Proton Beam Monitor Upgrades for the J-PARC Neutrino Extraction Beamline

Megan Friend

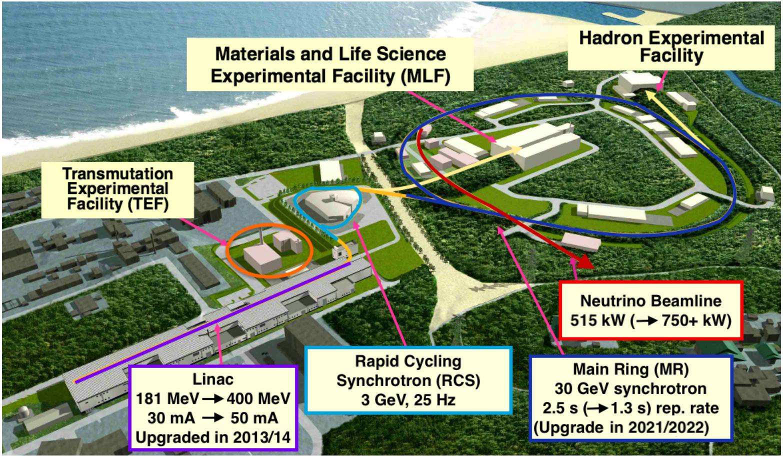
High Energy Accelerator Research Organization (KEK)

NuFACT2022
August 4, 2022

Outline

- Overview of J-PARC and the J-PARC Neutrino Beamline
- Proton Beam Monitors at the J-PARC Neutrino Extraction Beamline
- Some Issues with Present Proton Beam Monitors
- Upgrades + Handling for Proton Beam Monitors

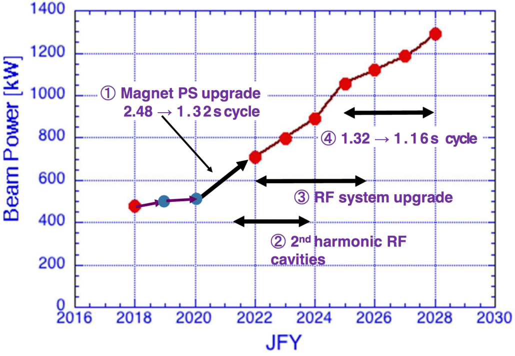
J-PARC Accelerator



- J-PARC = Japan Proton Accelerator Research Complex
- Accelerates proton beam to 30 GeV by:
  - 400 MeV Linac (linear accelerator) → 3 GeV RCS (Rapid Cycling Synchrotron) → 30 GeV MR (Main Ring)
- MR design beam power: 750 kW (currently ~515 kW)

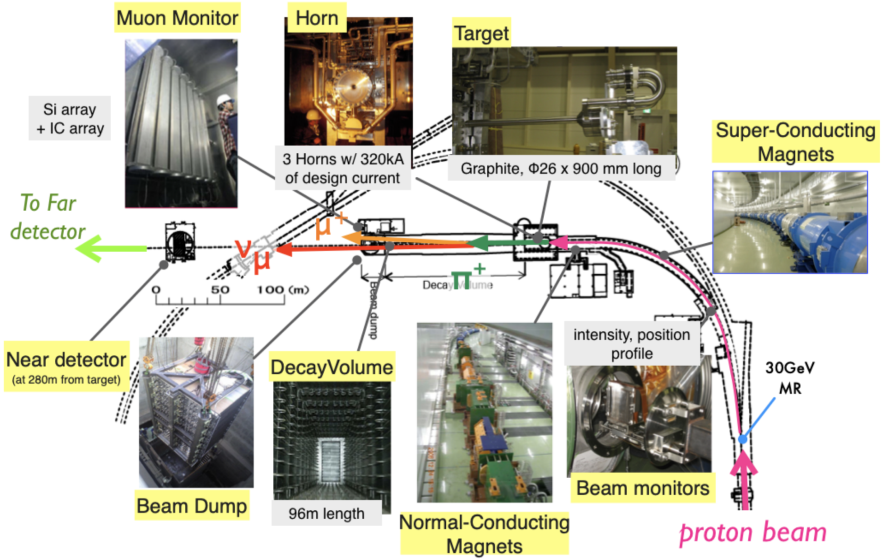
J-PARC Beam Power Upgrades

- Was : $\sim 2.65 \times 10^{14}$ protons per pulse (over 8 bunches) with 2.48 s repetition rate (~515 kW)
- Upgrading MR power supplies now to reach 1.36 s repetition rate
  - RF improvements can allow for further decrease to 1.16 s
- Other MR improvements to increase protons per pulse for 1.3MW
- Various upgrades to J-PARC neutrino beamline needed to accept high power beam



	Achieved		Target
Beam power [MW]	0.5	~x3	1.3
# of protons per pulse	2.6×10^{14}	+30%	3.2×10^{14}
Rep. Time [sec]	2.48	~1/2	1.16

J-PARC Neutrino Beamline



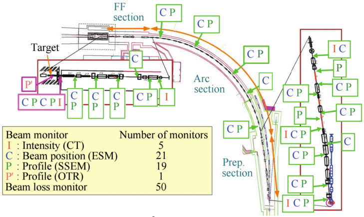
Why Is Proton Beam Monitoring Important?

- Required for beam diagnostics and tuning
- Required to correctly steer the proton beam/protect beamline equipment
  - Continuously impinging too narrow beam on the target or beam window could cause serious damage
  - Even one shot of mis-steered high-intensity beam can seriously damage equipment

    → Need continuous monitoring
- Information from proton beam monitors is used as input into the neutrino flux prediction simulation
  - For neutrino oscillation experiments + neutrino cross section measurements
  - Need well-understood and well-controlled proton beam for world-class neutrino physics results

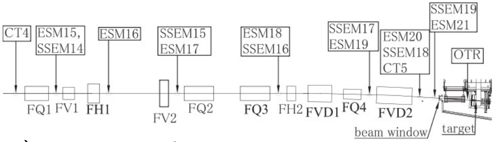
J-PARC Neutrino Beamline Proton Beam Monitors

Primary Beamline Monitors



Final Focusing Section

Beam Direction ⟶



- 5 CTs (Current Transformers) – monitor beam current
- 50 BLMs (Beam Loss Monitors) – monitor beam loss
- 21 ESMs (Electrostatic Monitors) – monitor beam position

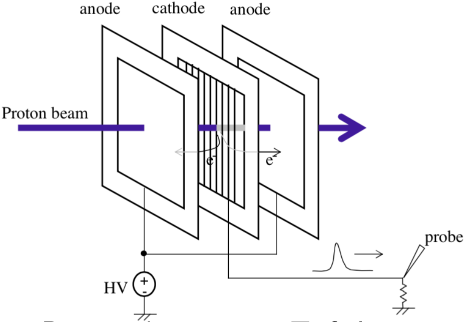
↥ These are non-interacting and should work stably even at 1.3MW ↥

