ISBN: 978-3-95450-201-1 doi:10.18429/JACoW-IBIC2018-MOPB07

BEAM PARAMETER MEASUREMENTS FOR THE J-PARC HIGH-INTENSITY NEUTRINO EXTRACTION BEAMLINE

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Abstract

Proton beam monitoring is absolutely essential for the J-PARC neutrino extraction beamline, where neutrinos are produced by the collision of 30 GeV protons from the J-PARC MR accelerator with a long carbon target. Continuous beam monitoring is crucial for the stable and safe operation of the extraction line high intensity proton beam, since even a single misfired beam spill can cause serious damage to beamline equipment at 2.5×10^{14} and higher protons-per-pulse. A precise understanding of the proton beam intensity and profile on the neutrino production target is also necessary for predicting the neutrino beam flux with high precision. Details of the suite of monitors used to continuously and precisely monitor the J-PARC neutrino extraction line proton beam are shown, including recent running experiences, challenges, and future upgrade plans.

OVERVIEW OF J-PARC AND THE NEUTRINO PRIMARY BEAMLINE

The J-PARC proton beam is accelerated to 30 GeV by a 400 MeV Linac, a 3 GeV Rapid Cycling Synchrotron, and a 30 GeV Main Ring (MR) synchrotron. Protons are then extracted using a fast-extraction scheme into the neutrino primary beamline, which consists of three sections containing a series of normal- and super-conducting magnets used to bend the proton beam towards a neutrino production target. Generated neutrinos travel 295 km towards the Super-Kamiokande detector for the Tokai-to-Kamioka Long-Baseline Neutrino Oscillation Experiment (T2K) [1], which started operation in 2009.

Table 1: J-PARC Proton Beam Specifications

	Protons/Bunch	**Spill Rate**
Current (2018)	3.13×10^{13}	2.48 s
Upgraded (2021~)	$2.75 \rightarrow 4.00 \times 10^{13}$	1.32→1.16 s

The J-PARC 30 GeV proton beam has an 8-bunch beam structure with 80 ns (3σ) bunch width and 581 ns bucket length. J-PARC currently runs at 485 kW with the plan to upgrade to 750+ kW in 2020 and 1.3+ MW by 2026. This will be achieved by increasing the beam spill repetition rate from the current one spill per 2.48 s, to 1.32 s and finally 1.16 s, along with increasing the number of protons per bunch from $\sim 3 \times 10^{13}$ to 4×10^{13}, as shown in Table 1.

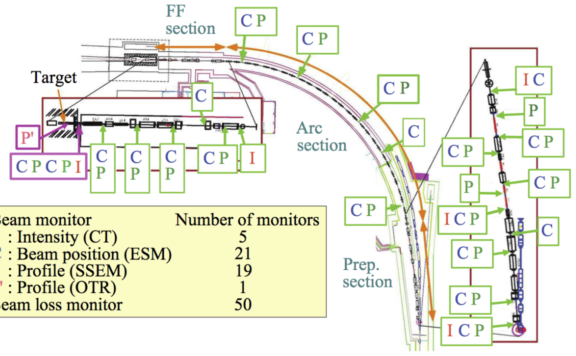

Figure 1: Beam monitor positions along the neutrino primary beamline.

The 30 GeV proton beam is extracted into the neutrino beamline preparation section. In the preparation section, the position and width of the extracted beam are tuned by normal-conducting magnets in order to match the beam optics in the following arc section, where the beam is bent by 80.7° using super-conducting combined function magnets. Finally, in the final focusing section, normal-conducting magnets are used to direct the beam downward by 3.647° and tune the beam position and size to focus the beam onto the center of the neutrino production target.

Beam monitoring is essential for protecting beamline equipment from possible mis-steered beam as part of a machine interlock system, where even a single mis-steered beam shot can do serious damage at high intensities. Information from proton beam monitors is also used and as an input into the T2K physics analysis, and imprecisions on proton beam measurements can have a direct effect on the precision of the final T2K physics results.

MONITORS IN THE J-PARC NEUTRINO PRIMARY BEAMLINE

The proton beam conditions are continuously monitored by a suite of proton beam monitors along the neutrino primary beamline, as shown in Fig. 1.

Five Current Transformers (CTs) are used to continuously monitor the proton beam intensity. Fifty Beam Loss Monitors (BLMs) continuously measure the spill-by-spill beam loss and are used to fire an abort interlock signal in the case of a high-loss beam spill. Twenty-one Electro-Static Monitors (ESMs) are used as Beam Position Monitors to continuously monitor the beam position and angle.

