Development of New Proton Beam Monitors for J-PARC 1.3 MW Upgrade

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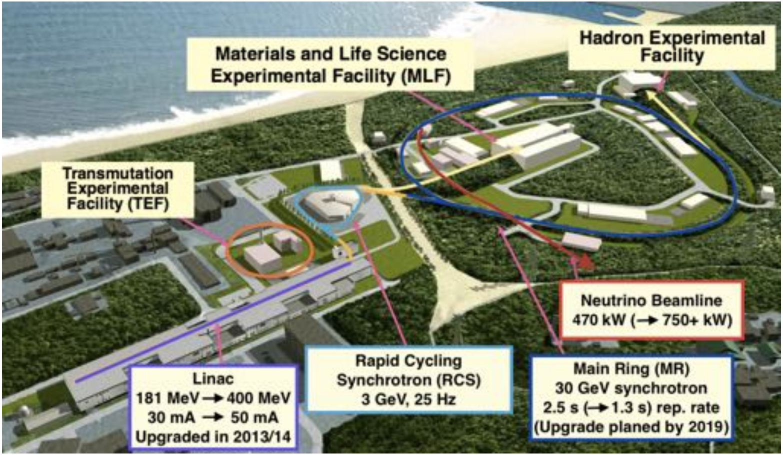
Outline

- Overview of J-PARC Neutrino Beamline + Proton Beam Monitors Used There
- Some Issues with Present Proton Beam Monitors
- New Profile Monitor Development
- Other 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

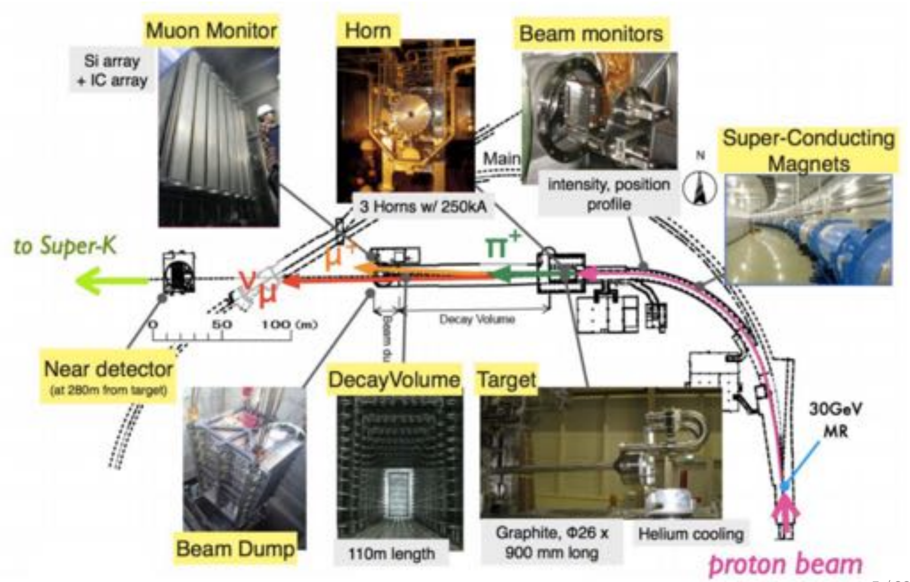
Beam Power	485kW (achieved)	750kW (proposed) [original]	1MW (demonstrated)	1.3MW (proposed)
# of protons/ pulse	2.4×10^{14}	2.0×10^{14} [3.3×10^{14}]	2.6×10^{14}	3.2×10^{14}
Operation cycle	2.48 s	1.3 s [2.1 s]	1shot	1.16 s

+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 Y. Sato, NuFACT2019, Plenary

- Upgrades to J-PARC neutrino beamline needed to accept high power beam Y. Oyama, NuFACT2019, WG3

J-PARC Neutrino Beamline

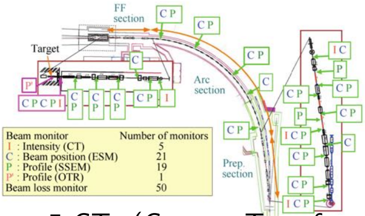


Why Is Proton Beam Monitoring Important?

