BEAM PROFILE MONITOR AT THE 1 MW SPALLATION NEUTRON SOURCE

Shin-ichiro Meigo*, Motoki Ooi, Kiyomi Ikezaki, Tomoyuki Kawasaki, Hidetaka Kinoshita, Atsushi Akutsu, Masaaki Nishikawa and Shinpei Fukuta, J-PARC center, JAEA, 319-1195, Japan
Hiroshi Fujimori, J-PARC center, KEK, 305-0801, Japan

Abstract

Since 2008, the Japanese Spallation Neutron Source (JSNS) of J-PARC has produced a high-power proton beam of 300 kW. In order to operate with high intensity beam such as 1 MW, a reliable profile monitor system is required. Beam profile monitor system was developed by using SiC sensor wires. Since pitting erosion was found at the vessel of the spallation neutron target at other facility of SNS, the beam current density at the target should be kept as low as possible. In order to decrease the beam density, a beam flattering system based on a non-linear optics with octupole magnets was developed. It was found that the beam profile at the target obtained with the Multi Wire Profile Monitor (MWPM) showed flat distribution and showed good agreement with the design calculation. Furthermore, the present status of the development of the profile monitor is also described.

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, we 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.

Recently, pitting damage became evident in the mercury target container [7], and the extent of the damage is proportional to the fourth power of the peak current density of the proton beam. After operating the beam at high power, significant pitting damage was observed at the spent mercury target vessel at JSNS and at the Spallation Neutron Source in Oak Ridge National Laboratory [8, 9]. Using linear optics (i.e., quadrupole magnets) for beam transport, the peak current density can be reduced by expanding the beam at the target. However, beam expansion increases heat in the vicinity of the target, where shielding and the neutron reflector are located. Therefore, the peak current density is limited by the heat induced in the vicinity of the target. At the JSNS, the minimum peak current density is expected to be 9 μA/cm^2, which gives a thermal energy density at the target of 14 J/cm^3/pulse [10]. Because the pitting damage goes as the fourth power of the peak density, scanning the beam with a deflecting magnetic field will not mitigate the pitting damage.

Beam profile monitoring plays an important role in comprehending the damage to the target. Therefore it is very important to watch continuously the status of the beam at the target at the JSNS especially for the peak current density. We have developed a reliable beam profile monitor for the target by using Multi Wire Profile Monitor (MWPM). In order to watch the two dimensional profile on the target, we have also developed the profile monitor based on the imaging of radiation of the target vessel after beam irradiation. In this paper, the present status of the beam monitor at the spallation neutron source is described.

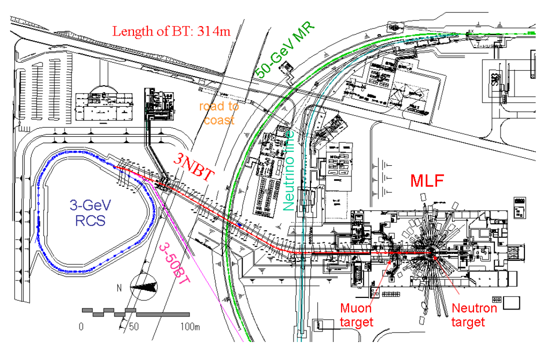


Figure 1: Plan of rapid cycling synchrotron (RCS) at the Materials and Life Science Experimental Facility (MLF) at J-PARC.

BEAM MONITOR SYSTEM AT THE BEAM TRANSPORT TO THE TARGET

Silicon Carbide Sensor Wire

In order to obtain the characteristics of the proton beam, diagnostic system based on a Multi Wire Profile Monitor

