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FIRST BEAM PROFILE MEASUREMENTS BY BEAM INDUCED FLUORESCENCE AT THE J-PARC NEUTRINO EXTRACTION BEAMLINE

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Abstract

A Beam Induced Fluorescence (BIF) profile monitor is under development at the J-PARC neutrino extraction beamline, where neutrinos are produced using 30 GeV protons from the J-PARC MR accelerator. Towards the goal of continuously and non-destructively measuring the 1.3 MW proton beam profile spill-by-spill using fluorescence from proton interactions with injected gas, a full working prototype monitor was installed in the beamline in 2019. The prototype includes a scheme for pulsed injection of N_2 gas into the ultra-high vacuum beampipe and two optical readout arms, a conventional one using an Image Intensifier coupled to a CID camera, along with an array of optical fibers coupled to a Multi-Pixel Photon Counter array. Initial beam tests of the system were carried out in early 2020, and BIF light was successfully observed in both optical systems. Details of the prototype monitor, along with first proton beam profile measurement results, will be shown. Improvement plans towards continuous operation of the new profile monitor will also be discussed.

J-PARC AND THE NEUTRINO EXTRACTION BEAMLINE

The J-PARC Main Ring (MR) accelerator currently provides a 515 kW 30 GeV beam to the J-PARC neutrino extraction beamline for the T2K experiment [1]. The beam structure consists of eight ~13 ns (1σ) bunches with a bunch spacing of 581 ns. Currently, ~2.65×10^{14} protons per spill are supplied with a spill repetition rate of 2.48 s, while upgrades are planned to increase the number of protons per spill to 3.2×10^{14} and decrease the repetition rate to 1.16 s.

The position and profile of the proton beam extracted into and propagated through the neutrino extraction beamline must be continuously monitored to prevent any damage to equipment due to mis-steered beam, as well as to understand the proton beam properties as inputs into physics analyses.

Currently, the beam profile is measured by a suite of 19 Segmented Secondary Emission Monitors (SSEMs), 18 of which can only be used periodically or during beam tuning. This is because each SSEM causes 0.005% beam loss, which is enough to cause radio-activation of and possibly even damage to beamline equipment. Of course, this loss is proportional to the beam power, and the total induced loss will increase as the number or protons per pulse and beam spill repetition rate are increased.

Development towards a continuous, non-destructive beam profile monitor is therefore underway. Due to the large number of protons per bunch, and therefore the relatively high beam-induced space-charge field in the J-PARC neutrino extraction beamline, a Beam Induced Fluorescence (BIF) monitor [2] was chosen as a suitable profile monitor candidate. The BIF monitor detects light induced by de-excitation of gas which has been excited or ionized by interactions with incident protons. The longitudinal and transverse pattern of the induced fluorescence should match that of the original proton beam, allowing for an indirect measurement of the proton beam position and profile.

J-PARC NEUTRINO BEAMLINE BEAM INDUCED FLUORESCENCE MONITOR

Development of the J-PARC neutrino extraction beamline BIF monitor has been underway since 2015, with a full working prototype installed in the beamline in 2019 [3]. A a photograph of the installed prototype is shown in Fig. 1.

The monitor includes of a series of valves for gas injection into the beam pipe, as well as transparent fused quartz windows mounted on the bottom and side of the beam pipe to allow fluorescence light to escape. The inner surface of the beampipe near the interaction region is coated with a 1-μm-thick coating of Diamond Like Carbon in order to minimize reflections within the beampipe. As shown in Fig. 2, two separate optical focusing and transport systems are used – one mounted on the side of the beam pipe to make a measurement of the vertical transverse beam position and profile, and one mounted on the bottom of the beam pipe to make a measurement of the horizontal beam properties.

The vertical beam measurement arm consists of a series of lenses and mirrors to focus the light downwards onto an array of silica core optical fibers. These optical fibers are used to transport the fluorescence light away from the high-radiation area near the beamline and into a lower-radiation environment inside a subtunnel ~30 meters away, where an array of Multi-Pixel Photon Counters (MPPCs) is used to detect the light.