↧ These are interacting and may degrade at high beam power ↧

- 19→18 SSEMs (Segmented Secondary Emission Monitors) + 2 WSEMs (Wire SEMs) – monitor beam profile during beam tuning
- 1 OTR (Optical Transition Radiation) Monitor – monitors beam position and profile at target

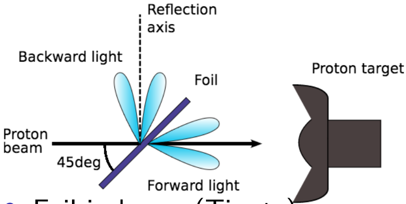
How to Measure the Proton Beam Profile

Segmented Secondary Emission Monitor (SSEM)



- Protons hit 3x 5μm Ti foils
- Secondary electrons are emitted from segmented cathode plane and collected on anode planes
- Compensating charge in each cathode strip is read out by ADC

Optical Transition Radiation Monitor (OTR)

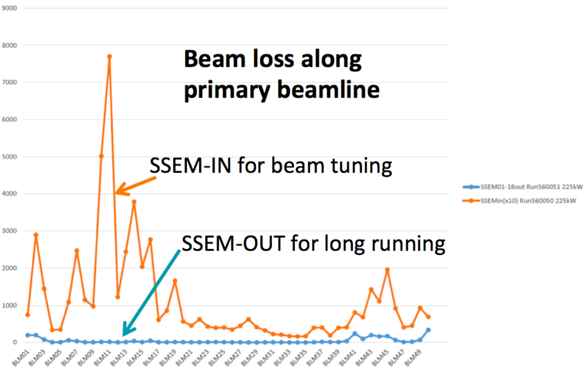


- Foil in beam (Ti, etc)
- Optical Transition Radiation produced when charged particles travel between two materials with different dielectric constants
  - OTR light proportional to beam profile
  - Light detected by rad-hard camera in low-rad area

Why Is Non-Destructive (+ Minimally-Destructive) Proton Beam Monitoring Important?

- Standard monitors measure the beam profile by intercepting the beam – they are *destructive* and cause *beam loss*
  - Absolute amount of beam loss is proportional to beam power and volume of material in the beam
- Beam loss can cause :
  - Irradiation of and damage to beamline equipment
  - Increased residual radiation levels in the beamline tunnel
- Foils in the beam may degrade
  - Rate of degradation increases as the beam power increases
- The beam profile must be monitored continuously
  - So, R&D for J-PARC proton beam profile monitors that work well at high beam power is ongoing
  - Remote exchange procedure for existing profile monitors is also essential

Measured Beam Loss Due to SSEMs

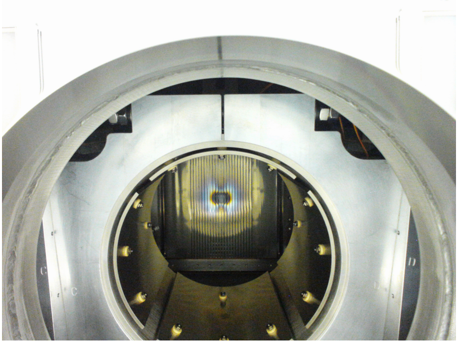


- Beam loss when SSEMs are IN is quite high
  - ~0.005% beam loss at each SSEM
- Can cause radiation damage, activation of beamline equipment
  - SSEMs upstream of the neutrino target station cannot be used continuously
  - SSEM1-18 are only used during beam tuning and optics checks

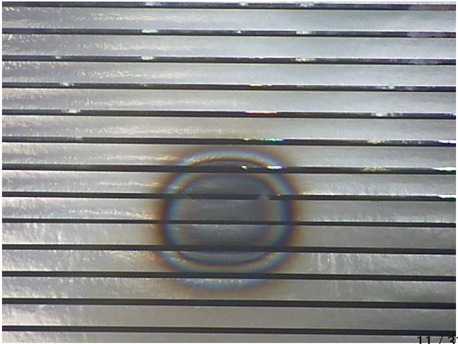
SSEM Foil Discoloration

- SSEM19 is the most downstream SSEM and is used continuously
- SSEM19 foil inspection was performed in summer 2017 (downstream side) and fall 2018 (upstream side)
  - Significant discoloration of SSEM19 foils observed
  - No significant signal degradation, but plan to replace the monitor head in 2023

Downstream side after
~2.3×10^{21} Incident Protons



Upstream side after
~3.2×10^{21} Incident Protons



New WSEM Beam Profile Monitor

- New Wire Secondary Emission Monitor (WSEM) designed to measure proton beam profile in J-PARC neutrino beamline
- Monitor beam profile using twinned 25 μm Ti wires
  - Exact same principle as SSEMs but with reduced material in the beam → reduced beam loss
  - C-shape allows monitor to be moved into and out of the beam while the beam is running (!)
    - Wires mounted at 45° so they can measure X and Y
  - Developed in collaboration with engineers at FNAL, supported as a US/Japan collaboration project

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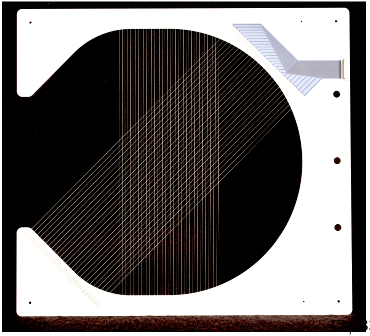
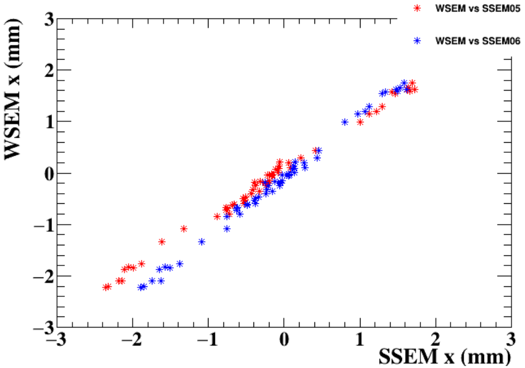


WSEM Performance, Status

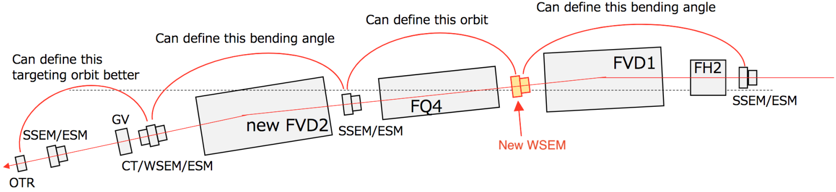
- Beam loss by WSEM lower than SSEM by factor of ~10
- WSEM resolution, precision equivalent to SSEM
- No issue during long-term stress test
  - 160 hours in 460~475kW beam
    ~ 5.6×10^{19} incident protons

WSEM vs SSEM x :



- Replaced SSEM18 with WSEM in December 2018
  - Since beam loss is significantly lower with WSEM, can use WSEM18 continuously in case of SSEM19 failure
  - Working stably since 2018