* meigo.shinichiro@jaea.go.jp

ISBN 978-3-95450-176-2

(MWPM) was developed. Principle of the MWPM is simple to observe the amount of the electron emission by the interaction of the beam at the wire. As a material of sensitive wire, usually tungsten wire is selected due to large emission amount of the electron and having high temperature melting point. In the present system, silicon carbide (SiC) was chosen due to the high resistance of the radiation [11], which can survive for 80 DPA. Due to the interaction, the beam loss is caused, which is one of issues of the high intensity proton accelerator and the optimization of the beam loss is important. The angular differential cross section of Rutherford scattering is proportional to square of atomic number of wire material. Therefore wire material with low atomic number has advantage for beam loss. Here, we compare property between tungsten and SiC. Since the average atomic number of SiC is 10, the differential cross section of SiC becomes 1/55 times of the cross section of tungsten. In order to obtain the angular distribution after scattered by the wire is calculated with revised DECAY-TURTLE [12] by Paul Scherrer Institute (PSI) [13]. It was recognized that SiC wire than tungsten gives less influence on the beam. In order to estimate of the lifetime of monitor wire, the displacement cross section of DPA is calculated with NMTC/JAM [14]. By the calculation, it is found that the DPA cross section of SiC and tungsten for 3-GeV proton is 278 and 7997 b respectably, which shows that DPA of the tungsten is about 29 times larger than SiC. SiC was chosen as wire of as a standard model of the profile monitor at the 3NBT.

Multi Wire Profile Monitor

The view of MWPM is shown in Fig. 2. Along the beam transport line, 15 sets of movable MWPMs are placed to measure the beam profile. The MWPM frame has 31 wires of SiC with the spacing pitch of 6 mm for each horizontal and vertical direction. We employed the SiC wire having diameter of 0.1 mm, which has a tungsten core of 0.01 mm and is coated with 1 μm of pyrolytic carbon. The wire frame made of aluminum oxide with purity more than 95 % is selected due to the high radiation resistance. In order to sustain with the fixed tension, wires are kept by the holder with spring, which gives the unique tension of 0.6 N to the wire. The frame of wires is placed in the vacuum chamber made of titanium, which is selected by the following reason, good vacuum characteristics and low activation. In order to avoid unnecessary irradiation of the wires, the frame can retract and moves like the pendulum motion. During the profile measurement, the beam loss due to the scattering at wires was observed by the beam loss monitor. For the practical aspect, beam loss cased at the MWPM can be utilized to calibrate the beam loss monitors.

For the actual high intensity beam tuning, it is important to know the beam parameter. The intrinsic parameters of the beam transport was confirmed by observing response of beam position for the kick angle of the steering magnet. By the observation of the beam width by the MWPMs, the Twiss parameter and the beam emittance can be acquired.

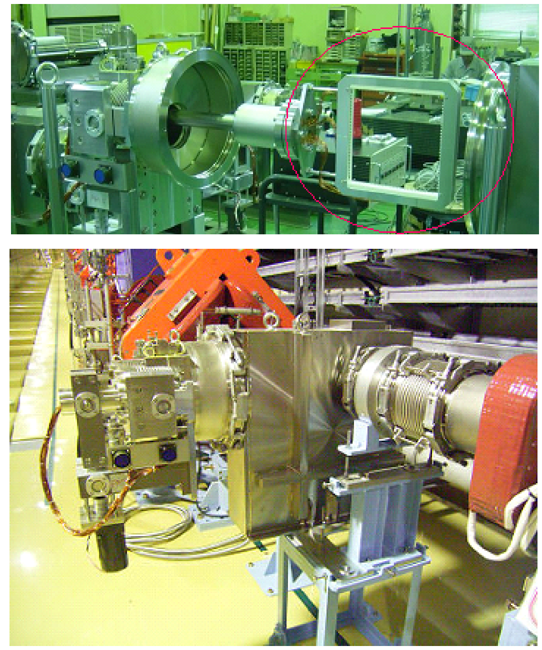


Figure 2: Movable MWPM placed at the beam transport line. (top: MWPM and frame inside the vacuum chamber. bottom: MWPM and chamber placed in the beam transport line).

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 decrease the difficulties of the exchange work and decrease of the shielding, we combined the beam monitors with a Proton Beam Window (PBW) for 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 distance between the target and the PBW is 1.8 m, which gives reliable profile at the target. In Fig. 3, the MWPM placed at the center of vacuum chamber of the PBW is shown. In order to avoid exceed 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. Io calibrate 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 important for reduction 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 view of the

ISBN 978-3-95450-176-2

beam halo monitor is shown in Fig. 4. We placed two types of beam halo monitors to obtain the thermal information by thermocouple and the emission of electron by electrode. Since the emission of electron indicates relative intensity of the beam halo, the beam halo relative intensity, 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 procedure was normally performed in actual beam operation.

