BEAM INDUCED FLUORESCENCE MONITOR R&D FOR THE J-PARC NEUTRINO BEAMLINE

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Abstract

Proton beam monitoring is essential for the J-PARC neutrino beamline, where neutrinos are produced by the collision of 30 GeV protons with a long carbon target. Along with continued upgrades to the J-PARC beam power, from the current 420 kW to 1.3+ MW, there is also a requirement for monitor upgrades. A Beam Induced Fluorescence monitor is under development, which would continuously and non-destructively measure the proton beam profile spill-by-spill by measuring fluorescence light from proton interactions with gas injected into the beamline. Monitor design is constrained by the J-PARC neutrino beamline configuration, where a major challenge will be getting sufficient signal to precisely reconstruct the proton beam profile. R&D for a pulsed gas injection system is under way, where injected gas uniformity and vacuum pump lifetime are main concerns. Design of a light detection system is also under way, where light transport away from the high radiation environment near the proton beamline, as well as fast detection down to very low light levels, are essential.

J-PARC PROTON BEAM OVERVIEW

The J-PARC proton beam is accelerated to 30 GeV by a 400 MeV Linac, a 3 GeV Rapid Cycling Synchrotron, and a 30 GeV Main Ring (MR) synchrotron. Protons are then extracted using a fast-extraction scheme into the neutrino beamline, which consists of a series of normal- and superconducting magnets used to bend the proton beam towards the neutrino production target for generation of a neutrino beam pointing towards the Super-Kamiokande detector for the T2K Long-Baseline Neutrino Oscillation Experiment [1]. Beam monitoring is essential for both protecting beamline equipment from possible mis-steered beam, as part of a machine interlock system, and as input into the T2K analysis.

Table 1: J-PARC Proton Beam Specifications

	Protons/Bunch	Spill Rate
Current (2016)	2.75×10^{13}	2.48 s
Upgraded (2018~)	$2.75 \rightarrow 4.00 \times 10^{13}$	1.30→1.16 s

The J-PARC 30 GeV proton beam has an 8-bunch beam structure with 80 ns (3σ) bunch width and 581 ns bucket length. J-PARC currently runs at 420 kW with the plan to upgrade to 750+ kW by 2018 and 1.3+ MW by 2026. This will be achieved by increasing the beam spill repetition rate from the current 1 spill per 2.48 s, to 1.3 s and finally 1.16 s, along with increasing the number of protons per bunch from 2.75×10^{13} to 4×10^{13} as shown in Table 1. With this increased beam power comes increased necessity for minimally destructive beam monitoring, as each of the currently-in-use beam profile monitors cause 0.005% beam loss (where all but the most down-stream beam profile monitor is remotely inserted into the beam orbit only during beam tuning).

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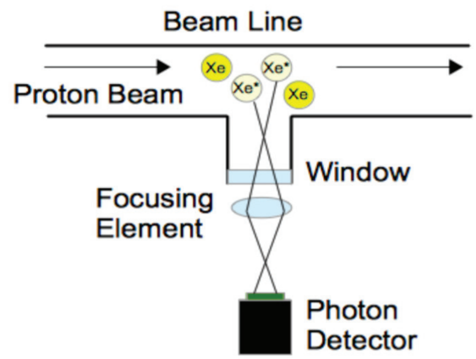

Figure 1: Schematic diagram of BIF monitor.

The proton beam spot size varies along the neutrino line from ~2–8 mm (1σ) and is ~4.2 mm at the neutrino production target. Current non-destructive beam position monitors continuously measure the beam position with a precision of 450 μm, while destructive monitors measure the beam width with a precision of 200 μm during beam orbit tuning. Any new monitoring system should exceed this beam position precision and match this beam width precision if possible.

Development of a new non-destructive Beam Induced Fluorescence (BIF) monitor [2] for the J-PARC neutrino beamline is underway. In a BIF monitor, the beam profile is measured when the passing beam ionizes some of the gas particles in the beamline. The particles then fluoresce when returning to the ground state, and the transverse profile of this fluorescence light will match the transverse profile of the proton beam. A simple BIF monitor schematic is shown in Fig. 1.

NON-DESTRUCTIVE MONITOR REQUIREMENTS

The BIF monitor must be designed taking into account the specific requirements of the J-PARC neutrino beamline as given below.

