DEVELOPMENT OF BEAM INDUCED FLUORESCENCE MONITOR FOR NON-DESTRUCTIVELY PROFILING MW PROTON BEAM AT THE J-PARC NEUTRINO BEAMLINE

S. Cao*, M. Friend, K. Sakashita, High Energy Accelerator Research Organization, Tsukuba, Japan
M. Hartz[1], Kavli IPMU (WPI), University of Tokyo, Tokyo, Japan
[1]also at TRIUMF, Vancouver, Canada
A. Nakamura[2], Okayama University, Okayama, Japan

Abstract

A Beam Induced Fluorescence (BIF) monitor is under development for non-destructively monitoring the future MW-power proton beam at the neutrino extraction beamline at J-PARC. The 30 GeV protons are bombarded onto a graphite target, producing one of the most intense neutrino beams in the world for the Tokai-to-Kamioka (T2K) long-baseline neutrino oscillation experiment, where beam profile monitoring is essential for protecting beamline equipment and understanding the neutrino flux. For the BIF monitor, gas is injected into the beam pipe and the spatial distribution of the fluorescence light induced by proton-gas interactions is measured, allowing us to continuously and non-destructively monitor the proton beam profile. However, the specifications of the beamline require us to carefully control the gas localization by pulsed injection. Radiation hardness of all monitor components and profile distortion caused by space charge effects must also be considered. We will show how to address these challenges and realize a working prototype.

J-PARC MW PROTON BEAM FOR NEUTRINO INTENSITY FRONTIER

Accelerator-Based Neutrino Research

One of the most striking discoveries of 20^{th} century is that neutrino has non-zero mass, which contradict to the prediction of the so-called Standard Model of the elementary particles. The conclusion has been drawn from a well-established phenomenon, neutrino oscillation, in which neutrino, who is produced with a definite flavor (electron, muon, tau), can change into other flavors after traveling some distance. This quantum mechanic phenomenon has been realized as a great tool for exploring the fundamental laws of physics. One of the most stimulating physics is Charge-Parity (CP) violation in the leptonic sector. Recently T2K experiment provides a hint on this at 2σ C.L. [1]. The result is statistically limited and for providing a more significant sensitivity, higher intense neutrino beam(s) and bigger detector(s) are desired.

J-PARC, One of the Most Intense $\nu_\mu(\overline{\nu}_\mu)$ Beam

J-PARC Neutrino Experimental Facility has been built to deliver one of the most intense beams of $\nu_\mu(\overline{\nu}_\mu)$ for the neutrino research. Neutrino beam is made from the decay-in-flight of pions and kaons, which are produced when 30 GeV proton beam from Main Ring (MR) are guided and hit on the graphite target. More detail description of the neutrino beam can be found at [2]. At present, J-PARC operate stably at around 485kW with an intensity of 2.5×10^{14} protons-per-pulse (ppp). The plan [3] is to upgrade to MW-power beam by reducing the cycle repetition from 2.48 s to 1.3 s, and increasing the beam intensity to 3.2×10^{14} ppp.

Present Beam Profile Monitors

There are two types of profile monitors being used at the J-PARC neutrino beamline: Segmented Secondary Emission Monitor (SSEM) and Wire Secondary Emission Monitor (WSEM). The detail can be found at [4]. Both are categorized as the destructive type of monitors. Each SSEM causes 0.005% beam loss and WSEM lessens it by a factor of ten. With MW-power beam, it is challenging to have a continuous operation of these conventional beam monitors due to the high irradiation, the risk of beamline component damage and the potential built-up residual dose which limits the machine maintenance time. Thus it is well-motivated for developing the non-destructive beam profile monitor(s).

DEVELOPMENT OF A BIF PROTOTYPE

Design Considerations

As discussed in [5], the space charge effect in the J-PARC neutrino beamline is too high to be counteracted by the typical Ionization Profile Monitors magnet. It thus was the practical choice to focus on a BIF-based prototype. To have enough photons for light detection system, the vacuum level near the fluorescence detection region must be degraded while maintaining an average vacuum level of 10^{-4} Pa at the ion pumps for the lifetime consideration and 10^{-6} Pa at the superconducting (SC) section for the safety reason. N_2 gas is selected due to its high light yield. Fluorescence spectral induced by proton-N_2 interactions spreads from 380 ns to 470 ns with a peak at $\sim$ 390 ns. However, N_2 is relatively light and can be drifted largely due to the space charge field, consequently distorting the reconstructed profile. A fast photon catcher but non-vulnerable to the magnetic field is considered as a viable solution, which points us to Multi-pixel Photon Counter (MPPC). However, MPPC is not radiation-hard enough to function well and durably near the beamline environment. The practical use is to transport the light with radiation-hard optical fibers to sub-tunnel where the radiation level is suppressed and MPPC can be placed.

