New Proton Beam Monitors for the J-PARC Neutrino Beamline

Megan Friend

High Energy Accelerator Research Organization (KEK)

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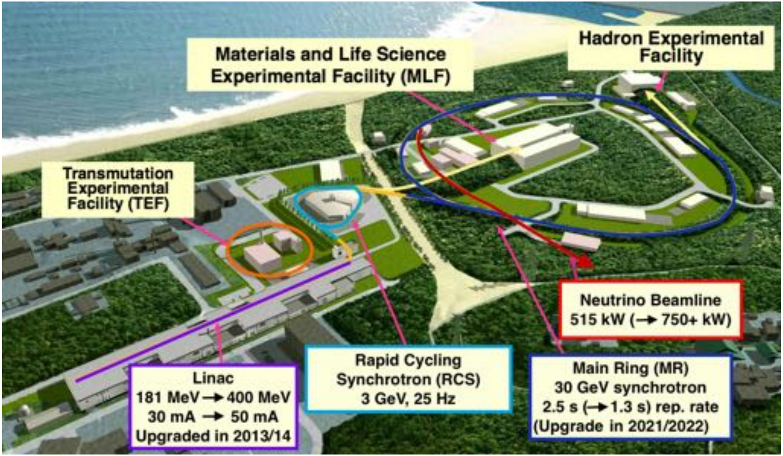
Outline

- Overview of J-PARC, the J-PARC Neutrino Beamline, and the Proton Beam Monitors Used There
- Some Issues with Present Proton Beam Monitors
- New Proton Beam Profile Monitor Development
- Bonus Slide!

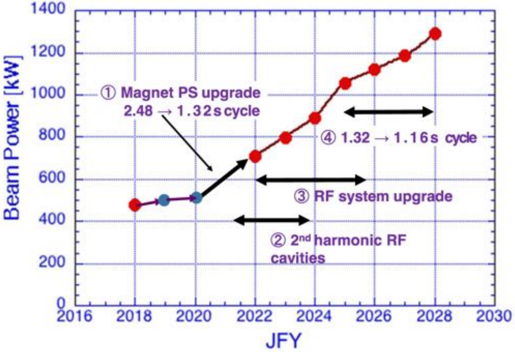
J-PARC Accelerator



- 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)

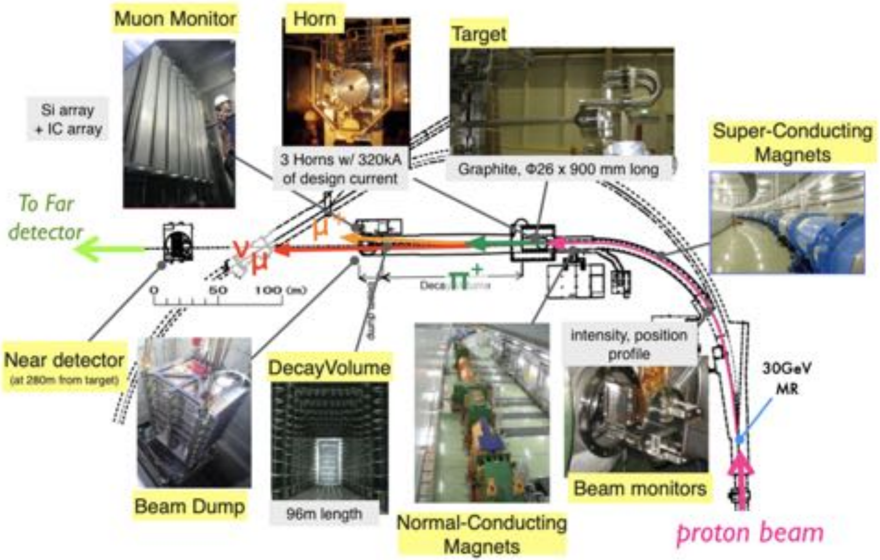
J-PARC Beam Power Upgrades

- Currently : ~ 2.65×10^{14} protons per pulse (over 8 bunches) with 2.48 s repetition rate (~515 kW)
- Upgrade MR power supplies now to reach 1.3 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 (see J-PARC Beamline talk on 9/10)



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

J-PARC Neutrino Beamline

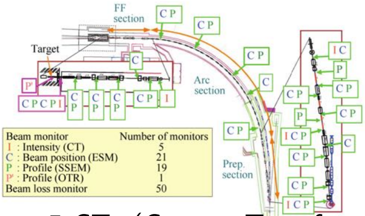


Why Is Proton Beam Monitoring Important?