Since wires at the MWPM placed at the PBW are fixed type and continuously irradiated to the beam, long lifetime wire is required. The profile monitor at the PBW is important 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 of nitric acid produced by the radiolysis around the target. We decided to change the 1st PBW already received the integration beam power of 2000 MWh to the new one. Until 2000 MWh, the wires still gave normal signals and after irradiation they were not found serious damage by inspection.

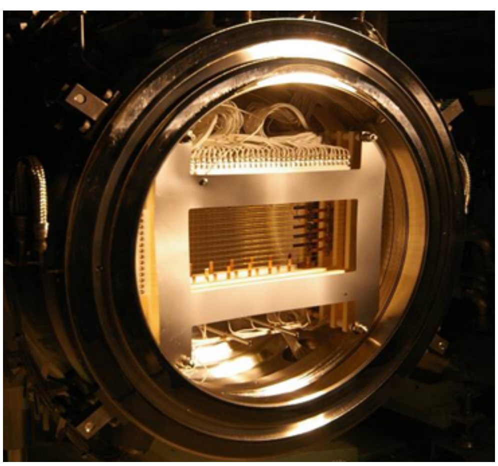


Figure 3: MWPM and beam halo monitors placed at the Proton Beam Window (PBW).

All signals of MWPM is transfer to the local control room by twisted pare cables with high radiation harding. As for the MWPM of the PBW, Mineral Insulator Cables (MICs) are applied because the cables receives quite high radiation does more than 1 MGy. The signal is fed to the inverter amp (Technoland N-GK 160 32ch Inverter AMP) and fed to the charge collective ADC (Technoland C-TS 301B) with the integration time range of 3 μs, which has integration charge range of -3000 pC in total and is driven by the CAMAC bus. The signals on the CAMAC bus are read out via crate controller of Toyo CC/NET. All signals is controlled by the EPICS [15] and is data base server based on PSQL server.

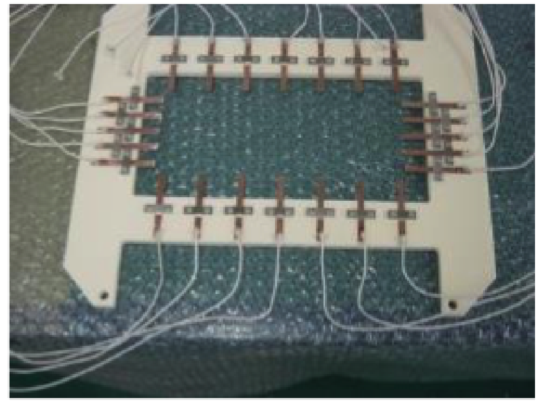


Figure 4: Thermocouple type of beam halo monitors placed at the Proton Beam Window (PBW).

In Fig. 5, the beam profile at the PBW obtained by the present system is shown. Each result is fitted by the Gaussian and base distribution for every second. Result of the center position and the width is utilized to watch the status of beam injected to the target.

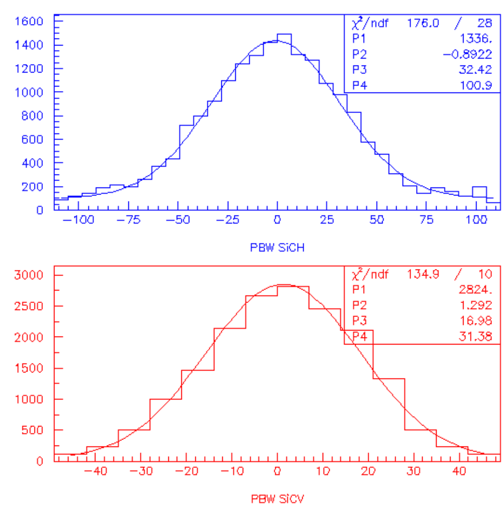


Figure 5: Beam profile obtained by the MWPM located at the proton beam window for 0.3 MW beam. Top and bottom graph shows the result for horizontal and vertical direction, respectively.