The horizontal beam measurement arm consists of a more conventional light detection system – two lenses focus the induced fluorescence light onto a gated Micro-Channel Plate (MCP) based Image Intensifier, which is coupled to a

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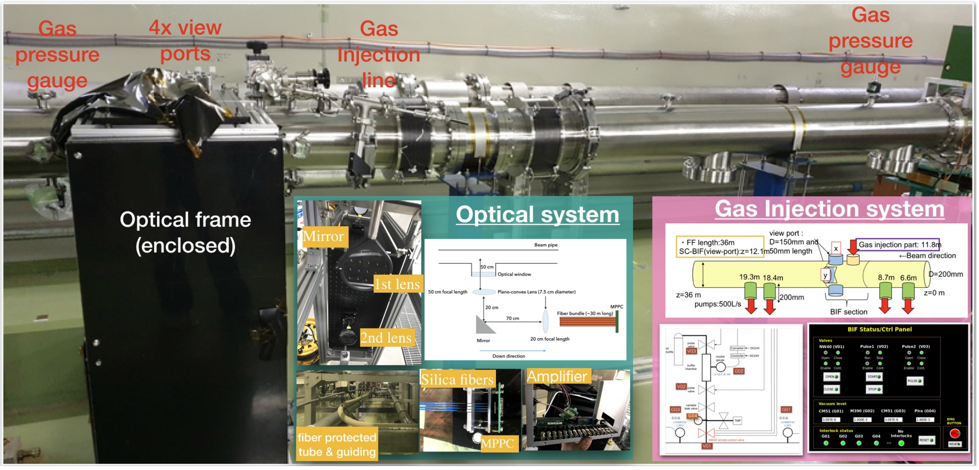

Figure 1: Photograph of the installed prototype BIF monitor.

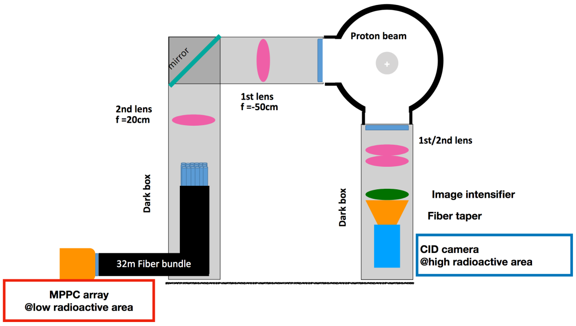

Figure 2: Schematic diagram of the BIF monitor optical systems.

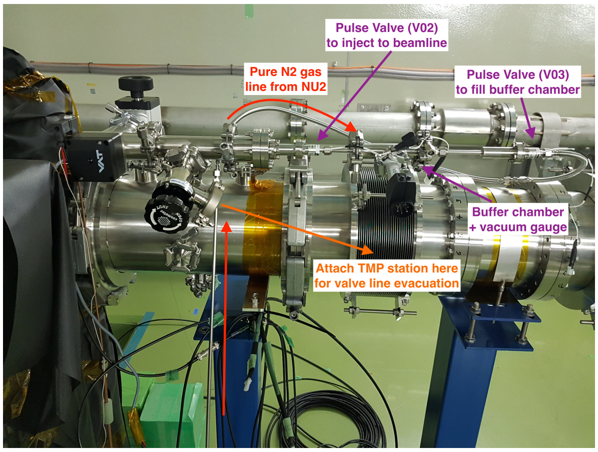

Figure 3: Photograph of the gas injection system for the installed prototype BIF monitor.

radiation-hard Charge Injection Device (CID) camera by a fiber taper. Gating of the Image Intensifier allows for integration of all BIF light over each 5 μs beam spill.

MPPCs have a ns-level response time and single-photon sensitivity. They are therefore very useful for detecting photons at low light levels, as well as for understanding any time-dependence of the beam induced fluorescence light. Measurement of the time-dependence is essential at the J-PARC neutrino beamline, since the measured beam profile could be distorted if ionized gas moves in the relatively high beam-induced space charge field before BIF light is produced.

The Image Intensifier and CID camera arm, on the other hand, has the advantage that it is high-resolution, as well as being relatively radiation hard. This means that the system can be mounted directly to the beampipe, without the additional complication of transport to a lower radiation environment.

First in-situ beam tests using the full working system were carried out in early 2020.

GAS INJECTION SYSTEM

The gas injection system is designed to provide a localized pressure bump of $\sim 1\times10^{-2}$ Pa when the beam passes, while allowing the pressure to fall back to the standard level of 1×10^{-5} Pa between spills. This is achieved using a pulsed gas injection system with sub-ms-long gas pulses injected directly before each beam spill. N_2 gas is used currently, although upgrades to different gas types may be possible.

A buffer chamber upstream of the pulsed gas injection valve, filled periodically by another pulse valve, helps to prevent continuous injection of gas in case of valve failure. A remotely-controlled pneumatic valve is also installed downstream of the gas injection system, where an interlock system closes this valve in case any pressure along the beamline or within the BIF valve injection line becomes higher than a set threshold.

A photograph of the gas injection system is shown in Fig. 3.

Pumping is done by 500 L/s ion pumps installed at various locations along the beamline. New pumps specifically for the BIF monitor were installed 1.7 and 2.8 m upstream of the gas injection point.

