High Power Target Monitoring at J-PARC Neutrino Extraction Beamline

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High Energy Accelerator Research Organization (KEK)

Rad-Hard Beam Instrumentation Workshop
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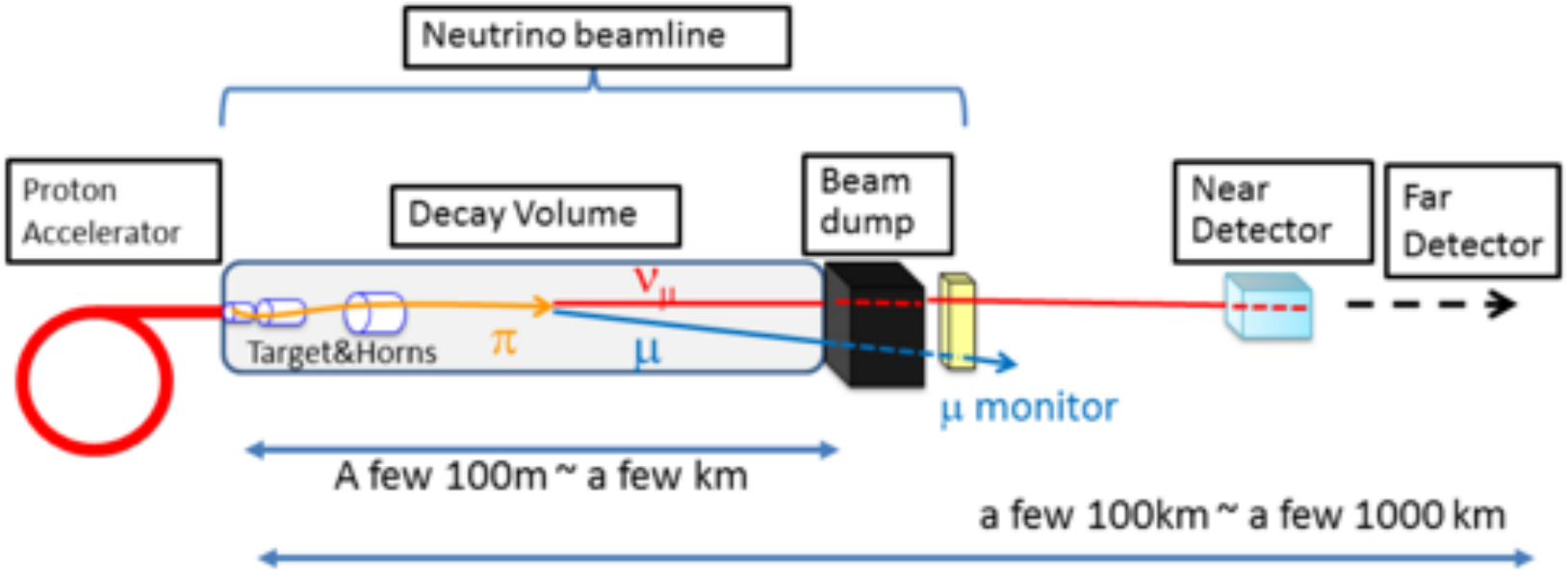
Outline

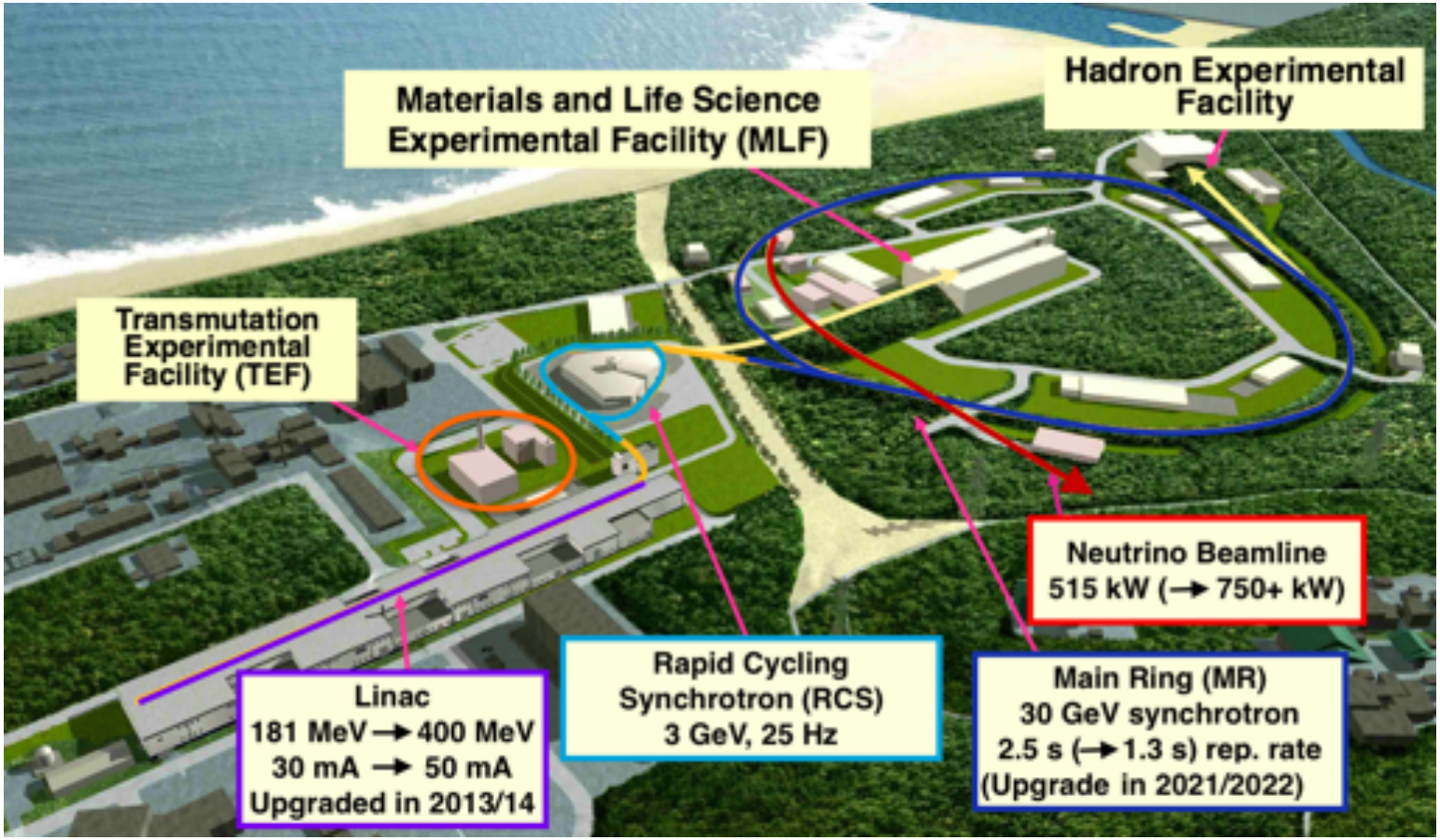
- The J-PARC Neutrino Beamline and Neutrino Production Target
- Monitoring the Neutrino Production Target
  - Target Temperature Monitoring
  - Target Cooling Gas Impurity Monitoring
  - Proton Beam Monitoring
  - Muon Monitoring
  - Neutrino Monitoring

The J-PARC Neutrino Beam



- 30 GeV protons from J-PARC accelerator hit a 90-cm-long monolithic carbon target and produce π's, K's, etc
- Outgoing hadrons are sign selected + focused in three electro-magnetic focusing horns
- π's decay into (mostly) μ's and ν_μ's in a $\sim$100-m-long decay volume
- The decay μ's are monitored using a muon monitor and stop in shielding, while the ν's continue on to the near and far detectors