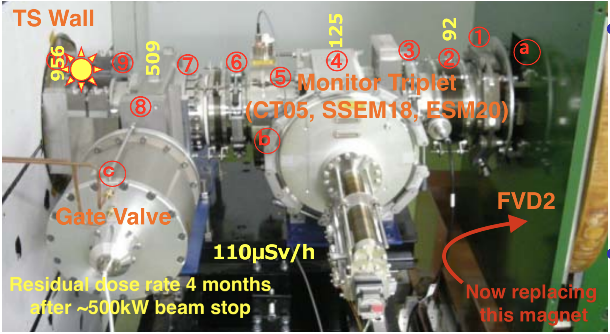
WSEM Plan



- Next steps for WSEM at J-PARC:
  - Add additional WSEM to final focusing section of beamline for further constraint of beamline optics at the target (2022?)
    - Studies underway to understand impact of new monitor on beam optics constraint
  - Test carbon nano-tube (CNT) wires as more robust upgrade option
    - Procured 50μm and 25μm diameter CNT from Japanese company Hitz (high-quality, uniform surface)
    - Fabrication of CNT-mounted frame for J-PARC ongoing by engineer at FNAL now (US/Japan collaboration)
    - Install in J-PARC neutrino extraction beamline in 2022 or 2023(?)

Final Focusing Section Remote Handling

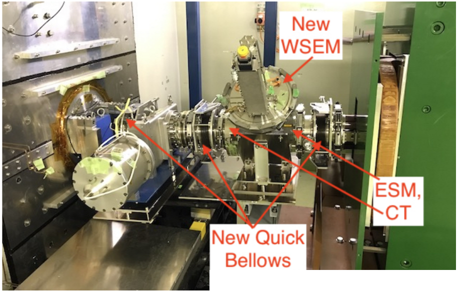
- Residual radiation dose at most downstream end of primary proton beamline is high
  - Due to backscattering from the neutrino production target, beam window, etc
  - Residual dose reaches >1mSv/hr on contact weeks after beam stop, even at 500kW beam power
    - Proportional to integrated POT – will increase with higher beam powers, longer running time

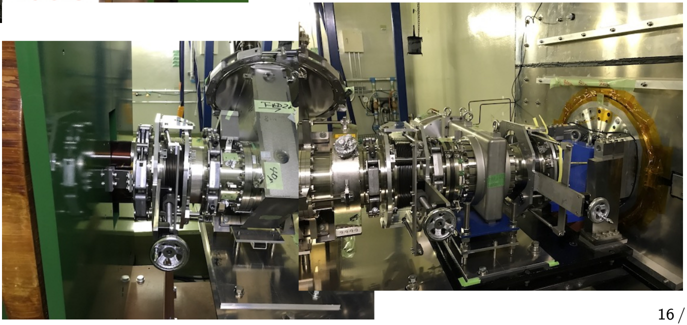


- Make space for quick, hands-on maintenance by reducing length of most downstream bending magnet – new magnet installed summer 2021
- Long-term upgrade: move to fully remote maintenance scheme

Final Focusing Section Remote Handling

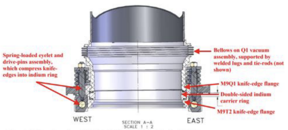
Current configuration:

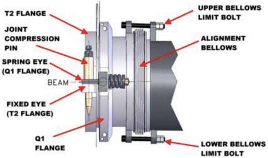


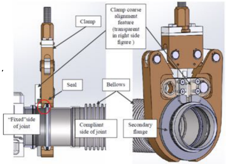


Longer-Term Primary Beamline Maintenance Scheme Plan

- Quick, hands-on maintenance will not be sufficient for long-term, 1.3 MW HK running
  - Expect residual dose at 1 foot will reach 600 μSv/h after 1.3 MW ×40 months operation
- Now considering additional future upgrades towards fully remote maintenance scheme
  - Replace several flanges with remote operation flanges
    - Pillow seals are currently used at neutrino beamline Target Station, but difficult at primary beamline
    - Considering new remote flange technologies
  - Improved crane system
  - Other ideas ?
- Discussion with various remote-handling experts ongoing

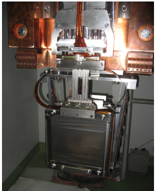






SSEM19 Exchange

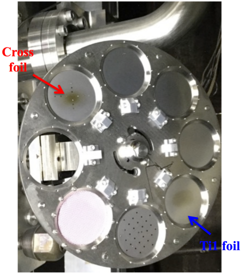
- SSEM19 sits at the bottom of monitor stack, between primary and secondary beamlines
  - Very difficult to access
  - Highly radioactive, so requires full remote handling
- Now developing procedure for SSEM19 exchange – first mockup tests done
  - Cables interfere with remote manipulator jig – need to improve
- Watch first mockup test on YouTube!
  - Mockup disconnection:
    `https://www.youtube.com/watch?v=fA8R7n0eFDI`
  - Mockup connection:
    `https://www.youtube.com/watch?v=PG2Km-rdlB0`
  - Mockup spent cable handling:
    `https://www.youtube.com/watch?v=tgkIkr-AEtE`
  - Mockup new cable handling:
    `https://www.youtube.com/watch?v=a6atAl1LUTo`



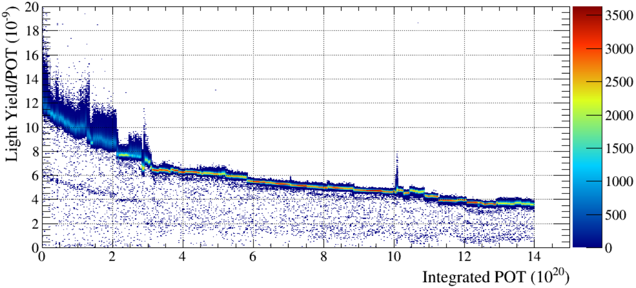
OTR Light Yield Decrease

- OTR foil discoloration seen after incident :
  - $\sim 5 \times 10^{20}$ POT on Ti Foil
  - $\sim 11 \times 10^{20}$ POT on Cross Foil
- Gradual decrease of OTR light yield
  - Due to radiation-induced darkening of leaded-glass fiber taper
    - Coupled to CID camera to shrink OTR image

Foil Discoloration :

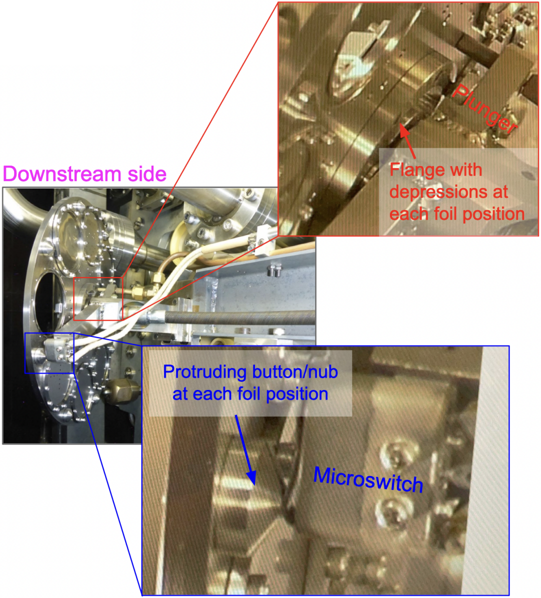


OTR Normalized Light Yield (Stability) :



