J-PARC Neutrino Beamline Proton Beam Monitors

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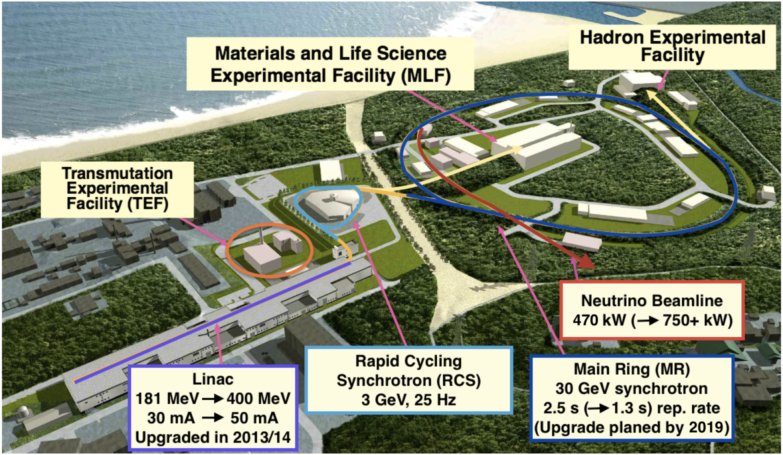
Outline

- Neutrino Primary Proton Beam Monitors
    - Overview
    - Upgrades

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 ∼485 kW)

J-PARC Beam Power Upgrades

Beam Power	485kW (achieved)	750kW (proposed) [original]	1MW (demonstrated)	1.3MW (proposed)
# of protons/ pulse	2.4×10^{14}	2.0×10^{14} [3.3×10^{14}]	2.6×10^{14}	3.2×10^{14}
Operation cycle	2.48 s	1.3 s [2.1 s]	1shot	1.16 s

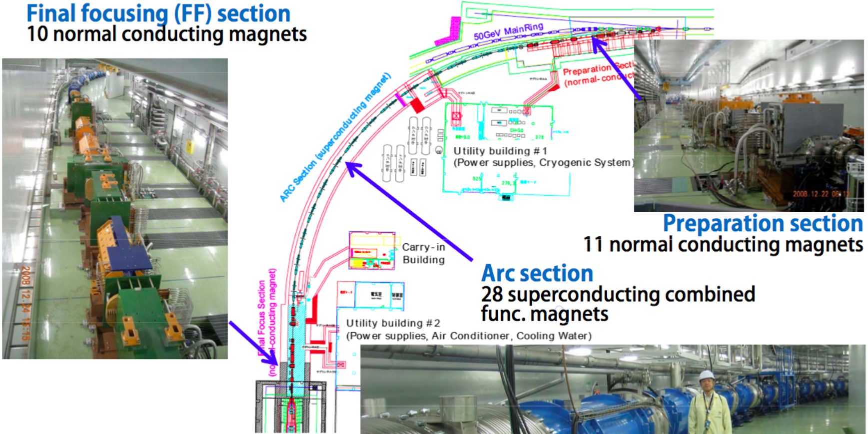
+25%

+18%

- Currently : 485 kW with 2.48 s repetition rate
  - 500+ kW achieved during beam tests
- Plan to upgrade MR power supplies in 2021/2022 to reach 1.3 s repetition rate
  - RF improvements can allow for further decrease to 1.16 s
- Plan to improve beam stability, reduce MR beam losses to increase number of protons per pulse

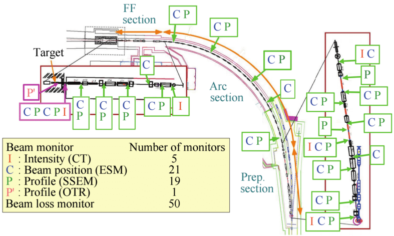
- Upgrades to J-PARC neutrino beamline needed to accept high power beam

Primary Proton Beamline

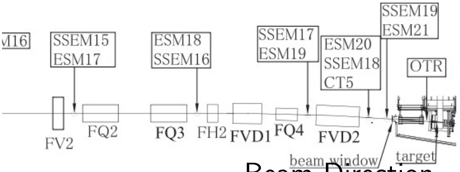


- Beam orbit (and beam loss) should be firmly controlled anytime.