The proton beam profile (beam position and width) is monitored bunch-by-bunch during beam tuning by a suite of 19 Segmented Secondary Emission Monitors (SSEMs) distributed along the primary beamline, where only the most downstream SSEM (SSEM19) is used continuously. An

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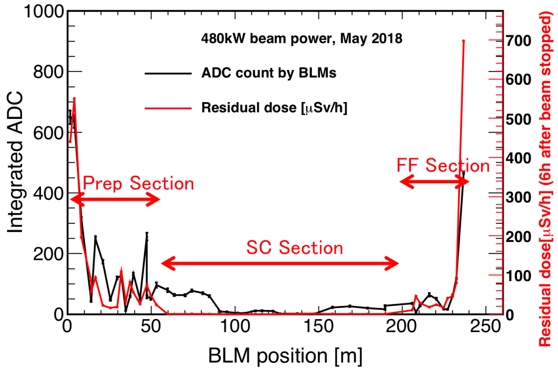

Figure 2: Beam loss and residual radioactivity along the beamline.

Optical Transition Radiation Monitor (OTR) [2], placed directly upstream of the production target, also continuously monitors the beam profile spill-by-spill.

Other beam parameters, such as the beam angle, twiss parameters, and emittance at the production target are extrapolated by a fit to several downstream SSEMs and the OTR during beam tuning. The beam position and angle at the target is continuously monitored spill-by-spill by a fit to several ESMs, SSEM19 and the OTR during standard running, while the other proton beam parameters are extrapolated by scaling the data from beam tuning runs (where all SSEMs are in the beam) with spill-by-spill SSEM19 and OTR information when SSEMs 1–18 are not in the beam.

CONTINUOUS BEAM LOSS, INTENSITY, AND POSITION MONITORING

Beam Loss Monitors

The spill-by-spill beam loss along the beamline is measured by Toshiba Electron Tubes&Devices E6876-400 BLMs, which are wire proportional counters filled with an Ar-CO_2 mixture. The signal from each BLM is integrated during each beam spill and if the signal from any BLM exceeds a set threshold, a beam abort interlock signal is fired. The beam loss and measured residual radioactivity along the J-PARC neutrino primary beamline are shown in Fig. 2.

Current Transformers

The bunch-by-bunch beam intensity is measured by CTs, which are fabricated in-house and consist of a ferromagnetic core made of FINEMET® (nanocrystalline Fe-based soft magnetic material) from Hitahi Metals with a 50-turn toroidal coil inside a stainless steel and iron outer casing.

Periodic calibration of the CT readout electronics is necessary. Precise absolute calibration is also essential – the current systematic error on the number of protons is 2.7%, but a calibration campaign to reduce errors to <2% is ongoing.

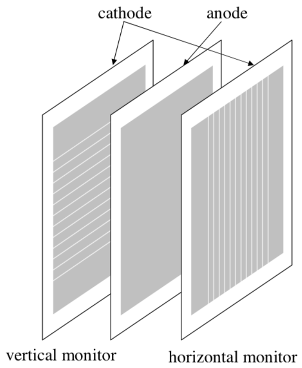

Figure 3: T2K Segmented Secondary Emission Monitor design.

Electrostatic Monitors

The bunch-by-bunch beam position is measured by ESMs, which have four segmented cylindrical electrodes surrounding the proton beam orbit (80° coverage per electrode). The ESM beam position measurement precision is better than 450 μm, including 20–40 μm measurement fluctuations, 100–400 μm alignment precision, and 200 μm other systematic uncertainties. Possible methods to improve the ESM measurement precision are currently under consideration.

BEAM PROFILE MONITORING

Segmented Secondary Emission Monitors

The proton beam profile along the primary beamline is measured by a suite of 19 SSEMs.

Each SSEM consists of two 5 μm-thick titanium foils stripped horizontally and vertically, with a 5 μm-thick anode HV foil between them, as shown in Fig. 3. The strip width ranges from 2 to 5 mm, optimized according to the expected beam size at each monitor. When the proton beam passes through the SSEM, secondary electrons are emitted from each strip in proportion to the number of protons hitting the strip; the beam profile can be reconstructed by doing a Gaussian fit to the positive polarity signal from the strips.

Due to the $\sim 3 \times 10^{-5}$ interaction lengths of material, one SSEM causes 0.005% beam loss. Therefore, only the most downstream SSEM (SSEM19), which sits in a high-radiation environment near the production target, can be used continuously; others are remotely moved into the beam during beam tuning.

