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CHALLENGES IN CONTINUOUS BEAM PROFILE MONITORING FOR MW-POWER PROTON BEAMS

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Abstract

Continuous beam profile monitoring of the high-power proton beam is essential for protection of beamline equipment, as well as for producing high-quality physics results, in fixed-target extraction beamlines. Challenges in continuous profile monitoring include degradation of materials after long-term exposure to the proton beam, as well as beam loss due to that material intercepting the beam, which can additionally cause activation of nearby equipment. An overview of various profile monitoring techniques used in high-power neutrino extraction beamlines, issues faced so far at beam powers up to several hundred kW, and some possible future profile monitoring solutions for MW-class beamlines will be discussed.

HIGH-POWER EXTRACTION BEAMLINES FOR NEUTRINO EXPERIMENTS

The study of neutrinos by long-baseline neutrino oscillation experiments offers a unique opportunity to probe fundamental open questions in physics. One important open question relates to the possibility that CP violation in neutrinos may help explain the abundance of matter over anti-matter in the Universe.

Neutrinos are produced and detected in three distinct “flavors”, associated with each of the three charged leptons. It has been observed that when neutrinos propagate they can also change flavor, or “oscillate”, with a probability proportional to the distance traveled and inversely proportional to the energy of the neutrino. Long-baseline neutrino oscillation experiments, where a neutrino beam of one flavor is produced and, after traveling a distance of hundreds of kilometers, neutrinos of another flavor are detected, can therefore be used to probe the fundamental properties of the neutrino.

A high-power neutrino production beamline is essential for making a precise measurement of neutrino oscillations. A neutrino super beam is generally produced by a high-energy, high-intensity proton beam incident onto a long, radiation-tolerant target. Pions and other hadrons generated by this process are focused in a set of electro-magnetic focusing horns. The hadrons are then allowed to decay in a long decay volume, where pions decay into muons and muon-neutrinos. The muons are then stopped in a beam dump, while the remaining neutrinos travel through the earth as a relatively pure beam of muon-neutrinos.

Currently running neutrino oscillation experiments include the T2K experiment [1], with a beam produced at the neutrino extraction beamline of the Japan Proton Accelerator Research Complex (J-PARC) Main Ring (MR) synchrotron in Japan, and the NOνA experiment [2], which uses the NuMI beamline at Fermi National Accelerator Laboratory (FNAL) in the United States.

Plans exist to upgrade the J-PARC MR accelerator and neutrino beamline towards future measurements with higher neutrino fluxes [3], including for the future Hyper-Kamiokande experiment [4]. A new neutrino facility at FNAL, the LBNF facility for the DUNE long-baseline neutrino oscillation experiment, is also under design now [5].

Beam profile monitoring is essential to stably run these fixed-target neutrino production beamlines.

J-PARC and FNAL Proton Beams for Neutrino Extraction Beamlines

As summarized in Table 1, the J-PARC MR 30 GeV proton beam has an 8-bunch beam structure. The J-PARC MR currently runs at 485 kW with the plan to upgrade to 750+ kW by 2022 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 pulse (ppp) from $\sim 2.4 \times 10^{14}$ to 3.2×10^{14}.

The FNAL NuMI beamline utilizes a 700+ kW, 120 GeV proton beam with 588 bunches per spill. The beam intensity is 5.4×10^{13} ppp with a plan to increase to 6.5×10^{13} ppp. The duty cycle is 1.333 s, with plans to decrease to 1.2 s.

The beam spot size must be kept large enough to prevent damage to the target and beam window. The higher number of ppp and protons-per-bunch at the J-PARC neutrino extraction beamline necessitates a larger beam spot size than at NuMI.