Neutrino Primary Proton Beam Monitors



Beamline Final Focusing Section



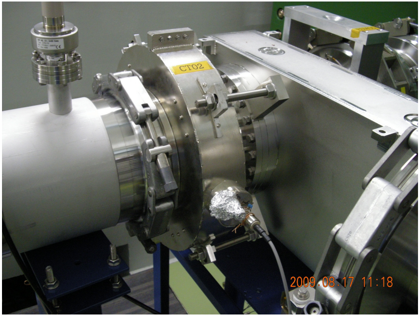
Beam Direction ⟶

- Beam monitors are essential for protecting beamline equipment and understanding proton beam parameters for neutrino flux MC
- 5 CTs (Current Transformers) – monitor beam intensity
- 50 BLMs (Beam Loss Monitors)
- 21 ESMs (Electrostatic Monitors) – monitor beam position
- 19→18 SSEMs (Segmented Secondary Emission Monitors) – non-continuously monitor beam profile
- 1 OTR (Optical Transition Radiation) Monitor – continuously monitors beam at target → See talk by G. Santucci
- MUMON (Muon Monitor) – continuously monitors secondary muon beam position and profile → See talk by T. Honjo

CTs

5 CTs (Current Transformers)

- Monitor proton beam intensity
  - Ferromagnetic core made of FINEMET® from Hitahi Metals
  - 50-turn toroidal coil
- Biggest issue : calibration !
  - CT's calibrations have drifted by $\sim$2% with respect to one another over the full T2K run
  - Direct systematic error on cross section measurements
    - Cancels in near/far fit for neutrino oscillation analysis

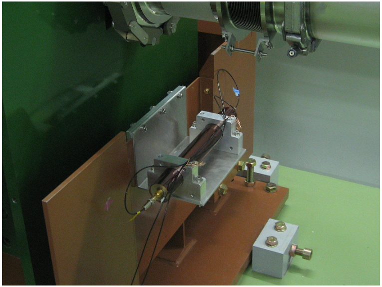


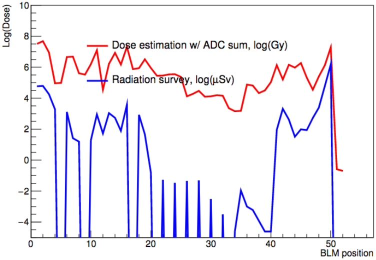
- Calibration campaign under way
  - Absolute calibration + analysis method update was done in 2014
    - Took calibration data with CT02 $\rightarrow$ extrapolate number of POT to CT05 using beam data
  - Data for direct absolute calibration of CT05 taken in 2018
  - Absolute CT error still being finalized, but error should be reduced 2.7%$\rightarrow$<2% after re-calibration campaign

BLMs

50 BLMs (Beam Loss Monitors)

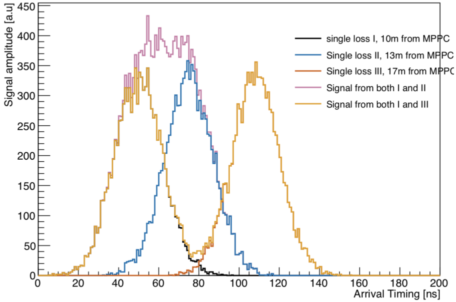
- Wire proportional counter filled with an Ar-CO_2 mixture
- Continuously monitor beam loss
- The BLM signal is integrated during each beam spill, and if it exceeds a threshold a beam abort interlock signal is fired
- BLMs have been working stably
- R&D for new BLM upgrade ongoing :
    - OBLM – BLM by optical fiber
    - Particles hit optical fiber + produce cherenkov or scintillation light
    - Photon detector at end of the fiber
    - Good timing resolution to give loss position information in the case of localized loss

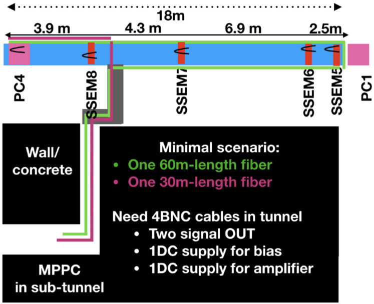




Optical-BLM R&D

Expected (optimistic) signal resolution :





