Challenges in Continuous Beam Profile Monitoring for MW-Power Proton Beams

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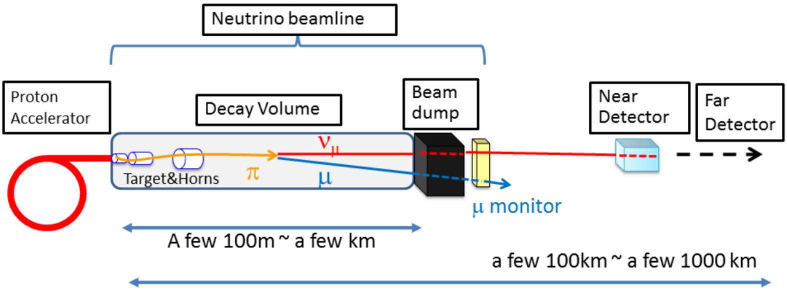
Outline

- High-Energy, High-Power Neutrino Beamlines
- Continuous Proton Beam Transverse Profile Monitoring
- Continuous Monitoring Challenges
- New Profile Monitor Development

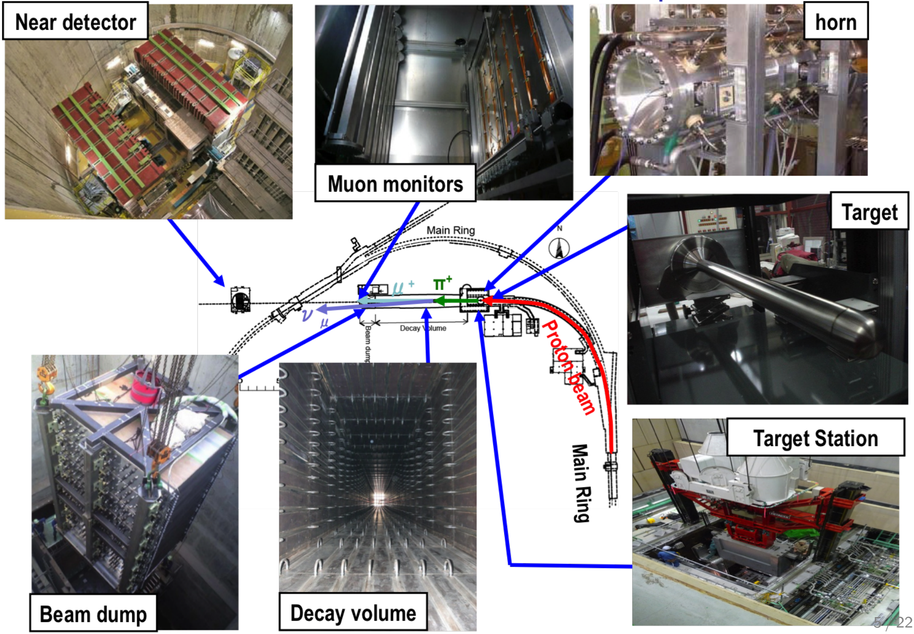
High-Energy, High-Power Neutrino Beamlines

Neutrino Beam Production



- Slam high-energy high-intensity proton beam into long target
- Focus outgoing hadrons in electro-magnetic focusing horns
- Pions decay to muons and muon-neutrinos in long decay volume
- Stop interacting particles in beam dump; neutrinos continue on to near and far detectors for neutrino experiments
  - Instrument beam dump to continuously monitor muon beam
- Number of neutrinos is proportional to number of protons incident on the target – maximize proton beam power to maximize flux

J-PARC Neutrino Beamline Components



Proton Beams for Neutrino Experiments

J-PARC neutrino beamline for the T2K + future Hyper-K experiments, etc.

- Beam Energy: 30 GeV
- Beam Power: 500 kW $\rightarrow$1.3 MW
- Beam Intensity: 2.4E14 ppp $\rightarrow$ 3.2E14 ppp
- Beam Bunches: 8
- Pulse Length: 4.2 μs
- Duty cycle: 2.48 s $\rightarrow$ 1.16 s
- Beam spot size at target: 4 mm
- Running since: 2009

NUMI neutrino beamline @FNAL for the NOνA experiment, etc.

