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INVESTIGATION OF AN OPTICAL-FIBER BASED BEAM LOSS MONITOR AT THE J-PARC EXTRACTION NEUTRINO BEAMLINE*

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Abstract

Optical fibers, which at once generate and guide Cherenkov light when charged particles pass through them, are widely used to monitor the beam loss at accelerator facilities. We investigate this application at the J-PARC extraction neutrino beamline, where a 30 GeV proton beam with eight bunches of ~13 ns (1σ) bunch width and 581 ns bunch interval, is extracted from the Main Ring, transported, and hit onto a graphite target to produce a highly intense beam of neutrinos. Three 30 m-length 200 µm-core-diameter optical fibers, which are arranged flexibly to form 60 m- or 90 m-length fibers, were installed in the beamline. The beam loss signal was observed with the Muti-Pixel Photon Counters. We discuss the result and prospects of using optical fibers for monitoring and locating the beam loss source.

J-PARC EXTRACTION NEUTRINO BEAMLINE

J-PARC extraction neutrino beamline, detailed in [1], provides one of the most intense beams of $\nu_\mu(\overline{\nu}_\mu)$ for the research concerning neutrino particles, whose its massiveness is the only experimental evidence so far beyond the description of the Standard Model of elementary particles. To extract the 30 GeV proton beam from Main Ring and transport it toward a graphite target for neutrino production, the 238 m-length beamline is instrumented with 21 normal magnets (eight steering, four dipole, and nine quadrupole magnets) and 14 doublets of superconducting combined function magnets. The neutrino beamline receives a beam in a so-called fast-extraction mode, where each beam spill consists of eight bunches of ~13 ns (1σ) bunch width and 581 ns bunch interval. In 2020, J-PARC operates stably at around 515 kW with an intensity of 2.65×10^{14} protons-per-pulse (ppp). J-PARC accelerator and neutrino beamline [2] plan to upgrade to MW-power beam by reducing the cycle repetition from 2.48 s to 1.16 s and increasing the beam intensity to 3.2×10^{14} ppp. To realize the MW beam, equipment robustness against high intensity, beam loss tolerability, handling the radioactive waste, and precisely and continuously monitoring the beam profile are essential. This work concerns merely the beam loss monitor (BLM), including the experience of operating the gas-based BLM system and investigation of using optical fiber-based BLM (O-BLM) as a complementary option for monitoring the beam loss.

GAS-BASED BLM

Proportional counter with a mixture of Ar and CO_2 (Canon Electron Tubes & Devices E6876-400) [3] was chosen to monitor the spill-by-spill beam loss. There are 50 BLMs distributed along 238 m-length beamline, one shown in Fig. 1, and they are integrated into the Machine Protection System (MPS), allowing us to abort the next beam spill in case the spill-integrated BLM signal with the latest spill is higher than a pre-defined threshold.

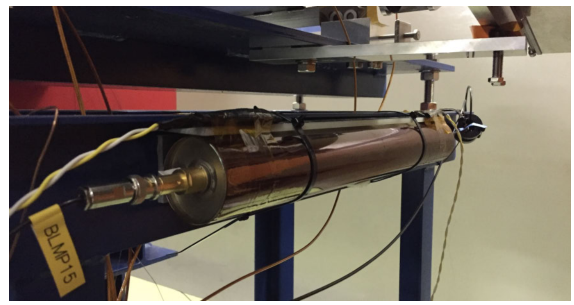

Figure 1: A gas-based BLM installed under the magnet.

Figure 2 shows the beam loss distribution along the beamline. The beam loss is high near the extraction point (at ~0 m position), a collimator (at ~45 m position), and at the most downstream due to backscattering of proton beams on the beam window, production target, and intercepting beam profile monitor. The beam loss is quiet along the superconducting magnet section (from 54 m to 201 m positions).