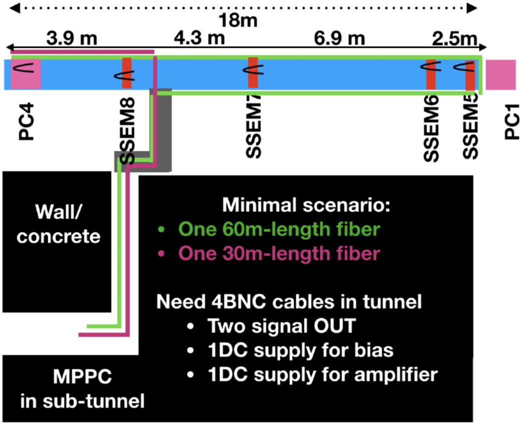
Assuming :

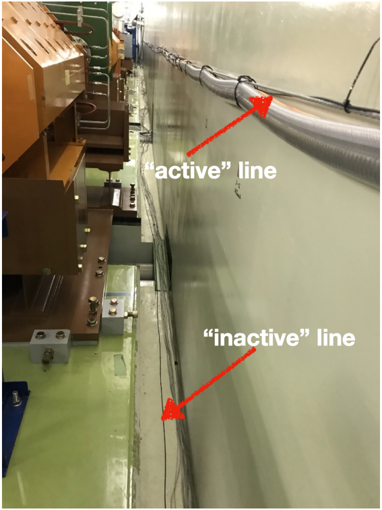
- Proton speed: 3.3ns/meter
- Light in fiber: 5ns/meter
- Signal separation: 8.8ns/meter if layout fiber such that earlier signal reaches MPPC in advance
- Bunch width: ∼13ns (dominant factor in discriminating the response timing)
- Signal readout resolution 5ns
- No additional smearing by geometrical effects
- Background≪signal

→ Signal peaks are well-separated if two signal-inducing loss positions are separated by $>\sim$7m

Optical-BLM R&D

- Installed 2 optical fibers along the beamline for first beam test (yesterday!)
- Read-out by MPPCs in subtunnel behind shielding

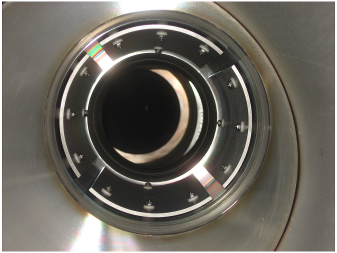




ESMs

21 ESMs (Electrostatic Monitor)

- Four segmented cylindrical electrodes surrounding the proton beam orbit
- Non-destructively, continuously monitor the proton beam position

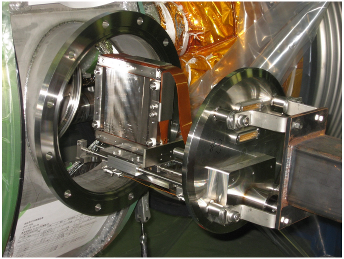


- Precision on the beam position measurement is better than 450 μm
  - Including resolution + alignment
  - However, ESMs are currently mainly used for monitoring stability of beam position, rather than for calculating absolute beam position
- Now thinking of ways to improve the ESM measurement precision
  - Re-calibration campaign needed
  - Considering analysis update (peak search $\rightarrow$ signal integration) to improve measurement stability

SSEMs

19 →18 SSEMs (Segmented Secondary Emission Monitor)

- Measure beam profile during beam tuning by secondary emission from Ti foil strips
- Two 5-μm-thick titanium foils stripped horizontally and vertically, with a 5-μm-thick anode HV foil between them
  - Strip width : 2∼5 mm, optimized according to expected beam size

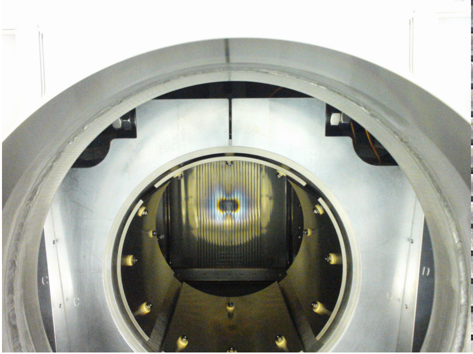


- 1 SSEM causes 0.005% beam loss → Only most downstream SSEM (SSEM19) can be used continuously
  - Others remotely move into and out of the beamline
  - SSEM19 used continuously → Need to carefully check any possible degradation as integrated POT on monitor increases

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 2020 or 2021

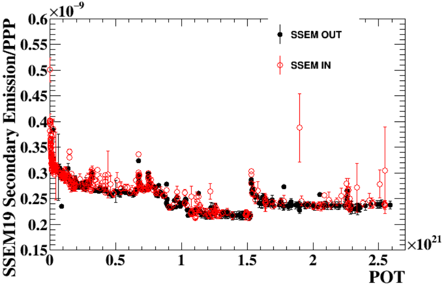
Downstream side after $\sim 2.3 \times 10^{21}$ Incident Protons