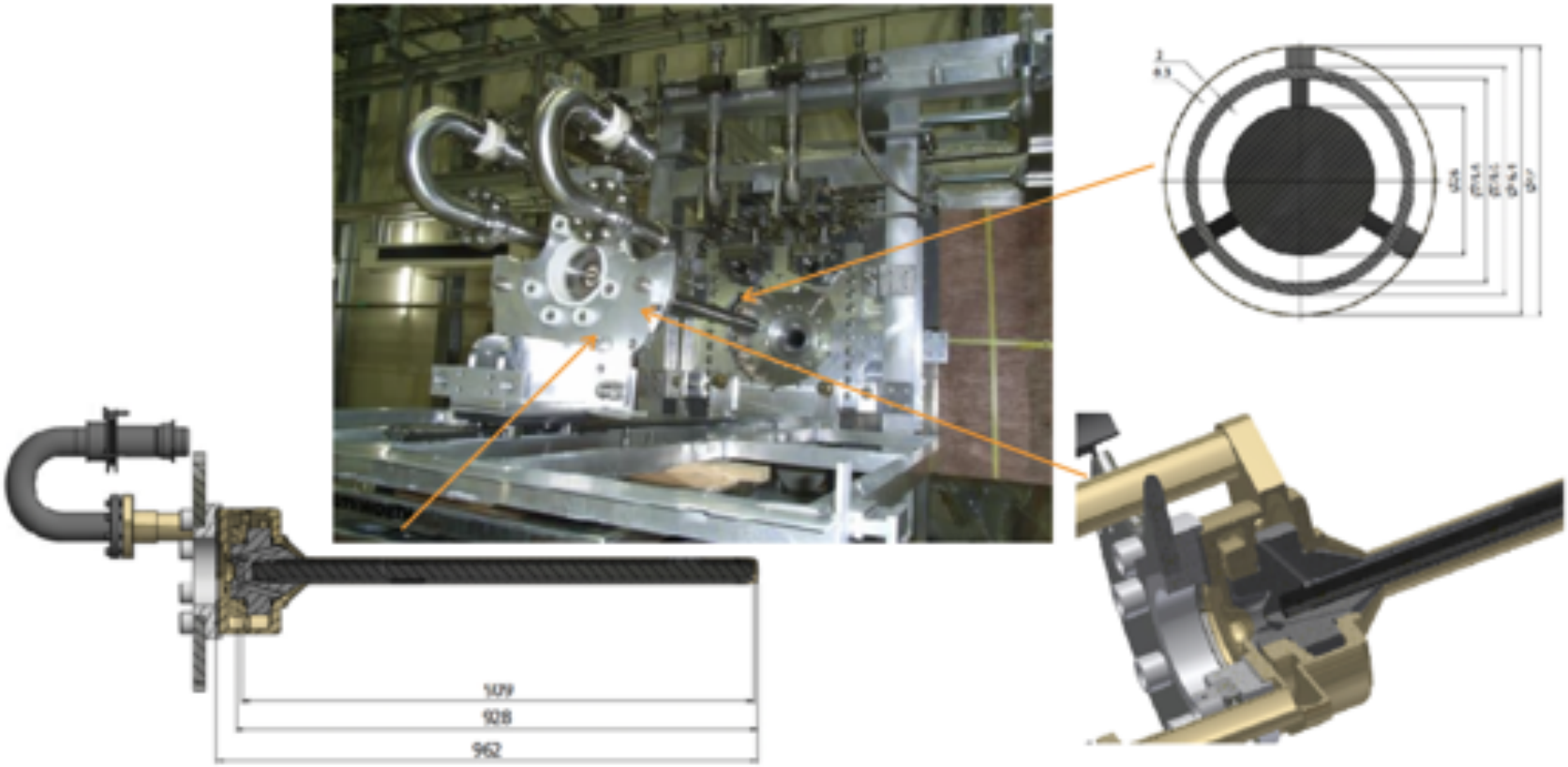
J-PARC High Power Proton Accelerator



- J-PARC Main Ring synchrotron delivers 30 GeV protons to J-PARC neutrino beamline in 8 ∼30ns long bunches
- Last year: $\sim 2.65 \times 10^{14}$ protons every 2.48 seconds = 515 kW
- Undergoing upgrades towards delivering $\sim 3.2 \times 10^{14}$ protons every 2.48→1.32→1.16 seconds (515kW→>700kW→1.3 MW)

The J-PARC Neutrino Production Target

- Monolithic graphite target, ∼90-cm-long, 26mm diameter, cantilevered mounting
- Two co-axial pipes for He gas cooling and Ti-alloy target container
- Upstream structure for single-side He gas port



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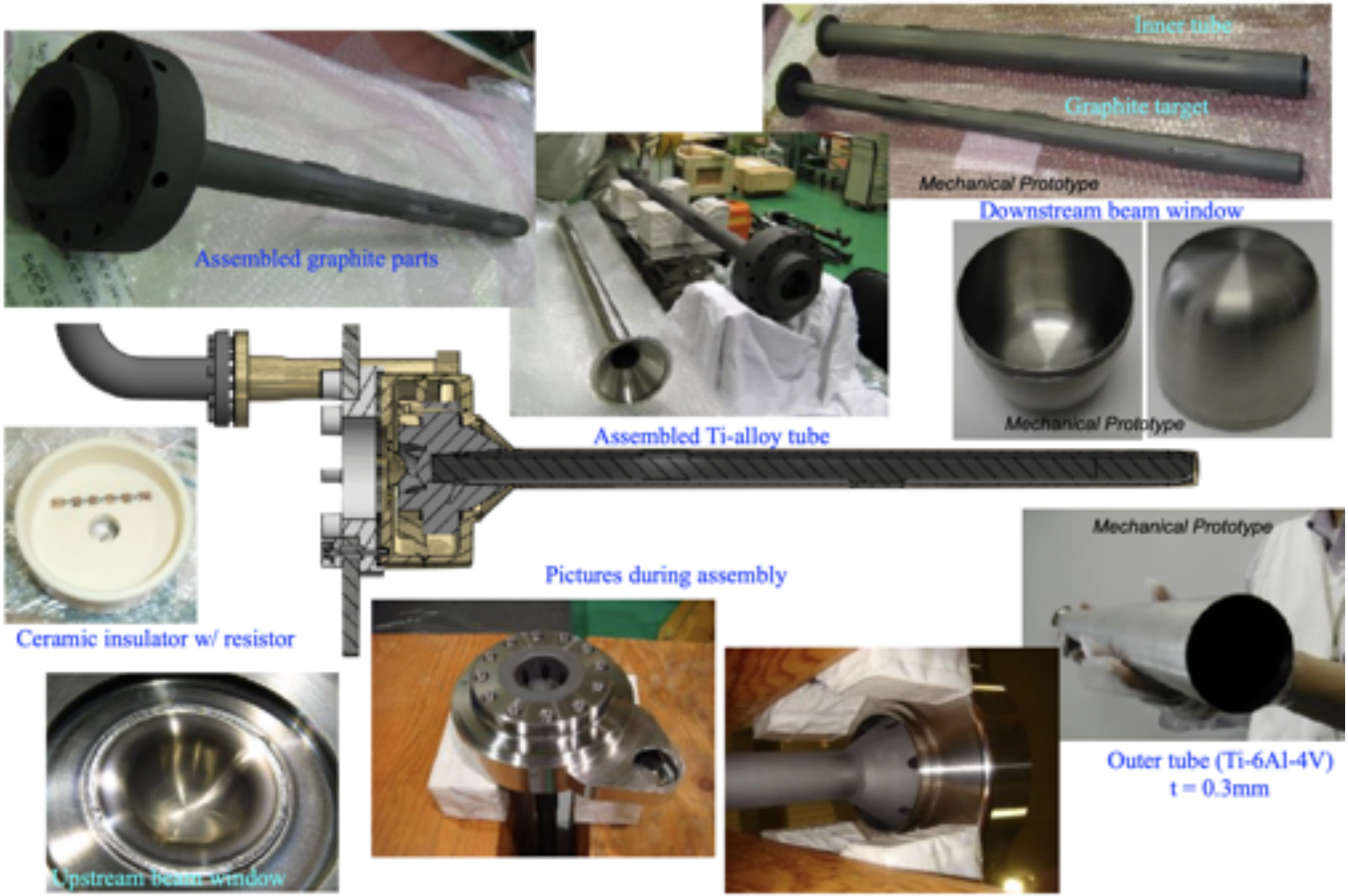
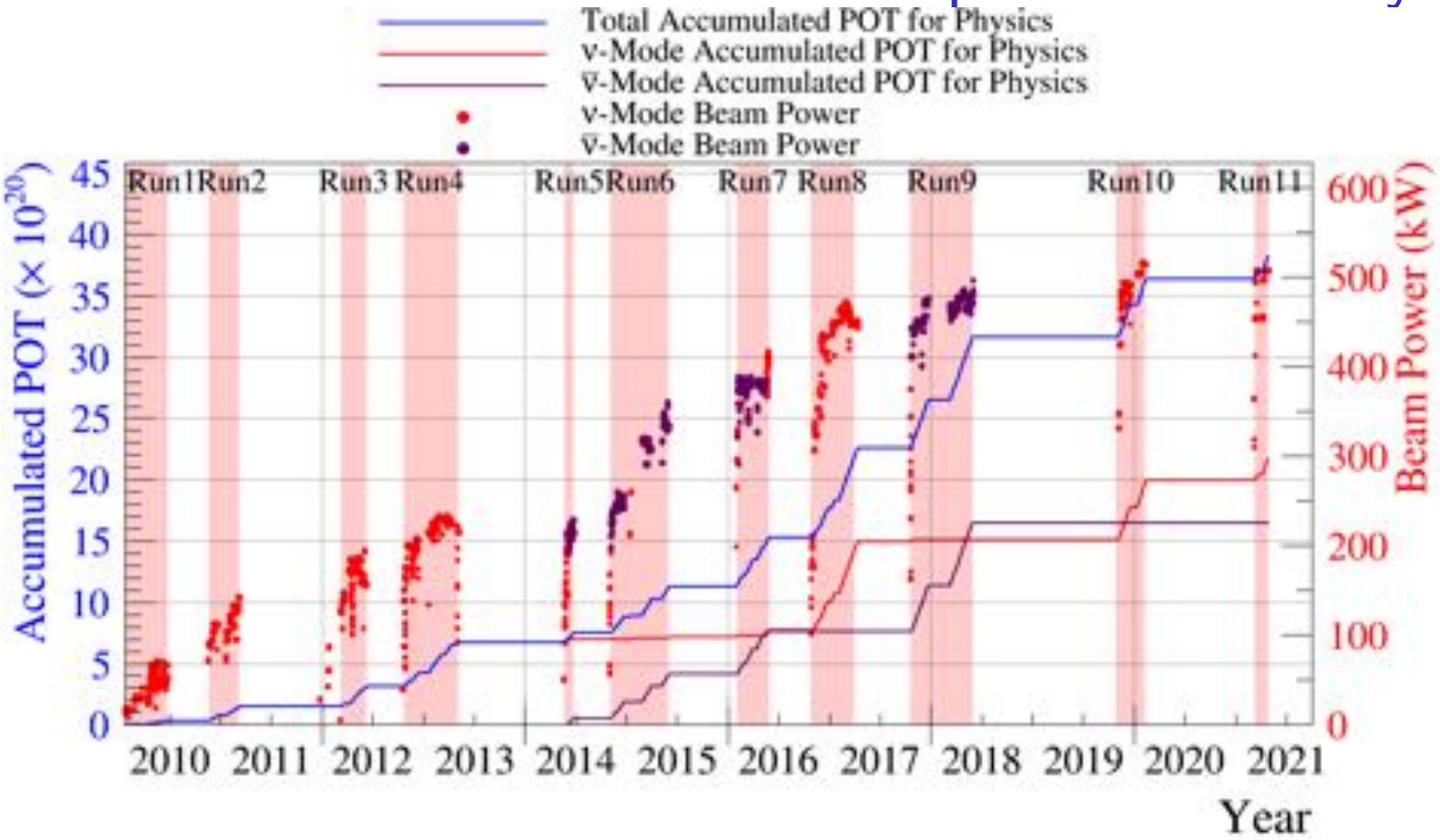
The J-PARC Neutrino Production Target