OTR Operational Issues

- Rotate disk remotely using motor to switch OTR foils
- Motor is stopped by micro-switch and plunger engages to disk flange when a foil is in position
- Recently had a few issues with OTR disk rotation:
    - Rotation torque became high – due to damage to Ti flange caused by stainless steel plunger ball ?
    - Micro-switch not activating at some disk positions



OTR Tests (Feb~March 2022)

- Dedicated test of OTR microswitch issue in early 2022
- Remote manipulation needed (spent Horn 1 and OTR)
- Small (~50μm) misalignment between disk and microswitch found

OTR Tests (Feb~March 2022)

- Dedicated test of OTR microswitch issue in early 2022
- Remote manipulation needed (spent Horn 1 and OTR)
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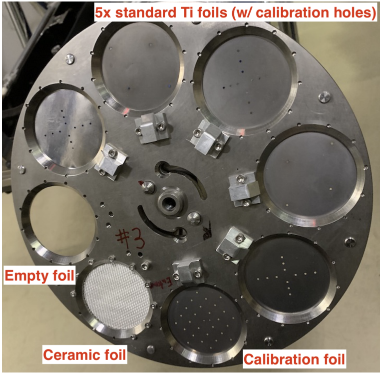
OTR Upgrades

- Decrease in OTR light yield observed
  - Due to radiation-induced darkening of optical component (fiber taper)
  - Upgrading optical system to use easily-replaceable fiber taper now (York University)
- Useful to have backup procedure for OTR calibration + foil position information
  - Add holes to all OTR target foils – can be used to cross check foil position by back-lighting
  - Upgrade to thinner foil for improved stress tolerance

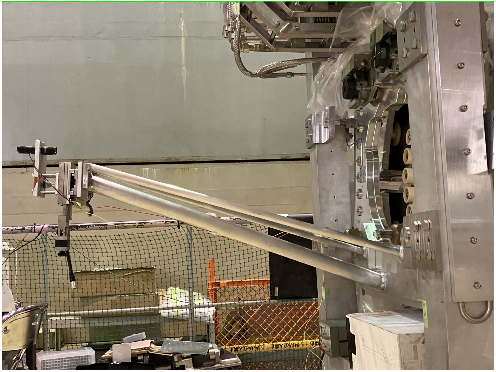


OTR target disk

- Upgrading OTR readout for 1Hz operation, Windows → Linux (ICL)
- New OTR disk will be installed in the beamline in late 2022, new DAQ will be used as main one from next beam run

OTR Alignment/Installation

- New calibration light sources and support structure to confirm the OTR disk/foil position during OTR installation
  - Essential for confirming/reproducing new and old OTR disk alignment
  - Points along horn axis and is focused at the OTR disk foil
  - Laser/flashlight is held by rigid structure attached to the horn frame



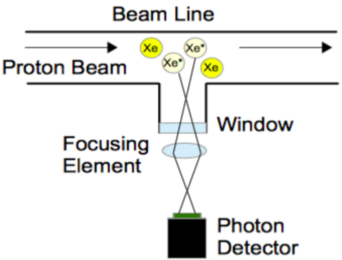
Installation of new calibration light source on Horn 1 at J-PARC in April~May 2022

OTR Alignment/Installation

- Test installation of new OTR disk on mock Horn 1 by OTR group members in May 2022
- Actual installation of new OTR on new Horn 1 will take place later this year
    - Horn 1 is new (not radioactive), but horn support module is used – actual installation work must be done using remote handling

Beam Induced Fluorescence (BIF) Monitor

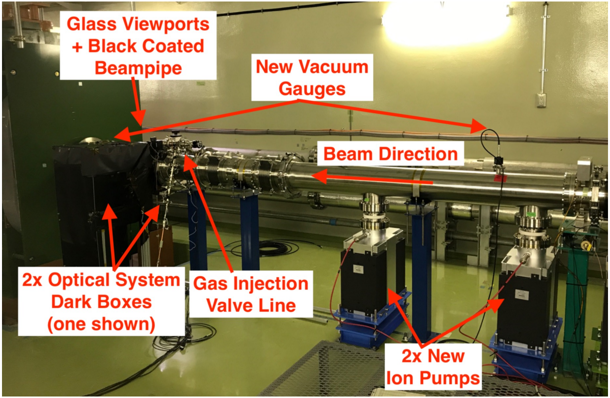
- Uses fluorescence induced by proton beam interactions with gas injected into the beamline
  - Protons hit gas (i.e. N_2) inside the beam pipe
  - Gas molecules are excited or ionized by interaction with protons
  - Fluoresce during de-excitation with same profile as proton beam



- Continuously and non-destructively monitor proton beam profile
  - 5×10^{-8}% beam loss for 1m of gas at 10^{-2}Pa
    - $\sim 10^{-5}$x less beam loss than 1 SSEM
- Locally degrade vacuum level from $\sim 10^{-5} \rightarrow \sim 10^{-2}$ Pa to observe ~1000 BIF photons/spill at photodetector – Challenging!
  - Essential to optimize gas injection + light transport/detection
- Monitor development ongoing since 2015 – collaboration between KEK, IPMU/TRIUMF, Okayama Univ.

M. Friend *et al.*, Proceedings of IBIC2020, WEPP34, 2020

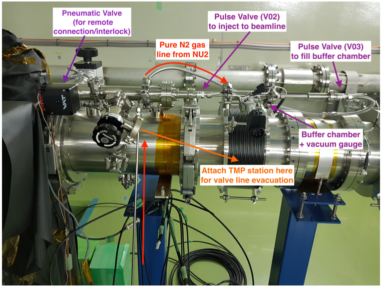
BIF Monitor Prototype



- Installed full working prototype monitor in J-PARC neutrino extraction beamline in 2019
  - Pulsed gas injection system
  - 2x optical systems (for horizontal + vertical readout)
- Took beam study data during 2020 + 2021 T2K beam runs
  - Fully non-destructive, so can take study data during physics run!