PROFILE MONITOR BY IMAGING PLATE

Imaging Plate Attached to Target After Beam Irradiation

For achievement good performance at the neutron source, enough gap is not remaining between the target and the vicinities to place any devices for the beam profile measurement. During the first beam commissioning, the beam profile was obtained by the activation technique with 0.3 mm thickness aluminum foil placed at the target vessel. After extraction the foil from the target, an imaging plate (IP: Fuji

ISBN 978-3-95450-176-2

Firm BAS-SR 2040) attached to the foil to read the distribution. The observed beam shape was clear gaussian and no skew. After the first beam commissioning, the target was already activated and the radiation around the target was extremely high such as several tenth Sv/h so that a remote handling technique was required to obtain the beam profile. We have developed an activation technique by utilizing the IP instead of using the foil. The IP is attached to the mercury target vessel by the remote handling as shown in Fig. 6. The radiation at the entrance of the hot cell was several tenth of μSv/h so that human can access at the entrance. The IP contained the holder was attached to the crane at the hot cell in the MLF by human access. By the crane, the IP approached to the target and contacted with the target by help of the master slave manipulator as shown in Fig. 6. After about 10 min exposure and the extraction of the IP, the image of radiation was observed by the IP reader . Since the exposed dose of the IP exceeded the acceptance of the reader, which is several micro Sv, the IP was irradiated by the UV room right for several minutes to reduce the recorded does. After this procedure, the image of the IP can be measured by the IP reader without any saturation. We already obtained the profile result of 500 kW beam with short duration such as several days after the beam stopped, the profile for 1 MW can be observed with long cooling duration of the radiation.

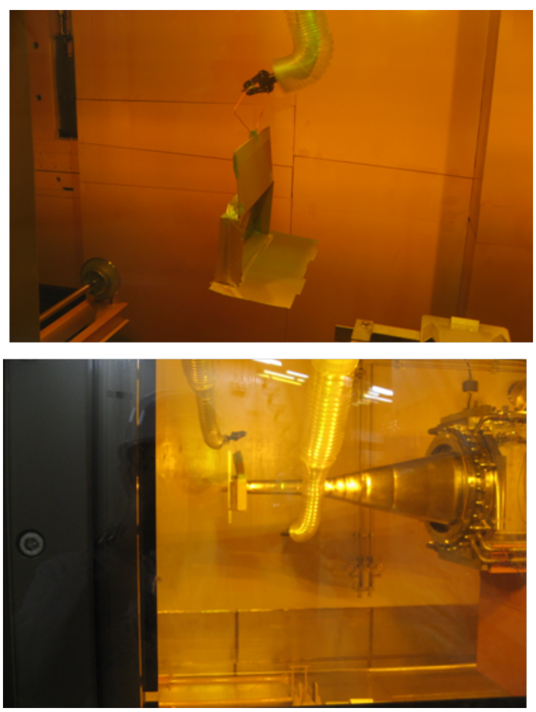


Figure 6: Activation technique using Imaging Plate (IP) located on the target vessel performed after irradiation at hot cell of the MLF. (top) IP holder placed at crane (bottom) IP attached by the master slave manipulator.

Figure 7 shows the beam profile obtained by the activation technique with the IP after 120 kW beam operation. In the distribution, it is shown that a clear Gaussian peak exists

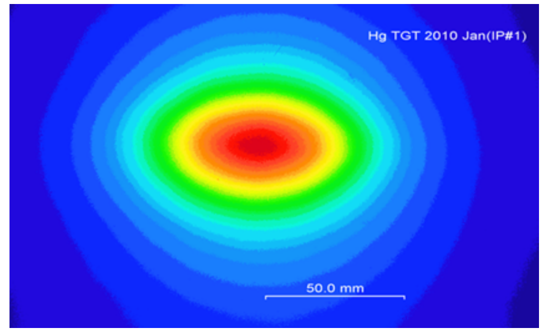


Figure 7: 2Dl beam profile obtained by the IP attached to the mercury target vessel.

without skew of the beam, which was also presented by foil activation technique.