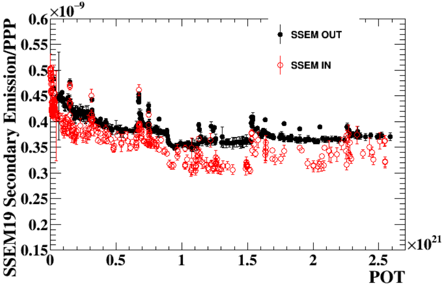
Upstream side after $\sim 3.2 \times 10^{21}$ Incident Protons

SSEM19 Secondary Emission Stability

SSEM19X Secondary Emission



SSEM19Y Secondary Emission



- Secondary emission/PPP vs integrated incident POT
  - SSEM19 secondary emission doesn't seem to be degrading (other than initial "burn in") $\rightarrow$ generally stable
  - Some jumps correlated with beam power
  - Upstream plane (SSEM19Y) can "see" if upstream SSEM18 is IN or OUT of beam – effect by emitted electrons from upstream SSEM
- Will continue to use SSEM19 continuously for now, plan to exchange during summer 2020 or 2021

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 may increase 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

New WSEM Beam Profile Monitor

- New Wire Secondary Emission Monitor (WSEM) designed to measure proton beam profile in J-PARC neutrino beamline
  - Developed in collaboration with engineers at FNAL, supported as a US/Japan collaboration project
- Monitor beam profile using twinned 25 μm Ti grade 1 wires
  - Exact same principle as SSEMs but with reduced material in the beam $\rightarrow$ 10x reduced beam loss
  - C-shape allows monitor to be moved into and out of the beam wile the beam is running
  - Now considering other wire materials (carbon, CNT, SiC) to further improve robustness

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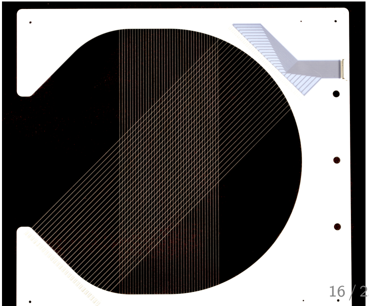
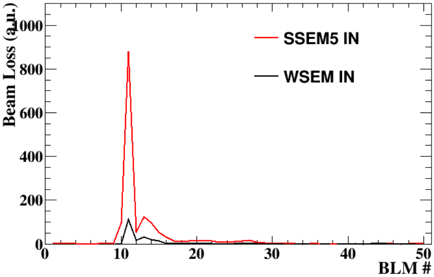


WSEM Beam Loss Check

- 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 :

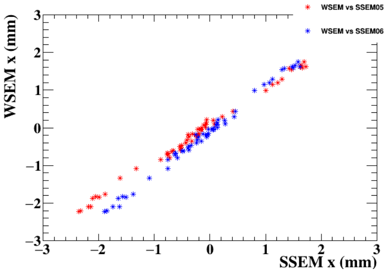


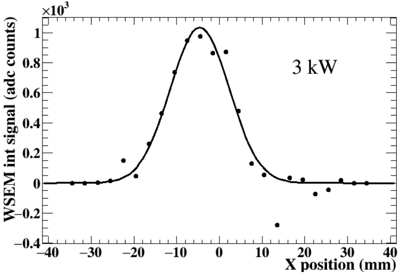
Monitor	Strip Size	Area in Beam (mm^2)	Measured Signal (a.u.)	Volume in Beam (mm^3)	Measured Loss (a.u.)
SSEM	2∼5mm×5μm	7.07	60300	0.106	872
WSEM	25μm⌀x2	0.24	2300	0.007	112
Ratio SSEM/WSEM	–	29.5	26	15.1	7.8

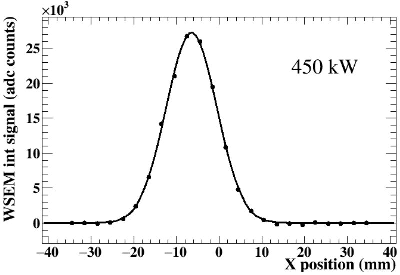
WSEM Signal Check

- WSEM resolution, precision equivalent to SSEM
  - Position measurement precision 0.07mm, stability ±0.15mm
  - Width measurement precision 0.2mm, stability ±0.1mm
- No issue during long-term stress test
  - 160 hours in 460∼475kW beam $\sim 5.6 \times 10^{19}$ incident protons