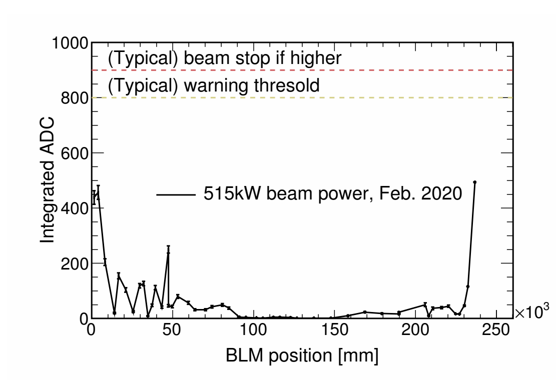

Figure 2: Beam loss distribution with the gas-based BLMs along the 238 m-length extraction neutrino beamline.

With more than ten year operation of BLM, it is well-established that the gas-based BLM functions stably and reliably. The most downstream BLM placed in the highest radioactive area comparing to other BLMs, has signals linearly proportional to the beam power, providing us a useful beam-based calibration to check BLM response regularly and no degrading indication observed. For semi-offline monitoring and analysis, the BLM signal is sampled 30 MHz with

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a Analog-to-Digital convertor (ADC), providing a measure of the beam (in)stability and thus feedback to the accelerator experts. The beam loss measurement near the extraction point is particularly useful for beam commissioning and optic tuning since it allows us to predict the loss coming from the extraction system. Besides, it is found that the integrated signal of BLM is proportional to the residual dose which is measured directly a few hours after the beam stop.

There are additional features which we wish to have in a complete BLM system, including but not limited to (i) bunch-by-bunch (in)stability monitor, (ii) capability to locate the loss source, (iii) sensitivity to thermal and fast neutrons, and (iv) beam halo detection. Those motivate us to investigate the usage of optical fibers and fast-response photosensor as an alternative method to monitor the beam loss.

OPTICAL FIBER-BASED BLM

Using optical fiber for monitoring the beam loss is well-established method in many facilities where the beam of a charged particle (proton, electron) is delivered in a few ns or shorter pulse [4–6]. With long-pulsed beam such as J-PARC extraction neutrino beamline (~13 ns), the possibility to take advantage of the optical fiber as a beam loss monitor needs further investigation.

General concept and specification

Fundamentals of the optical fiber used as the electromagnetic and hadronic calorimeter can be found in [7]. Charged particles generate Cherenkov light when passing through the optical fiber, which also plays a role as a light guider to the fast photosensor. The number of observed photons is essentially proportional to the flux of charged particles, i.e beam loss. A concept of optical fiber-based BLM (O-BLM) is shown in Fig. 3. While the speed of protons closes to the speed of light, 3.3 ns/m, the speed of photon propagation in the fiber is about 5.0 ns/m. For the loss signal separation, it is important to arrange the fiber-photosensor system such that particles incident on the fiber earlier produce Cherenkov light which reaches the photosensor earlier. The optimal arrangement can achieve a signal separation of up to 8.3 ns/m. Considering a proton beam bunch width of ~13 ns and signal readout resolution in a few ns, a simple simulation shows that the two loss sources are well-separated if two signal-induced positions separated by a physical gap of ~7 m. One can lift this limit by adding more fiber segment between the two loss sources to effectively increase the time separation.

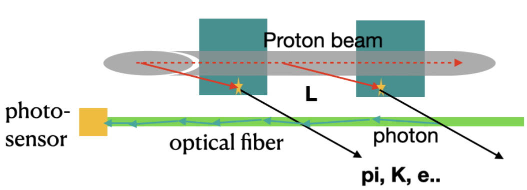

Figure 3: Concept of optical fiber-based BLM to monitor and locate the beam loss.