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Space-Charge Effects

Beam space-charge effects are a major contributor to the choice of developing a non-destructive Beam Induced Fluorescence Monitor, rather than the alternative Ionization Profile Monitor (IPM) [3]. As shown in Fig. 2, the transverse field from the charge of the proton beam itself can reach as high as 4×10^6 V/m for a 2 mm width bunch containing 1.5×10^{13} protons. Acceleration of ions or electrons in this field would distort the measured beam profile, where a highly impractical magnet of >1 T would be required to counteract this effect in an IPM.

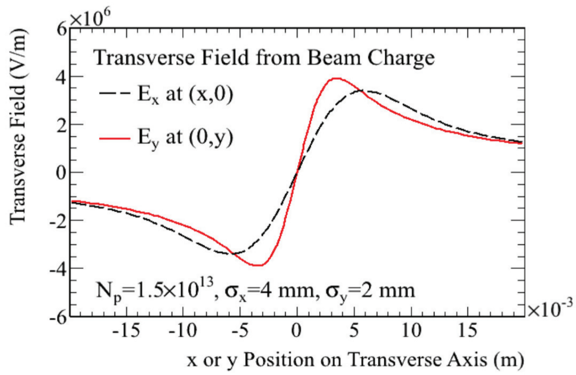

Figure 2: Transverse field induced by proton beam space-charge.

Space charge effects can also cause distortion of the BIF profile if particles ionized by the beam passage move in the beam field before fluorescing. In this case, choosing a gas with a short fluorescence lifetime or a large mass can help to mitigate this distortion. Another option is to use fast photosensors with ns-timescale readout or gated timing such that only early fluorescence light is measured.

Gas Choice

Because the residual gas level in the J-PARC neutrino beamline is around 1×10^{-6} Pa, which would yield ~1 detected photon after the passage of 2×10^{14} protons with reasonable acceptance and efficiency assumptions, injected gas must be used for this monitor.

Table 2: Relative measured fluorescence parameters of N_2 and Xe gas from Ref. [4].

	λ (nm)	Lifetime (ns)	keV/photon Lost	Cross Section (Relative)
N_2	68	380-470	3.6	Xe x 3.3
Xe	6, 51	380-640	46	Xe x 1

Detailed fluorescence data exists for N_2 and Xe [4], as shown in Table 2, so these gas choices have been considered so far. N_2 produces about 10 times more light than Xe, due to its higher cross section and lower energy loss per visible photon generated, but has a slower fluorescence lifetime and is lighter than Xe, making it more susceptible to profile distortion due to drift in the high space-charge field, as shown in Fig. 3. However, making a fast timing cut reduces both this drift, as shown in Fig. 4, and the amount of light collected from N_2, effectively equalizing the performance of the two gasses.

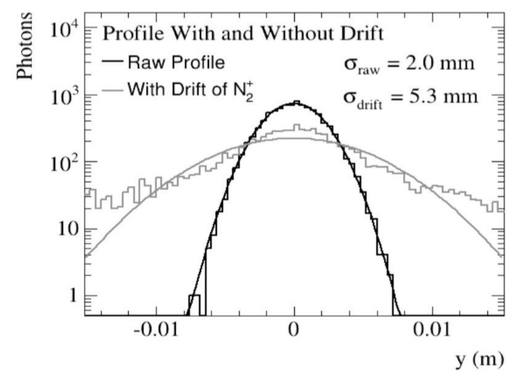

Figure 3: True beam profile and measured beam profile after drift in the beam induced space-charge field.

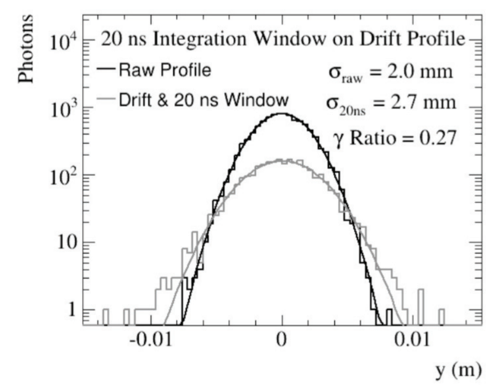

Figure 4: True beam profile and measured beam profile after drift in the beam induced space-charge field after a timing cut.