- Beam Energy: 120 GeV
- Beam Power: 700-750 kW $\rightarrow$ 1 MW
- Beam Intensity: 5.4E13 ppp $\rightarrow$ 6.5E13 ppp
- Beam Bunches: 588
- Pulse Length: 11 μs
- Duty cycle: 1.333 s $\rightarrow$ 1.2 s
- Beam spot size at target: 1.3 mm $\rightarrow$ 1.5 mm
- Running since: 2005

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LBNF neutrino beamline @FNAL for the future DUNE experiment

- Beam Energy: 60-120 GeV
- Beam Power: 1.2 MW $\rightarrow$ 2.4 MW

Under Design

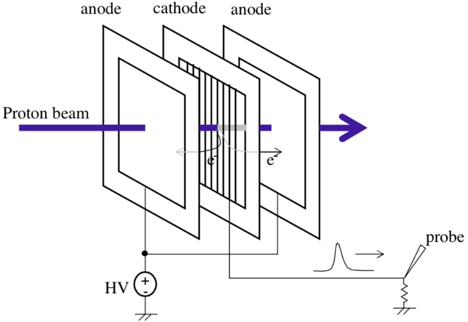
Continuous Proton Beam Transverse Profile Monitoring

Why Is Extraction 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
    $\rightarrow$ Need continuous monitoring
  - At J-PARC NU beamline, a beam abort interlock signal is fired if :
    - Beam position becomes significantly offset from centered
    - Beam density at target becomes $N_p/(\sigma_x \times \sigma_y) < 2 \times 10^{13}$ ppp/mm^2
- 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

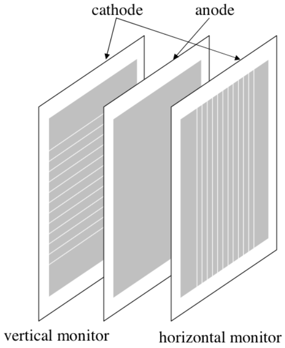
J-PARC NU Segmented Secondary Emission Monitor (SSEM)

SSEM Principle



- Protons interact with foils
- Secondary electrons are emitted from segmented cathode plane
- Compensating charge in each strip is read out as positive polarity signal
- Used continuously 3.2 m upstream of the neutrino production target

J-PARC NU SSEM

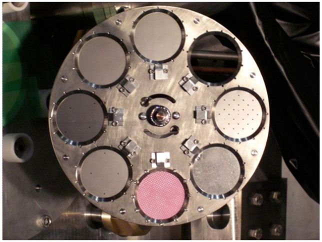


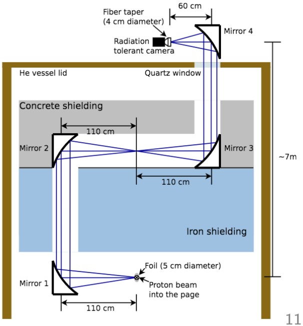
- Single anode plane between two stripped cathode planes
- 5 μm thick Ti foils

J-PARC NU Optical Transition Radiation Monitor (OTR)

- Continuously monitors beam profile directly upstream of the target
- OTR light is produced when charged particles travel between two materials with different dielectric constants
- Monitors backwards-going light from 50-μm-thick Ti foil
  - Light is directed to TS ground floor by a series of 4 mirrors and then monitored by a rad-hard CID camera
- Rotatable disk w/ 8 foil positions; currently :
  - 4x Ti alloy (for physics running)
  - 1x ceramic (for low-intensity tuning)
  - 1x cross-pattern holes
  - 1x calibration holes
  - 1x empty

S. Bhadra *et al.*, *Nucl. Instr. and Meth. A* vol. 703, 45-58, 2013

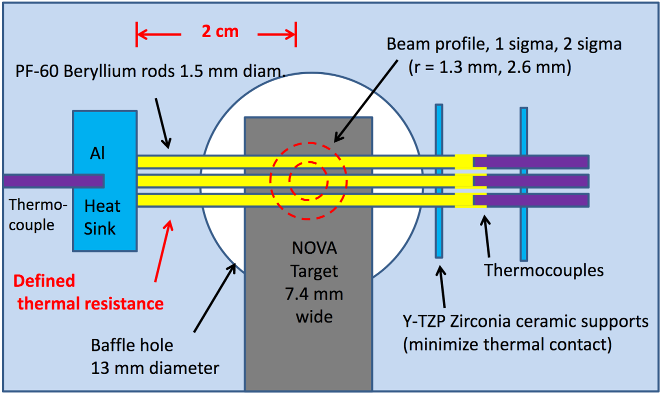




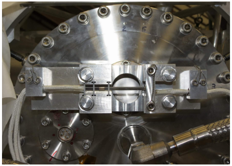
NUMI "Hylen Device" Principle and Design