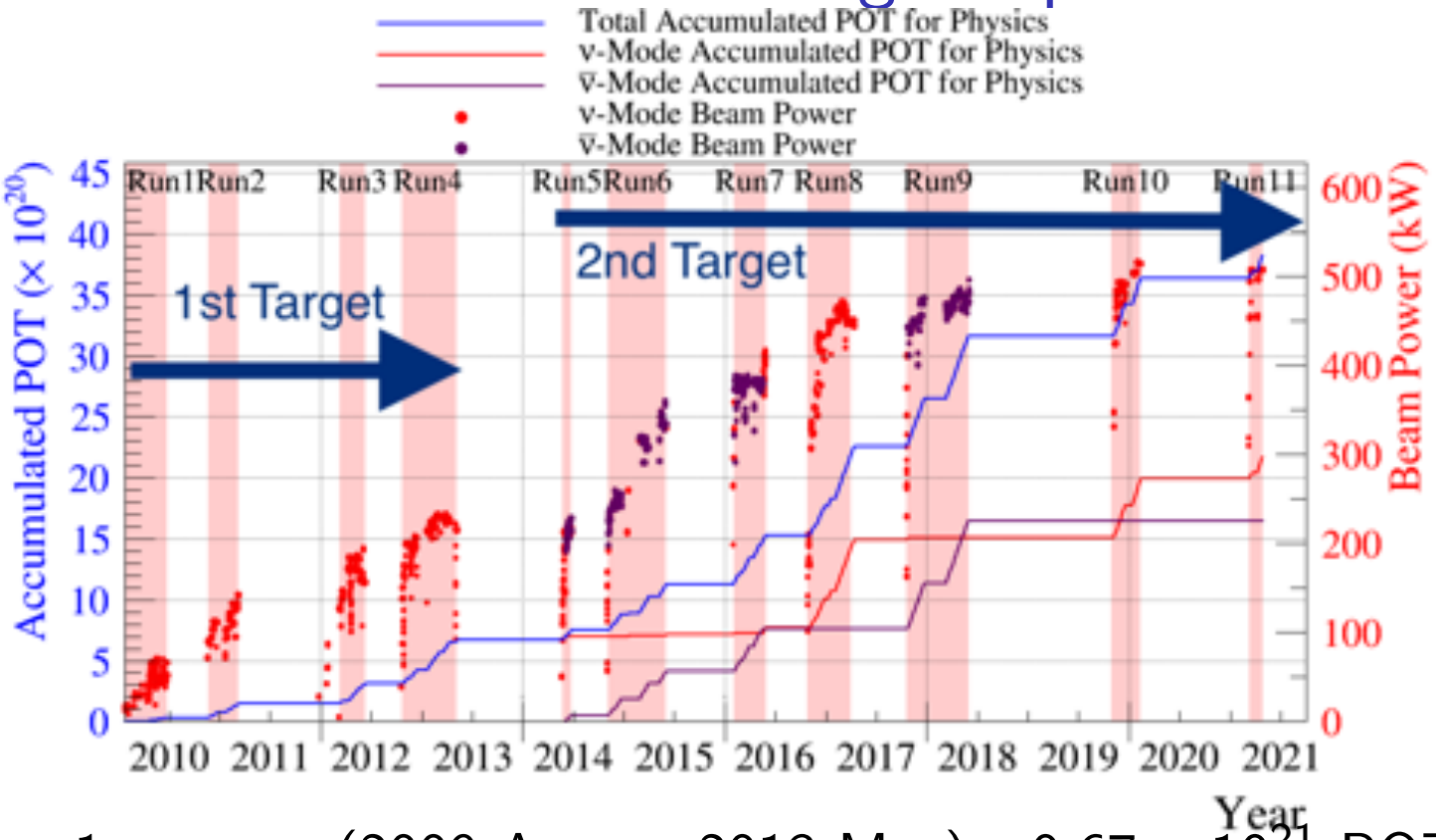


Beamline Operation History



- T2K commissioning from 2009∼, physics data-taking from 2010∼
- Gradually ramped up proton beam power from a few kW → 515 kW
- Exchanged target in 2013
- So far, have accumulated a total of:
  2.17×10^{21} ν-mode + 1.65×10^{21} $\bar{\nu}$-mode protons on two targets

