ISBN: 978-3-95450-201-1 doi:10.18429/JACoW-IBIC2018-WEPC08

OPTICAL SYSTEM OF BEAM INDUCED FLUORESCENCE MONITOR TOWARD MW BEAM POWER AT THE J-PARC NEUTRINO BEAMLINE

S. Cao*, M. Friend, K. Sakashita, High Energy Accelerator Research Organization (KEK), Tsukuba, Japan
M. Hartz[1], Kavli IPMU (WPI), University of Tokyo, Tokyo, Japan
[1]also at TRIUMF, Vancouver, Canada
A. Nakamura, Okayama University, Okayama, Japan

Abstract

A Beam Induced Fluorescence (BIF) monitor is being developed as an essential part of the monitor update toward MW beam power operation at the J-PARC neutrino beamline. By measuring the fluorescence light from proton-gas interactions, the BIF monitor will be used as a continuous and non-destructive diagnostic tool for monitoring the proton beam profile spill-by-spill, with position and width precision on the order of 200 µm. The main challenge lies in collecting a sufficient amount of fluorescence light for the beam profile reconstruction while controlling the beam-induced noise with the current beamline configuration. A study is presented with a particular focus on the optical system under development, which allows us to transport fluorescence light away from the high radiation environment near the proton beamline and detect the optical signal with a Multi-Pixel Photon-Counter-based fast readout.

J-PARC NEUTRINO BEAMLINE: TOWARD MW BEAM

The J-PARC complex [1] is serving as a producer of the most intense neutrino beam in the world to one of the world-leading neutrino oscillation experiment, Tokai-to-Kamioka (T2K) [2]. A J-PARC neutrino beamline is designed to guide protons extracted from Main Ring (MR), bend 80.7° toward the T2K far detector, Super-Kamiokande, before bombarding onto a graphite target in order to producing charged pions and kaons which are then decayed into ν_μ (or $\overline{\nu}_\mu$) in flight. Recent results from T2K experiment shows that the CP conserving values of CP violation phase, which is presented in the leptonic mixing matrix, fall outside of 2σ of confidence and credible intervals of measured range [3]. To further study CP violation in the leptonic sector, increasing the neutrino beam power is essential and play a role as the main driver for the neutrino intensity frontier. Since the start of user operation in 2010, the MR beam power has been increased steady and operated stably in 485 kW with an intensity of 2.5×10^{14} protons-per-pulse (ppp) at a repetition cycle of 2.48 s in 2018. Toward MW beam power, J-PARC aims to reduce the repetition cycle to 1.3 s and increase the beam intensity up to 3.2×10^{14} ppp by 2026.

To realize MW beam, beam loss handling and continuous monitoring the beam profile with high precision are crucial. Description of the beam loss and beam profile monitors in J-PARC neutrino beamline can be found elsewhere [2]. Among these monitors, Segmented Secondary Emission Monitors (SSEM), which are used to monitor the beam profile including the beam center and beam width, are considered critically requiring an upgrade toward MW beam due to limitations discussed in the next section.

CURRENT BEAM PROFILE MONITOR AND THEIR LIMIT

In general, to measure the proton beam profile, material is inserted into the beamline. In J-PARC neutrino beamline, there is a suite of nineteen SSEMs, each of monitor consists of two 5-µm-thick Titanium (Ti) foils stripped vertically and horizontally along with a Ti foil of same thickness between thme. The strip withd is about from 2 cm to 5 cm, depending on the beam size at the installed position. Precision of the SSEM measurement on the beam width can be achieved up to 200 µm. However this method leads to 0.005% beam loss per SSEM. Due to this large amount of loss, only the most downstream SSEM is used continuously during normal operation, while others are inserted occasionally into the beamline for operation only during beam tuning periods. A Wire Secondary Emission Monitor (WSEM) has been developed with the same principle as the SSEM but using wires instead of strips to mitigate the beam loss. With WSEM, the beam loss can be reduced by factor of ten. However, continuous monitoring by a WSEM is still questionable, since even 0.0005% beam loss can cause serious problems, specifically the irradiation and damage of beamline components and a residual dose increase which makes maintenance become difficult. Thus, it is crucial to develop a non-destructive (or minimally destructive) beam profile monitor for the future operation of J-PARC at MW beam power.