The SSEM position measurement precision and stability are 0.07 mm and ~±0.15 mm, respectively. The SSEM width measurement precision and stability are 0.2 mm and ~±0.07 mm, respectively.

Optical Transition Radiation Monitor

An OTR, shown in Fig. 4, continuously monitors the beam profile directly upstream of the production target.

The OTR active area is a 50 μm-thick titanium-alloy foil, which is placed at 45° to the incident proton beam. As

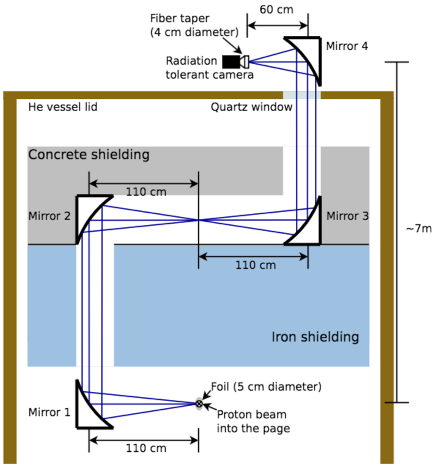

Figure 4: Schematic of the T2K Optical Transition Radiation monitor.

the beam enters and exits the foil, visible light (transition radiation) is produced in a narrow cone around the beam. The light produced at the entrance transition is reflected at 90° to the beam and directed away from the high-radiation environment near the neutrino production target by four aluminum 90° off-axis parabolic mirrors to an area with lower radiation levels. OTR light is then collected by a leaded glass fiber taper coupled to a charge injection device (CID) camera, which records an image of the proton beam profile spill-by-spill.

The OTR target foils sit in a rotatable disk with 8 foil positions, allowing for various OTR target types. A Ti 15-3-3-3 (15% V, 3% Cr, 3% Sn, 3% Al) foil without holes was originally designed for standard continuous data-taking, although recently a foil with 12 small holes in a cross pattern has been used without any issue.

Measured Proton Beam Envelope

The horizontal proton beam envelope along the J-PARC primary beamline, as measured by the 19 SSEMs and the OTR during beam tuning, is shown in Fig. 5. The model calculation can reproduce the SSEM-measured optics very well, although the OTR measured width is consistently higher than the expectation. This discrepancy may be caused by using the OTR in a He environment, rather than in vacuum; background studies, with the aim of understanding this effect, are ongoing.

PROFILE MONITOR DEGRADATION

A photograph of the upstream side of the SSEM19 foil after ~2.3×10^{21} incident protons is shown in Fig. 6. Although no significant decrease in the secondary emission yield has been observed,[1] the foil has darkened significantly.

The same SSEM19 monitor head has been used since the beginning of T2K. A procedure for exchanging SSEM19, which is in a relatively inaccessible location behind a shield wall separating the primary beamline and the production target, is currently being developed.

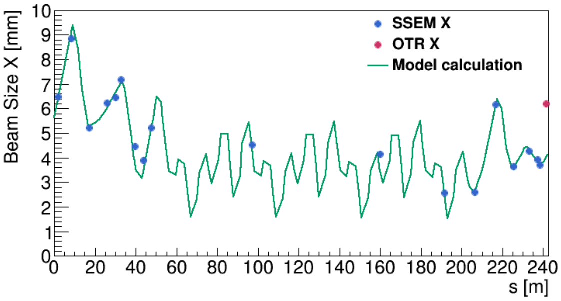

Figure 5: Horizontal beam envelope in the J-PARC neutrino beamline measured by the SSEMs and OTR.

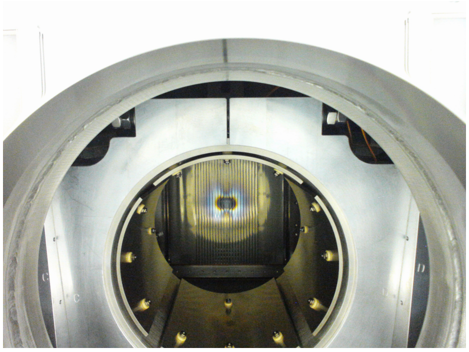

Figure 6: SSEM19 after ~2.3×10^{21} incident protons.

A photograph of the OTR foils and a plot of the OTR light yield as a function of integrated protons is shown in Fig. 7. The OTR foils have darkened where the beam hits. Some degradation of the OTR light yield is observed; currently this is thought to be due to both foil darkening and the radiation-induced darkening of the fiber taper used to shrink the OTR light image onto the CID camera sensitive area.