Table 1: Specifications of the J-PARC MR and FNAL NuMI Proton Beams

	J-PARC MR	**FNAL NuMI**
Beam Energy	30 GeV	120 GeV
Beam Power	500 kW → 1.3 MW	700-750kW → 1 MW
Beam Intensity	2.4E14 ppp → 3.2E14 ppp	5.4E13 ppp → 6.5E13 ppp
Beam Bunches	8	588
Pulse Length	4.2 µs	11 µs
Duty Cycle	2.48 s → 1.16 s	1.333 s → 1.2 s
Beam Spot@Target	4 mm	1.3 → 1.5 mm

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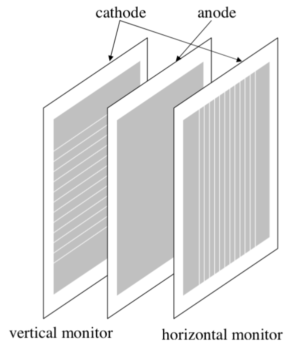

Figure 1: J-PARC neutrino extraction beamline Segmented Secondary Emission Monitor design.

The beam intensity at the future LBNF beamline at FNAL will have a beam energy of 60–120 GeV and an initial beam power of 1.2 MW, which will be upgraded to reach 2.4 MW.

The position and width of the proton beam directly upstream of the neutrino production target must be carefully monitored in order to protect various components from possible mis-steered high-intensity beam, especially as the proton beam power is increased beyond 1 MW. Delicate components include the beam window separating the Target Station (TS) from the high-vacuum beamline, the target itself, focusing horns, and other various components housed in the TS. Information from proton beam monitors is also used as an input into neutrino physics analyses.

CONTINUOUS PROTON BEAM PROFILE MONITORING

Continuous beam position monitoring is important, and can be carried out non-destructively using a variety of devices, including standard Beam Position Monitors (BPMs), as described in detail for the J-PARC neutrino extraction beamline in Ref. [6]. Continuous proton beam profile monitoring is also essential for protecting beamline equipment, but is more challenging.

Segmented Secondary Emission Monitor

In the J-PARC neutrino extraction beamline, the proton beam is continuously monitored by a Segmented Secondary Emission Monitor (SSEM) 3.2 m upstream of the neutrino production target.

The 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. 1. The strip width is 3.5 mm in both horizontal and vertical. 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.

The bunch-by-bunch 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.

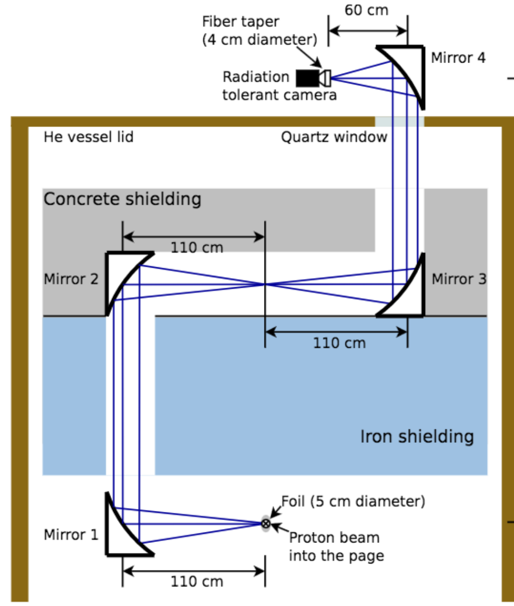

Figure 2: Schematic of the J-PARC extraction beamline Optical Transition Radiation monitor.

The continuously-used SSEM serves an essential purpose for equipment protection – if the beam density at the target becomes $N_p/(\sigma_x \times \sigma_y) < 2 \times 10^{13}$ ppp/mm^2, a beam abort interlock signal is fired.

Optical Transition Radiation Monitor

An Optical Transition Radiation Monitor (OTR), shown in Fig. 2, continuously monitors the beam profile directly upstream of the J-PARC neutrino production target [7].

The OTR active area is a 50-µm-thick titanium-alloy foil, which is placed at 45° to the incident proton beam. As the beam enters and exits the foil, visible light (transition radiation) is produced in a narrow cone around the beam. The light is directed away from the high-radiation environment near the neutrino production target by four mirrors to the lid of the TS, which has lower radiation levels than the area near the production target. 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.