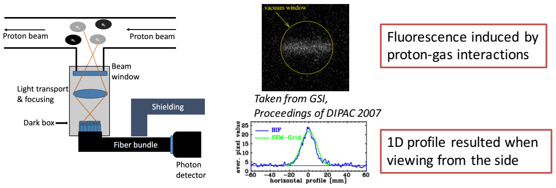

Figure 1: A BIF schematics has been built in the J-PARC neutrino beamline.

BIF MONITOR: PRINCIPLE AND A WORKABLE CONCEPT

In general, a BIF monitor makes uses of the fluorescence induced by proton beam interactions with gas in the beamline.

---

* cvson@post.kek.jp

The measured transverse profile of the fluorescence light should match with the transverse proton beam profile.

Specification of the J-PARC Neutrino Beamline

A BIF monitor is under development at the J-PARC neutrino beamline [4] with some requirements to meet the strict conditions in the beamline. First, gas needs to be injected with a gas injection system, since in normal operation, the residual gas level in the beamline is only 10^{-6} Pa, which can not produce enough fluorescence light for observation. Second, a method for dealing with the space charge effect, which is due to the very large transverse field of the proton beam itself, needs to be considered to mitigate or correct the distortion of the beam profile reconstructed from fluorescence of ions which can move in the field. One feasible solution for this is to use a fast readout system, for example using Multi-Pixel Photon Counters (MPPC) as photosensors. The 10-ns-level time resolution of MPPCs allows us to study the profile distortion caused by the space charge effect. Finally, operation in a high radiation environment should be considered for each detection component. For instance, MPPCs are not radiation-hard. Consequently MPPCs should be operated in the sub-tunnel where the radiation level is significantly suppressed by concrete shielded walls. As a result, an optical fiber transport system, which is used to guide the light from the beamline to the sub-tunnel, needs to be used and must be radiation-hard. Fig. 1 shows a workable schematic of the BIF monitor in the J-PARC neutrino beamline.

A Workable Concept of BIF Monitor

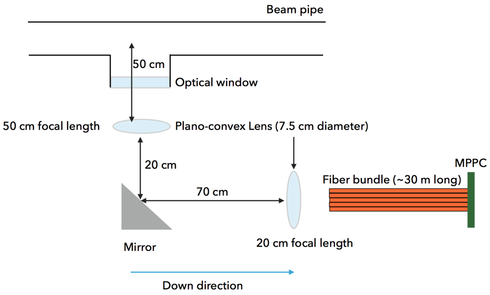

Figure 2: A workable concept for a light transport and focusing system with a fast readout using MPPCs. A 45° downward-mounted mirror is needed to direct light from beamline level to the floor before transporting it to the sub-tunnel using optical fibers.

For the beam profile measurement, the number of fluorescence photons recorded by the BIF photosensor is the key factor. The detected number of photons is proportional to the number of incident protons per spill, number of photons produced per each proton and the overall detection efficiency, as expressed in Eq. 1

$$N_{\gamma}^{\mathrm{det}} = N_p \times N_{\gamma}^{p} \times \epsilon_{\mathrm{all}}. \qquad (1)$$