We use the multimode pure-silica high-OH optical fibers [8] with a core diameter of 200 µm and a numerical aperture (NA) of 0.22 for the measurement setup. Although each batch fiber is 30 m in length, it is flexible to extend the fiber length by using the optical coupling. The optical fiber is an insulator, which allows us to safely lay the fiber on the magnet or directly attach to the beam duct, as shown in Fig. 4. For ns-level response and invulnerable to the strong

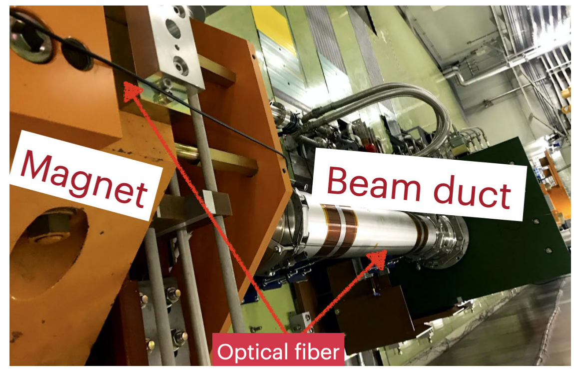

Figure 4: Optical fibers are attached on top of the magnet and the beam duct.

magnetic fields in the beamline, Hamamatsu Multi-Pixel Photon Counter (MPPC) is chosen to read out the signal from the optical fibers. However, MPPC is not radiation-hard enough to operate in a highly radioactive area near the beamline. Guiding the optical fiber to a lower radioactive area, where the MPPC can be placed, is introduced as a solution. The low afterpulse S12571-025 MPPC type [9] has a sensitive size of 1.0 mm×1.0 mm. To position the fiber on the MPPC precisely, we mount MPPC on a round PCB which are housed in a plate with built-in FC-coupler connector. Figure 5 shows detail of the measurement setup for investigating the possibility of loss location.

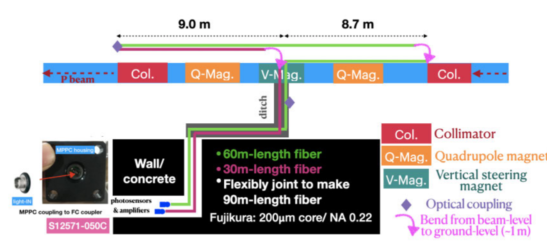

Figure 5: Measurement setup for locating the beam loss source with the optical fiber-based BLM prototype.

In the measurement setup, there are three 30 m-length fiber which is laid out in the way such that we can easily joint to make 60 m- and 90 m-length fibers. The whole setup covers a range of 17.7 m of the beamline, placing between two collimators and passing over two quadrupole magnets and one vertical-steering magnet. In a nominal setup, we consider two readouts for 60 m- and 30 m-length fibers. Relative electronic latency between two readouts is ~ a few ns. A 17.7 m-length segment of the first fiber is placed at the

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beam-level; the rest is placed on the ground or the ditch, which is about 1 m lower. For the second fiber, a 9 m-length segment is placed at the beam-level. Although it is expected that a significantly higher amount of loss particles would be incident on the beam-level segment, the signal can also be generated in the ground-level segment.

O-BLM signal and conventional functionalities

MPPC signal, amplified by a stand-alone amplifier board in the tunnel, is sent ~ 130 m to the electronic rack located on the ground level and read out by oscilloscope or 30 MHz-sampling ADC[1], which is identical to the gas-based BLM. The beam loss signals with an O-BLM and a gas-based BLM are shown in Fig. 6. The bunch structure is observed more clearly with the O-BLM. We take data with the O-BLM and the nearby gas-BLM at the same period with the same DAQ and check the correlation of the signal amplitude between them. The result, shown in Fig. 7, presents a strong correlation between the O-BLM signals and nearby BLMs (BLM-01,10,16)[2] but reduced with faraway (~190 m) BLM-50 indicating that the O-BLM are accepting the same loss source as the gas-based BLM. We also check the stability of the signal of the O-BLM in comparison to the gas-based BLM. This is very important, particularly when one considers integrating the system into MPS since the instability of the signal amplitude can reduce the reliability of the system. In Fig. 8, we compare the stability of the signal of the first peak for two gas-BLM and two O-BLM. It is showed that the stability of the O-BLM amplitude is not as good as that of the BLM. Also, the signal of the 60 m-length fiber seems less stable than the 30 m-length fiber. Those needs further investigation.