Injection of gas followed by a full pumpdown of the beamline for each beam spill with a 2.48 or 1.16 s repetition rate

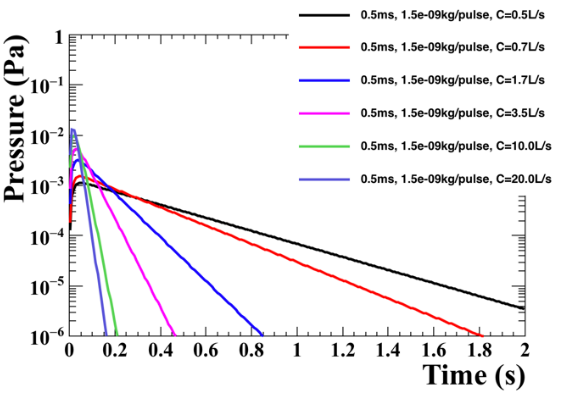

Figure 4: Estimation of the expected pressure bump when a 500 µs-long gas pulse of 1.5×10^{-9} kg is injected assuming different values for the valve conductance.

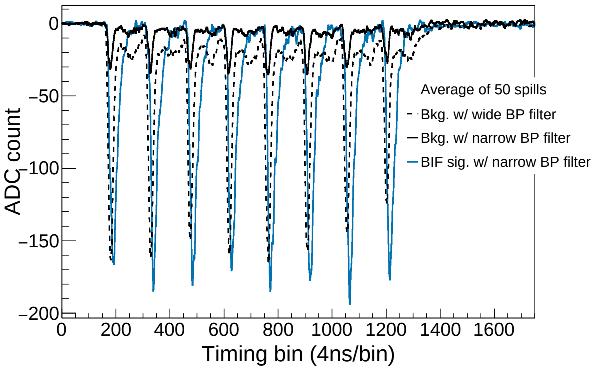

Figure 5: Observed beam-induced background on an optical fiber before and after background mitigation (with optical filtering of 400±200 nm and 400±40 nm respectively). The observed BIF signal light after mitigation is also shown.

requires fast injection and fast pumpdown. This is achieved by reducing the conductance of the gas injection valve line as much as possible. Estimates of the conductance of the currently installed gas line based on data taken so far show that a conductance of only ∼1 L/s has been achieved, while conductance of around 10 L/s is desired, as shown in Fig. 4.

MITIGATING BACKGROUNDS

Beam induced background on both optical systems must be mitigated in order to maximize the BIF signal to background ratio.

The Image Intensifier was found to produce a constant beam-induced background of $\sim 2.5 \times 10^6$ photons/spill over the full surface area, most likely due to incident beam loss on the MCP. This was reduced by a factor of ∼0.6 by installing a concrete hut around the optical system placed under the beamline. Improvements in shielding could further reduce this background, although increasing the Image Intensifier gain could increase it.

Cherenkov light produced by beam loss particles incident on the optical fiber array near the beamline also constitute a considerable background. This background was reduced by aggressive optical filtering, where wavelengths outside of 400±40 nm were cut, while the expected wavelength of the BIF light is 390 nm [4]. An optical baffle was also installed to select light outgoing from the fibers at angles <12°. The observed background and BIF light from the optical fibers before and after background mitigation is shown in Fig. 5. Various studies were also performed to extract the wavelengths of the induced background light and the BIF light, and results will be released in a future publication.

FIRST PROFILE MEASUREMENTS

A series of in-situ beam tests were carried out, with different quantities of gas injected into the beamline at different times relative to the beam spill. A clear BIF signal was observed with injected gas down to $\sim 1 \times 10^{-8}$ kg/pulse. The intensity of the observed light was clearly correlated with the amount of injected gas and was correlated between the two optical systems. The shape of the injected gas pulse could be clearly mapped out by adjusting the relative timing between the beam spill and gas injection.

The measured and extracted vertical beam profile from the optical fiber and MPPC array is shown in Fig. 6. Analysis of the MPPC data is ongoing to extract information about the time-dependent distortion of the profile due to space charge effects.

The measured horizontal and longitudinal beam profile from the Image Intensifier and CID camera system is shown in Fig. 7. A 1D projection of the extracted horizontal profile is also shown.

The measured horizontal and vertical beam widths are relatively consistent with the expected beam width at the BIF monitor location based on an optics fit to neighboring profile monitors. The measured vertical beam position is also consistent with neighboring monitors, while additional alignment and calibration of the camera system is necessary to confirm that the horizontal beam position is also consistent.

A precise calculation of the number of produced photons as a function of the quantity of injected gas or the expected gas pressure is underway.

IMPROVEMENTS TOWARDS A WORKING MONITOR

Various upgrades to the BIF monitor working prototype are necessary before continuous use is possible.