"Hylen" Device

At the NuMI beamline at FNAL, a Hylen Device, shown in Fig. 3, sits directly upstream of the neutrino production target [8]. This device consists of three 1.5 mm diameter beryllium rods connected to individual thermocouples at one end and a common heat sink at the other. The difference in temperature between the rod and the heat sink should

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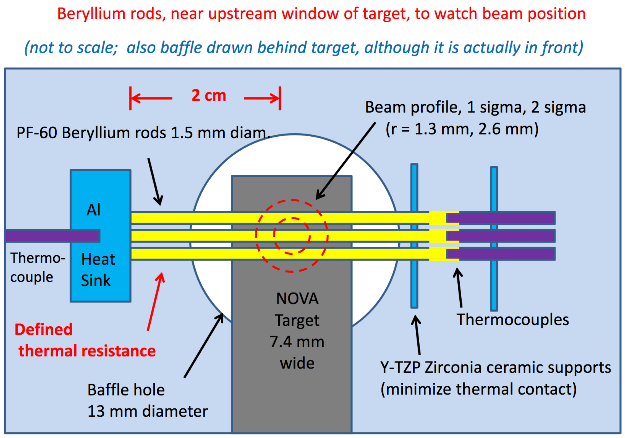

Figure 3: Schematic of the Hylen Device.

be proportional to the beam power deposition in the rod multiplied by the rod's thermal resistance. The beam profile can be derived from the difference in measured temperatures for the different rods, allowing for a coarse beam profile reconstruction.

This device is simple and robust. Since it is made of the same material as the beam window, it is known to be radiation hard and should last as long as the window itself. Since the temperature change of the rod is a bulk phenomenon, rather than a surface effect, surface degradation of the rods should not affect the profile measurement. Readout of the temperature of the thermocouples can be performed at the sub-minute timescale.

CONTINUOUS MONITORING CHALLENGES

Challenges arise with each continuous beam profile monitoring method described above.

SSEM Challenges

Each J-PARC neutrino beamline SSEM causes 0.005% beam loss due to consisting of $\sim 3 \times 10^{-5}$ interaction lengths of material. It is therefore impossible to use these monitors continuously outside of the high-radiation environment near the neutrino production target, i.e. more than 3.2 m upstream of the target in the case of the current J-PARC extraction beamline configuration. One SSEM, SSEM19, is placed at this location and is used continuously.

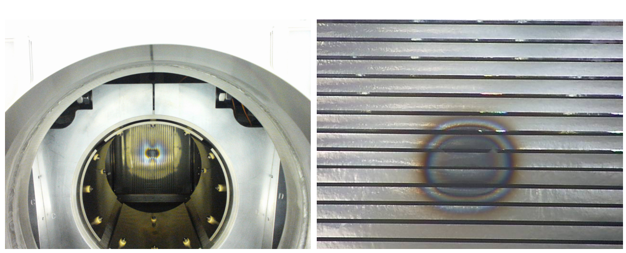

Figure 4: A photograph of the SSEM19 downstream (upstream) foil after 2.3×10^{21} (3.2×10^{21}) incident protons is shown on the left (right).

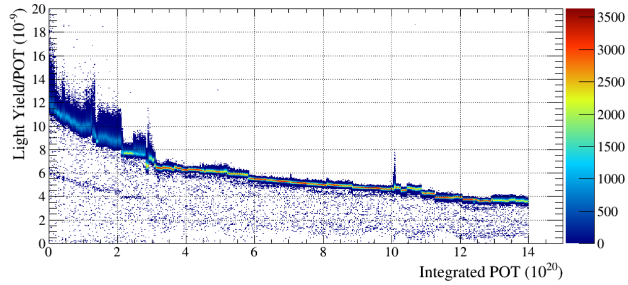

Figure 5: OTR yield decrease over $\sim 1.4 \times 10^{21}$ incident protons.

A photograph of the downstream (upstream) side of the SSEM19 foil after $\sim 2.3 \times 10^{21}$ ($\sim 3.2 \times 10^{21}$) incident protons is shown in Fig. 4. Although no significant decrease in the secondary emission yield has been observed,[1] the foil has darkened significantly. The darkening may indicate that the foil has become brittle and could be at risk for breakage.

OTR Challenges

The J-PARC neutrino OTR also causes significant beam loss and therefore can also be used only directly upstream of the neutrino production target.