BIF Gas Injection System

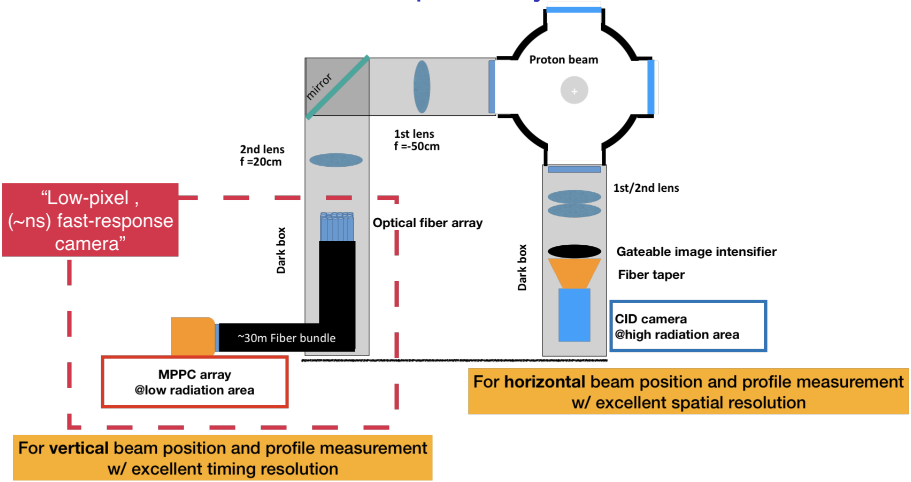
- Goals :
  - Safely inject specified amount of N_2 gas into the beamline at the beam timing
    - Stop injection if trouble
    - Minimize injected gas amount to maintain ion pump lifetime
  - Monitor injected gas amount + gas profile at BIF interaction point
- BIF gas system consists of :
  - 2 pulse valves with a buffer chamber between them
  - Control system :
    - 1st pulse valve fills buffer chamber when pressure becomes low
    - 2nd pulse valve pulsed using beam trigger – injection length + timing can be precisely controlled
  - Interlock system closes pneumatic valve if pressure exceeds threshold
  - Vacuum gauges



Jan 2020 valve line photo

- Gas system generally has been working stably
- Unfortunately, required amount of gas injected to see clear BIF signal is ~10x more than original design

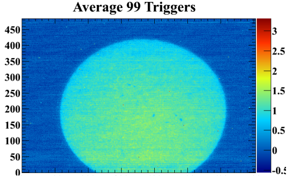
Optical System Overview



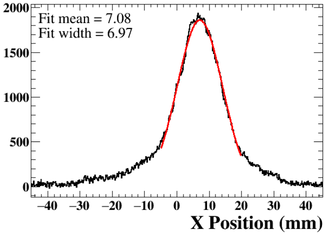
- Simultaneously observe BIF light in 2 independent optical systems
- Windows at top + right side of beampipe can be used for calibration LEDs or additional detection systems

Camera (Horizontal) Measurement

Beam-induced background on Image Intensifier :



Fit of X position and width:



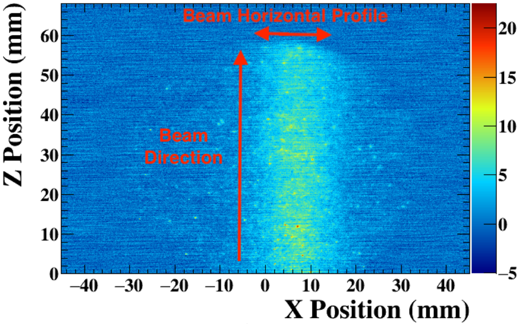
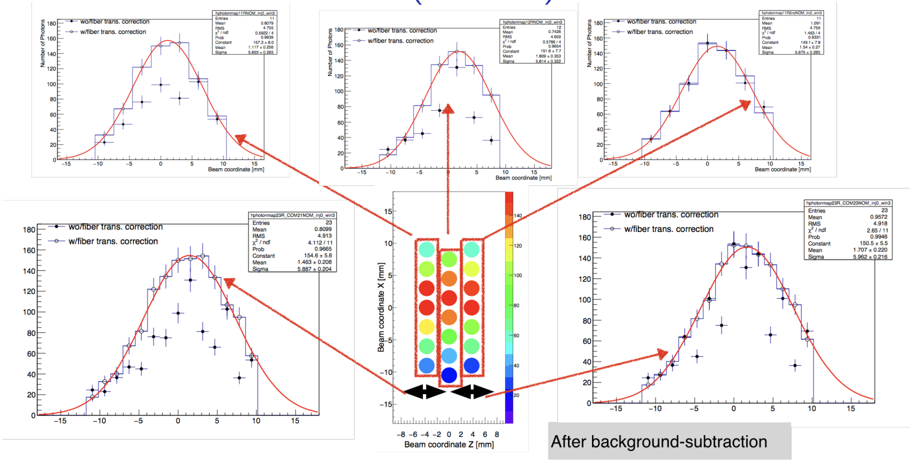


Image at camera after background subtraction (1 spill)

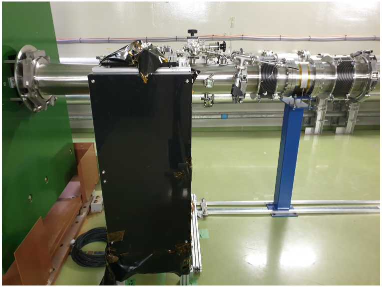
- Clear beam signal across camera sensor
- Gaussian fit to extract beam position + profile

MPPC (Vertical) Measurement



- Clear vertical beam profile measured in optical fiber array after background subtraction + fiber-by-fiber transmission correction applied

Planned Upgrades to BIF



- Now upgrading housing + mechanical support for optical systems
  - Improve alignment of optical components
  - Reduce space used along beamline
- Also upgrading image intensifier – 2-stage MCP (1000x higher gain) + optimized photocathode (lower beam-induced background)
- Now also working to improve gas injection system
  - Required amount of injected gas to see clear BIF signal is ~10x more than original design
  - Possible to further reduce valve conductance to speed up gas pulse?
  - Additional pumping required?
- Aim to use BIF continuously (prescalled) during next beam run

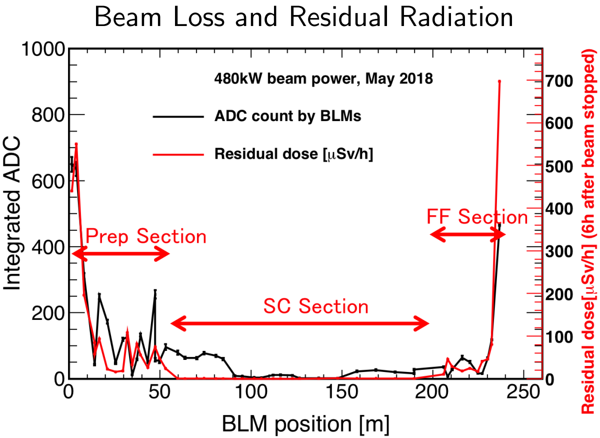
Conclusion

- Upgrades to proton beam monitors and handling ongoing :
  - Wire Segmented Emission Monitor (WSEM) – reduced beam loss
    - Working stably since 2018
    - New WSEM will be installed soon
  - Remote and semi-remote handling development for WSEM and SSEM exchange ongoing
  - Optical Transition Radiation Monitor (OTR)
    - Several upgrades in 2022
    - Installation of new OTR on new Horn 1 in 2022
  - Beam Induced Fluorescence Monitor (BIF) – non-destructive + robust monitor
    - Full prototype tested in 2020/2021
    - Upgrades to working prototype towards (pre-scalled) continuous monitoring in 2022

