Development of Beam Induced Fluorescence Monitor for Non-Destructively Profiling MW Proton Beam at the J-PARC Neutrino Beamline

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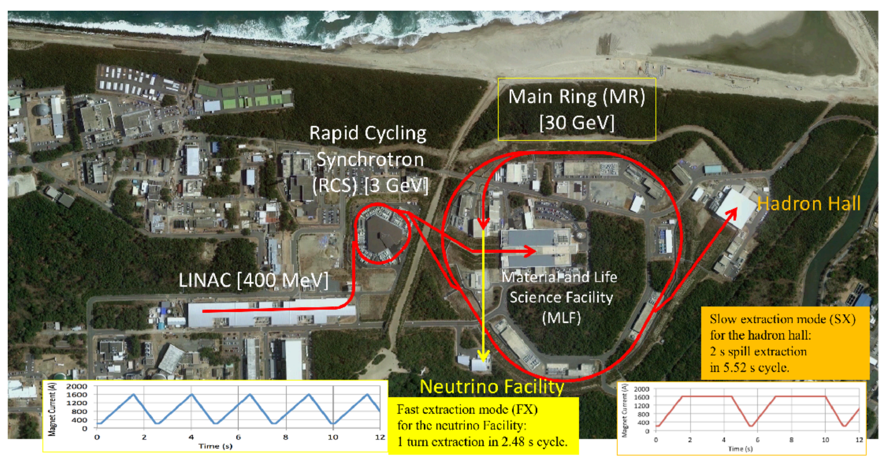
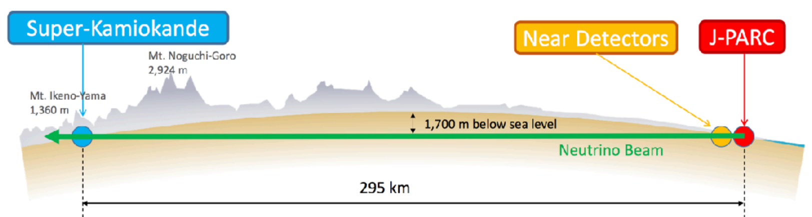
A Beam Induced Fluorescence (BIF) monitor is under development for non-destructively monitoring the future MW-power proton beam at the neutrino extraction beamline at J-PARC. The 30GeV protons are bombarded onto a graphite target, producing one of the most intense neutrino beams in the world for the Tokai-to-Kamioka 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 J-PARC 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 we can address these challenges and realize a working prototype monitor.

J-PARC MW Proton Beam for Neutrino Intensity Frontier

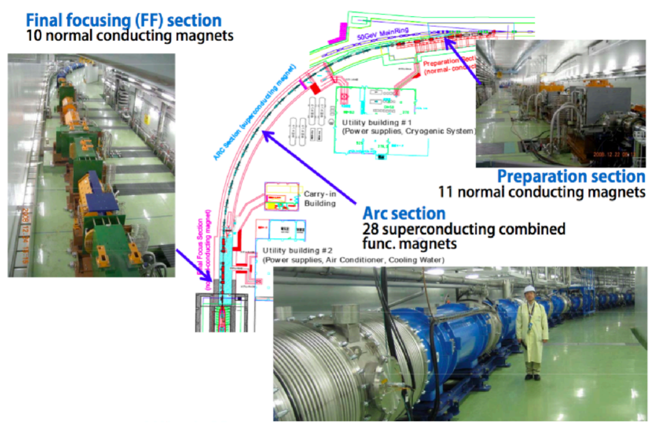


J-PARC neutrino beamline for guiding proton extracted from MR toward T2K far detector and producing nearly pure muon (anti) neutrino beam

J-PARC complex[1] delivers of the most intense neutrino beam in the world to on-going T2K[2] and future T2HK[3] experiments

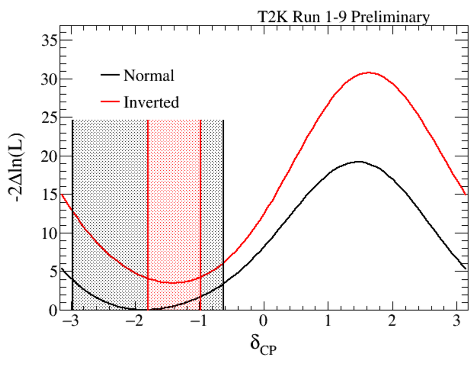


The experiments aim to reveal mysteries of neutrino by measuring precisely the *neutrino oscillation* phenomenon, which is beyond the description of Standard Model.