---

* cvson@post.kek.jp

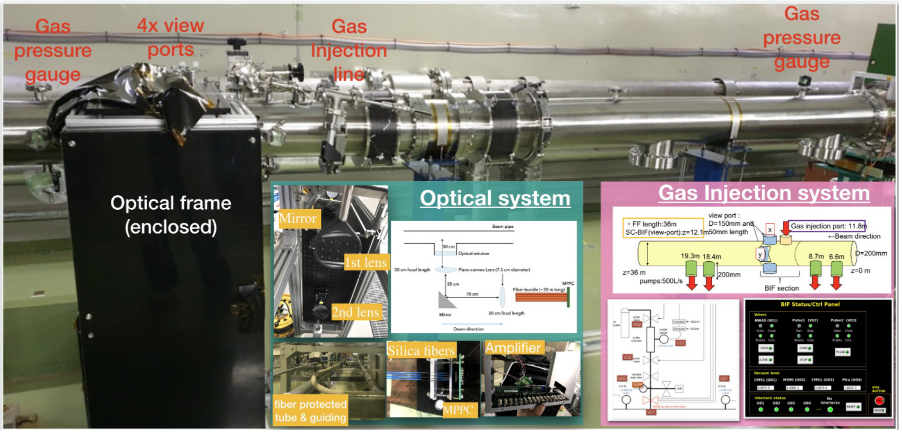


Figure 1: A BIF working prototype has been instrumented in the J-PARC neutrino beamline since summer 2019.

Since the beam-induced fluorescent photons are emitted in all direction, the signal detection efficiency strongly depends on the aperture of the optics. Our choice for the light transport directly from the beamline is an optic system of two 75 mm-diameter UV fused silica plano-convex lenses which focus the light onto an array of optical fibers. One lens has a focal length of 50 cm and the other 20 cm. This system shrinks the image by a factor of 2.5, allowing to reduce effectively the number of fibers for covering the desired detection area. A large mirror is mounted at 45° to turn the optical system 90° for a portable setup. The bundle of optical fibers is installed right at the focal points of the second lens to transport light to the sub-tunnel. The core size and numerical aperture (NA) of the selected optical fibers are traded off between the cost-effective and the signal detection efficiency. Thorlabs silica-core multimode fiber, FT800UMT, is our choice with a core diameter of 800 µm, a cladding diameter of 830 µm and NA of 0.39. Overall detection efficiency is $\sim 5 \times 10^{-5}$ which mainly dominated by the angular acceptance of the 1st lens aperture. To have ~1000 photons detected, the vacuum level near the detection region must be degraded locally from 10^{-5} Pa to 10^{-2} Pa. A COMSOL simulation of the steady-state gas injection shows that this degrade can be achieved by a continuous injection of 2×10^{-7} kg/s. However, this also causes an unacceptable degrade of the vacuum near the iron pump and the SC section. An accomplishable solution is to pulse the gas at the proton beam frequency and with a reasonably small duty factor to limit the amount of the gas injected in the beamline.

R&D Timeline and Installation

The BIF R&D project was started from JFY2015 with a test vacuum chamber and simulation of the light transport system. In JFY2016, gas uniformity was studied with the simulation and with a test vacuum chamber; a prototype of the pulsed gas system was designed and built, and parts of the light transport system were tested. In JFY2017, a complete gas inlet vacuum system had been built and tested; a complete light transport and detection system were tested, and a beam test of degrading the vacuum in NU beamline had been done by stopping the gas pumps. In JFY2018, we installed most parts of prototype monitor in NU beamline final-focusing section for gas injection tests and first BIF signal observation. In JFY2019, final parts of the complete monitor are being installed. As shown in Fig. 1, a complete prototype is essentially ready for the beam test.