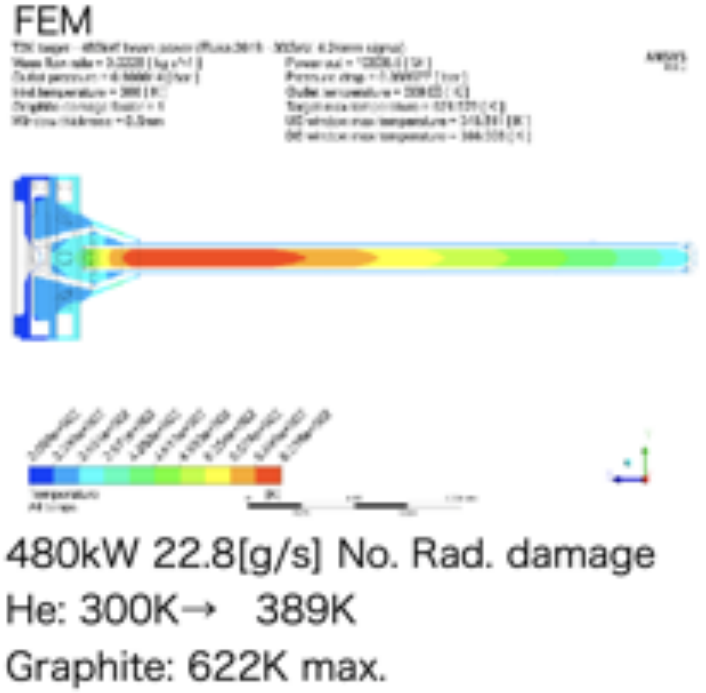
Target Operation History

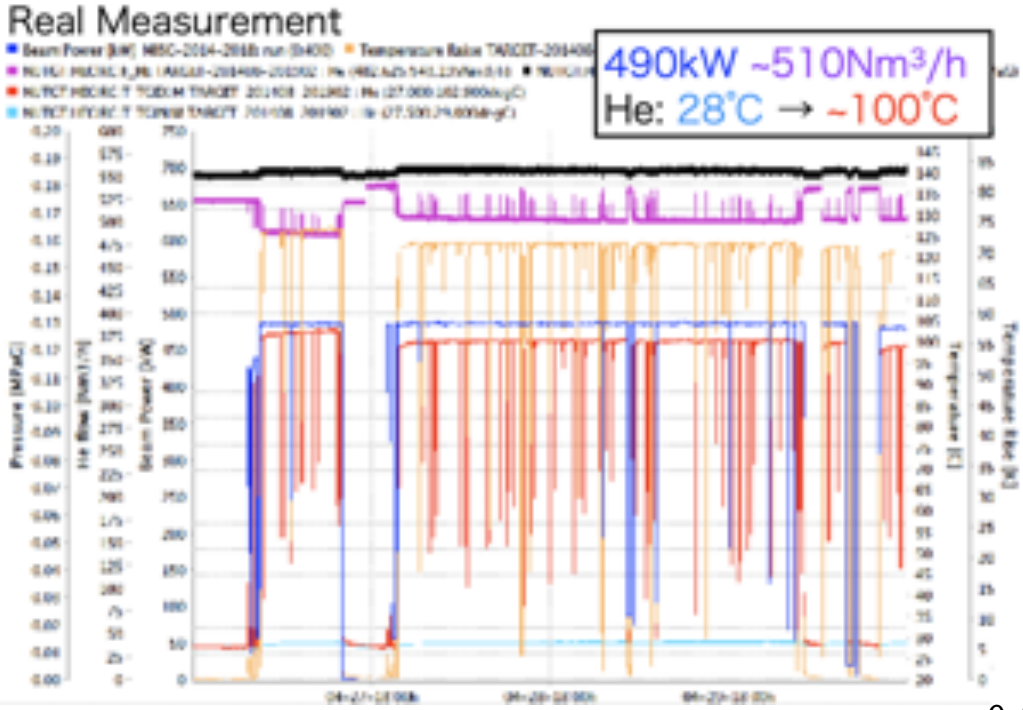


- 1st target (2009 Apr. $\sim$ 2013 May) : 0.67×10^{21} POT:
  - Max beam power $\sim$230 kW
  - No significant trouble, but replaced when Horn 1 was replaced
- 2nd target (2014 May $\sim$ 2022 Summer) : 3.15×10^{21} POT:
  - Max beam power $\sim$515 kW
  - He leak at "ceramic break" $\rightarrow$ Fixed in 2015 by remote maintenance
- 3rd target will be installed this summer

Temperature Monitoring

- Continuously monitor the temperature of the target frame
- Continuously monitor the temperature of the He gas used for cooling the target at both the inlet and outlet
  - Requirements: Graphite temperature $\lesssim$ 700°C
    He gas temperature $\lesssim$ 200°C
  - With 490kW beam, He flow of ~25 g/s:
    - Measured temperature increase from 28°C → 100°C : ΔT = ~72°C
  - Simulated 480kW beam, He flow of ~23 g/s : expect ΔT = ~89°C
    - Consistent considering difference in conditions + measurement point





He Gas Impurity Monitoring

- Periodically sample target cooling He gas
  - Impurity measurement by gas-chromatography: O_2, CO, CO_2, H_2, CH_4, N_2
    - Check the CO/CO_2 concentration in order to detect indication of oxidization of graphite (oxidization should be avoided)
    - If we observe large CH_4 concentration, it indicates that the target graphite temperature is too low w.r.t the optimal operation point where radiation damage is relatively small
  - Tritium measurement
- Example impurity measurement after 2018 run (5.6×10^{20} POT @$\sim$480kW):
  - CO and CO_2 increase observed (caused by O_2 contamination?)
  - If we assume all from target loss, $\sim$0.1% mass reduction per 1×10^{21} POT – acceptable, but better to reduce

Impurity [ppm]	CO_2	H_2	O_2	N_2	CH_4	CO
2018/3/5	0	0	1	3	0	0
2018/5/31	118	489	0	26	41	371

[Bq/L]	^3H Total	(HTO)	(HT)
2018/3/5	n/a		
2018/5/31	543	(471)	(18)

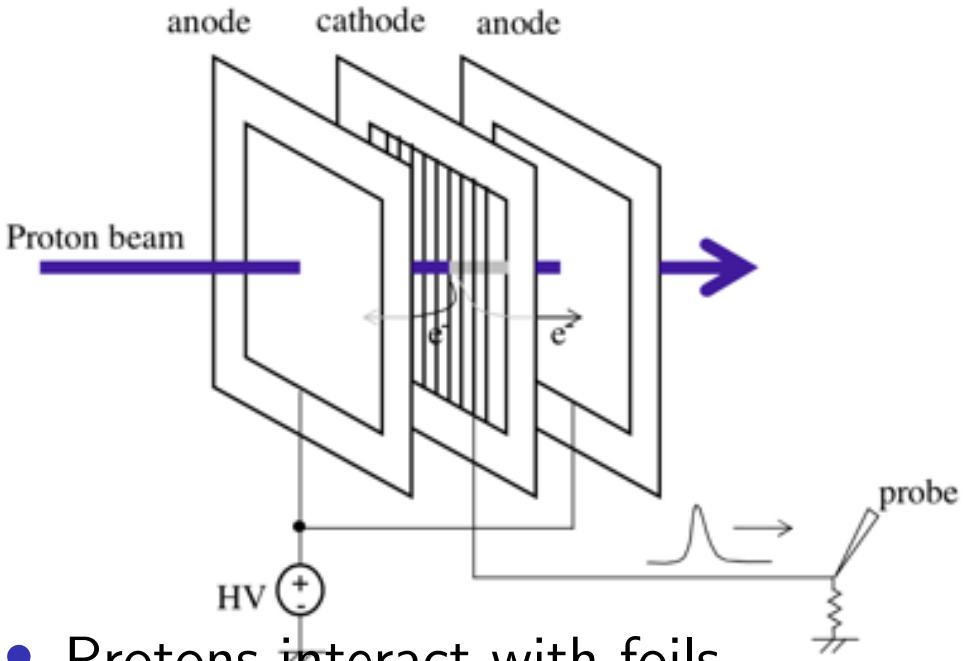
He Gas Impurity Monitoring Upgrades

- Several planned upgrades:
  - Will add H_20 contamination measurement
  - From 3rd target, Ti-alloy case can stand against vacuum evacuation $\rightarrow$ It may be possible to measure the outgas contents from target during each maintenance (weekly beam-off) period
  - Also considering to add continuous monitoring of radio-activity of He gas (already implemented at other J-PARC facilities – MLF and HEF)

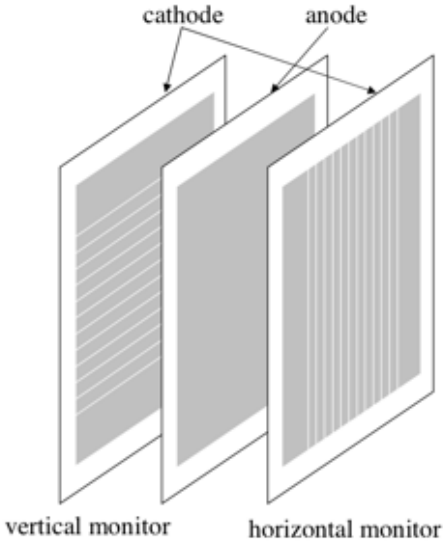
Proton Beam Monitoring

- Continuously monitor the proton beam intensity, position, angle, and width at the target with a series of proton beam monitors installed along the beamline
  - Ensure that the beam position is centered at the target
    - Within the safety tolerance of the target and other components
    - Precision physics also requires centered beam with small incident angle
  - Ensure that the beam width is suitable
    - Within the safety tolerance of the target and other components – want wider, less intense beam for target safety $\rightarrow$ proton beam *density* should be kept below limit
    - For physics – want narrower beam at high intensity for as many protons as possible reaching the production target
- Use SSEM and OTR near the target for continuous profile monitoring (see following slides)

Proton Beam Monitoring – Segmented Secondary Emission Monitor (SSEM)



J-PARC NU SSEM



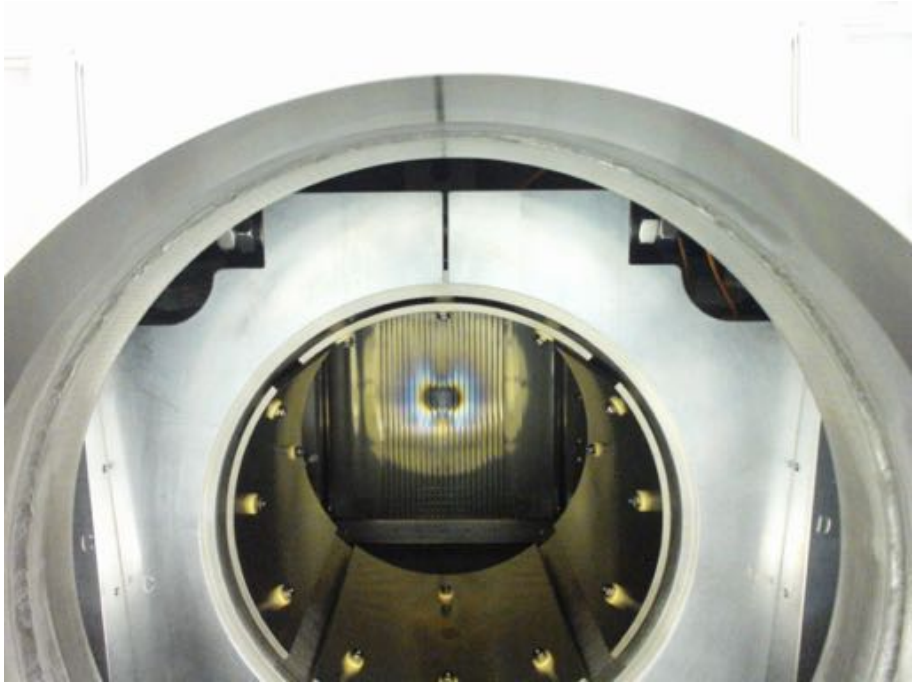
- Protons interact with foils
- Secondary electrons are emitted from segmented cathode plane
- Compensating charge in each strip is read out as positive polarity signal
- Used continuously 3.2 m upstream of the neutrino production target