For this study, one thousand photons detected is used as our target for the optical system development. For the J-PARC beam, the number of incident protons per spill, N_p is set to be 2.5×10^{14} protons. For N_2 [5], which is tentatively selected as our injected gas, number of photons produced per proton, assuming a signal integrated over 2 cm in the beam axis, is calculated to be $N_{\gamma}^{p} = 1.25 \times 10^{-5} \times P_{\mathrm{gas}}$, where P_{gas} is the gas pressure at the BIF interaction point. The overall detection efficiency is calculated based on a feasible configuration, shown in Fig. 2, to be $\epsilon_{\mathrm{all}} = 4.1 - 7.1 \times 10^{-5}$ which consists of multiple sub-factors: (i) an acceptance and efficiency of lenses and mirror of 0.99×10^{-3} which dominated by the geometrical acceptance of the first lens, (ii) a fiber collection efficiency of 0.22–0.38, (iii) a 40-m fiber transmission efficiency of 0.66, (iv) a fiber-to-MPPC coupling transmission of 0.95, and (v) a MPPC photon detection efficiency of 0.3. These factors are either verified experimentally or derived from the manufacturer spec sheet. As a result, to achieve 10^3 photons with the estimated detection efficiency, gas at the monitoring point needs to be at a pressure of 5.6–9.8×10^{-3} Pa. This level of gas pressure localization is a benchmark for the gas injection system which is under development. Figure 3 shows a COMSOL simulation of a gas system designed to achieve 10^{-2} Pa near the beam view ports while maintaining an average vacuum level of 10^{-4} Pa at the ion pumps and 10^{-6} Pa at the superconducting magnet section entrance. To achieve this state, 2×10^{-7} kg/s N_2 gas is injected with an 0.5% of duty factor. The gas non-uniformity, which can make the observed beam profile distorted, is also studied, and simulations show that a fluctuation in gas density smaller than 5% can be achieved. Studies with the test vacuum chambers are underway in order to understand the gas flow dependence on the chamber shape and benchmark the gas system simulation.

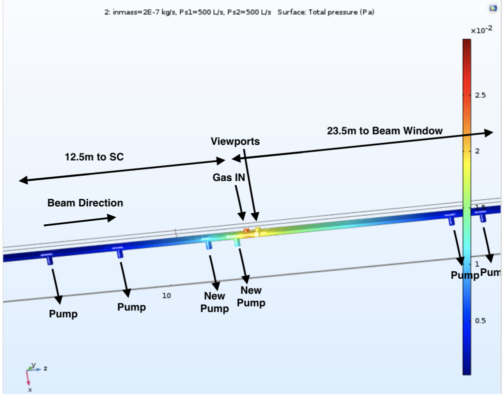

Figure 3: COMSOL simulation of a gas system design.

Monte Carlo Simulation of the Optical System

The optical system is simulated with the GEANT 4 optical photon simulation tool in order to validate our calculation. Almost all components of the optical system shown in Fig. 2 are included. Optical characteristics of the beam window and lenses are set to the manufacturer specification. The mirror reflectance is set to 90%. Optical fibers are simulated but with a 40 cm length. The photon inefficiencies at both fiber ends are considered, but the fiber attenuation is not simulated. This factor can be absorbed by reducing the number of photons generated. The gas pressure profile, proton-gas interactions, space charge effects and the photosensors are not included in the simulation, but will be considered in the future.

Assuming the gas pressure and detection and fiber transport efficiency described above, a total of 5×10^6 photons with 390 ns wavelength (mimicing light production from N_2 gas) are simulated with the X-view centered at 0 while the Y-view center is varied from −10 mm to 10 mm. The beam width is set to 2 mm (1 σ) for both X and Y- view. Figure 4 shows the fiber layout and the light pattern collected at the photosensor plane. A total of 978 photons are collected in the case of the centered beam. This is equivalent to 2×10^4 acceptance and efficiency, agreeing with our calculation.

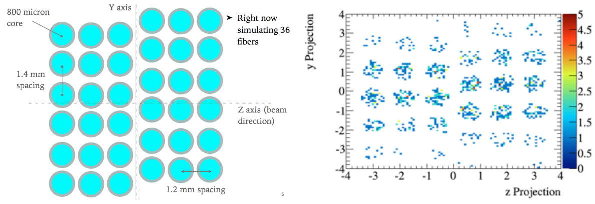

Figure 4: A studied fiber collection layout (left) and photon pattern at the photosensor plane (right).

By integrating the photons along the z-axis, i.e. proton beam axis, we can reconstruct the beam profile in the y-axis as shown in Fig. 5. Further studies are conducted by varying the position of the y-view center. Figure 6 shows good linearity of the reconstructed values of the y-view center to the true value.