Like SSEM19, the OTR foils have darkened where the beam hits the foil. The OTR light yield as a function of integrated incident protons is shown in Fig. 5. Significant degradation of the OTR light yield is observed. This is mostly due to the radiation-induced darkening of the fiber taper used to shrink the OTR light image onto the CID camera sensitive area, but may also be partly due to degradation of the foils themselves.

Radiation damage studies of used OTR foils are currently ongoing by the RaDIATE collaboration [9].

Hylen Device Challenges

As with the SSEM and OTR, the Hylen Device causes significant beam loss and can only be used directly upstream of the neutrino production target. Because the temperature change of the beryllium rods is a relatively slow process and equilibrium temperature is required to make a reasonable profile measurement, this device has a ~9 second characteristic timescale and requires a few minutes of steady beam to reach stability. The device also requires an order 1°C temperature difference between the heat sink and the rod to make a measurement. It therefore has a limited practical power range and cannot be used for low-intensity beam tuning.

PROFILE MONITOR UPGRADES

At the J-PARC neutrino beamline, two new profile monitor options are being developed.

Wire Secondary Emission Monitor

A Wire Secondary Emission Monitor (WSEM) for the J-PARC neutrino extraction beamline has been developed

[1] An initial burn-in period before $\sim 5 \times 10^{19}$ incident protons was seen.

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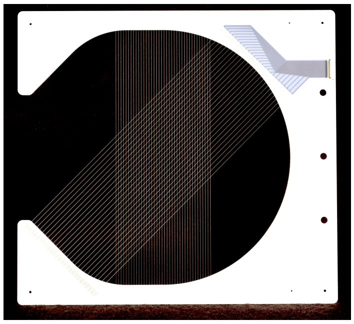

Figure 6: WSEM prototype monitor head.

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. 6, has been fabricated and installed in the J-PARC neutrino extraction beamline for testing. The WSEM is very similar to profile monitors used during beam tuning and orbit spot checks in the NuMI beamline, however the design is modified to fit the requirements of the J-PARC neutrino extraction beamline.

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. The WSEM was also placed in the J-PARC neutrino extraction beamline proton beam for 160 hours of continuous 460~475 kW running, corresponding to ~ 5.6×10^{19} incident protons, without any observed issue.

Because beam loss is reduced by a factor of ~10, the newly developed WSEM can be used continuously at a location up to 4.5m upstream of the J-PARC neutrino production target, just upstream of the wall separating the primary proton beamline tunnel from the TS. A WSEM was installed 4.3 m upstream of the target in 2018 and will be fully commissioned in late 2019. This monitor is intended to only be used continuously in the case of a failure of SSEM19.

Upgraded WSEM wire materials, such as Ti Grade 5, carbon, and carbon nanotube wires, are being considered as possibly more robust alternatives.

Beam Induced Fluorescence Monitor

R&D for continuous, non-destructive profile monitoring by a Beam Induced Fluorescence Monitor (BIF) in the J-PARC neutrino extraction beamline is also underway [10]. This monitor measures the profile of fluorescence light induced by proton beam interactions with N_2 gas injected into the beamline.

The pressure in the beamline must be degraded from the residual gas pressure of order 10^{-5} Pa up to $\sim 10^{-2}$ Pa in order to precisely reconstruct the proton beam profile. A residual gas pressure of 10^{-2} Pa corresponds to a beam loss of 5×10^{-10}, and this level of beam loss should be within the acceptable range for continuous use. A BIF monitor can therefore be used continuously in the J-PARC neutrino extraction beamline.

A full prototype monitor, including a pulsed gas injection system, light transport by 800 µm diameter silica core optical fibers, and light detection by an array of Multi-Pixel Photon Counters (MPPCs), has been installed in the J-PARC neutrino extraction beamline.

First beam tests of this monitor will be carried out in late 2019.

CONCLUSION

Continuous proton beam profile monitoring is essential for safely and stably running long-baseline neutrino oscillation experiments. Issues with monitor longevity and stability have been observed at intermediate proton beam intensities and may become more severe at higher intensities. Monitor development is underway in order to be able to safely make continuous beam profile measurements at beam powers beyond 1 MW.

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