Beam loss and beam profile monitors are placed along the beamline, details can be found elsewhere[4]

T2K data[5] indicates *CP violation* in the leptonic sector, which may explain *the matter-anti-mater asymmetry* in the Universe.



A scenario for upgrading J-PARC beam

Table 1: Summary of the MR operation parameters for the current and proposed beam power.

Beam power	485 kW (achieved)	511 kW (demonstrated)	750 kW (proposed)	1.3 MW (proposed)
Beam energy	30 GeV	30 GeV	30 GeV	30 GeV
Beam intensity (ppp)	2.5×10^{14}	2.6×10^{14}	2.0×10^{14}	3.2×10^{14}
Repetition cycle	2.48 s	1 shot	1.32 s	1.16 s

MW beam power is a main driver for neutrino intensity frontier. To realize MW beam, beam loss handling and continuous monitoring the beam profile with high precision are crucial.

[1]KEK-REPORT-2002-13 [2]NIMA 659, 106(2011) [3]arXiv:1805.04163 [4]IBIC2018 MOPB07 [5]to be published

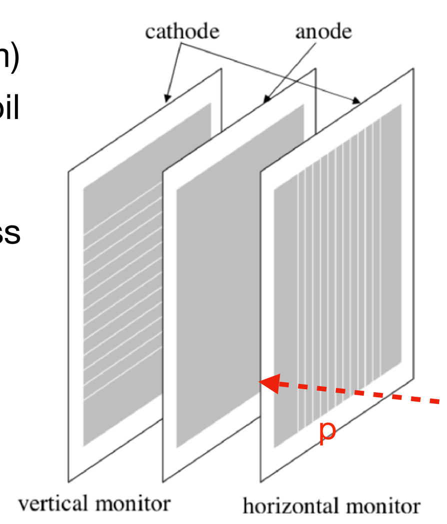
Proton Beam Profile Monitors in Use[1]

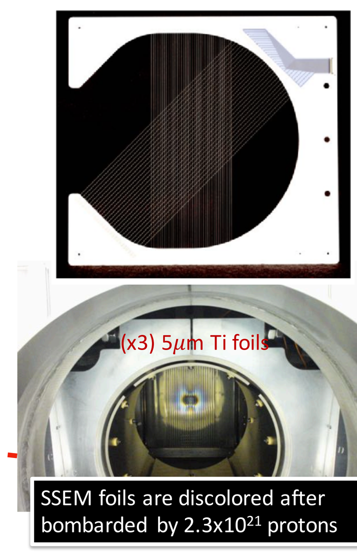
General principal: *Intercept a proton beam with material inserted into the beamline*

- **SSEM**: Two 5-μm-thick Ti foils stripped (2-5mm) vertically and horizontally, with same thick Ti anode foil between them → cause 0.005% beam loss
- **WSEM**: Like SSEM but using 25-$\mu m\phi$ Ti wire, beam loss is reduced by factor of 10

High beam loss can cause serious problems:

- Irradiation/damage of the beamline components
- Increase residual dose → difficult for maintenance