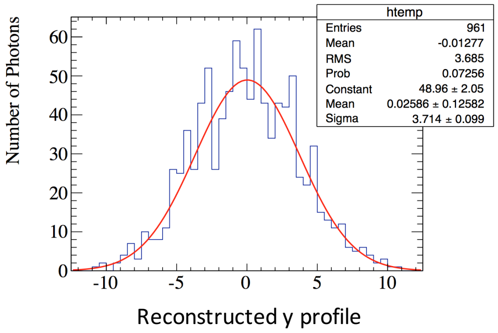

Figure 5: Reconstruction of the y-view beam profile.

Other Option for Light Detection

In addition to developing an optical system with MPPCs as the baseline option, another option, which uses a Microchannel Plate (MCP) gated image intensifier coupled to a radiation-hard Charged Injection Device (CID) camera by a fiber taper, is being considered. This option gives better position resolution than the optical fiber array. While it is tested that a CID camera can withstand the high radiation environment near the beamline, MCP survival in such conditions needs to be confirmed. Also the gain of a single stage MCP is just ~ 5×10^3, much smaller than the 10^6 gain of MPPCs. Thus, to get enough photons for beam profile reconstruction, a dual stage MCP should be used. Another issue is that the minimum MCP gate time of 30 ns makes it difficult to mitigate any slow background component. With a CID camera, each integrated spill is stored, and any distortion by space charge effects should be corrected by other measurements or simulation.

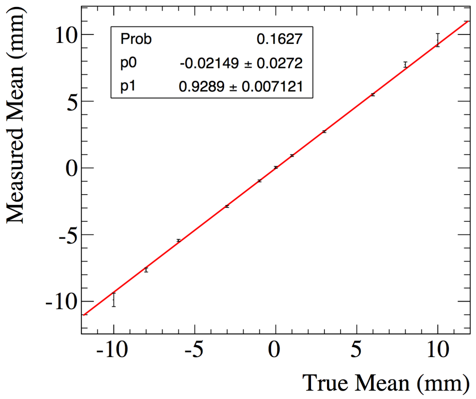

Figure 6: Reconstructed mean of y centers vs. true inputs.

OPTICAL SYSTEM INSTALLATION & BEAM-INDUCED NOISE STUDY

Optical System Design and Installation

During the J-PARC beam operation from October 2017 to May 2018, an optical transport and focusing system was designed and installed in the J-PARC neutrino beamline, in order to study the beam-induced noise and mechanic feasibility of the system as shown in Fig. 7. For the fiber-to-MPPC coupling, a design is developed as shown in Fig. 8, allowing us to insert and remove the fiber easily without using glue. For the last week of J-PARC beam operation,

Figure 7: Optic system with frame installed in J-PARC neutrino beam line with front view (left) and inside with two lenses and 45° downward-mounted mirror (right).

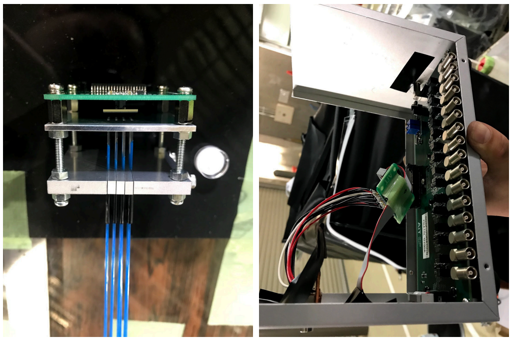

Figure 8: Fiber-to-MPPC coupling structure (left) and multi-channel amplifier board housing (right).

the system was connected to the beamline DAQ, allowing us to study the beam-induced noise in correlation with other beam monitors.

