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

Megan Friend

High Energy Accelerator Research Organization (KEK)

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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 = 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

<table>
<thead>
<tr>
<th>Beam Power</th>
<th>485kW (achieved)</th>
<th>750kW (proposed) [original]</th>
<th>1MW (demonstrated)</th>
<th>1.3MW (proposed)</th>
</tr>
</thead>
<tbody>
<tr>
<td># of protons/pulse</td>
<td>2.4 x 10^{14}</td>
<td>2.0 x 10^{14} [3.3 x 10^{14}]</td>
<td>2.6 x 10^{14}</td>
<td>3.2 x 10^{14}</td>
</tr>
<tr>
<td>Operation cycle</td>
<td>2.48 s</td>
<td>1.3 s [ 2.1 s ]</td>
<td>1 shot</td>
<td>1.16 s</td>
</tr>
</tbody>
</table>

- 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
    \[\rightarrow\] 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 5\(\mu\)m 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 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

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 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
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:

<table>
<thead>
<tr>
<th>Monitor</th>
<th>Strip Size</th>
<th>Area in Beam (mm²)</th>
<th>Measured Signal (a.u.)</th>
<th>Volume in Beam (mm³)</th>
<th>Measured Loss (a.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSEM</td>
<td>2~5mm×5µm</td>
<td>7.07</td>
<td>60300</td>
<td>0.106</td>
<td>872</td>
</tr>
<tr>
<td>WSEM</td>
<td>25µmØ×2</td>
<td>0.24</td>
<td>2300</td>
<td>0.007</td>
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Ratio:

SSEMS/WSEM = 29.5

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Ratio:

SSEMS/WSEM = 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
    ~ $5.6 \times 10^{19}$ incident protons
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
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.

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
    - \(10^{-5}\) Pa \(\rightarrow\) \(10^{-2}\) 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 ~400 µs 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
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!

Backup Slides
• 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

- 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 \( N_p / (\sigma_x \times \sigma_y) < 2 \times 10^{13} \text{ ppp/mm}^2 \)
    - Beam position becomes significantly offset from centered

- Originally, SSEM lifetime only estimated up to \( \sim 10^{20} \text{ protons/cm}^2 \)
- However, no issue seen at \( \sim 3 \times 10^{21} \text{ protons (4x4mm beam spot)} \)
- 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