GAS INJECTION SYSTEM

To understand the gas flow dependence on the chamber shape and benchmark the gas injection simulation, two different test vacuum chambers (length of 840 mm and 1020 mm) of 150 mm diameter are used. By comparing the experimental test results with the COMSOL and Molflow simulations, it is confirmed that the steady-state simulation matches the measured pressure in test chambers.

Design and Installation

A straight 3.5 m beamline section is allocated for the BIF monitor, which is 12.5 m downstream of the SC section exit. The latest configuration, as shown in Fig. 1, consists of two pulsed valves of Parker Hannifin Series 9, a buffer chamber between them, two vacuum gauges (one in the buffer chamber line and one connected to the main beamline). The pulsed valve can pulse down to 160 µs. A variable leak valve is included, allowing to further adjust the gas flow. NW40 pneumatic valve, which can be remotely controlled and quickly closed in case of an issue, is installed between the injection line and the gas inlet. The BIF beamline section is designed modularly for the flexibility of rearrangements of the parts. It is essential to integrate into a gas injection interlock system and a remote valve control system. All valves must be automatically closed if the measured pressure in the beamline going beyond the acceptable limit. Also, it is desired to remotely see the valve status, start and stop the injection run and set the threshold for the nearby beamline pressure gauges. In spring 2019, the fabricated BIF beamline duct has been installed in the beamline following by the placement of the gas injection line.

ISBN: 978-3-95450-204-2 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2019-TUPP024

Steady-State Gas Injection Test

A test, in which the valve is opened continuously, is performed to validate the steady-state simulation of the gas system and to extrapolate to the pulsed injection. Fig. 2 shows the data-MC comparison for the pressures recorded by the cold-cathode gauges at both upstream and downstream positions of the BIF beamline section corresponding to the different net fluxes of the injected gas. The disagreement at the upstream position is being investigated.

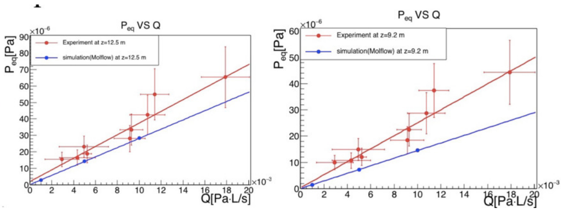


Figure 2: Data-MC comparison of pressures at downstream (left) and upstream (right) at different injected gas fluxes.

Pulsed Gas Injection Test

A test, in which the valve is automatically pulsed repeatedly with a set open and close time, is conducted to validate the pulsed simulation and directly measure the pressure distribution during the real BIF operation. The Fig. 3 shows the result for the pulsed injection. It is showed that the measured pulse is slower than our expectation. It can be due to either the slow gauge response or real. If it is real, the suspected is the small aperture of the gas injection valve.

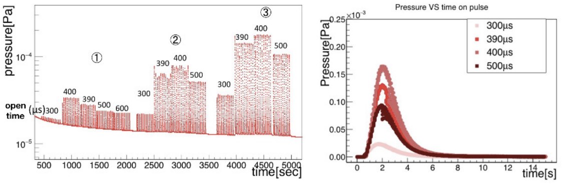


Figure 3: The left shows the gauge pressure recorded during the pulsed injection with three buffer chamber pressures: ①: 3×10^3 Pa, ②: 6×10^3 Pa, ③: 1.5×10^4 Pa. The right shows comparison of pressure versus the valve opening time.

OPTICAL SYSTEM

Design and Installation

The baseline option is to focus and transport the light in the beamline with the lens and mirror system; the light is transported to the sub-tunnel with the 30 m long optical fibers and readout with the photosensors. MPPC array (4x4), Hamamatsu S13361-6050, is selected as our main photosensor due to its excellent photon counting capability; hight gain; hight efficiency at our the photon spectral range; low noise, cross talk, and after-pulse; and compact package. The signal is amplified before transmitting from the tunnel to the ground for DAQ. Overall signal detection efficiency is validated with the GEANT4 optical photon simulation tools. Our optical components, including the beam window, the optic lens, the optical fibers are silica-based products for best survival in the radiation environment. Hardness of these components had been tested in the beamline and no severe degradation of the light transmission had been found. The lens and mirror system has been tested for the spatial resolution and depth of the field with a laser source and CCD camera. The optical fibers have been installed and tested with the real beam operation. It is found that the beam-induced background is significant and must be suppressed [6]. Also, by attaching the fiber directly to the beam window, it is confirmed that there is no significant light observed in the beamline when the proton beam passing through.