Beam-Induced Noise Study

To study the beam-induced noise, 40-m long silica fibers with both 400 µm and 800 µm diameter cores were installed near the beam line. The numerical aperture of the fibers is 0.39. For studies shown in this section, a Hamamatsu S13361-3050AE-04 4x4 MPPC array is used with the 16 channel amplifier board, PBA16L-G750A, developed by AiT Instruments. The waveform is recorded by a newly developed Flash Analog-to-Digital Converter (FADC) named CAVALIER (250 MHz sampling), noise from single spill is shown in Fig. 9. The average waveform from ~ 1000 spills is shown in Fig. 10. The data are taken with a black-cap covering the beamline end of the fiber. In other words, the observed signal here is from fiber itself when the proton beam passes through the beamline. An eight-peak noise structure corresponds to the eight bunches of the proton beam. It is observed that the noise has two parts: peak (or fast) noise and slow noise. While the peak noise is suspected to be from Cherenkov or scintillation light in the fiber, the slow noise may be from neutrons which may come from backscattering from the target. An effort to shield the background with concrete and polyethylene shows a visible reduction of the slow noise but not of the peak noise. By using the data recorded at various beam intensities, we find that the noise is proportional to the beam intensity and has a strong correlation to the beam loss recorded by a nearby Beam Loss Monitor (BLM), as shown in Fig. 11. At 480kW beam operation, the integrated charge of this noise is equivalent to ~ 160 photoelectrons per beam spill for the peak noise and around the same level for the slow noise. A simulation study concludes that the un-subtracted noise level should be kept lower than around 20 photoelectrons per spill. Thus, to realize the BIF monitor, it is important to understand and suppress this beam-induced noise.

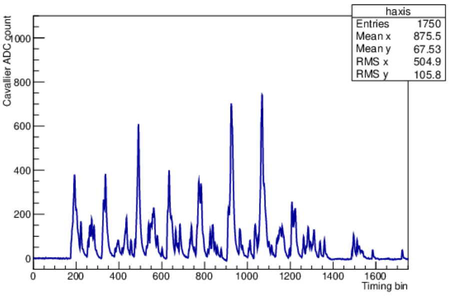

Figure 9: ADC distribution of single beam spill.

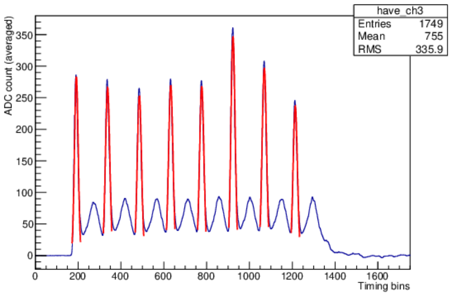

Figure 10: Averaged ADC distribution of ~ 1000 spills. Red are with Gaussian fit on the found peaks of distribution.

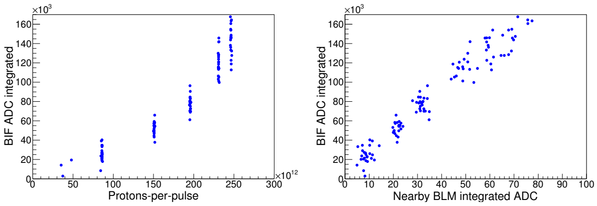

Figure 11: Dependence of noise to the beam intensity (left) and strong correlation of noise to the beam loss (right)

SUMMARY AND PROSPECT

In summary, a concept of a BIF monitor as an upgrade option for monitoring the future MW beam at J-PARC is introduced. A BIF optical system has been designed and installed in the J-PARC neutrino beamline. Noise induced by the proton beam is observed with silica-core optical fibers. There are on-going efforts to understand and suppress this noise. We plan to build a full working prototype of the BIF optical system in 2018. The next target is to observe real BIF signal by injecting gas into the beamline.

ACKNOWLEDGEMENT

This work was supported by the JSPS KAKENHI grant system (Grant No. 16H06288).

REFERENCES

[1] Y. Yamazaki *et al.*, KEK-REPORT-2002-13.

[2] K. Abe *et al.*,Nucl. Instrum. Meth. A **659**, 106 (2011)

[3] K. Abe *et al.*, arXiv:1807.07891 [hep-ex].

[4] M. Friend *et al.*, doi:10.18429/JACoW-IBIC2016-WEPG66

[5] J. Bosser *et al.*, Nucl. Instrum. Meth. A **492**, 74 (2002)