WSEM vs SSEM x :

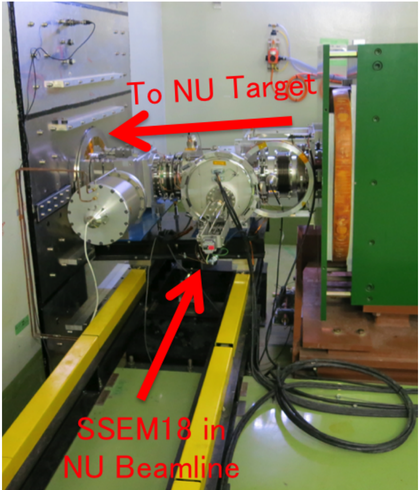






SSEM18→WSEM Exchange

- Replaced SSEM18 with WSEM in December 2018
  - Since beam loss is significantly lower with WSEM, can use WSEM18 continuously in case of SSEM19 failure
  - Complete testing during upcoming J-PARC neutrino beam time



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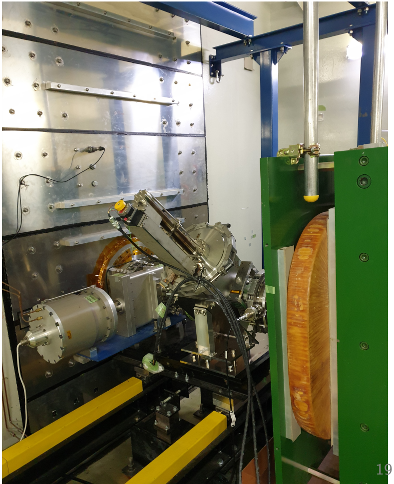
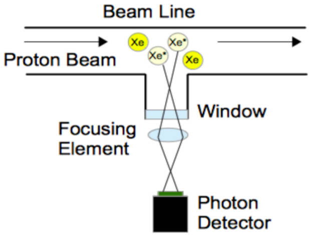


Beam Induced Fluorescence (BIF) Monitor

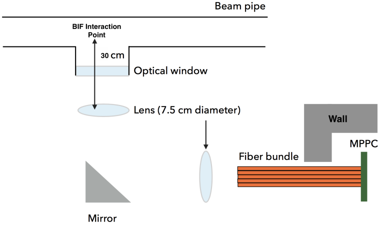
- Uses fluorescence induced by proton beam interactions with gas injected into the beamline
  - Protons hit gas (i.e. N_2) inside the beam pipe
  - Gas molecules are excited or ionized by interaction with protons, then fluoresce during de-excitation
- Continuously and non-destructively monitor proton beam profile
  - $5 \times 10^{-8}\%$ beam loss for 1m of gas at 10^{-2}Pa
    - $\sim 10^{-5}$x less beam loss than 1 SSEM



- Monitor development ongoing – collaboration between KEK, IPMU/TRIUMF, Okayama Univ.

M. Friend *et al.*, Proceedings of IBIC2016, WEPG66, 2016
S. Cao *et al.*, Proceedings of IBIC2018, WEPC08, 2018
S. Cao *et al.*, Proceedings of IBIC2019, 2019

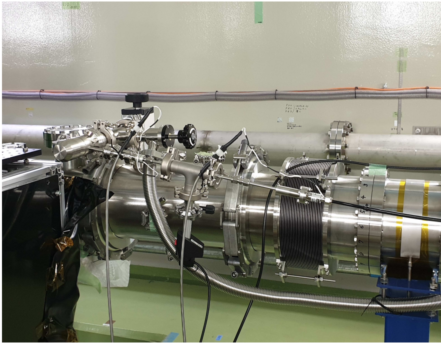
Beam Induced Fluorescence (BIF) Monitor



- Now doing R&D for various components :
- Gas injection :
  - For ∼1000 photons/spill, need to **locally** degrade vacuum level $\sim 10^{-5}$Pa $\rightarrow \sim 10^{-2}$Pa
- Light transport and focusing : Must be radiation hard
- Light detection :
  - Must work in/near radiation environment
  - Must work down to very low light levels
  - Must be fast to compensate for drift of ions in beam space-charge
- Installing full working prototype in beamline now!