An optical frame which houses the lens and mirror installed in fall 2017 while in early of 2019, 14 optical fibers have been fabricated and installed in the tunnel. 13 out of 14 fibers are from Thorlabs with NA of 0.39 while the other is from Fujikura with NA of 0.22. To lay out the small, long and fragile fibers, protective tubes are used. The alignment between the optic lens to the light-in end of the fiber and the light-out end fiber to MPPC is very important. A cage rod system has been adopted for these couplings, allowing us a precise auto-alignment and flexibility to integrate other optic components such as the bandpass filter and engineering diffuser for light spectral study and calibration.

Calibration of the Optical System

For a precise reconstruction of the proton-induced fluorescence profile, it is important to understand the optical behavior of each component in the optical system. MPPC response to single photon can be varied channel-by-channel. To calibrate this response, a fast LED driver guided by the optical fibers is used to impinge photons directly onto MPPC. Fig. 4 shows one typical charge response of one channel and the calibration of single photoelectron in term of the number of ADC counts. It shows the capability of single p.e counting of MPPC and it shows the responses of all MPPC channels are not much different. Small spatial separation of the active area of the channels can lead to the cross-talk in which the light out from one channel can go into the nearby MPPC channel. Fig. 5 illustrates the cross-talk and a concept of the optical baffler to mitigate the cross talk and the result shows that the cross talk is suppressed with the optical baffle.

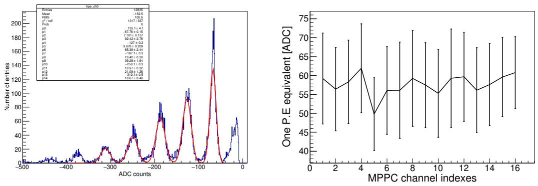
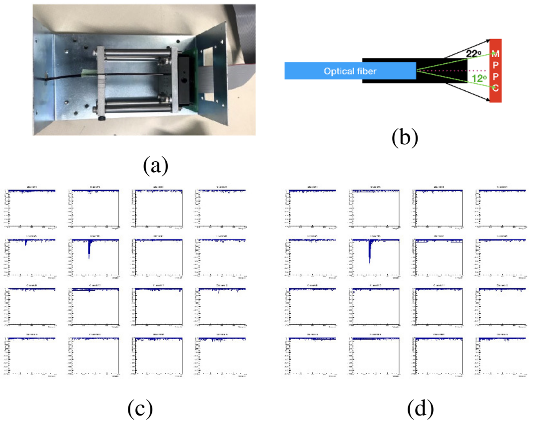


Figure 4: Left: a typical response of one MPPC channel to light source of few photons (the left, peak from right to left corresponding to pedestal, 1 p.e, 2 p.e and so on); right: one p.e equivalence (in ADC unit) of all 16 MPPC channels

The transmission inefficiency can be different fiber by fiber and thus a relative correction needs to be applied for the



(a) (b)

(c) (d)

Figure 5: Setup (a), an optical baffle concept (b) and cross-talk measurements without (c) and with (d) optical baffle.

beam profile reconstruction. For this calibration, a Thorlabs engineered diffuser is used for providing a uniform light source. The uniformity has been checked by coupling the diffuser directly to the MPPC arrays, as showed in Fig. 6 (left). The relative fiber transmission is then measured by inserting the optical fibers between the diffused light source and MPPC arrays. As showed in Fig. 6 (right), there is quite uniform transmission efficiency among the optical fibers.