J-PARC Neutrino Beamline Upgrade Technical Design Report on arXiv : `https://arxiv.org/abs/1908.05141`

Backup Slides

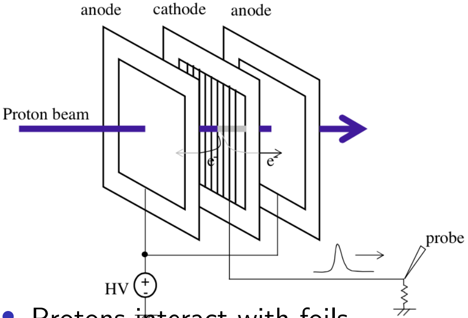
Beam Loss + Residual Radioactivity



- The beam loss level must be kept approximately as low as the present loss level
- The beam loss and residual radioactivity are highest at the most upstream and downstream ends of the neutrino primary beamline

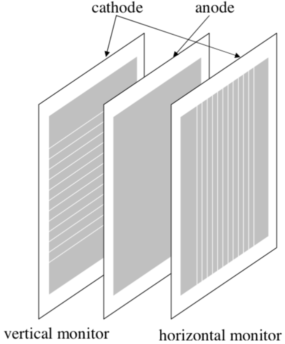
J-PARC NU SSEM Principle and Design

SSEM Principle



- Protons interact with foils
- Secondary electrons are emitted from segmented cathode plane and collected on anode planes
- Compensating charge in each cathode strip is read out as positive polarity signal

J-PARC NU SSEM

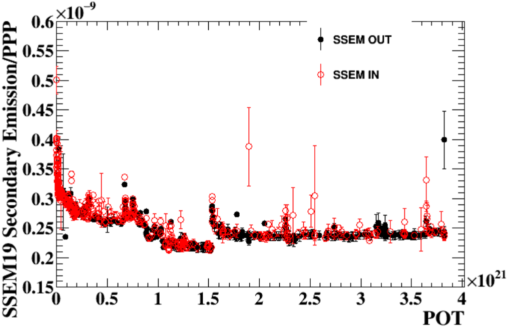


- Single anode plane between two stripped cathode planes
- 5 μm thick Ti foils

SSEM19

SSEM19 must be used continuously

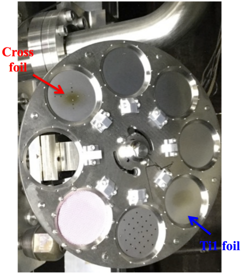
- For continuous monitoring of beam position, width at the beam window + target
  - A beam abort interlock signal is fired in order to avoid potential damage to the beam window/target if :
    - Beam density @target $N_p/(\sigma_x \times \sigma_y) < 2 \times 10^{13}$ ppp/mm^2
    - Beam position becomes significantly offset from centered
- Originally, SSEM lifetime only estimated up to ~10^{20}protons/cm^2
- However, no issue seen at ~3.8×10^{21}protons (4×4mm beam spot)
- Important to monitor degradation as total integrated POT increases



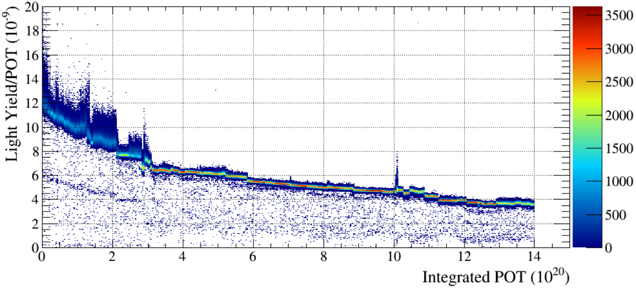
OTR Stability

- OTR foil discoloration seen after incident :
  - $\sim 5 \times 10^{20}$ POT on Ti Foil
  - $\sim 11 \times 10^{20}$ POT on Cross Foil
- Gradual decrease of OTR light yield
  - Originally believed due to foil degradation...
  - Actually due to radiation-induced darkening of leaded-glass fiber taper
    - Coupled to CID camera to shrink OTR image

Foil Discoloration :



OTR Normalized Light Yield (Stability) :

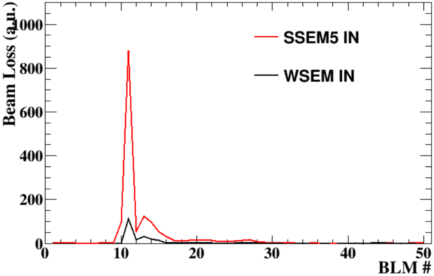


WSEM Beam Loss Check

- Prototype WSEM installed in J-PARC neutrino beamline 2016~
- Checked performance during various beam tests

- Beam loss by WSEM lower than SSEM by factor of ~10
  - Note: BLM acceptance is different for SSEM vs WSEM
  - Residual radiation @SSEM18 is 1.2mSv/hr at 475kW due to backscatter from TS
  - Residual radiation @WSEM due to continuous use at 465kW was 300μSv/hr

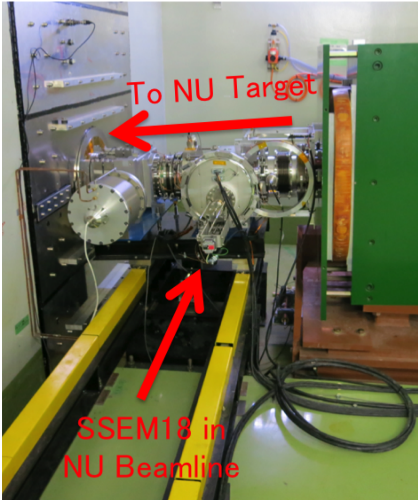
Loss due to WSEM vs that due to neighboring SSEM :

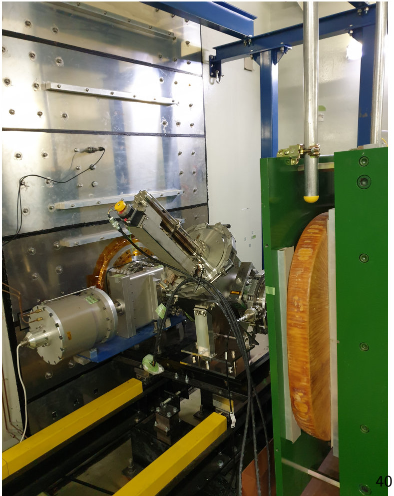


Monitor	Strip Size	Area in Beam (mm^2)	Measured Signal (a.u.)	Volume in Beam (mm^3)	Measured Loss (a.u.)
SSEM	2~5mm×5μm	7.07	60300	0.106	872
WSEM	25μm⌀x2	0.24	2300	0.007	112
Ratio SSEM/WSEM	–	29.5	26	15.1	7.8