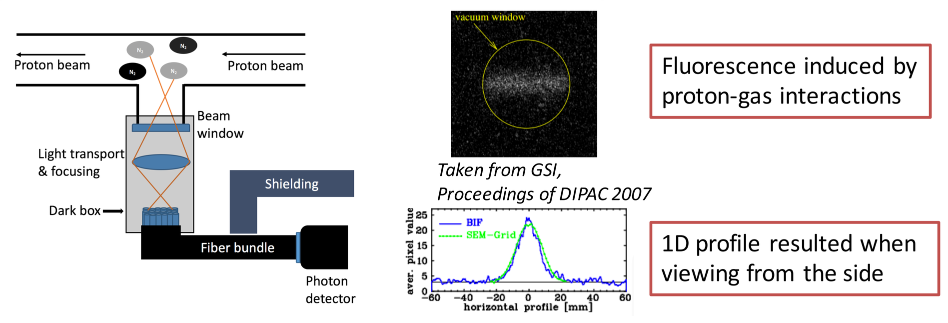




[1]IBIC2019 TUBO03

BIF: Principle and Specification of J-PARC neutrino beam line

General principle: *Uses fluorescence induced by proton interactions with gas injected into beamline. Transverse profile of fluorescence will match its of proton beam*



A BIF prototype has been built in the J-PARC neutrino beamline

BIF is under development[1,2] at J-PARC neutrino beamline with some required specifications:

- **Gas needs to be injected in the beamline**: gas normally at ~ 10^{-6} Pa, is not enough to see BIF signal. Gas need to be injected & pressure increased but only near measurement point
- **Method to deal with space charge effect**: fast readout is an option → use e.g Multi-pixel photon counters (MPPC)
- **High radiation environment**: MPPCs are not radiation-hard → operate at sub-tunnel. Optical fibers, to guide light from beamline to sub-tunnel, need to be radiation-hard