- 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

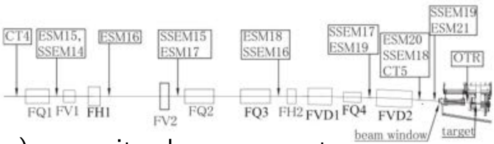
J-PARC Neutrino Beamline Proton Beam Monitors

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

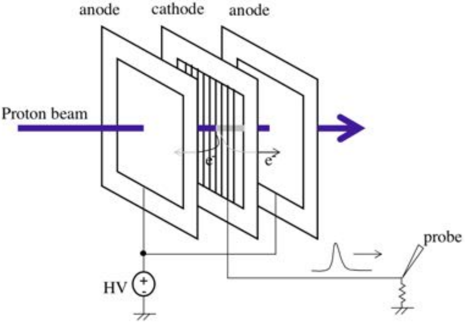
↥ These are non-interacting and should work stably even at 1.3MW ↥

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

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

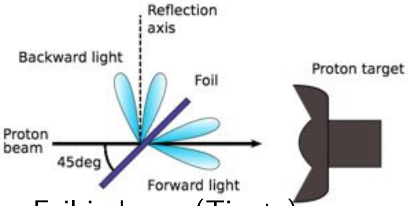
How to Measure the Proton Beam Profile

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)

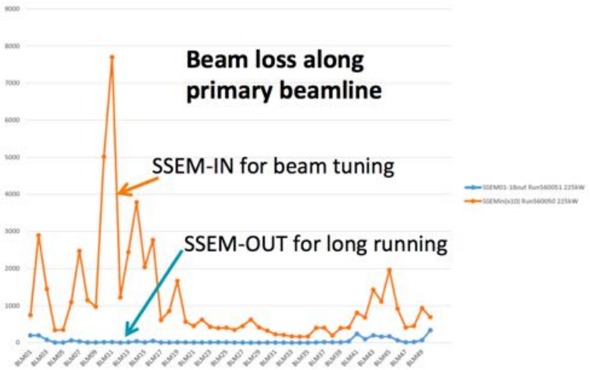


- Foil in beam (Ti, etc)
- Optical Transition Radiation produced when charged particles travel between two materials with different dielectric constants
    - OTR light proportional to beam profile
    - Light detected by rad-hard camera in low-rad area

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 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

Measured Beam Loss Due to SSEMs

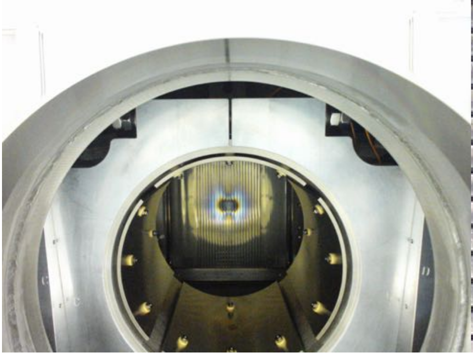


- Beam loss when SSEMs are IN is quite high
  - ~0.005% beam loss at each SSEM
- Can cause radiation damage, activation of beamline equipment
  - SSEMs upstream of the neutrino target station cannot be used continuously
  - SSEM1-18 are only used during beam tuning and optics checks

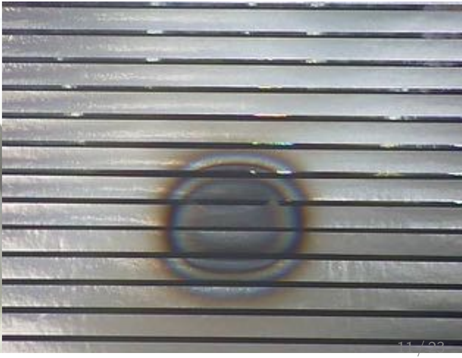
SSEM Foil Discoloration

- 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 2020 or 2021

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



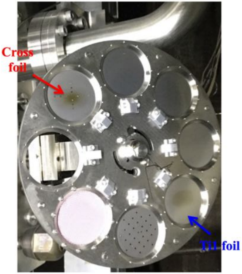
Upstream side after $\sim 3.2 \times 10^{21}$ Incident Protons



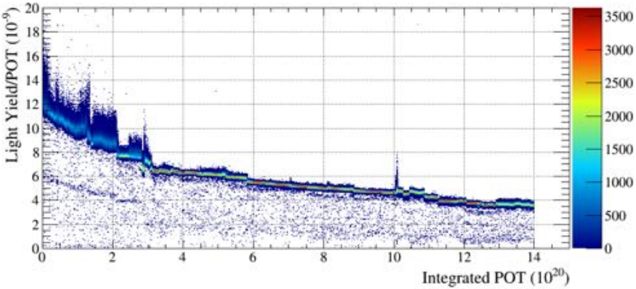
OTR Stability

- 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) :



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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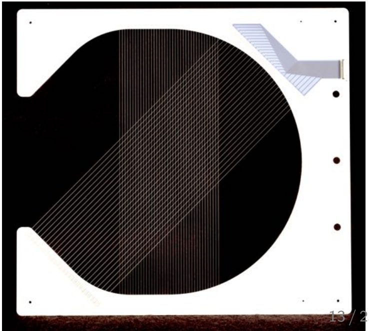
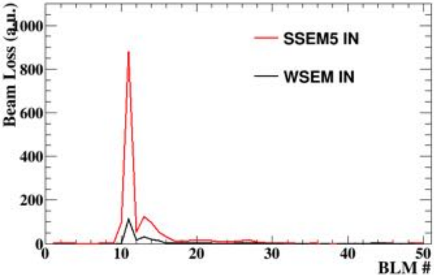