SSEM18→WSEM Exchange

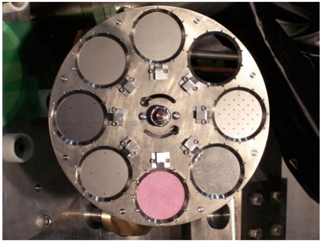
- Replaced SSEM18 with WSEM in December 2018
  - Since beam loss is significantly lower with WSEM, can use WSEM18 continuously in case of SSEM19 failure
  - In use stably since 2018

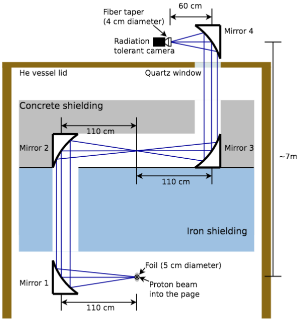




OTR Principle and Design

- Continuously monitors beam profile at the target, essential for beam tuning
- OTR light is produced when charged particles travel through foil
- T2K OTR monitors backwards-going light from 50-μm-thick Ti foil directly upstream of the target
    - Light is directed to TS ground floor by a series of 4 mirrors and then monitored by a rad-hard CID camera
- T2K OTR has rotatable disk w/ 8 foil positions; currently :
    - 4x Ti alloy (for physics running)
    - 1x ceramic (for low-intensity tuning)
    - 1x cross-pattern holes ← current foil
    - 1x calibration holes (for calibration by back-lighting)
    - 1x empty





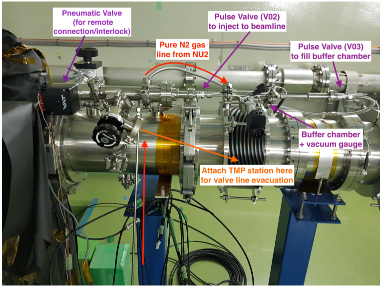
OTR Upgrades

- Decrease in OTR yield observed
  - Upgrade optical system to use easily-replaceable (inexpensive) fiber taper – regularly replace as it becomes dark

- Useful to have backup procedure for OTR calibration + foil position information
  - Add holes to all OTR target foils
    - Can be used to cross check foil position by back-lighting
    - Need to ensure foil robustness including additional holes – FEM simulations underway
  - Upgrade foil to use more robust, reflective material ?
    - Now using Ti-15-3-3-3 alloy
    - Considering possible benefit of moving to carbon (graphite) or Ti grade 5 (Ti-6Al-4V)
  - Upgrade OTR readout for 1Hz operation + Windows→Linux

BIF Gas Injection System

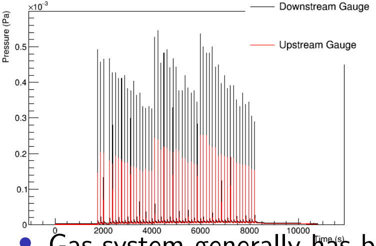
- Goals :
  - Safely inject specified amount of N_2 gas into the beamline at the beam timing
    - Stop injection if trouble
    - Minimize injected gas amount to maintain ion pump lifetime
  - Monitor injected gas amount + gas profile at BIF interaction point
- BIF gas system consists of :
  - 2 pulse valves with a buffer chamber between them
  - Control system :
    - 1st pulse valve fills buffer chamber when pressure becomes low
    - 2nd pulse valve pulsed using beam trigger – injection length + timing can be precisely controlled
  - Interlock system closes a pneumatic valve if beamline or valve line pressure exceeds threshold
  - Cold cathode vacuum gauges in the main beamline precisely measure pressure

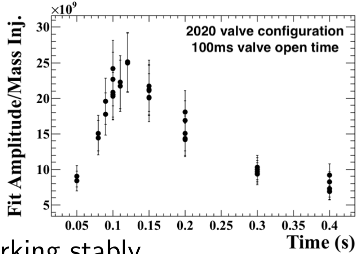


Jan 2020 valve line photo (was upgraded for 2021 run, further upgrades also planned)

Pulsed Gas Injection + Upgrade Plans

Pressure by vacuum gauges + gas pulse mapped out by BIF light:

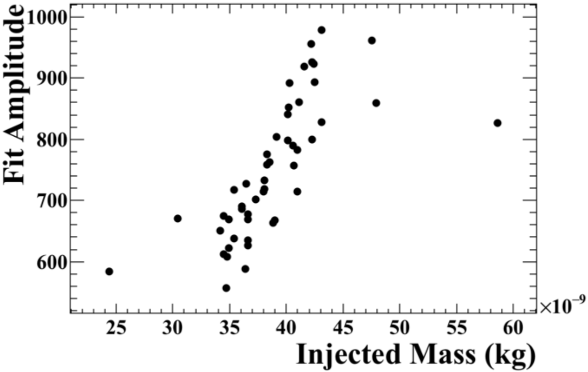




- Gas system generally has been working stably
  - Can control injected amount of gas by adjusting valve open time + buffer chamber pressure
  - Tested various amounts of injected gas, scanned gas injection timing relative to beam timing
- Unfortunately, required amount of gas injected to see clear BIF signal is ~10x more than original design
  - Due to broad/slow gas pulse due to low valve conductance
  - Increased conductance in 2021, improved compared to 2020 run
  - Considering ways to: further improve valve conductance, improve photon detection; or, prescale BIF measurement

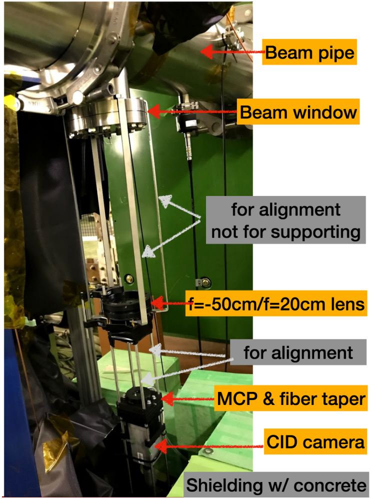
Is It Really BIF Light ?