- 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

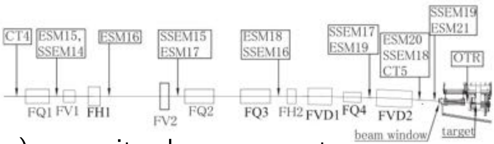
J-PARC Neutrino Beamline Proton Beam Monitors

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

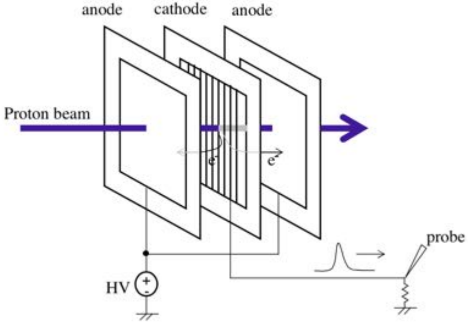
↥ These are non-interacting and should work stably even at 1.3MW ↥

↧ 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

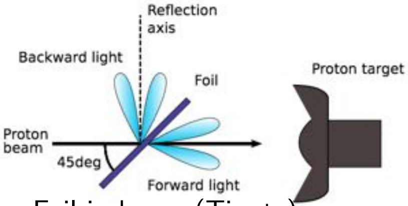
How to Measure the Proton Beam Profile

Segmented Secondary Emission Monitor (SSEM)



- Protons hit with 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)

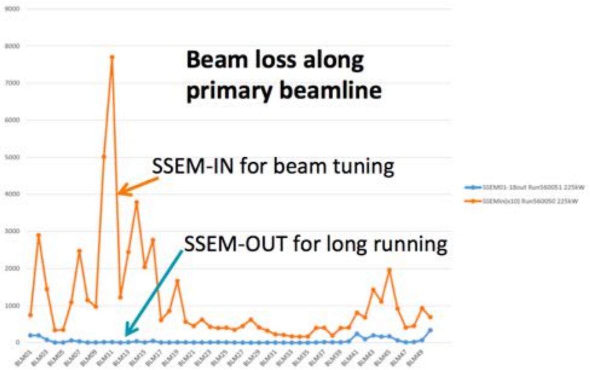


- Foil in beam (Ti, etc)
- Optical Transition Radiation produced when charged particles travel between two materials with different dielectric constants
  - OTR light proportional to beam profile
  - Light detected by rad-hard camera in low-rad area

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

Measured Beam Loss Due to SSEMs

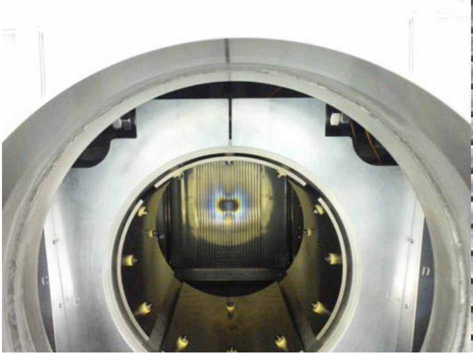


- Beam loss when SSEMs are IN is quite high
  - ~0.005% beam loss at each SSEM
- Can cause radiation damage, activation of beamline equipment
  - SSEMs upstream of the neutrino target station cannot be used continuously
  - SSEM1-18 are only used during beam tuning and optics checks

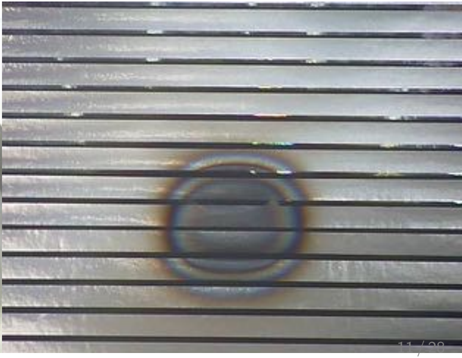
SSEM Foil Discoloration

- 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 wile 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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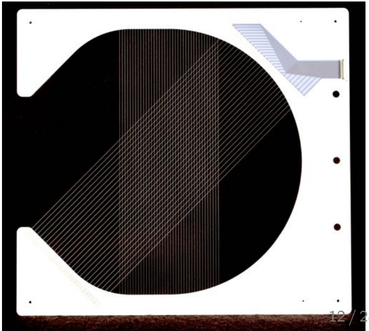
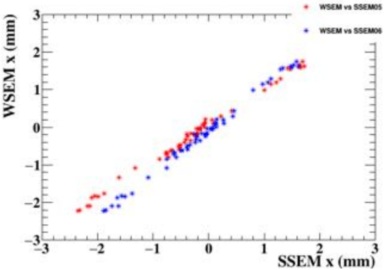