[1]IBIC2016-WEPG66 [2]IBIC2018-WEPC08

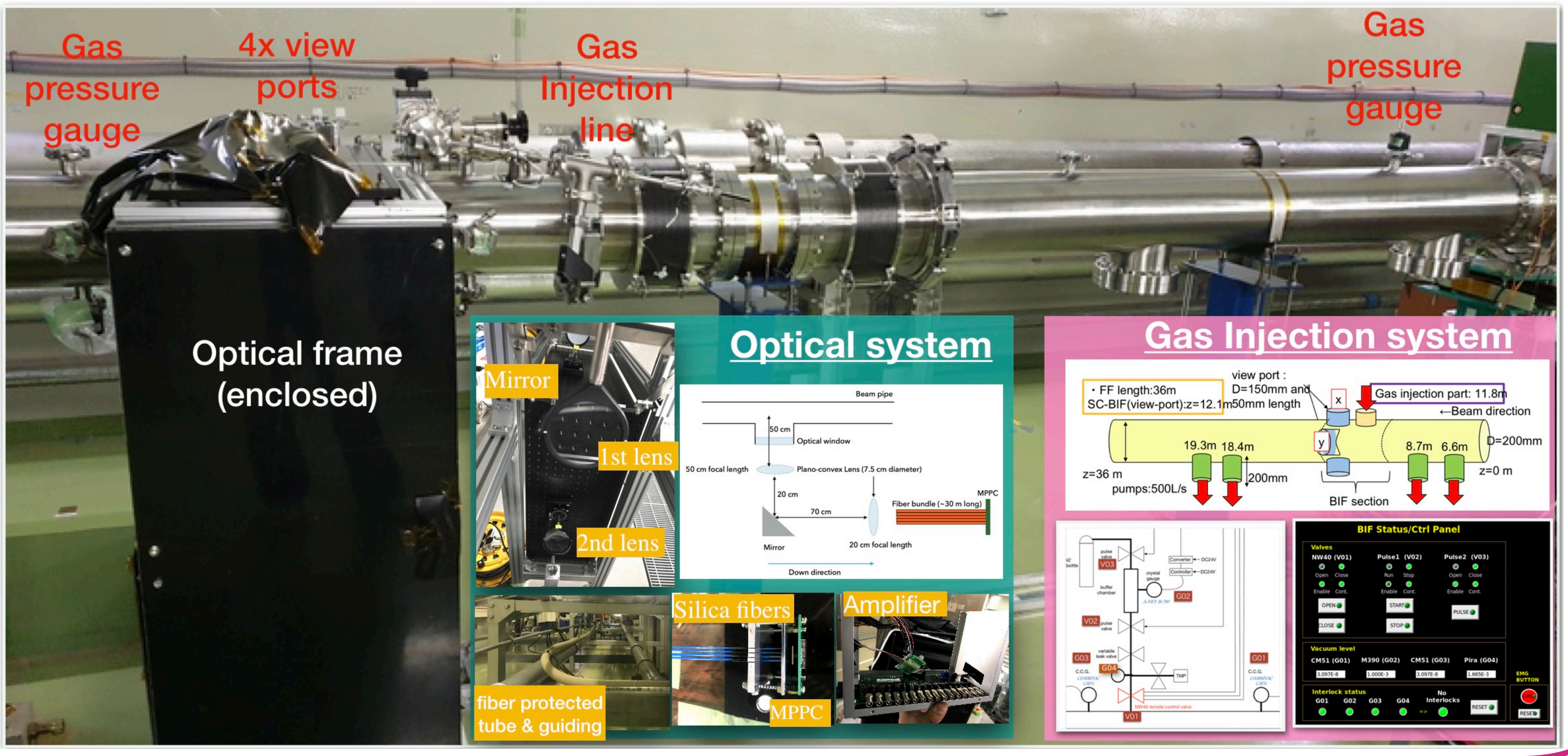
BIF R&D timeline

- **JFY2015**: Started with a test vacuum chamber; simulated the light transport system and tested parts of the light transport system
- **JFY2016:** Characterized the gas uniformity using the simulation and the test vacuum chamber; designed and built prototype of pulsed gas system; continued testing parts of light transport system
- **JFY2017**: built and tested a complete gas inlet vacuum system; built and tested a complete light transport and light detection system; conducted a beam test of temporarily degrading the vacuum in the NU beamline by stopping the gas pump
- **JFY2018**: Installed most parts of a prototype monitor in the NU beamline FF section for the gas injection tests and first BIF signal observation
- **JFY2019**: Install final parts of complete monitor

Readiness for fall 2019 proton beam

- Installed various components in the actual beamline, including
  - Series of gas injection valves for gas injection tests and pulsed gas injection for the true monitor
  - A complete prototype of the optical system with plano-convex lens, mirror, optical fibers and MPPC array
- Perform the gas injection tests

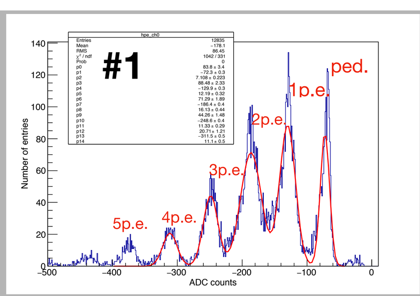
Aim for first observation of BIF light in this run.

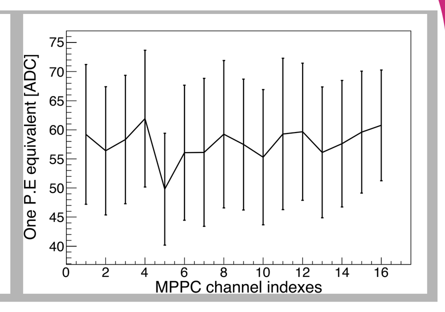


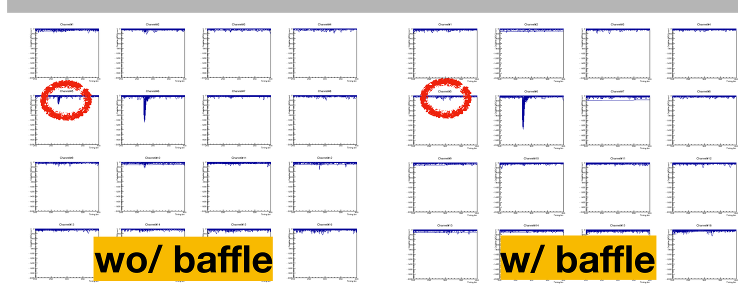
Calibration of the optical system

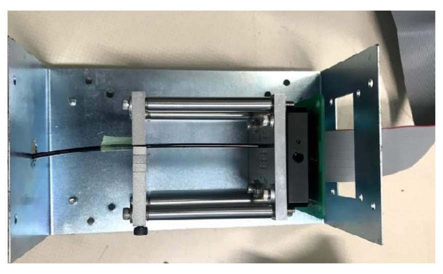
- MPPC channel-by-channel response to single photoelectron (p.e.), their gains can be different at same HV supply: use fast LED at low light (few photons)