The beam profile in horizontal distribution obtained by the IP is shown in Fig. 8. The distribution can be well described by the combinations of two Gaussian functions having small and large widths. The smaller one was thought to be the initial protons. The larger width was thought to be the secondary particles mainly neutrons or some background radiation. By using the shorter width, the primary beam width at the target can be obtained.

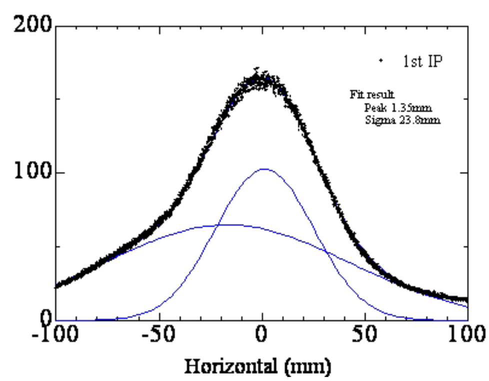


Figure 8: Beam profile in horizontal direction obtained by the IP with fitting of two Gaussian curves.

During beam commissioning using 300 kW, beam width was gradually expanded as each beam run. After each run, the beam width at the target was measured by the IP as well as observed by the MWPM. The beam width obtained by the IP considerably showed good agreement with result obtained by the MWPM including collection of the position by taking account of the beam gradient, which implies that reliable width can be obtained by the present profile monitor system. By using the MWPM, the present beam width can be obtained each beam pulse.

Machine Protection System

The beam monitoring at the target became quite important after target anomaly occurred at hadron experimental hall in J-PARC, which was caused by the malfunction of the slow extraction device and will not happen at the spallation

ISBN 978-3-95450-176-2

neutron source. For the safety, if any anomaly of the beam was found such as offset of the beam position, the beam should be immediately. The machine protect system (MPS) was developed, which cut out the beam immediately if either the beam position exceeded 5 mm offset or the beam peak density exceeded the threshold giving the peak heat density of 14 J/cm^3/pulse at the mercury target. Due to the MPS, high power beam operation such as 1 MW can be performed with high confident. Data of the beam profile for every shots are watched by the control system driven by the EPICS and are stored in data base.

DEVELOPMENT OF BEAM FLATTERING SYSTEM USING NON-LINEAR BEAM OPTICS

Distribution of the beam extracted from the RCS can be described well by a simple Gaussian [6]. With an ordinary beam optics, which is linear optics, the beam shape becomes a Gaussian at all place. By using non-linear optics, the beam particles located at the edge is bent to the center so that the distribution can become flat. In order to obtain flat shape for each horizontal and vertical direction, two octupole magnets is required. These octupole magnets can be placed at anywhere upstream of the target except the place where the phase advance between the magnet and the mercury target is an integer multiple of π. Since the targets had been irradiated by the beam for 5 years, the radiation dose around the targets is too high to place magnet. Therefore, two octupole magnets (OCT1, OCT2) are placed at upstream of the muon target as shown in Fig. 9.

In briefly, the fundamental of the beam flattering is based on the edge folding by the high order magnet of octupole magnet. By choosing appropriate octupole magnetic field, a flat beam distribution can be obtained as shown in Fig. 10.

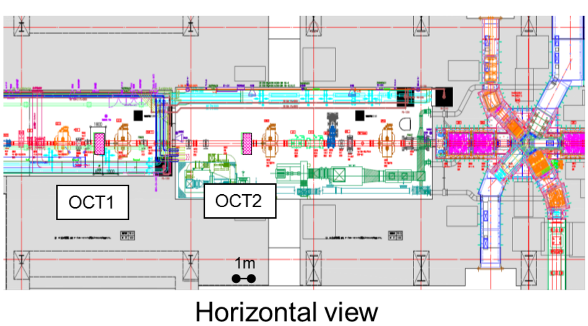


Figure 9: Plan of octupole magnets for beam flattening system, which is to be placed upstream of muon production target shown in right side.