- Single anode plane between two stripped cathode planes
- 5 μm thick Ti foils – each monitor causes 0.005% beam loss

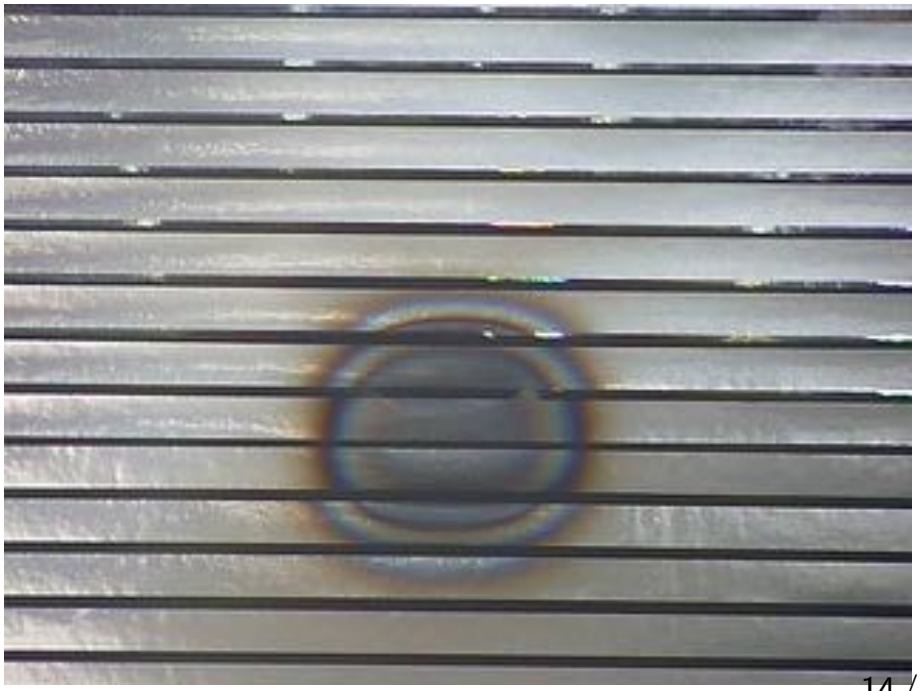
J-PARC NU SSEM Foil Discoloration

- 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 2023
    - Remote exchange mock-up tests underway now

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

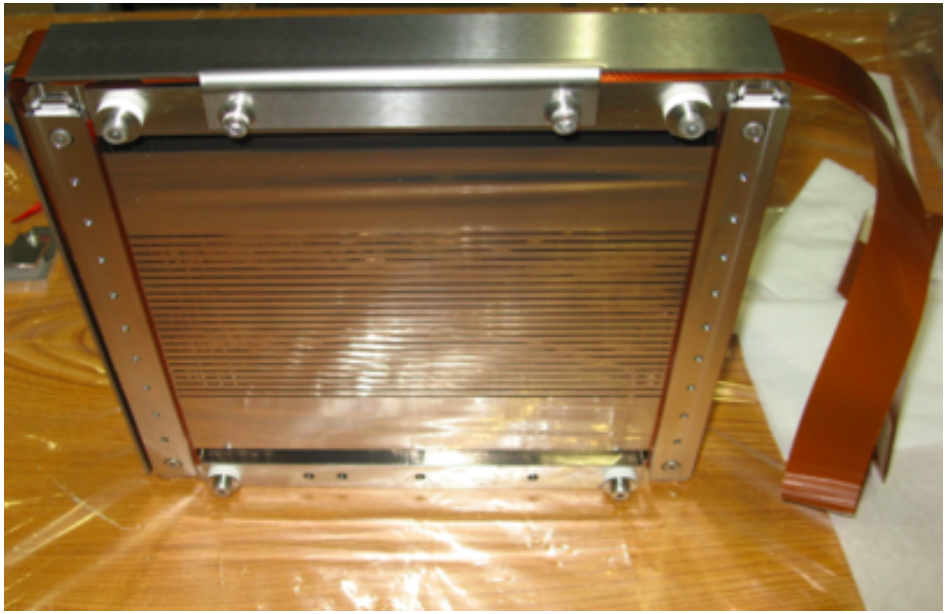


Upstream side after $\sim 3.2 \times 10^{21}$ Incident Protons



Reduce Material to Reduce Beam Loss

- Developed 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
    $\rightarrow$ 10x reduced beam loss
    $\rightarrow$ Can use continuously further upstream if necessary
  - Maintain signal size at low beam power by maximizing surface area
  - Beam test for 160 hours in 460$\sim$475kW J-PARC beam $\rightarrow$ no issue
  - Can further upgrade wire material to be more robust
    - Aiming to test carbon nanotube wire soon



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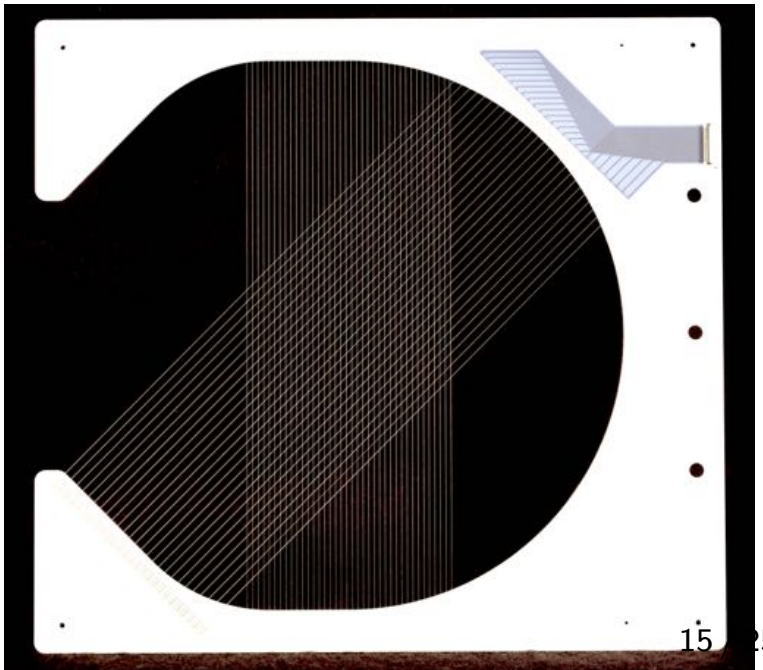
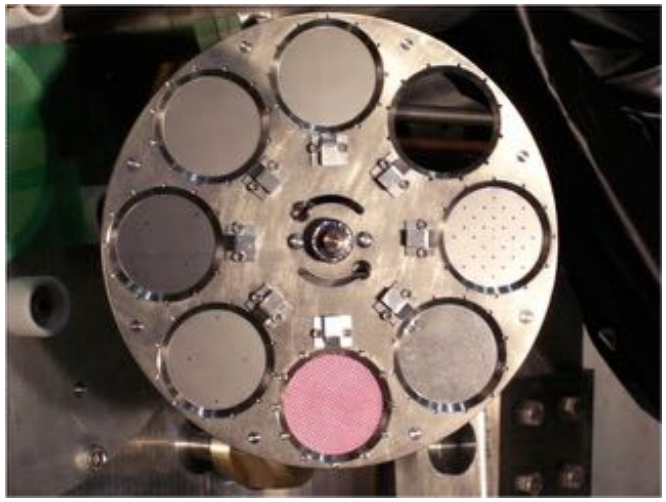
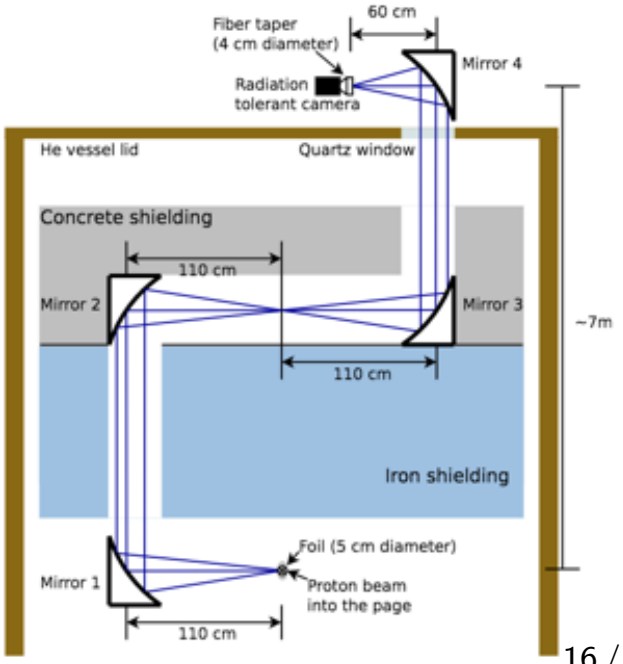


Proton Beam Monitoring – Optical Transition Radiation Monitor (OTR)