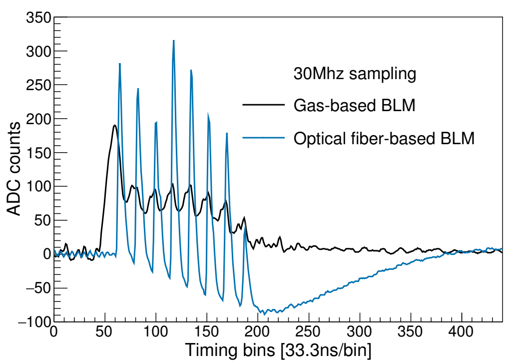

Figure 6: The signals with gas-based BLM and optical fiber-based BLM with 30 MHz sampling DAQ.

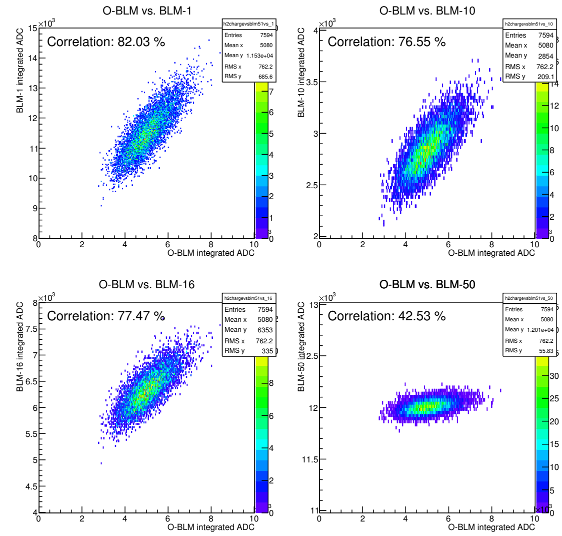

Figure 7: Correlation between the 60 m-length O-BLM with four gas-based BLM placed at four different locations: BLM-10 and BLM-16 are at the most upstream and the most downstream of the 60 m-length O-BLM respectively. BLM-01 and BLM-50 are 30 m upstream away and 190 m downstream from the O-BLM respectively.

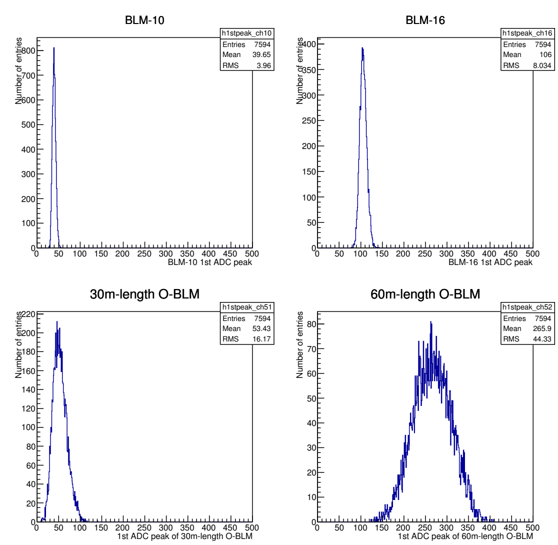

Figure 8: Stability of the signal observed with gas-based BLM and O-BLMs for more than 5 hours beam delivering. BLM-10 and BLM-16 are at the most upstream and the most downstream of the 60 m-length O-BLM respectively.

Loss source location

The O-BLM, taking advantage of the fast responses from both light production in the optical fiber and MPPC, essentially provides a very good time resolution (a few ns), and thus spatial resolution (1 m more or less). However, the O-BLM adopted here for the measurement is limited by a relatively long beam bunch width (~13 ns) and complexity of fiber guiding referred to Fig. 5. The MPPC signals recorded with the oscilloscope coming from different fibers is shown in Fig. 9. Signals from both 30 m- and 60 m-length fibers seem to have a two-peak structure for each bunch. The peak-to-peak interval for 60 m-length fiber is ~ 151 ± 10ns, while that of the 30 m-length fiber is just ~ 52 ± 15ns. When two fibers are joined to form 90 m-length fiber and the sig-