Beam Optics for Flattering System

In order to achieve flat distribution, the required octupole field is proportional to the inverse square of the beta functions at the octupole magnet. Due to the relative high momentum of the present beam, achievement of a large octupole field of the K is difficult. To obtain the flat shape with the realistic K of the octupole, we expand the beam at the octupole magnet to have large β function. Around the octupole magnet, since physical aperture of quadrupole magnets was fixed to 300 mm, we determined the aperture of the octupole magnet to 300 mm. In the linear beam optics, the admittance of the beam is designed to have 324 π mm mrad, which is given by the beam collimator placed at the RCS . A study of the RCS [16] showed that the transverse emittance will be as small as 250 π mm mrad. The beam admittance at the octupole was determined to 250 π mm mrad and the beta function at the octupole magnets was chosen to 200 m.

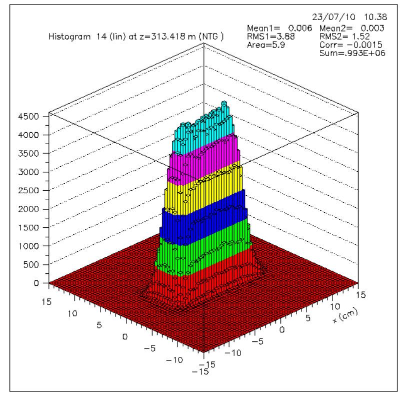


Figure 10: Flat beam distribution at the mercury target by using two set of octupole magnets.

Octupole Magnets

Based on the optics design, two pieces of the octupole magnet shown in Fig. 11 were fabricated. The designed field gradient is 800 T/m^3 with a bore diameter of 0.3 m and 0.6 m in length of pole and the current of 700 A. Using a hall prove, the field gradient was measured. It was confirmed that the magnetic field were in good agreement with the design calculation. In an actual beam operation, the beam centering at the octupole is important to avoid peak at the edge. To perform centering, beam position monitor was installed in each octupole magnet.

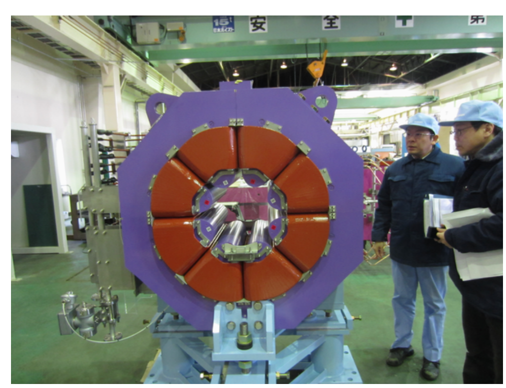


Figure 11: Fabricated octupole magnet with magnetic field gradient of 800 T/m^3.

ISBN 978-3-95450-176-2

Beam Profile with Non-linear Optics

In order to obtain the beam profile at the neutron source, SAD code is utilized, which provide beam information by fitting the result given by the MWPM placed at upstream of the octupole magnet. Also revised DECAY-TURTLE [12] by Paul Scherrer Institute (PSI) [13] is utilized to simulate multiple scattering at the muon target. Figure 12 shows results of beam profile for 800 kW beam with and without excitation of the octupole magnets. The beam profile shown in Fig. 12 was observed by the MWPM placed at the PBW. It can be found that considerable flat distribution can be obtained by the non-linear optics. The calculation results with and without excitation are also shown in Fig 12. The calculation results show good agree with the experiment ones 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.