Beryllium rods, near upstream window of target, to watch beam position

(not to scale; also baffle drawn behind target, although it is actually in front)



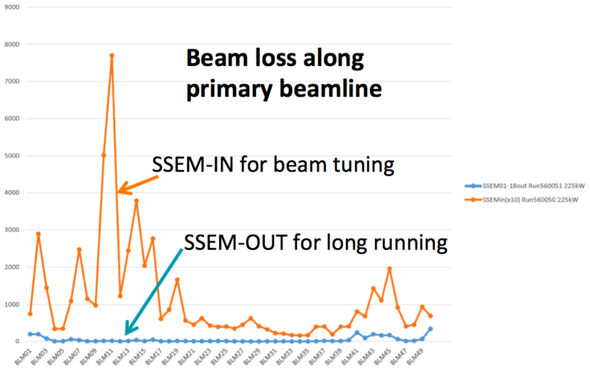
J. Hylen, "Thermal Position Monitor", NBI2014



- ΔT (Rod - Sink) $\propto$ (beam power deposition in rod)
  $\rightarrow$ Coarse profile derived from ratio of ΔTs of the different rods
- Thermocouples same material as the beam window – very robust
- ΔT is bulk phenomenon – surface degradation doesn't matter

Continuous Monitoring Challenges

J-PARC NU Beam Loss Due to SSEMs

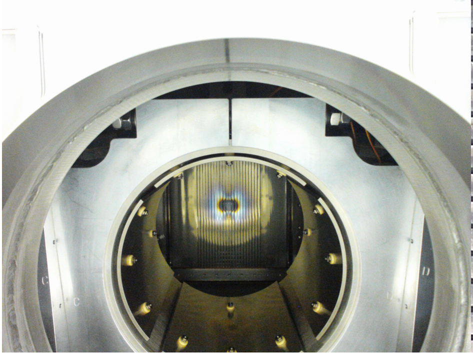


- Each SSEM causes ~0.005% beam loss
- Can cause radiation damage, activation of beamline equipment
  - SSEMs upstream of the neutrino target station cannot be used continuously – only used during beam tuning and optics checks

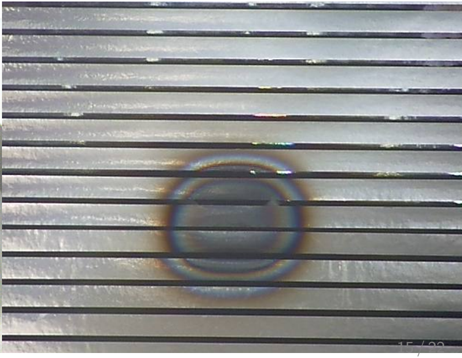
J-PARC NU SSEM Foil Discoloration

- Most downstream SSEM has been used continuously since 2009
- Foil inspection was performed in summer 2017 (downstream side) and fall 2018 (upstream side)
  - Significant discoloration of 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



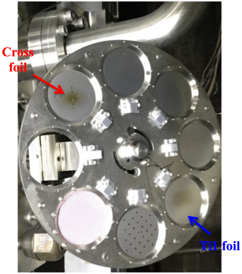
Upstream side after $\sim 3.2 \times 10^{21}$ Incident Protons



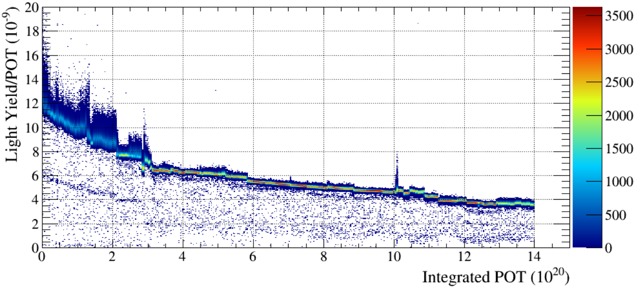
J-PARC NU OTR Stability

- 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 on CID camera
- Major foil failures of thin (few μm) foils possible