[1] To take advance of the O-BLM, faster sampling ADC is needed.
[2] There are strong correlation among BLMs indexed from 01 to 16

nal is read out in the same end as the original 60 m-length fiber, the second peak of the signal is enhanced significantly due to the contribution of 30 m-length fiber. This suggests that both original 30 m- and 60 m-length fibers receives the same loss source which makes the second peak in their waveform. Using the peak timing information, we estimate that one loss source is near the downstream collimator sketched in Fig. 5. The signal waveform recorded with 90 m-length fiber is fitted with double Gaussian distribution for each bunch. The peak-to-peak interval, shown in Fig. 10, is found to be 156.8 ± 9.8 ns and the withs of the first and second peaks are 42.2 ± 7.5 ns and 46.2 ± 8.3 ns respectively. These peak-to-peak intervals allow us to locate the second loss source, which is either (i)~18.9 m upstream from the previously found loss source, i.e close to the upstream collimator sketched in Fig. 5 or (ii) physically near the vertical steering magnet and charged particles generate the light near the ditch in Fig. 5. That the O-BLM signal widths are larger than the proton beam width may indicate that the loss source is not a point source but a fairly long segment of fiber is fired.

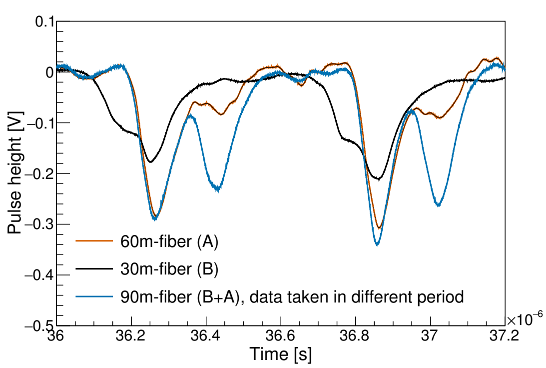

Figure 9: Beam loss, zoomed into first two bunches, observed with three fiber configurations. Data with 90 m-length fiber is taken in not the same period as other data.

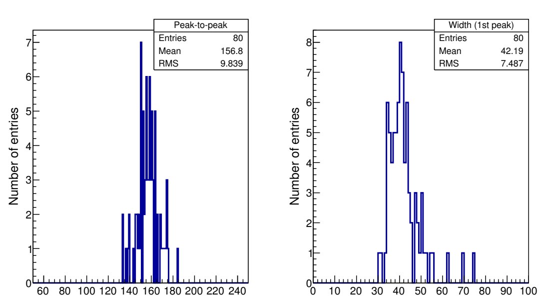

Figure 10: The peak to peak interval and the width of the first peak resulted from the double Gaussian fit per each bunch in the signal waveform with 90 m-length O-BLM.

SUMMARY AND PROSPECTS

We observed the beam loss using the optical fibers with a clear beam bunch structure thanks to the fast response of both optical fiber and MPPC. The portability of fiber allows us to install the fiber easily on the magnet and can attach directly to the beam duct. The signals observed with different fiber configurations indicate that the beam loss at the instrumented section may come from at least two loss sources. In short, O-BLM is a promising and economic option to (i) monitor the beam (in)stability on the bunch basic, and (ii) locate the beam loss source.

One of the most important tasks to realize the O-BLM in our beamline is to simplify the fiber layout to interpolate the loss sources intuitively from the signal waveform. It is ideal to put the fibers along with the beamline without guiding them to the sub-tunnel. In this direction, it is interesting to investigate other types of photosensors which are required to be radiation-hard, magnetic-invulnerable, fast-response, and wide dynamic range. To cover entire the 238 m-length beamline, one may need at least 4 fibers of 60 m-length since the fiber length is limited to a length of $\leq$ 60 m along the beamline due to the bunch interval. For the loss source locating purpose, it is important to determine precisely (in a few ns levels) the time where the proton beam arrives at a specific point in the beamline. Since it is almost impossible to use the beam trigger with such precision, one needs to determine it basing on the beam signal on a bunch-by-bunch basis. An economic approach is to read signals on each fiber in both ends and calibrate the electronic latency among the channels precisely. If those tasks can be overcome, such an O-BLM system can provide a great tool for beam diagnostics.

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