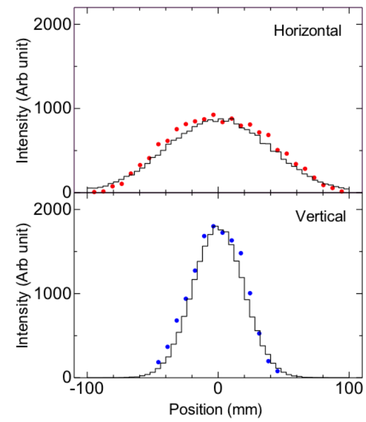
DEVELOPMENT NEW PROFILE MONITOR

Lifetime Estimation of the PBW

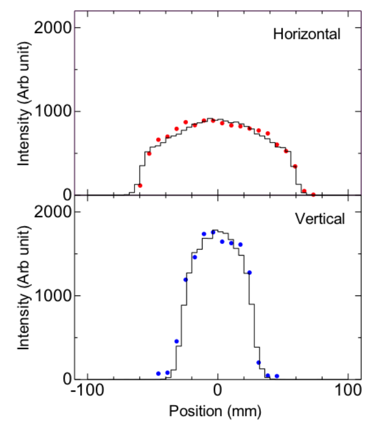
The MWPM placed at the PBW so that the lifetime estimation of the PBW is important. When the water was leaked from the PBW, enormous efforts and time will be necessary for restoring. If water leaked from the PBW to the vacuum side, the baking procedure will be necessary to reduce the outgas inside vacuum. We chose aluminum alloy as the material of the PBW, because SINQ at PSI had a good result for lifetime as a safety hull material of the target, At SINQ, the post irradiation examination (PIE) was already performed and material property was studied preciously. The lifetime can be thought to be determined by the embrittlement due to the helium caused by the spallation reaction. Therefore, helium gas production rate is important to estimation of the lifetime. Due to the difference of the proton energy, calculation should be made for gas production rate for the proton energy, whereas the SINQ is utilized 590-MeV protons. Since no experimental data exist for 3-GeV proton so that the validation of calculation can not be possible. In order to obtain gas production rate, we are planning to measure tritium production using thin aluminum foil placed at the beam dump. By using Q-mass analyzer, the hydrogen and helium gas production rate will be obtained. After measurement of the gas production rate for 3-GeV proton, more reliable lifetime can be obtained.

Development of New Profile Monitor

Until now the monitor wire survived up to 2000 MWh, which was at attached the first PBW, however, there is no evidence that the MWPM will survive for long duration of 1 MW beam. The lifetime of the PBW is expected as 2 years for 1 MW beam [17], which has proton fluence 2 × 10^{21} /cm^{-2} and the integral beam power of 10000 MWh. In order to observe 2D profile, a on-line type profile monitor is desired because the present 2D beam profile by IP can be obtained after the irradiation. Therefore we begun to develop a new beam profile monitors.



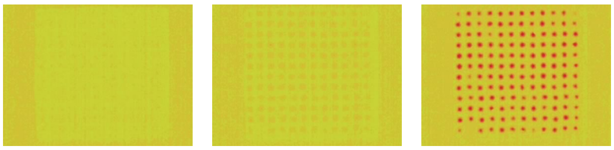
(a) OCT 0A



(b) OCT 698A

Figure 12: 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.

By observation of the thermal distribution at the target, the beam profile can be obtained. We developed an infrared camera system with bundled hollow-core fibers having length of 1 m. The hollow-core fibers were made of the quartz capillary-tube coated by polyimide. Since beam monitor is placed at the PBW, the radiation hardening of the monitor is required obviously. The capillary tube is made of inorganic material and the camera can be placed far away from the radiation source so that the infrared system can be thought to have enough high radiation hardening. As an examination of the system, the thermal distribution on the ceramic heater was observed by the infrared system. The result of the thermal image is shown in Fig. 13. A clear image of the ceramic heater was found. In the present system, capillary tube has only 12 × 12 channels, which may not be sufficient for the beam profile system. Although further R&D is required especially for increase the number of pixels, this infrared camera system is probably to be utilized as profile monitor in future.

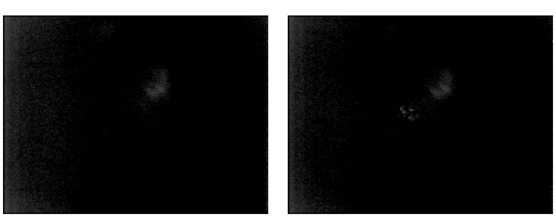


(a) 50 °C (b) 100 °C (c) 250 °C

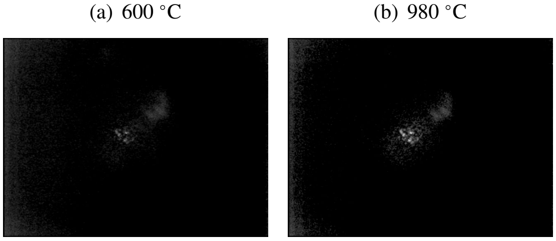
Figure 13: Images obtained by the infrared system for various temperature of ceramic heater.