- Yes !
- Signal size fully correlated with amount of injected gas
- No signal observed without gas injection
- Signal observed in both optical readout systems simultaneously



BIF Camera (Horizontal) Optical System

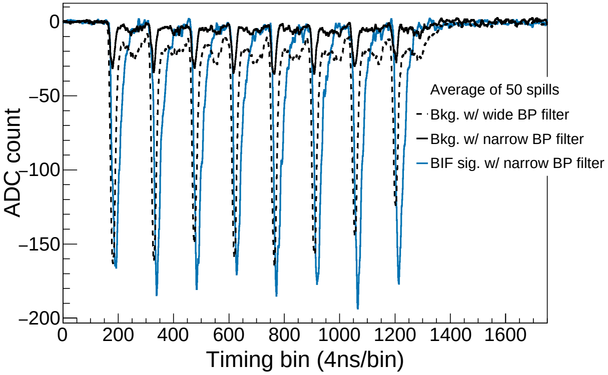
- Horizontal beam position + profile measured by:
  - 2x plano-convex lenses to focus BIF light onto
  - Micro-Channel Plate (MCP) based gateable Image Intensifier
  - Coupled to radiation-hard CID camera by silica fiber taper
  - Installed under the beamline at the BIF interaction point
  - Custom camera readout system developed at Imperial College London for T2K OTR
- Plan to upgrade image intensifier to one with a 2-stage MCP (1000x higher gain) + optimized photocathode (lower beam-induced background) for next run



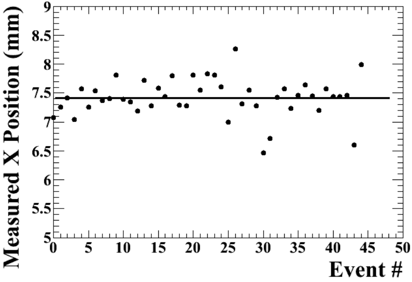
BIF camera system

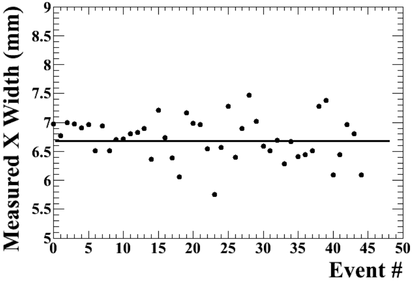
BIF Background Mitigation in Optical Fibers

- During initial BIF test runs, signal to beam-induced background ratio for optical fiber + MPPC readout arm was close to ~1:1!
- Reduced background size to ~1/12 of signal by optical filtering

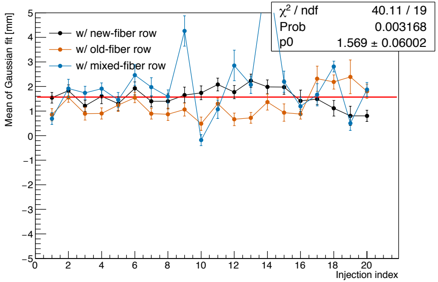


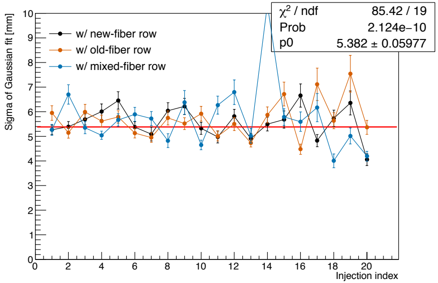
BIF Horizontal Measurement Stability



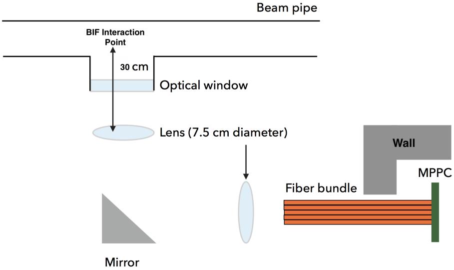


BIF Vertical Measurement Stability





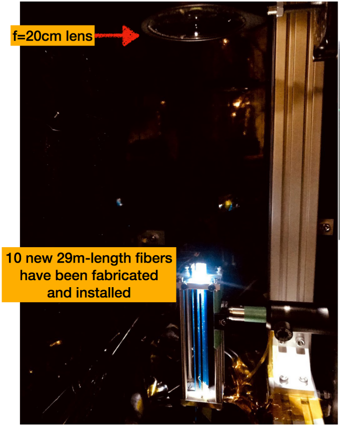
BIF Optical Fiber + MPPC (Vertical) Optical System



- Focus light from viewport on beampipe onto array of optical fibers
- Transport light away from high radiation environment near beampipe to optical sensors in lower-radiation subtunnel
  - Couple each fiber to MPPC
  - Inexpensive, fast, high gain
  - But not radiation hard
- Challenge : optimize transmission and collection efficiency to increase number of collected photons (expected)
- Unexpected challenge : beam-induced noise on optical fibers
  - Suspect Cherenkov light (on-timing) and neutrons (off-timing)
  - Mitigate by optical filtering

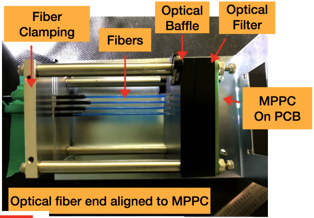
BIF Optical Fiber + MPPC (Vertical) Optical System

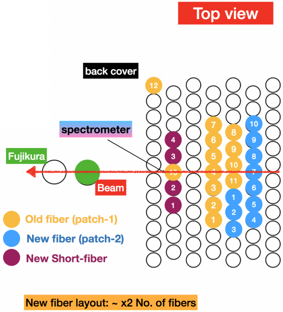
Optical fibers installed near beamline:



Installed 2x new fibers in Feb 2021

Optical fibers read out by MPPC array(s) at subtunnel :





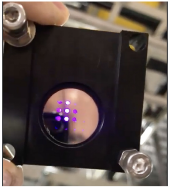
← Fiber layout at beamline side

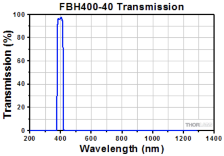
Background Mitigation in Optical Fibers

- During initial BIF test runs, signal to beam-induced background ratio for optical fiber + MPPC system was close to ~1:1!
- Reduced background size to ~1/12 of signal by optical filtering

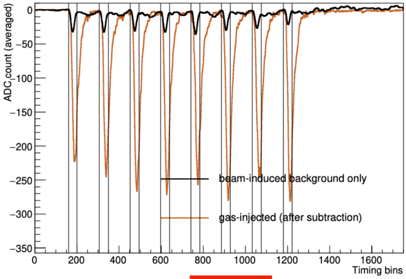
**S/B ratio depends on gas pressure pump*

One filter used to select signal w/ narrow wavelength





Bkg. ⟱ by x18.7
Sig. ⟱ by x2.5



Bkg. ~20 p.e.
Sig. ~250 p.e.

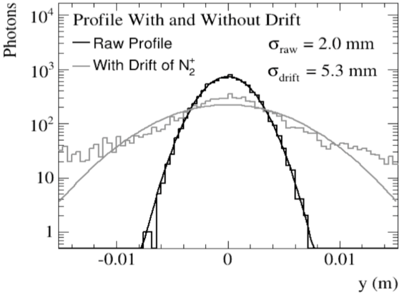
Signal/background ~10:1

Optical filter is effective to mitigate background in the optical fiber

Other Measurements by MPPC Readout

- Several other important measurements enabled by MPPC readout
  - J-PARC beam has world's largest number of protons per bunch – ~4e6 V/m beam-induced space-charge field
    - Concern that ionized particles would move in beam space-charge field → Measure time dependence of BIF profile by fast readout
  - Also interesting to measure optical spectrum of BIF light (+ beam-induced background light) using various optical filters

Pessimistic simulation result



Preliminary measurement