MPPC array 4x4 channels



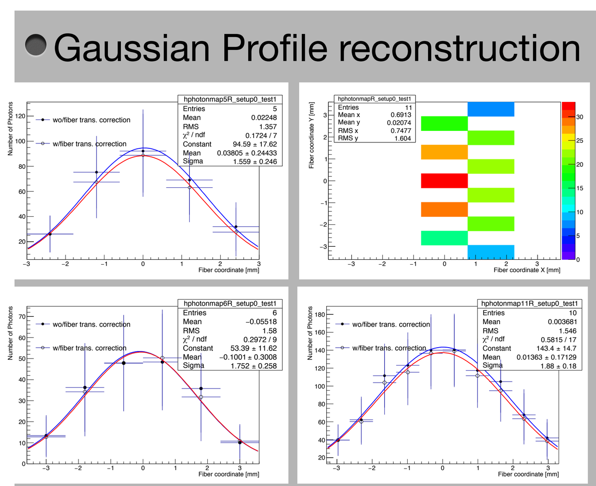






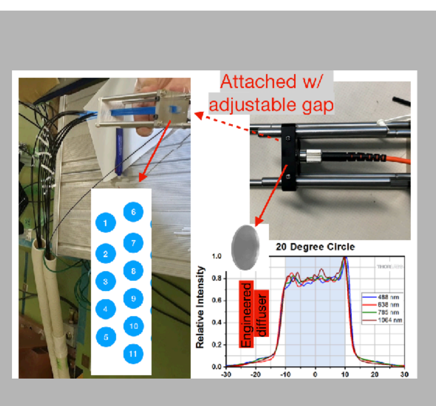
- Cross-talk btw. channels due to fiber-MPPC coupling must be taken into account if can't be taken elimination (by optimal setup and/or optical baffle

- Gaussian Profile reconstruction



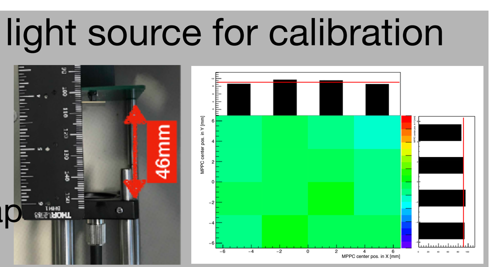
Demonstrated profile reconstruction

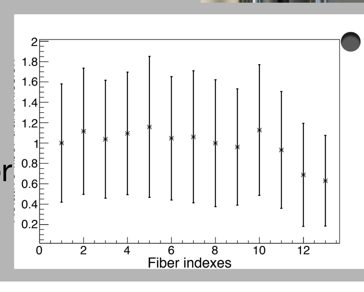
- Uniform light source for calibration



Cage rod system is designed for precise & effortless alignment

Diffuser coupled to MPPC at sufficient gap



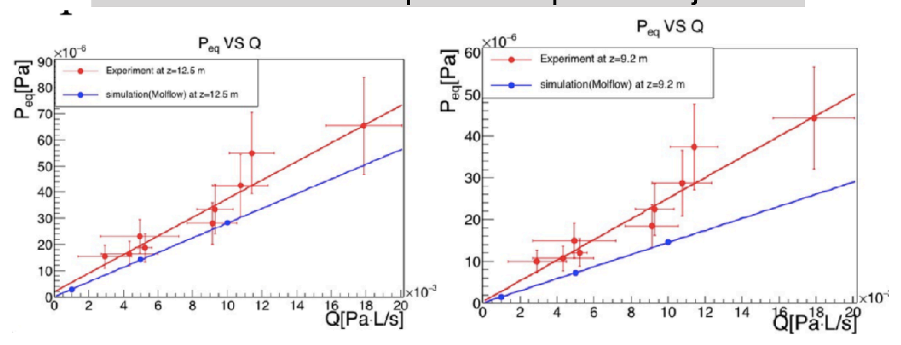


- Relative fiber transmission (normalized to fiber #1)