WSEM Performance, Status, Plan

- 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

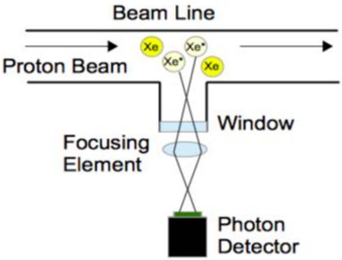
WSEM vs SSEM x :



- 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
- Next steps:
  - Add additional WSEM to final focusing section of beamline for further constraint of beamline optics at the target (2022?)
  - Test carbon nano-tube wires as more robust upgrade option (2022?)

Beam Induced Fluorescence (BIF) Monitor

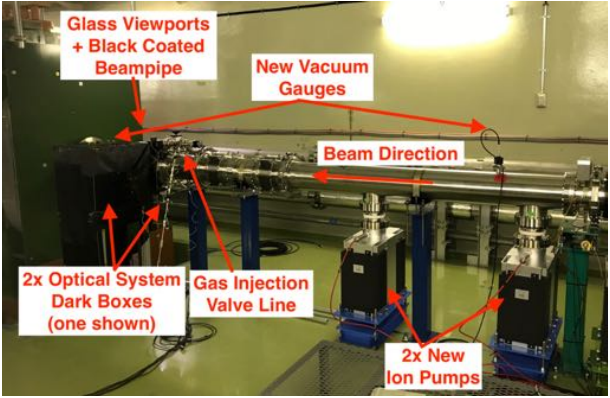
- Uses fluorescence induced by proton beam interactions with gas injected into the beamline
  - Protons hit gas (i.e. N_2) inside the beam pipe
  - Gas molecules are excited or ionized by interaction with protons
  - Fluoresce during de-excitation with same profile as proton beam



- Continuously and non-destructively monitor proton beam profile
  - 5×10^{-8}% beam loss for 1m of gas at 10^{-2}Pa
    - ~ 10^{-5}x less beam loss than 1 SSEM
- Locally degrade vacuum level from ~10^{-5} → ~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

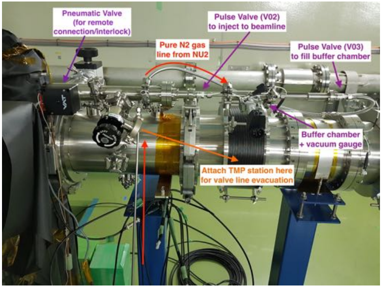
BIF Monitor Prototype



- 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

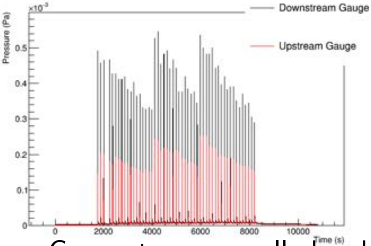
- Goals :
  - Safely inject specified amount of N_2 gas into the beamline at the beam timing
    - Stop injection if trouble
    - Minimize injected gas amount to maintain ion pump lifetime
  - Monitor injected gas amount + gas profile at BIF interaction point
- BIF gas system consists of :
  - 2 pulse 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 a pneumatic valve if beamline or valve line pressure exceeds threshold
  - Cold cathode vacuum gauges in the main beamline precisely measure pressure

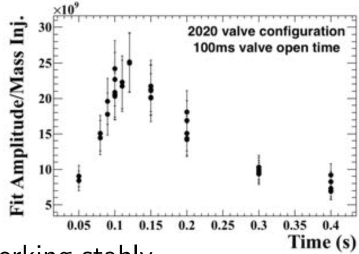


Jan 2020 valve line photo (was upgraded for 2021 run, further upgrades also planned)