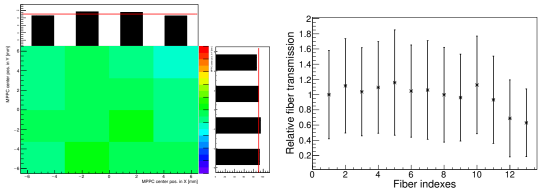


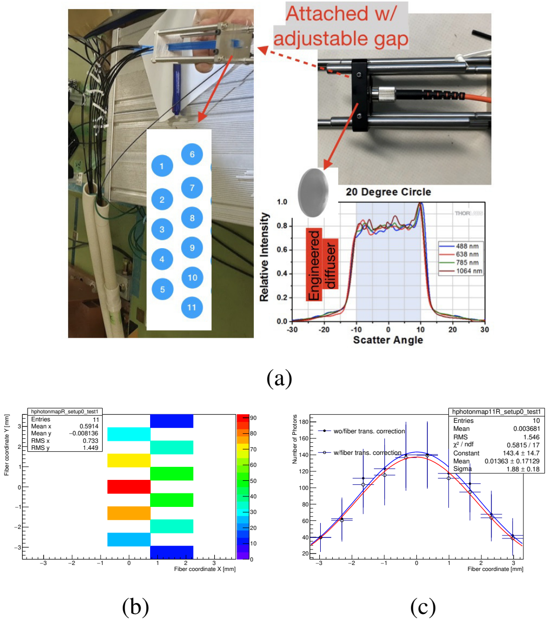
Figure 6: Left: uniform map of detected photons on all MPPC channels with diffused light source; right: Relative fiber transmission (normalized to fiber #1).

To demonstrate the capability of Gaussian profile reconstruction with optical fibers of 30m length and MPPC, a gap between the diffuser to the light-in end of optical fibers are closened. As shown in Fig. 7(a), the cage rode system allows us to couple fibers to diffuser light system and adjust the gap effortlessly without losing the alignment. Fig. 7(b) shows the photon-detected map and Fig. 7(c) shows the profile reconstruction with the gaussian fit.

The lens and mirror misalignment can distort the image and we plan to have a whole-system calibration by developing an LED calibration with above-mentioned diffuser and bi-convex lens to create a light pattern in the middle of beamline. Another important calibration item is the space charge effect. For this, we need the beam-based alignment along with the use of timing information of the signal waveform and use a different type of gas, for example heavier one.

BACKGROUND MITIGATION

To understand the background properties for background suppression, we plan for a spectrometer with MPPC and the optical bandpass filter to check the spatial and spectral distributions of the background. If backgrounds reach MPPC active surface at > 12° angle (the signal is expected to arrive at the lower angles), optical baffle or smaller NA optical fiber is helpful to suppress the background. For the background which reaches MPPC at a lower angle but at a different wavelength than the fluorescent light, other hopes are to use wavelength bandpass filter. To prevent reflection light which can distort the reconstructed profile, we plan for a black coating for the beampipe walls at the region where we expect to see the BIF light. We made a measurement of reflective light observation with Diamond-like Carbon (DLC) and Raydent. DLC shows promising light absorption and will be painted.



(a)

(b) (c)

Figure 7: Demonstration of profile reconstruction with fibers and MPPC: (a) setup with diffuser; (b) photon-collected maps; (c) profile reconstruction with data and gaussian fits

CONCLUSION

A workable BIF prototype as an upgrade option for monitoring the future MW-power proton beam at J-PARC neutrino beamline is being developed. Most of the parts for both the gas injection system and the optical system has been installed and tested. We aim for observing the real BIF light in fall 2019 with J-PARC beam operation.

REFERENCES

[1] K. Abe *et al.* “Search for CP Violation in Neutrino and Antineutrino Oscillations by the T2K Experiment with 2.2×10^{21} Protons on Target,” Phys. Rev. Lett. **121**, no. 17, 171802 (2018)

[2] K. Abe *et al.* “The T2K Experiment,” Nucl. Instrum. Meth. A **659**, 106 (2011)

[3] K. Abe *et al.* “J-PARC Neutrino Beamline Upgrade Technical Design Report,” arXiv:1908.05141 [physics.ins-det].

[4] M. Friend, “Beam Parameter Measurements for the J-PARC High-Intensity Neutrino Extraction Beamline,” doi:10.18429/JACoW-IBIC2018-MOPB07

[5] M. Friend *et al.* “Beam Induced Fluorescence Monitor R&D for the J-PARC Neutrino Beamline,” doi:10.18429/JACoW-IBIC2016-WEPG66

[6] S. Cao *et al.* “Optical System of Beam Induced Fluorescence Monitor Toward MW Beam Power at the J-PARC Neutrino Beamline,” doi:10.18429/JACoW-IBIC2018-WEPC08