WSEM Beam Loss Check

- 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 :

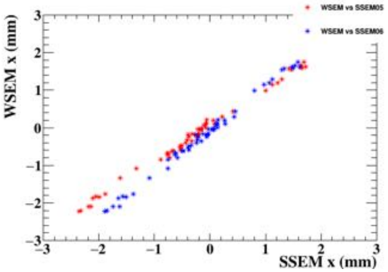


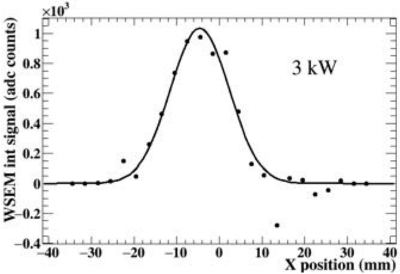
Monitor	Strip Size	Area in Beam (mm^2)	Measured Signal (a.u.)	Volume in Beam (mm^3)	Measured Loss (a.u.)
SSEM	2~5mm×5μm	7.07	60300	0.106	872
WSEM	25μm⌀x2	0.24	2300	0.007	112
Ratio SSEM/WSEM	–	29.5	26	15.1	7.8

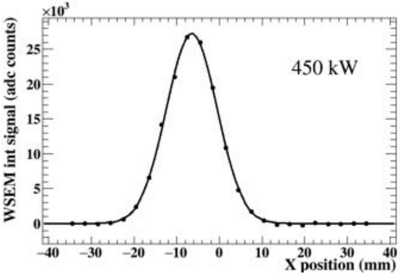
WSEM Beam Loss, Signal Check

- 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
    ~ 5.6×10^{19} incident protons

WSEM vs SSEM x :

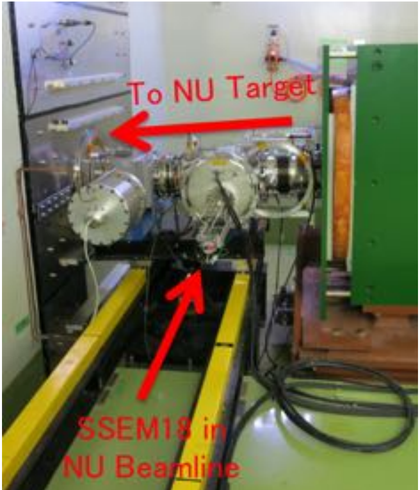






SSEM18→WSEM Exchange

- 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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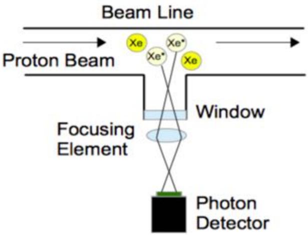
Beam Induced Fluorescence (BIF) Monitor

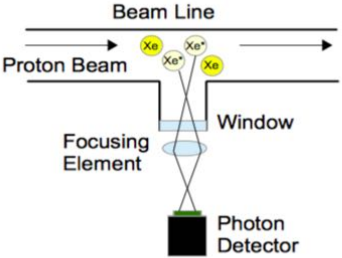
- Uses fluorescence induced by proton beam interactions with gas injected into the beamline
  - Protons hit gas (i.e. N_2) inside the beam pipe
  - Gas molecules are excited or ionized by interaction with protons, then fluoresce during de-excitation
- Continuously and non-destructively monitor proton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

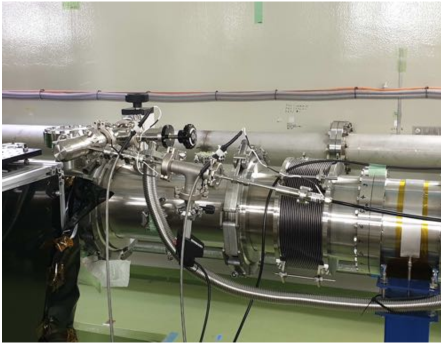
Beam Induced Fluorescence (BIF) Monitor



- 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!