Pulsed Gas Injection + Upgrade Plans

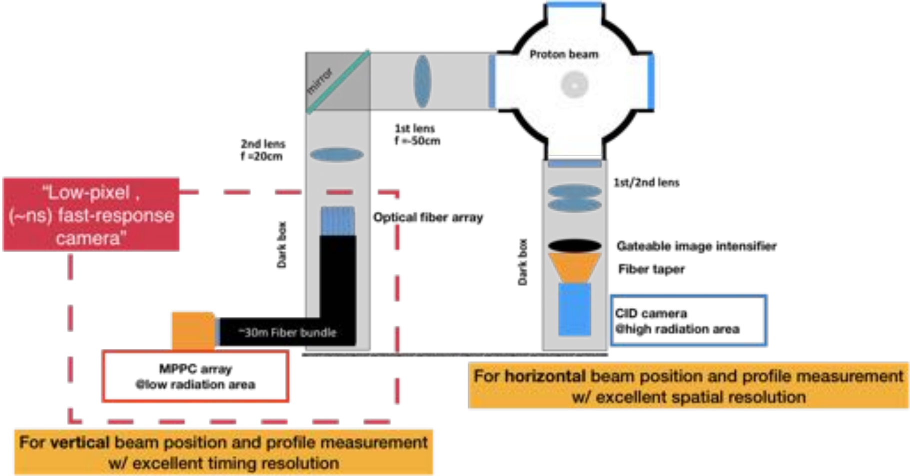
Pressure by vacuum gauges + gas pulse mapped out by BIF light:





- 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

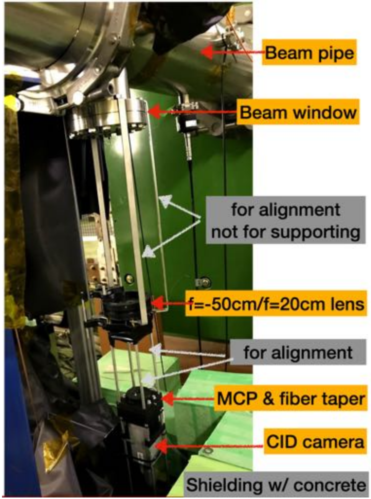
Optical System Overview



- 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

BIF Camera (Horizontal) Optical System

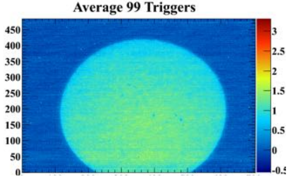
- Horizontal beam position + profile measured by:
  - 2x plano-convex lenses to focus BIF light onto
  - Micro-Channel Plate (MCP) based gateable Image Intensifier
  - Coupled to radiation-hard CID camera by silica fiber taper
  - Installed under the beamline at the BIF interaction point
  - Custom camera 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

Camera (Horizontal) Measurement

Beam-induced background on Image Intensifier :



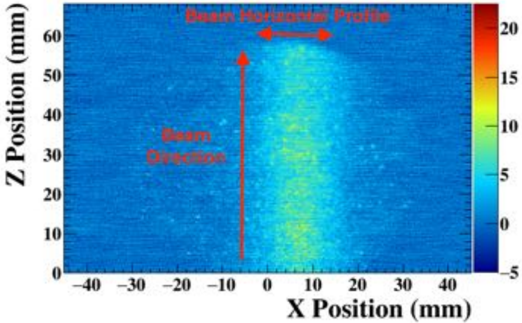
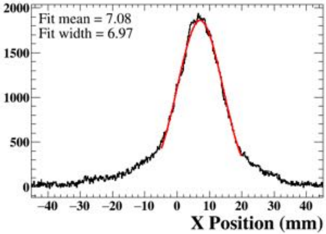


Image at camera after background subtraction (1 spill)

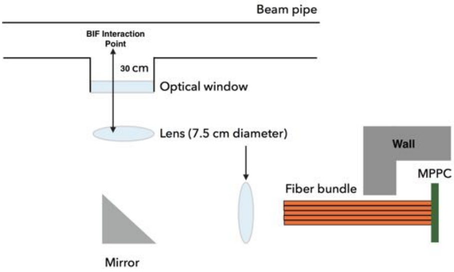
Fit of X position and width:



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

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

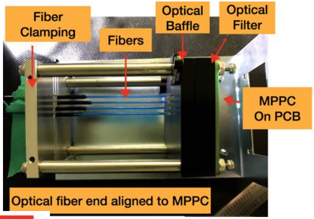
- Challenge : optimize transmission and collection efficiency to increase number of collected photons (expected)
- Unexpected challenge : beam-induced noise on optical fibers
  - Suspect Cherenkov light (on-timing) and neutrons (off-timing)
  - Mitigate by optical filtering

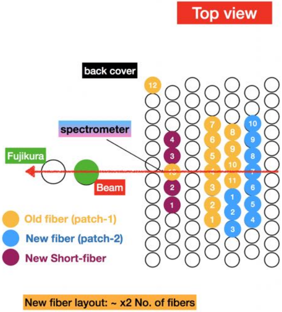
BIF Optical Fiber + MPPC (Vertical) Optical System

Optical fibers installed near beamline:

Installed 2x new fibers in Feb 2021

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

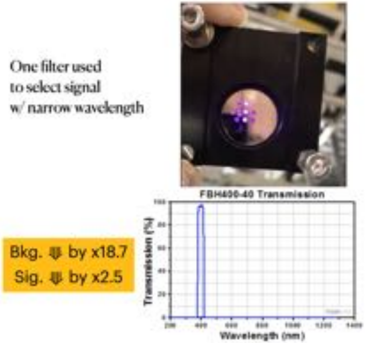




← Fiber layout at beamline side

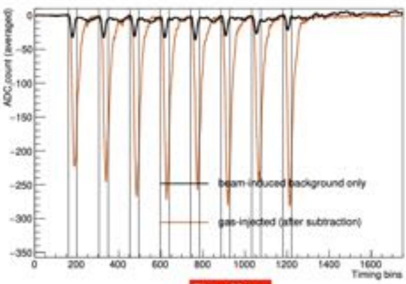
Background Mitigation in Optical Fibers

- 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



Optical filter is effective to mitigate background in the optical fiber

*S/B ratio depends on gas pressure pump

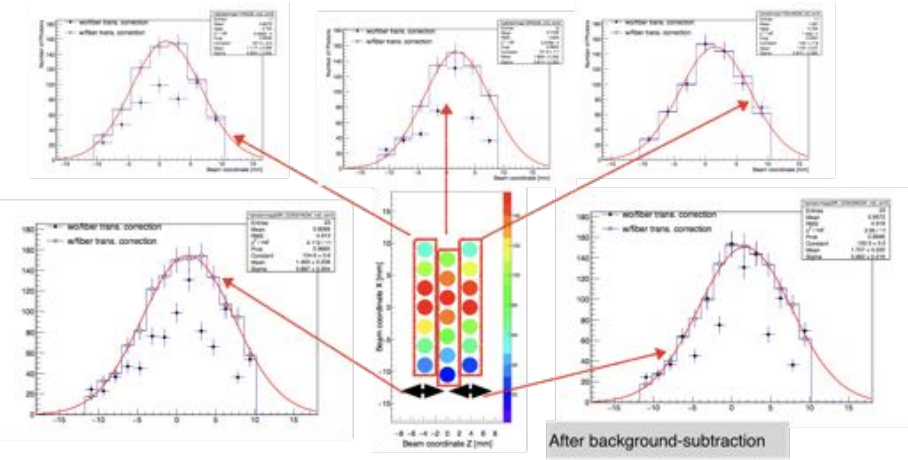


Bkg. ~20 p.e.

Sig. ~250 p.e.

Signal/background ~10:1

MPPC (Vertical) Measurement

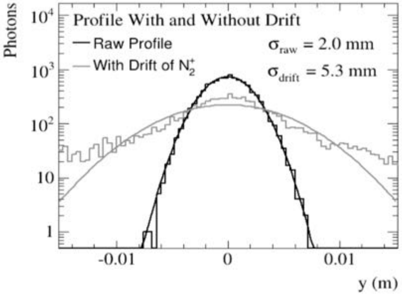


- Clear vertical beam profile measured in optical fiber array after background subtraction + fiber-by-fiber transmission correction applied

