nm with several unresolved shoulder peaks produced by the excitation state of Cr^{3+}. After the irradiation of Ar beam with 75 nA for 2.4 h to AF995R, it was found that the peak intensity decreased by 35% as shown in Fig. 7. In the first 0.2 h from the beginning, the intensity decreased rapidly. After the 0.2-h irradiation, the intensity decreased slowly and steadily, which can be fit well by one-dimensional function

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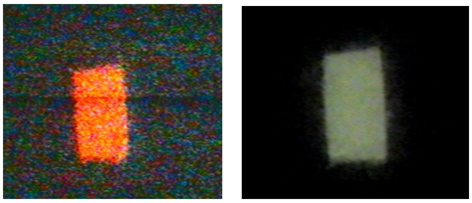


(a) AF995R (b) DRZ-High

Figure 6: Beam profile obtained with fiber imaging system for (a) AF995R and (b) DRZ-High. Beam shape was uniformed by nonlinear focus.

as shown in solid line in Fig. 8. The spectrum after the 2.4-h irradiation is also shown in Fig. 7. The intensity of the unresolved peak with wavelength region shorter than 694 nm had less decreased than one for 694 nm. It can be thought that the influence of degradation may mitigate by observing the light in short wavelength with optical filter cutting long wavelength.

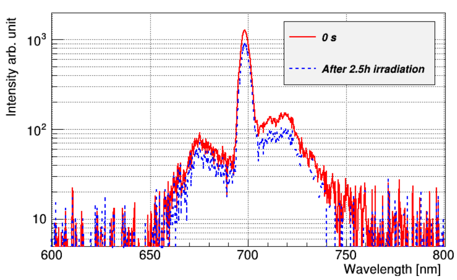


Figure 7: Spectrum of luminescence before and after irradiation of the Ar beam for 2.4 h.

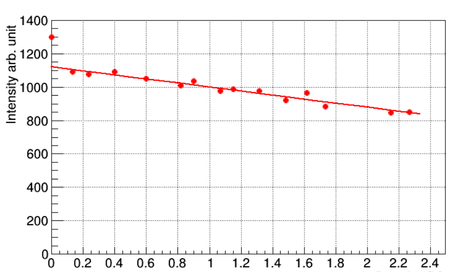
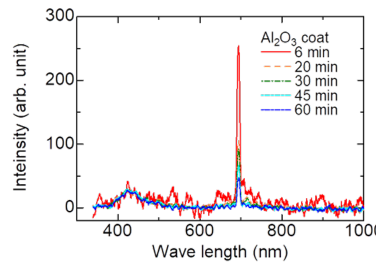


Figure 8: Trend of peak intensity for long duration irradiation of the Ar beam with 75 nA. Line shows result by linear fitting.

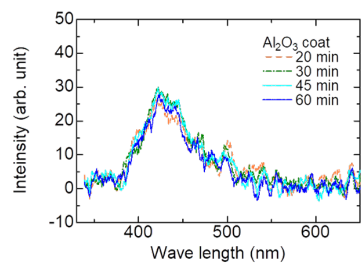
Development Luminescence Material for Profile Monitor

Many candidate materials have been examined to observe the degradation of light emission. As one of the candidate, AlO_2 paint with a low amount of Cr existing as an impurity was examined (Fig. 9).

Although the peak for Cr showed drastically decrease at 694 nm, the light in the shortwave length remained irrespectively to the beam amounts, which implies that the less degradation image can be obtained by using shortwave pass filter. It should be noted that the total intensity of the shortwave is smaller than the peak due to Cr ions. In future, the absolute photon intensity for the proton from 0.4 to 3 GeV will be examined at the beam transport system to the MLF. If the light yield is small, the intensity can be amplified by such as the image intensifier.



(a) Total wavelength



(b) Zoomed in short wavelength

Figure 9: Spectral intensity of AlO_2 paint for (a) total wavelength and (b) short wavelength for various irradiation time of the Ar beam.

CONCLUSION

For reliable beam operation at the spallation neutron source in J-PARC, beam monitor system with the MWPM and the halo monitor was developed. With the present MWPM, beam parameter such as the emittance and Twiss parameter can be obtained by several shots of the beam. To mitigate pitting erosion on the mercury target vessel, a beam transport system with nonlinear optics has been developed. By introducing nonlinear optics with octupole magnets, peak current density can be reduced by ≈30%, which decreases the damage of pitting erosion about 80%. For future facility in J-PARC aimed for the research and development of the ADS, profile monitor experiment has carried out with Ar beam. Although AlO_2 doped with Cr showed significant degradation of photoemission, AlO_2 paint showed to stand a high dose of the beam in the short wavelength.

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