Also we developed a profile monitor based on the bundled optical fibers with high radiation hardening (Fujikura FISR-20) having 20000 pixels and length of 5 m. By painting fluorescence material such as alumina at the target vessel, the beam profile can be observed with fluorescence, which already utilized at the SNS. In future, we will place the present fiber system at the PBW.

To observe anomaly target status exceeded heated, the image of fibers was obtained with the near infrared filter to cut the visible light. Figure 14 shows the direct image of the near infrared from the ceramic heater. The present near infrared system may be utilized for diagnostic system of the muon production target. Since the muon production target was the rotating target cooled by the radiation heat having any cooling channel, if the rotation stopped by certain cause then the temperature will arise rapidly eventually introduce break of the target. Due to the rotation target, observation of the temperature by the thermocouple was difficult. Normally the temperature of the target exceeded 1000 °C so that By the near infrared system, the anomaly of the target can be easily detected.



(a) 600 °C (b) 980 °C



(c) 11150 °C (d) 1300 °C

Figure 14: Images obtained by the near infrared system for various temperature of ceramic heater.

CONCLUSION

For reliable beam operation at the JSNS in J-PARC, beam monitor system with the MWPM and the halo monitor was developed. By using the MWPM, beam parameter such as the emittance and Twiss parameter can be obtained by several shots of the beam. To obtain two dimensional beam profile at the mercury target, a technique based on the activation technique with the IP was developed. Under the present system, high power beam operation such as 1 MW can be performed with high confident.

In order to reduce peak density of the beam current at the target, a non-linear beam optics with the octupole magnets was developed. By the present system, it was found that the flat shape can be obtained. The calculation simulation shows good agreement with the result obtained with the present profile monitor, which implies that the beam flattening can be achieved by the design of optics having large β function at the octupole magnet and an appropriate phase advance between the octupole and the mercury target. By the calculation including with the beam scattering on the muon production target, it is shown that the peak current density can be reduced about 30 % of the peak density without the non-linear beam optics.

ACKNOWLEDGMENT

This work is partly supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) KAKENHI Grant-in-Aid for Scientific Research (C) Grant no. 26390114.

REFERENCES

[1] The Joint Project Team of JAERI and KEK, JAERI-Tech 99-56, 1999.

[2] Y. Ikeda, Nucl. Instrum. Meth. **A600**, (2009) 1.

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

[4] S. Meigo, et al., Nucl. Instrum. Meth. **A562**, (2006) 569.

[5] S. Sakamoto, et al., Nucl. Instrum. Meth. **A562**, (2006) 638.

[6] S. Meigo, et al., Nucl. Instrum. Meth. **A600**, (2009) 41.

[7] M. Futakawa, et al., J. Nucl. Sci. Technol. **40** (2004) 895.

[8] T. Naoe, et al., J. Nucl. Mater. **450** (2014) 123.

[9] D. A. McClintock, et al., J. Nucl. Mater., **431** (2012) 147.

[10] S. Meigo, et al., MOPEB066, IPAC10 (2010).

[11] G. E. Youngbllood, et al., J. Nucl. Matler. , **258 - 263**, 1551 (1998).

[12] K.L. Brown, Ch. Iselin and D.C. Carey: Decay Turtle, CERN 74-2 (1974).

[13] PSI Graphic Turtle Framework by U. Rohrer based on a CERN-SLAC-FERMILAB version.

[14] K. Niita, et al., JAERI-Data/Code 2001-007 (2001).

[15] M. Ooi, et al., PO1.024-1, ICALEPCS10 (2005).

[16] H. Hotchi, et al., THPPP080, IPAC12 (2012).

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

ISBN 978-3-95450-176-2