Further alignment and calibration of the optical systems is necessary and is underway. Especially, mis-alignment of the fiber taper relative to the Image Intensifier or CID camera may be distorting the collected beam image shown in Fig. 7.

Currently, the required amount of gas injected for a clear beam profile measurement is $\sim 1 \times 10^{-8}$ kg/pulse, while the original design calls for injecting only 5×10^{-10} kg/pulse to maintain ion pump lifetime. Improvements in the valve line

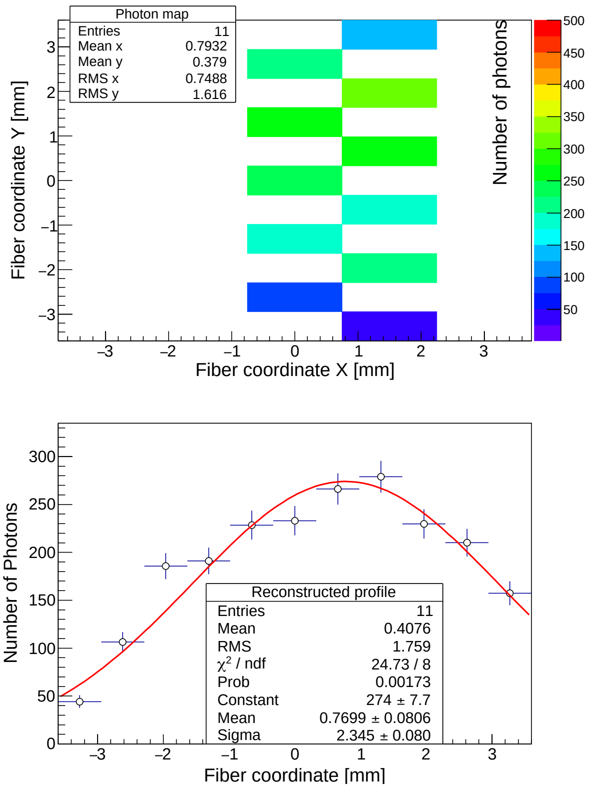

Figure 6: 2D (top) and 1D (bottom) measurements of the vertical proton beam profile (in optical system coordinates) by the optical fiber and MPPC array.

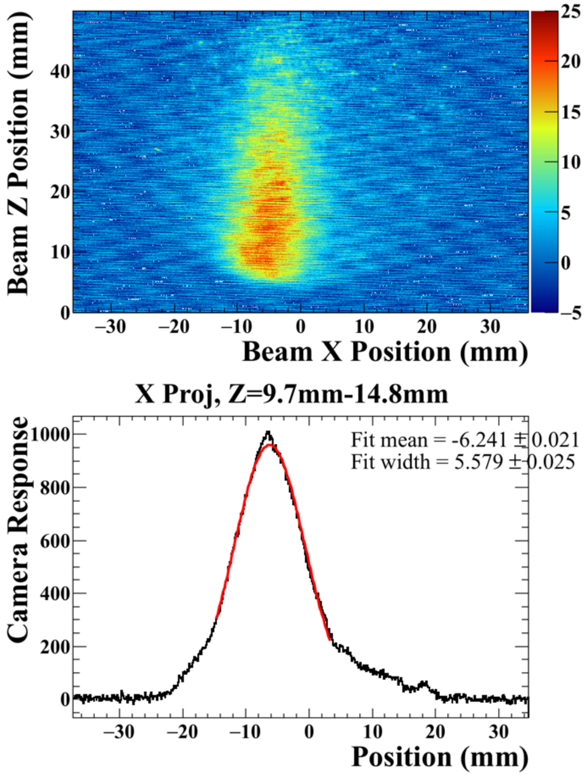

Figure 7: 2D (top) and 1D (bottom) measurements of the horizontal proton beam profile (in beam coordinates) by the Image Intensifier and CID camera.

conductance are planned, which should allow for the necessary pressure bump of $\sim 1\times10^{-2}$ Pa with $\sim 5\times10^{-10}$ kg/pulse injected, as shown in Fig. 4.

Additional optical fibers would help increase the amount of collected light. Shorter optical fibers leading to a radiation-hard photon detection system could reduce beam-induced backgrounds as well as loss of photons due to attenuation in the optical fibers. Such upgrades would also improve the signal to noise ratio and are under consideration now.

A higher gain Image Intensifier is also under consideration for the horizontal readout arm.

CONCLUSION

A working prototype BIF monitor has been installed in the J-PARC neutrino extraction beamline. First beam tests are promising and show that a clear beam profile can be reconstructed by two different optical detection systems. Upgrades are underway in order to increase the pressure bump at the BIF interaction region, as well as to increase the photon collection efficiency.

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