- 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 55-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

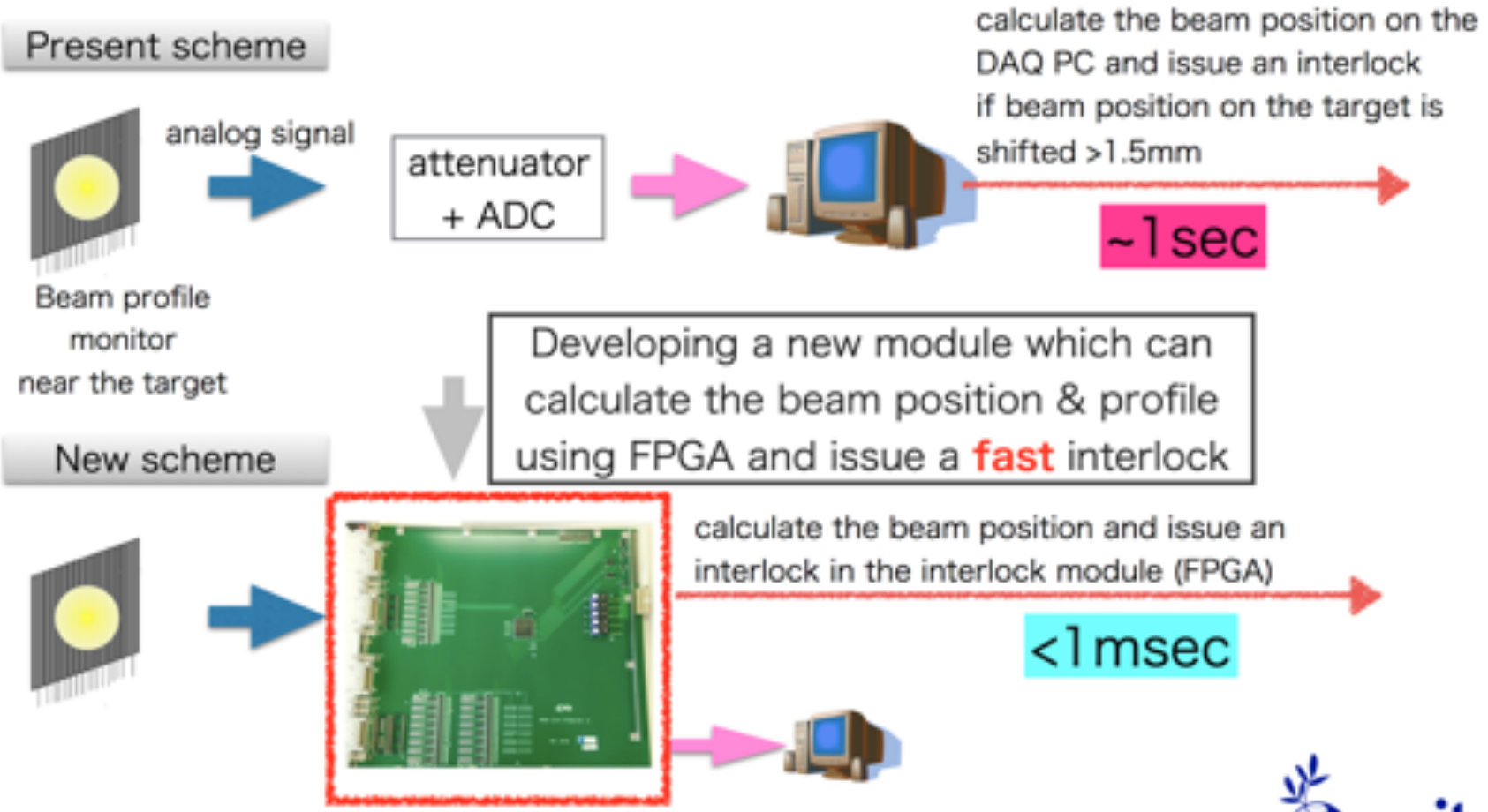
J-PARC NU Beamline OTR Upgrades

- 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
    - But, need to ensure foil robustness including additional holes – FEM simulations performed
  - Upgrade foil to be more robust
    - Have been using 55-μm-thick Ti-15-3-3-3 alloy
    - Planning to change 4/5 foils to 33-μm-thick Ti foils of same material for robustness at 1.3MW beam power

Interlock on Proton Beam Parameters

- Must quickly stop the beam if the proton beam position or width at the target is outside of safe limits
  - Use continuous SSEM position + width measurement
- New interlock system for fast beam interlock under development



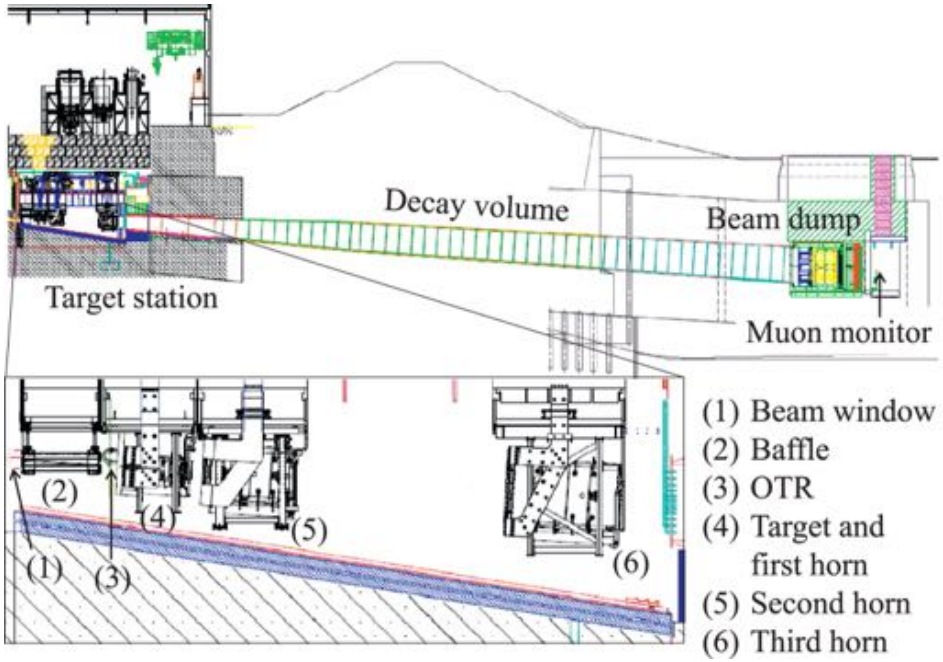
PAPILLON board : http://openit.kek.jp/project/beam_monitor_interlock/beam_monitor_interlock

Development: Okayama University, Tohoku University, KEK

Additional Checks

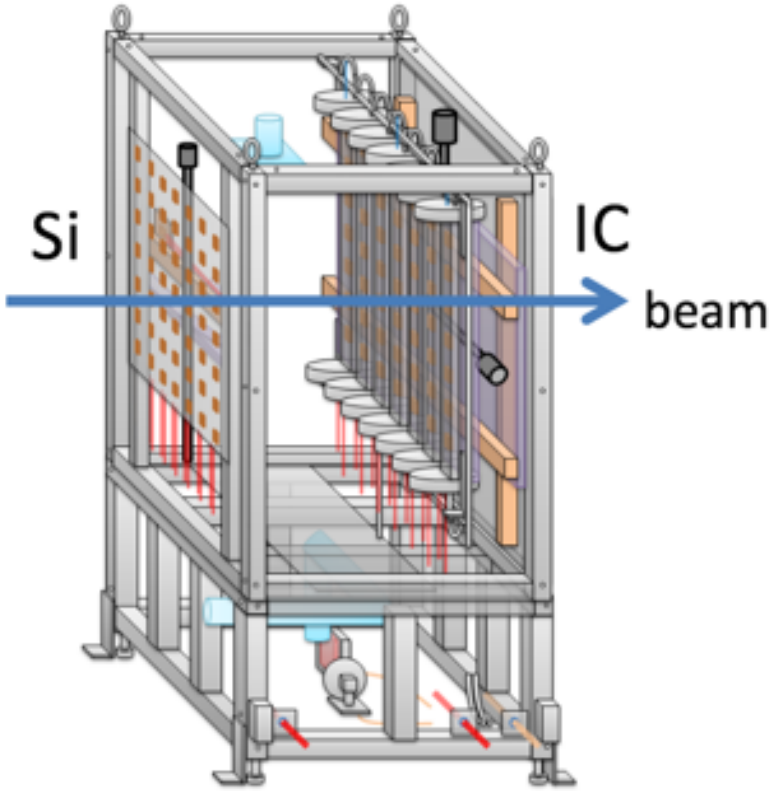
- Have also checked the correlation between the beam position at target and the signal size of most downstream Beam Loss Monitors

- Baffle sits directly upstream of the target, to protect downstream horns
  - 6 temperature sensors installed around the baffle
  - Idea to check temperature of baffle to understand beam position/profile + monitor target health