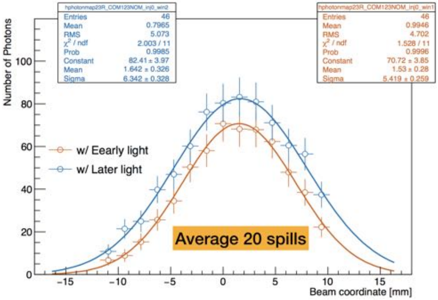
Other Measurements by MPPC Readout

- 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

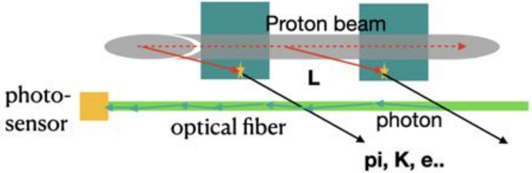


Bonus Slide! Optical Beam Loss Monitor

- Also starting development on Optical Beam Loss Monitor (O-BLM)
  - We found large beam-induced signal on optical fiber (Cherenkov light produced when beam loss particles hit fiber?)
  - Install optical fiber along beamline and use that signal to measure beam loss!
  - Use precise timing information to localize beam loss point
  - Can measure beam loss along the entire beamline with only a few electronics channels

Optical fiber installed in FF section of beamline →

O-BLM measurement principle

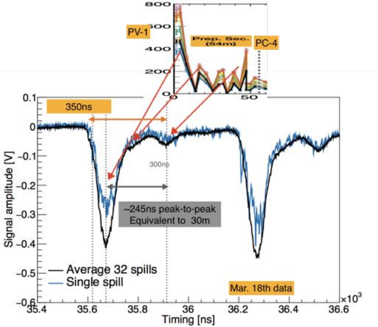


S. Cao *et al.*, Proceedings of IBIC2020, WEPP06, 2020

Bonus Slide! Optical Beam Loss Monitor

- Performed beam test of O-BLM during previous T2K beam run
- Covered 37 m of the neutrino extraction beamline FF section and 54 m of the prep. section with just 2 fibers (one 40 m and the other 60 m) and 3 electronics channels
- Setup is simple (fiber is laid out in a relatively straight line along the beamline)
- Optical readout with a (metal package) PMT or MPPC placed near the beamline

Peaks in O-BLM timing signal correspond to different loss points along the beamline :



- No issue observed during 1-month operation
    - However, radiation hardness of photosensor placed near the beamline needs further investigation

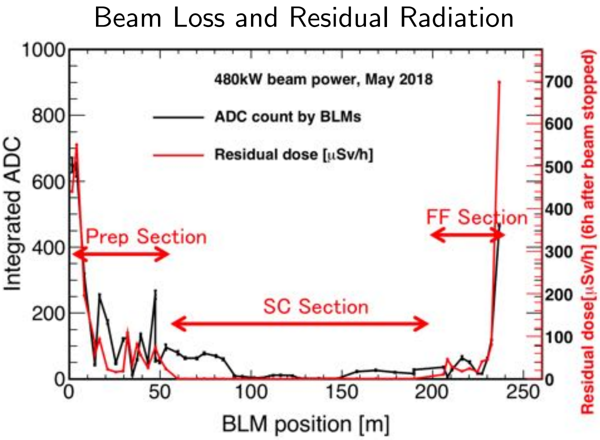
Conclusion

- New proton beam monitors :
  - Wire Segmented Emission Monitor (WSEM) – reduced beam loss
    - Working stably since 2018
  - 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
  - Optical Beam Loss Monitor (O-BLM) – new method for beam loss monitoring
    - Successfully tested in 2021