Radiation damage studies of used OTR foils are currently ongoing by the RaDIATE collaboration [3].

PROFILE MONITOR UPGRADES

At higher beam powers, the total integrated beam loss due to profile monitors, as well as the rate of profile monitor foil

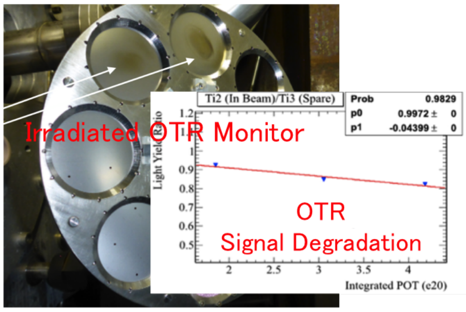

Figure 7: OTR foil darkening and yield decrease after ~4.2×10^{20} incident protons.

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[1] An initial burn-in period before ~5×10^{19} incident protons was seen.

Table 2: SSEM vs WSEM Parameters Calculated Assuming 3 mm Diameter Beam Spot Size and Measured During Beam Tests

Monitor	**Strip Size**	**Area in Beam (mm^2)**	**Measured Signal (a.u.)**	**Volume in Beam (mm^3)**	**Measured Loss (a.u.)**
SSEM	2∼5 mm × 5 µm	7.07	60300	0.106	872
WSEM	25 µm⌀ x2	0.24	2300	0.007	112
Ratio SSEM/WSEM	–	29.5	26	15.1	7.8

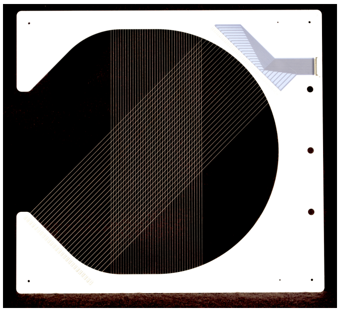

Figure 8: WSEM prototype monitor head.

degradation, will increase. Minimally- and non-destructive beam profile monitoring is therefore desired, and R&D for profile monitor upgrades is ongoing.

A Wire Secondary Emission Monitor (WSEM) has been developed as a joint project between J-PARC and FNAL. A prototype WSEM with twinned 25 µm Ti Grade 1, 3 mm pitch wires, shown in Fig. 8, has been fabricated and installed in the J-PARC neutrino primary beamline for testing.

Results of measurements of the induced beam loss, signal size, and measured width from the WSEM and neighboring SSEMs are shown in Table 2 and Fig. 9. Beam tests show that the beam loss due to the WSEM is reduced by a factor of ~10 compared to an SSEM. The WSEM resolution and precision are equivalent to those of the neighboring SSEMs. Beam profile reconstruction by the WSEM was also found to work well down to beam powers as low as a few kW.

Upgrades to the readout electronics for the SSEMs, and specifically development of a new, fast abort interlock module as part of the machine protection system at 1.3 MW beam power [4], are under way.

R&D for continuous, non-destructive profile monitoring by a Beam Induced Fluorescence Monitor (BIF) is also underway [5, 6].

CONCLUSION

The beam monitors in the J-PARC neutrino primary proton beamline are essential and have been operating stably since 2009. Although periodic calibration and analysis improvements may be necessary going forward, non-destructive beam monitors should work well even at 1.3 MW beam power. Intercepting profile monitors may degrade at higher beam powers, and R&D for improved profile monitoring is ongoing.

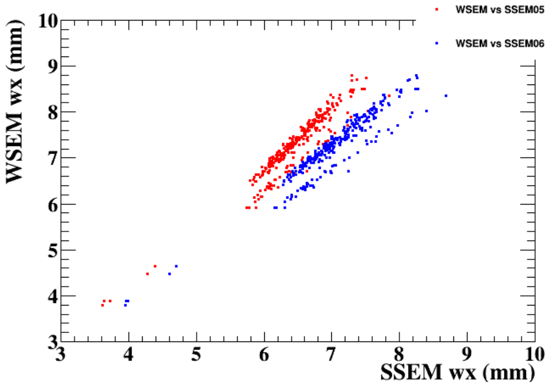

Figure 9: WSEM vs neighboring SSEM measured width. Note that the monitors are not installed in the same position along the beamline – changes in slope and offset of these curves are probably due to slight changes in the beam optics.

ACKNOWLEDGMENT

This work was supported as a US-Japan joint research project and by the JSPS KAKENHI grant system.

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