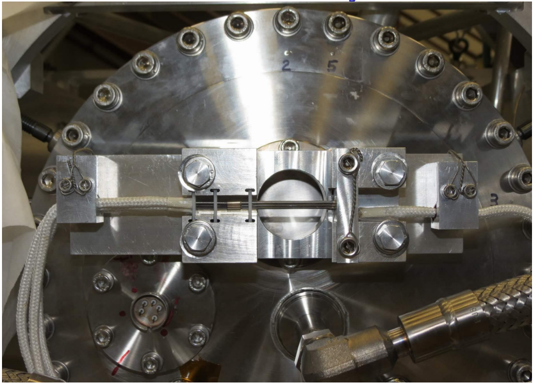
Foil Discoloration :



OTR Normalized Light Yield (Stability) :



NUMI "Hylen Device" Disadvantages



- Only 3 thermocouples means profile reconstruction is quite coarse
- Doesn't work pulse-by-pulse – requires stable beam operation
  - Characteristic timescale is ~9 s; wait ~1 minute for good stability
- Needs order 1°C temperature difference to provide reasonable measurement
  - Limited range
  - Doesn't work for low-intensity tuning

New Profile Monitor Development

Reduce Material to Reduce Beam Loss

- Developing wire profile monitors for J-PARC NU in collaboration with engineers at FNAL as a US/Japan collaboration project
- Developed monitor with twinned 25 μm Grade 1 Ti wires
    - Same principle as SSEMs but with reduced material in the beam
      → 10x reduced beam loss
      → Can use continuously further upstream
    - Maintain signal size at low beam power by maximizing surface area
    - Beam test for 160 hours in 460~475kW J-PARC beam → no issue
    - Can further upgrade wire material to be more robust
        - Ti Grade 5 ? Carbon filaments ? Carbon nanotube wire ?

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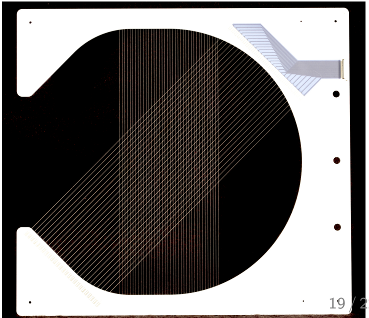
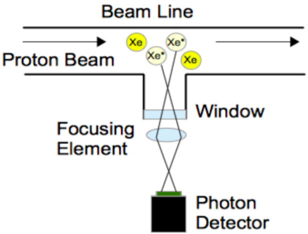


J-PARC NU Beamline OTR Upgrades

- 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)

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
    - $\sim 10^{-5}$x less beam loss than 1 SSEM



- Developing for J-PARC NU beamline :
  - Gas injection system
  - Light transport and focusing
  - Light detection system

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

Conclusion

- Continuous beam profile monitoring is essential for successfully running fixed target neutrino extraction beamlines
- Currently using various technologies without major issues
- Degradation of foils or wires may become an issue at higher beam intensities – upgrades and/or redundancy under development

Backup Slides

J-PARC Beam Power Upgrades

Beam Power	485kW (achieved)	750kW (proposed) [original]	1MW (demonstrated)	1.3MW (proposed)
# of protons/ pulse	2.4 x 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

NUMI "Hylen Device" Pros and Cons

CONs:

- Not a single pulse device, use with stable beam
  - characteristic time scale ~ 9 seconds; want ~ minute to get really stable
- Needs a couple deg. dT to provide measurement, limited to < 200 deg.
  - Limited beam power range, not a low intensity tune-up device

PROs:

- Simple, robust – *should be able to take anything the target window can take*
- Radiation hard
- Depends on a bulk volume phenomenon
  - *Surface degradation doesn't matter*
- Readout can be off-time of beam pulse
  - *Immune to noise pick-up, stray charge*
- Minimal utilities (*no vacuum, no gas, no water, no windows, …*)
- Can calibrate in-place *scan beam across rods*
  - Peak temperature when beam is pointed at rod
    (*no "electronic center" to be pre-calibrated as in a BPM*)
  - Simultaneously see ΔT ratios of the rods
- No maintenance

J. Hylen, "Thermal Position Monitor", NBI2014