BIF Monitor Gas Injection, etc

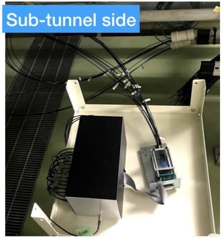
- Developed pulsed gas injection system
  - Inject $\sim$400μs gas pulse triggered by beam spill trigger
  - Two-stage pulse valve system with buffer chamber
    - Control pressure upstream of 2nd pulse valve + act as safety chamber in case of valve failure
  - Control + interlock system for gas injection also developed
- Black coating of beamline chamber to prevent reflected light (background)
  - Diamond-Like Carbon (DLC)

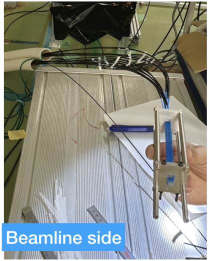


- Various tests of gas injection in a test chamber + the true beamline
  - To ensure valve stability + robustness
  - To compare measured gas flow to that predicted by simulation
  - To ensure that beamline components are not affected by injected gas
  - No issue found so far ! Planning gas injection beam test during upcoming neutrino beam run

BIF Monitor Light Transport and Detection System

Optical fiber array



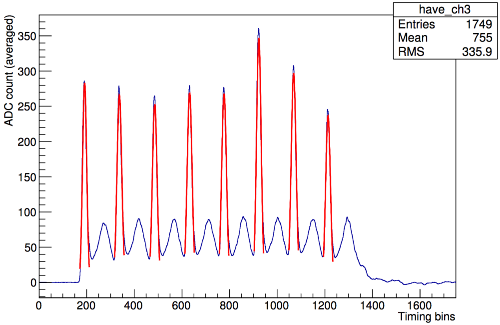


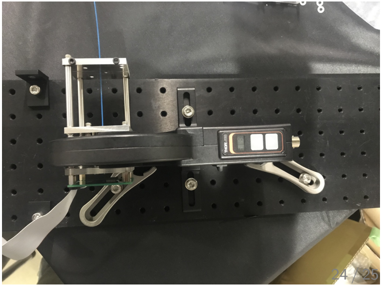
- Focus light from viewport on beampipe onto array of optical fibers
- Transport light away from high radiation environment near beampipe to optical sensors in lower-radiation subtunnel
  - Couple each fiber to MPPC
  - Inexpensive, fast, high gain
  - But not radiation hard

- 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)
  - Must mitigate by optical filtering or shielding or subtraction or...
- In parallel, developing more standard optical readout system – MCP-based image intensifier coupled to radiation-hard CID camera

Beam-Induced Noise On Optical Fibers

- Tested 800μm core silica optical fibers coupled to MPPC in planned BIF location during last beamtime (planned design)
- Found a large beam-induced background on the optical fibers :
  - $\sim$150 p.e.'s in-bunch timing + $\sim$150 p.e.'s out-of-bunch timing (c.f. expected 1000 detected BIF photons per spill / 30 fibers)
  - Suspect due to Cherenkov light (on-timing) and neutrons (off-timing)
  - Correlated w/ BLM44 – seems to be due to scattering from FQ2
  - Plan to mitigate by optical filtering – test next month !
  - If that doesn't work, shielding or background subtraction or ...





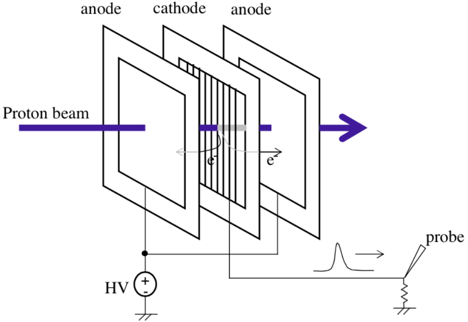
Conclusion

- Neutrino primary proton beam monitors generally working well
- Now working on R&D for reduced-loss and non-destructive proton beam profile monitoring

Backup Slides

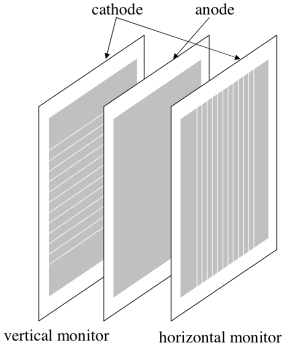
J-PARC NU SSEM Principle and Design

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