- Optic (lens and mirror) misalignment can distort the profile. This will be measured soon.
- Others: space charge effect can be complicated → need beam-based alignment; use timing info. (fast response from MPPC) of signal waveform and/or different type of gas (heavier)

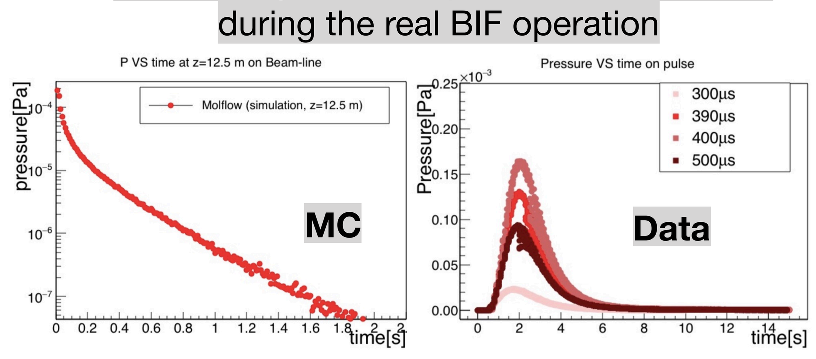
Gas injection test

Continuous injection for validate steady-state simulation and extrapolate to pulsed injection



It shows fairly consistent btw data and Monte Carlo simulation (Molflow developed by CERN) at downstream but not at upstream → on-going investigation

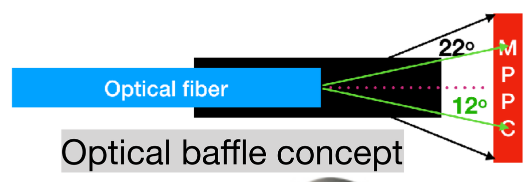
Pulsed injection for validating pulsed simulation and directly measure pressure distribution during the real BIF operation



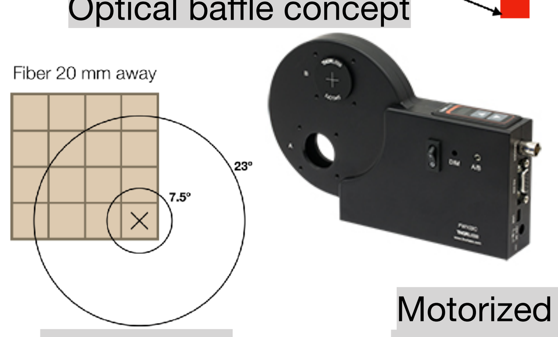
Either pressure gauge (and ion pump) response is slow or pressure pump is very long compared to the expected → on-going investigation

For background understanding and enhance S/N ratio

- Large background observed in the previous study: ~ 160 p.e equivalent with on-time bunch and same order with off-time bunches
- If background reach MPPC at large angle (>12°), **optical baffle** or smaller NA optical fiber are helpful. If it is at low angle, other hope is to use wavelength bandpass filter and shielding
- Plan for a **spectrometer with MPPC**, **optical bandpass filter** to check the spatial and wavelength distribution of the background



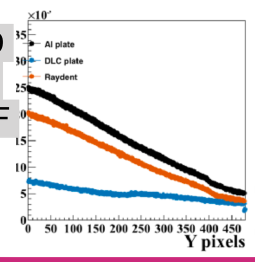
Optical baffle concept



MPPC-fiber spectromete

Motorized filter wheel

LED, CCD camera & replica BIF optic are used



Black coating for the beampipe walls: to prevent reflection light which can distort the reconstructed profile. Diamond-Like Carbon (DLC) shows promising light absorption (compared to Raydent)

In summary, a workable BIF prototype as an upgrade option for monitoring the future MW proton beam at J-PARC neutrino beamline is being developed. Most of the parts for both gas injection system and optical system have been installed and tested. The next target for fall 2019 is to observe the real BIF signal by injecting gas into the beamline.

Poster is presented at IBIC 2019, 7th - 12th Sept. 2019, Malmo, Sweden
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