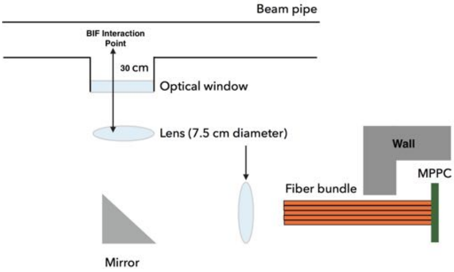
BIF Monitor Gas Injection, etc

- Developed pulsed gas injection system
  - Inject ~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



- 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

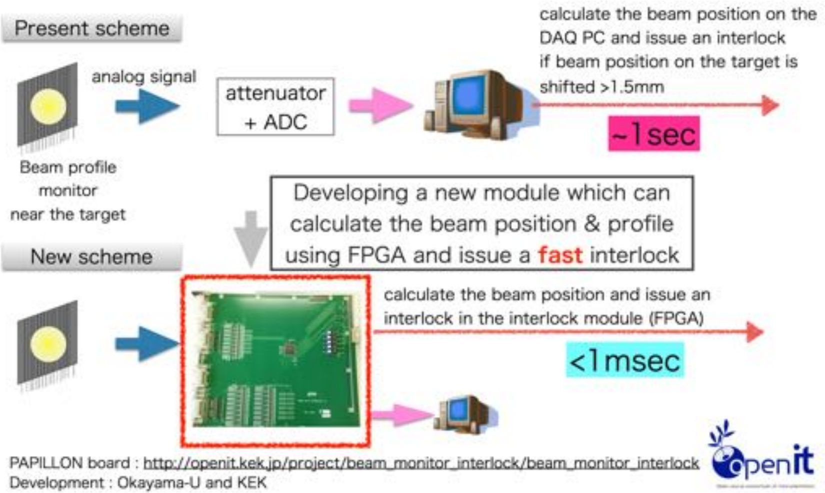
OTR Upgrades

- 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

DAQ and Interlock System Upgrades

- Beam spill repetition rate to be upgraded 2.48s→1.16s
  - Developed new ADC boards to reduce monitor readout latency
  - Developed new interlock module for fast beam interlock



K. Sakashita *et al.*, Proceedings of IBIC2018, MOOB04, 2018

Conclusion

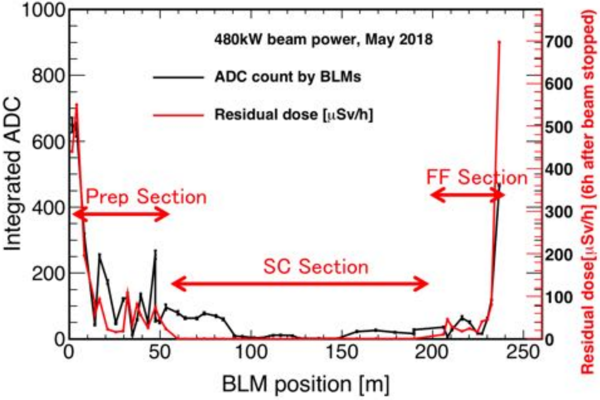
- Beam monitor development projects very mature
  - Wire Segmented Emission Monitor (WSEM) – reduced beam loss
  - Beam Induced Fluorescence Monitor (BIF) – non-destructive + robust monitor
  - OTR upgrades
  - DAQ + interlock upgrades
- All these monitor upgrades will be tested during upcoming J-PARC neutrino beamtime from November~
- Proton beam monitors in J-PARC neutrino primary beamline should be ready for 1.3MW beam very soon !

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

Backup Slides

Beam Loss + Residual Radioactivity

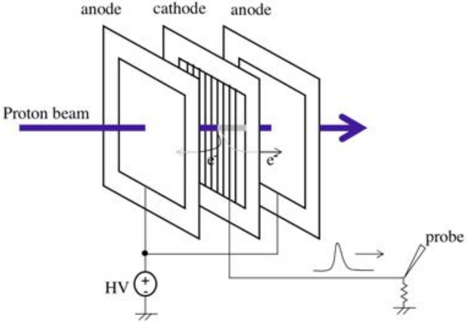
Beam Loss and Residual Radiation



- 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

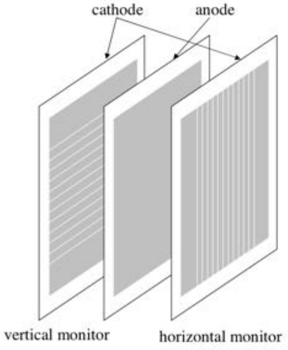
J-PARC NU SSEM Principle and Design

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

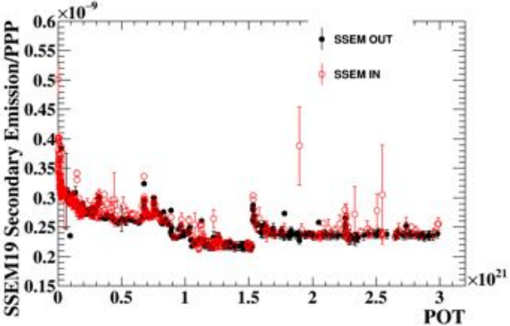


- Single anode plane between two stripped cathode planes
- 5 μm thick Ti foils

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 ~3×10^{21}protons (4×4mm beam spot)
- Important to monitor degradation as total integrated POT increases



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