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

Backup Slides

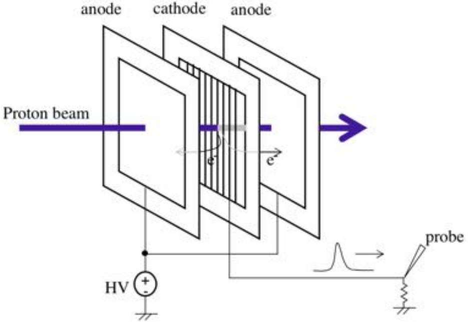
Beam Loss + Residual Radioactivity



- 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

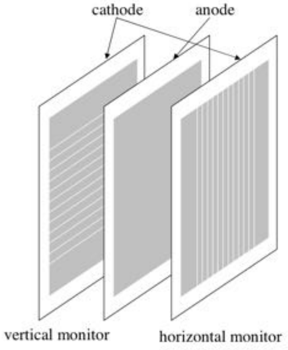
J-PARC NU SSEM Principle and Design

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

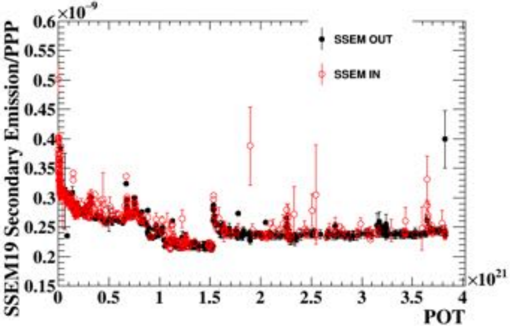


- Single anode plane between two stripped cathode planes
- 5 μm thick Ti foils

SSEM19 must be used continuously

SSEM19

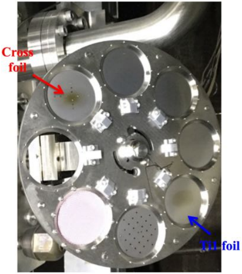
- For continuous monitoring of beam position, width at the beam window + target
  - A beam abort interlock signal is fired in order to avoid potential damage to the beam window/target if :
    - Beam density @target $N_p/(\sigma_x \times \sigma_y) < 2 \times 10^{13}$ ppp/mm^2
    - Beam position becomes 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



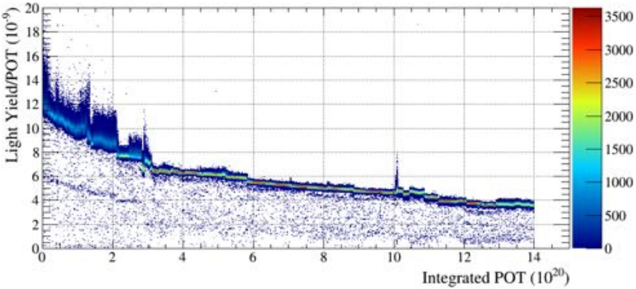
OTR Stability

- 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) :

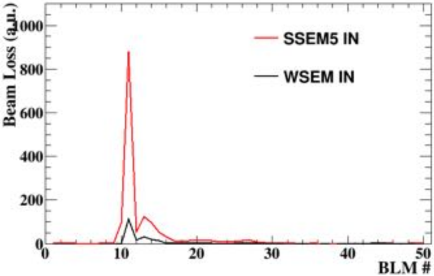


WSEM Beam Loss Check

- 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

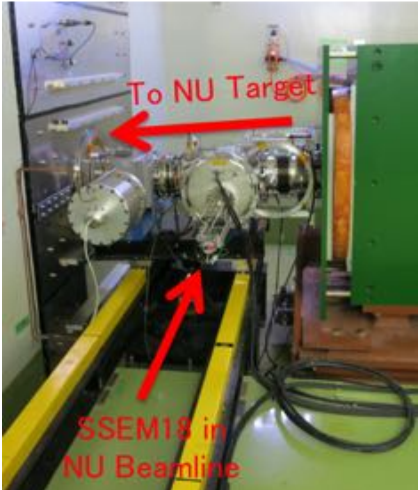
Loss due to WSEM vs that due to neighboring SSEM :



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



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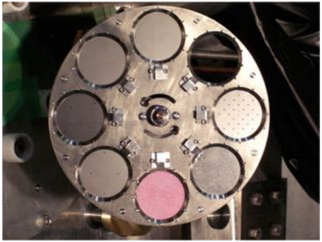
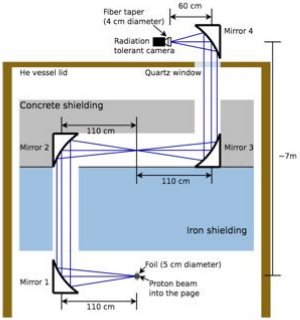
OTR Principle and Design