Muon Monitoring – MUMON

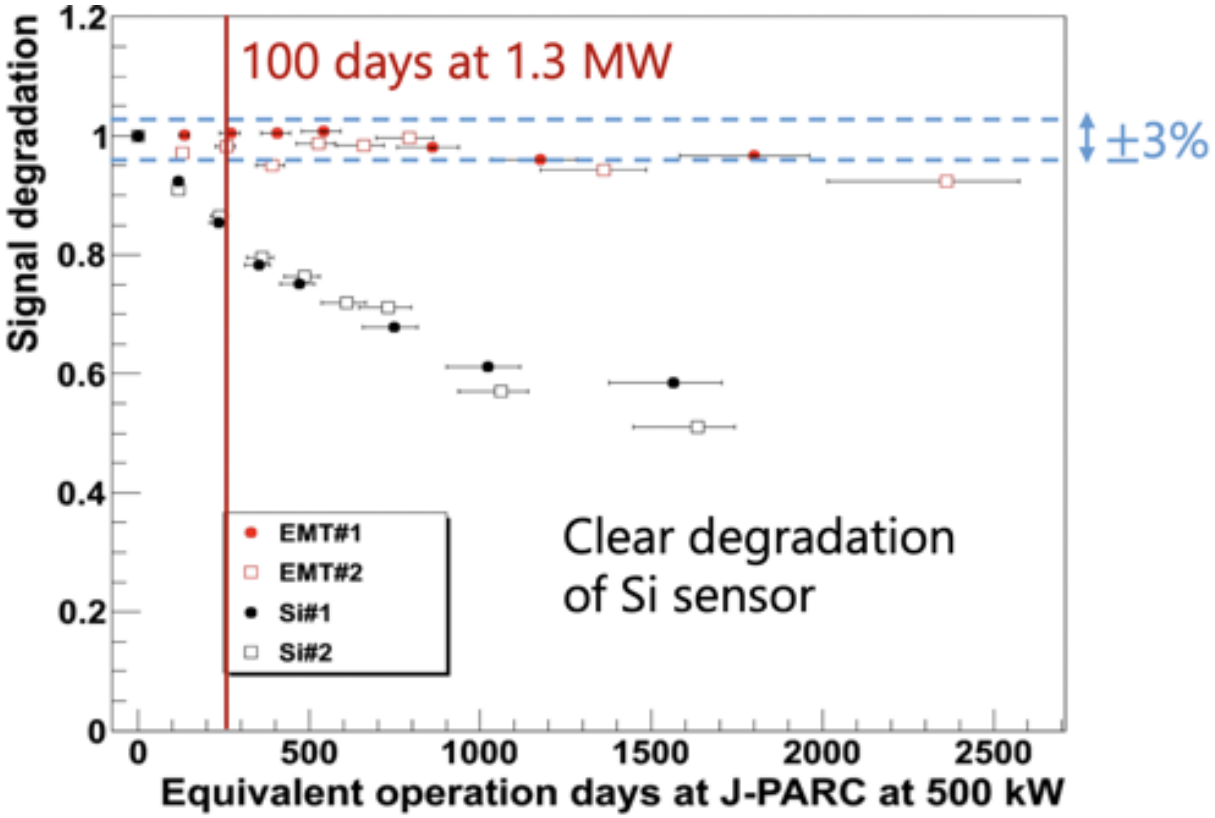
- Continuously measure secondary muon beam profile downstream of the decay volume, beam dump (>∼5 GeV muons)
  - Ensure alignment, healthiness of target, horns; proton beam position, angle at target; etc
- 2 redundant measurements of the muon beam profile, position using 7x7 arrays of sensors
  - Ionization chambers (IC)
  - Silicon photodiode sensors (Si)



- Unfortunately, old simulation studies show that the muon rate at our muon monitor does not significantly change if the target density is decreased by ∼5%
- Target density changes could cause changes in the measured muon beam position and profile, though

Muon Monitoring Upgrades

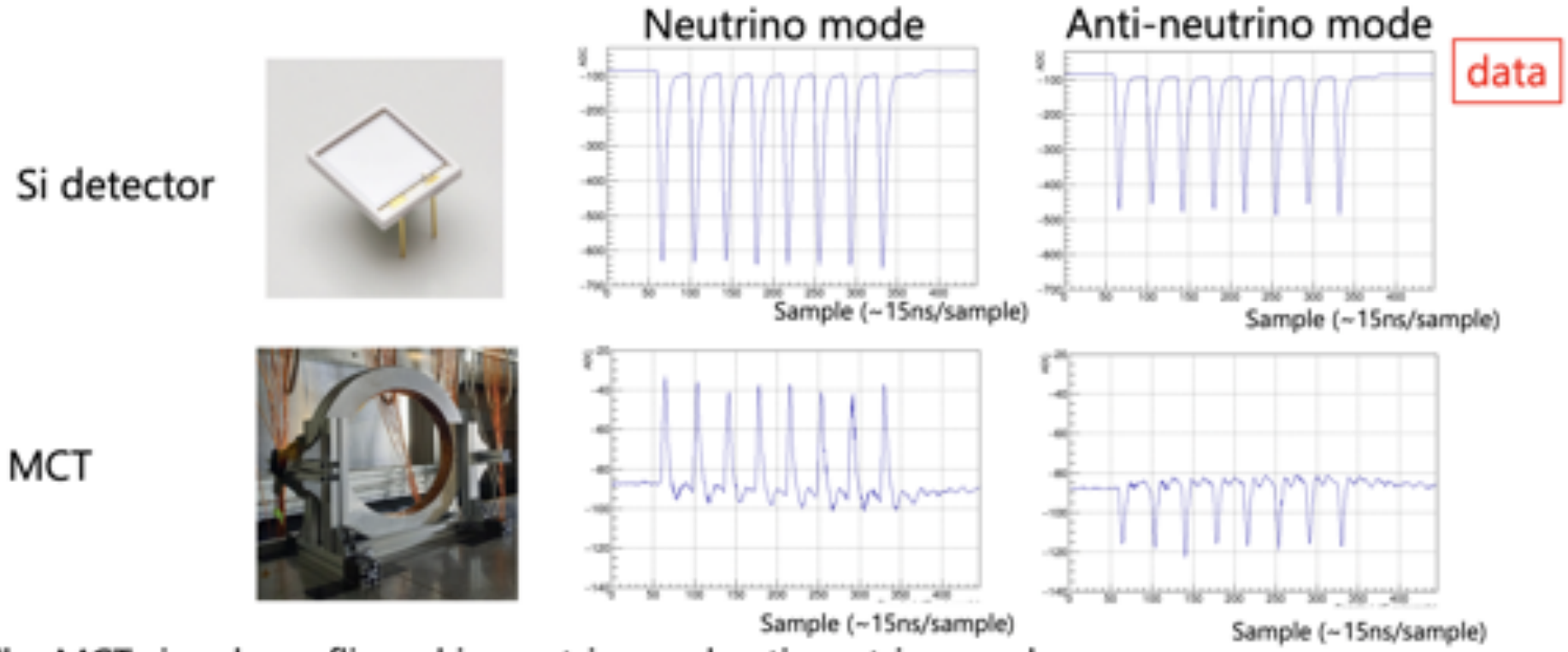
- Now developing EMT (PMT w/out photocathode) as more robust muon sensor option
  - Several beam dedicated tests carried out (@ELPH) – very promising results



NuFACT2021
(H. Nakamura)

Muon Monitoring Upgrades

- Also developing MCT (MUMON CT) for muon sign measurement
  - First in-situ beam test carried out – made first muon beam polarity measurement at J-PARC!



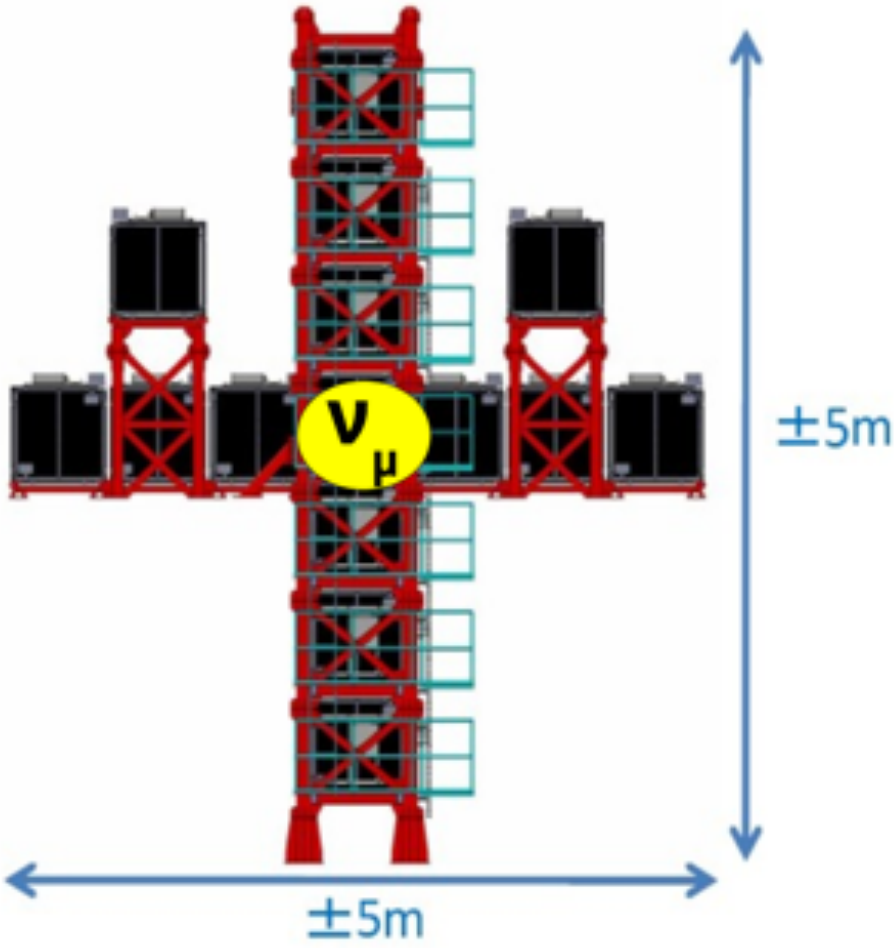
The MCT signal was flipped in neutrino and anti-neutrino modes.