Pump lifetime and performance should also be considered – standard beamline ion pumps work well with N_2; however new pumps (ie. turbo-molecular pumps coupled to scroll pumps with collected outflow) would probably be needed for injecting Xe gas. N_2 is therefore now being considered more practical, but other gasses are also under consideration.

MONITOR COMPONENTS

The main components of the BIF monitor are the gas injection, light transport and focusing, and light detection systems, as described below.

Gas Injection

Pulsed gas injection, with one pulse coming directly before each beam spill, is planned in order to limit the total amount of gas injected into the beamline. Pulse valves can be pulsed with <160 ms pulse times and at high repetition rate

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for continuous duty. This device is therefore being studied as an option for a pulsed gas source.

The configuration of the gas injection and vacuum pumps is also being studied, where pulsed gas injected and then allowed to diffuse into the beamline may be more cost effective and simple to use than a “gas sheet” configuration. However, vacuum pump lifetime must be considered, and excess particles impinging on any one pump could cause degradation to that one pump or overall degradation of the vacuum in the J-PARC neutrino beamline.

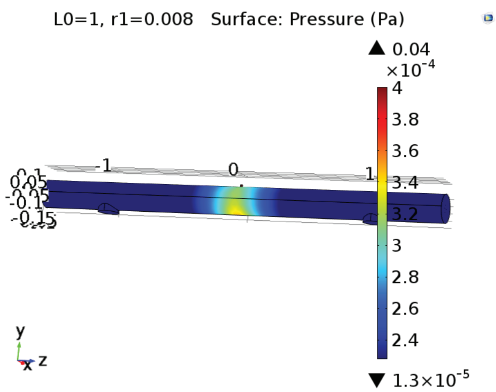

Figure 5: Pressure on the walls in a vacuum vessel simulated assuming steady-state gas injection by COMSOL Multiphysics®.

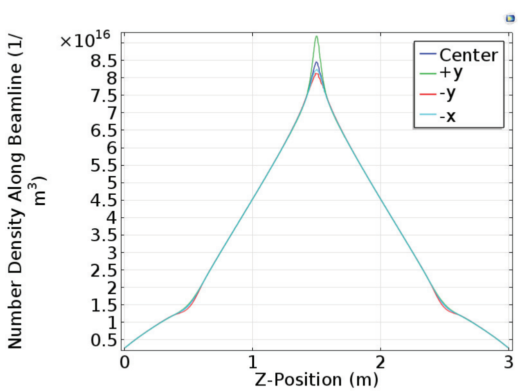

Figure 6: Number density of particles within a vacuum vessel simulated assuming steady-state gas injection by COMSOL Multiphysics®.

COMSOL Multiphysics® software is being used to model the system and understand gas uniformity and the number of incident particles on pumps in the beamline. As shown in Figs. 5 and 6, simulations show that gas uniformity improves away from the gas injection and pumping points.

Interlock in the case of a gas leak or injection valve malfunction is also essential in order to protect beamline equipment (and particularly super-conducting magnets in the beamline). Therefore an interlock system consisting of fast closing valves and gas pressure monitoring is also under consideration.

Light Transport and Focusing

Light transport away from the high-radiation area near the beamline is essential, as discussed below. A pair of plano-convex lenses with a long focal length and large diameter will be used to focus the light onto a detection element 1–2 m from the beampipe. Lenses rather than mirrors will be used, since it was determined using a Geant4 simulation that transported profile distortion is lower when lenses are used; lenses may also be more radiation hard. Large diameter lenses help to reduce losses or distortions of the light near the edges of the profile.

Light Detection

Light detection in a high radiation environment is particularly challenging, as ionizing particles impinging on detection components can cause noise and damage instrumentation. Two light detection options are currently under study with different advantages and disadvantages.

Optical Fibers and MPPC Option Multi-Pixel Photon Counters (MPPCs) are a potential inexpensive option for light detection. However, it is well known (and has been confirmed by the authors) that MPPCs are not robust to radiation and can quickly degrade in a high radiation environment. Therefore, using optical fibers to transport light away from the beamline, as shown as shown in Fig. 7, is one light detection option.