- 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



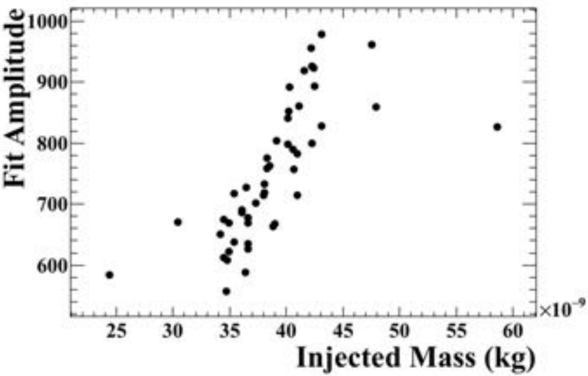


OTR Upgrades

- 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

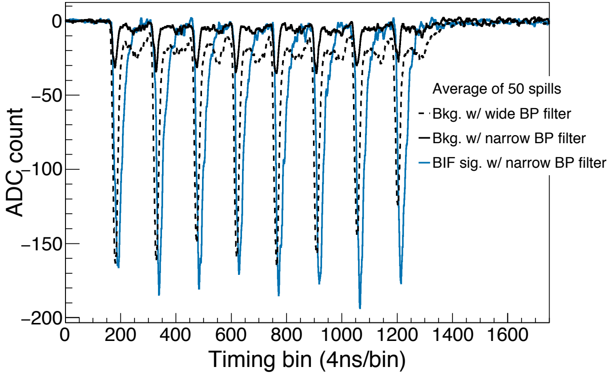
Is It Really BIF Light ?

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

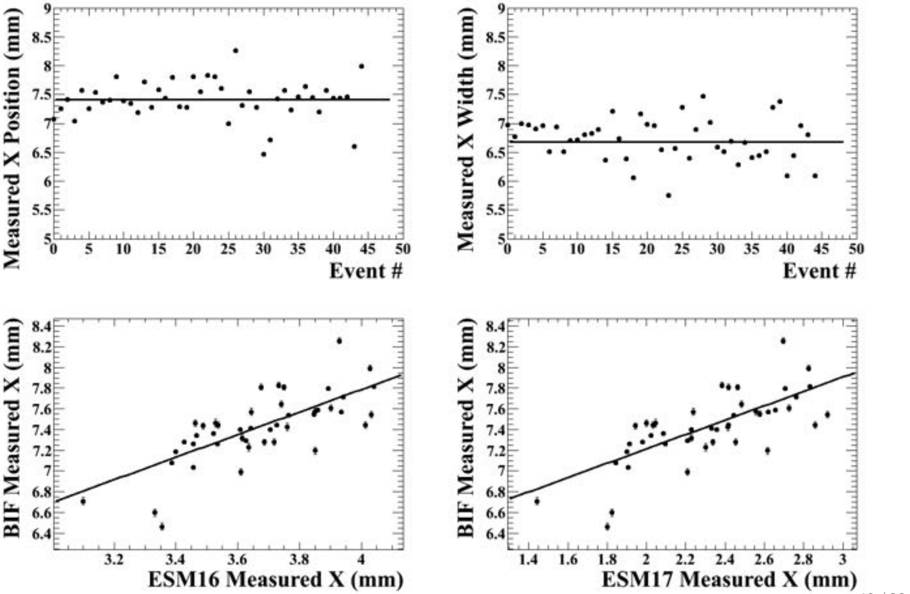


BIF Background Mitigation in Optical Fibers

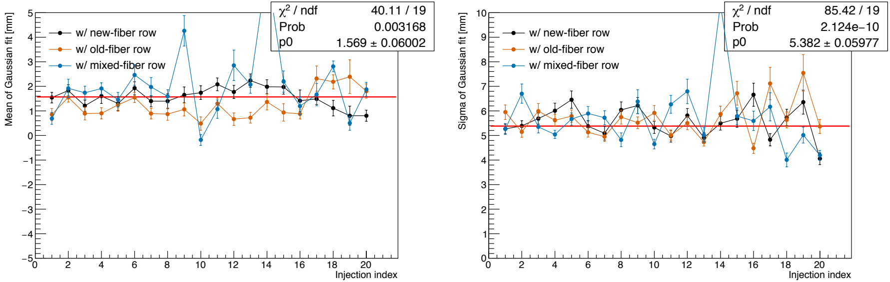
- During initial BIF test runs, signal to beam-induced background ratio for optical fiber + MPPC readout arm was close to ~1:1!
- Reduced background size to ~1/12 of signal by optical filtering



BIF Horizontal Measurement Stability



BIF Vertical Measurement Stability



- Position and width measurements relatively stable
- Fluctuations can be due to true changes in beam properties, or statistical fluctuation yielding insufficient photons for precise profile reconstruction