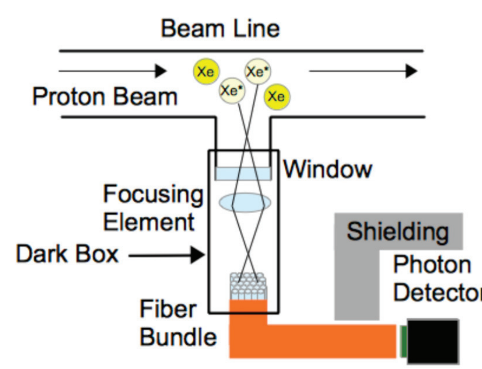

Figure 7: Light detection with optical fibers transporting light 10s of meters from the beamline to shielded MPPCs.

The authors have done various tests of both optical fibers and MPPCs in the high-radiation environment near the J-PARC beamline, and have found substantial noise induced in both components by the proton beam passage even ∼1 meter away from the beamline, as shown in Fig. 8 in optical fibers. It was found that shielding, particularly by the concrete walls of a sub-tunnel, could be used to reduce this noise, but careful consideration of the configuration of possible shielding and optical fibers is important.

One advantage of this configuration is the ability to do ns-timescale readout by a Flash Analog-to-Digital Converter (FADC). Readout of the MPPCs by FADC would allow for cutting out slow-timescale fluorescence light or even observing the distortion of the beam profile due to motion

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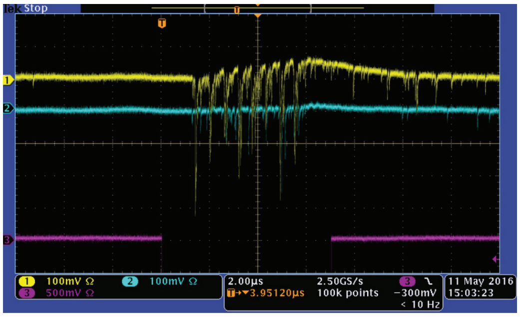

Figure 8: Noise test of silica-core optical fibers near the beamline, where the yellow curve corresponds to an unshielded fiber and the blue curve corresponds to a shielded one. Observed 8-peak noise structure corresponds to the 8-bunch J-PARC beam structure.

of ionized gas particles in the beam space-charge field as a function of time.

MCP and CID Option Light detection by a radiation-hard Charge Injection Device (CID) camera (where the camera controller is placed in a lower-radiation environment) is an option that has proven to work well even in high-radiation environments.

However, BIF light levels are too low and fast readout is impossible using a camera, such that coupling to a gatable image intensifier would be essential. Investigation of image intensification and gating by a Microchannel Plate (MCP) gatable image intensifier is under study, where an MCP could allow for gating times of <10s of ns and light amplification by a factor of $>10^4$. In this case, radiation hardness of the MCP is also essential, and substantial shielding or special design of a radiation-hard MCP may be necessary.

Preliminary images of a test pattern from an MCP and camera are shown in Figs. 9 and 10.

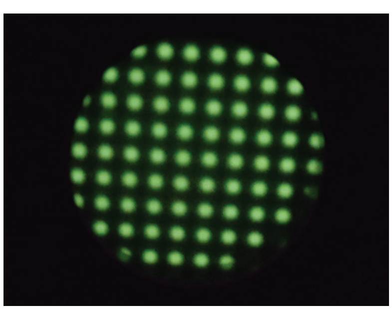

Figure 9: Light pattern imaged by MCP.

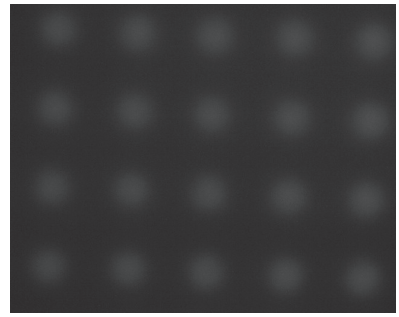

Figure 10: Light pattern from MCP imaged by camera.

CONCLUSION

Development of a BIF monitor for the J-PARC neutrino beamline is underway, including the design of a pulsed gas injection system, light transport system, and two light detection options. Installation of a working prototype monitor in the J-PARC neutrino beamline is planned in 2018.

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