→ First observation of the muon polarity change at MUMON!

Future task: estimate the number of particles passing through the MCT using the signal.

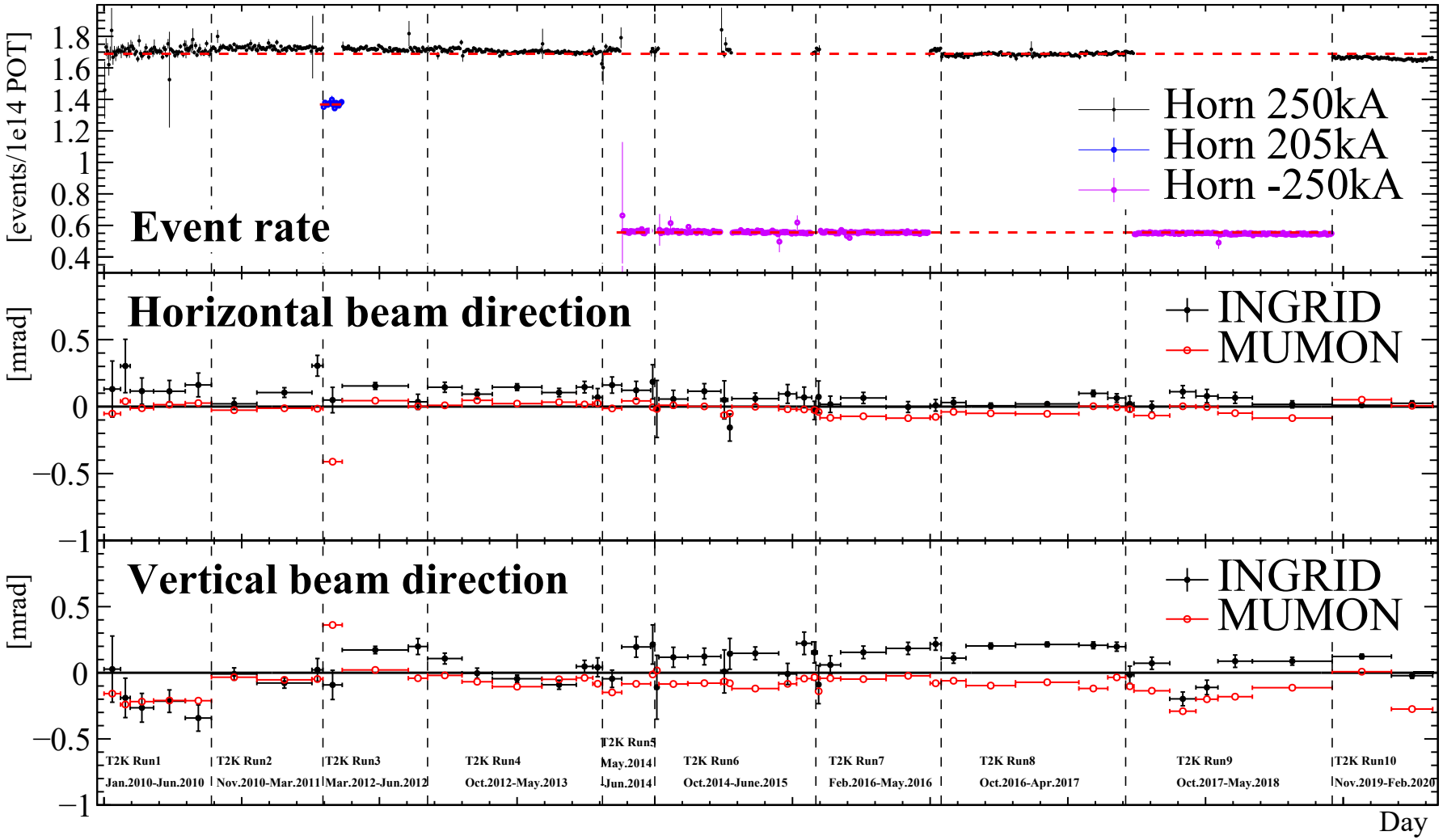
NuFACT2021 (H. Nakamura)

Neutrino Beam Monitoring – INGRID On-Axis Near Detector



- 14 identical modules arranged in a cross
- Each module consists of sandwiched iron plates and tracking scintillator planes
- Used to measure the neutrino beam stability and direction
- (Also used to measure cross sections/neutrino interactions)
- Sensitive to changes in target density, etc
- Can provide day-by-day informaion on neutrino beam (as opposed to spill-by-spill or even bunch-by-bunch)

J-PARC Neutrino Beam Stability



- Generally good stability of the muon and neutrino beam position, angle, and event rate over >10 years running

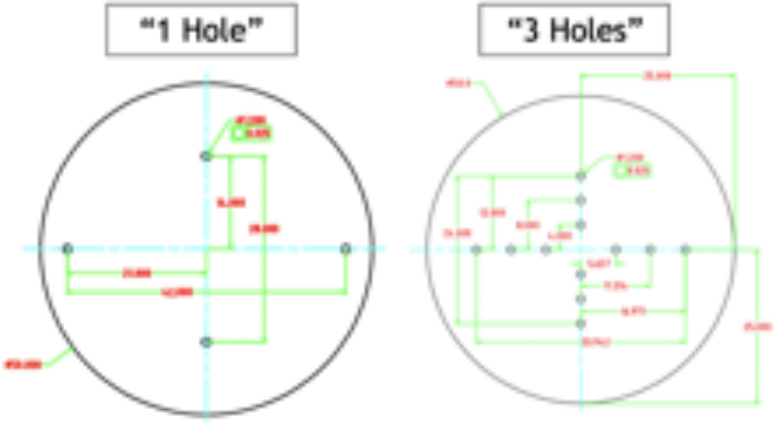
Conclusion

- Various methods used to monitor the J-PARC neutrino production target health:
  - Target cooling He gas temperature monitoring
  - Target cooling He gas impurity monitoring
  - Downstream muon and neutrino monitoring
- Maintain the target health by continuous proton beam monitoring + proper interlocks

J-PARC Neutrino Beamline Technical Design Report : arXiv:1908.05141

Backup Slides

Future of OTR in T2K's High Intensity Beam



Present – 50 um foil	No Holes	Holes
Temp [K]	526	529
Stress [Mpa]	133	235
Dep.Power [W]	0.80	0.78

Upgrade– 50 um foil	No Holes	Holes
Temp [K]	784	789
Stress [Mpa]	295	568
Dep.Power [W]	1.99	1.95

Marco Oriunno - SLAC

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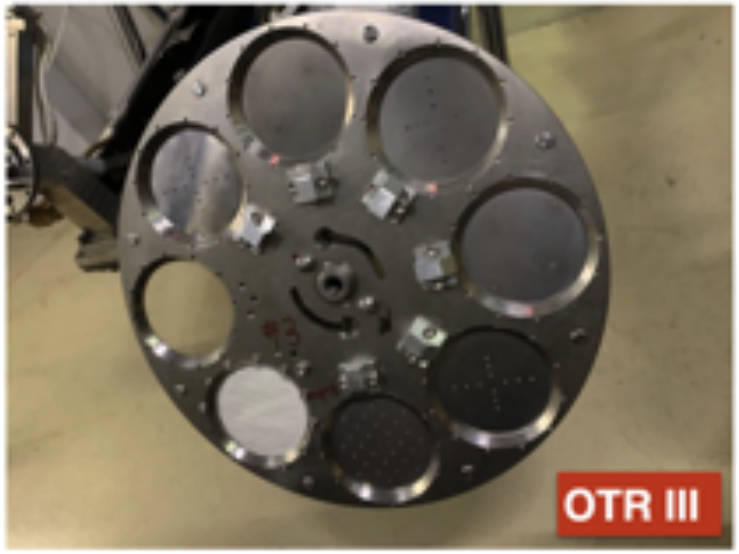
- Foil stress is much higher for upgraded beam (more than x2).
- Calibration holes also concentrate stress and increase the maximum stress by another factor of 2.



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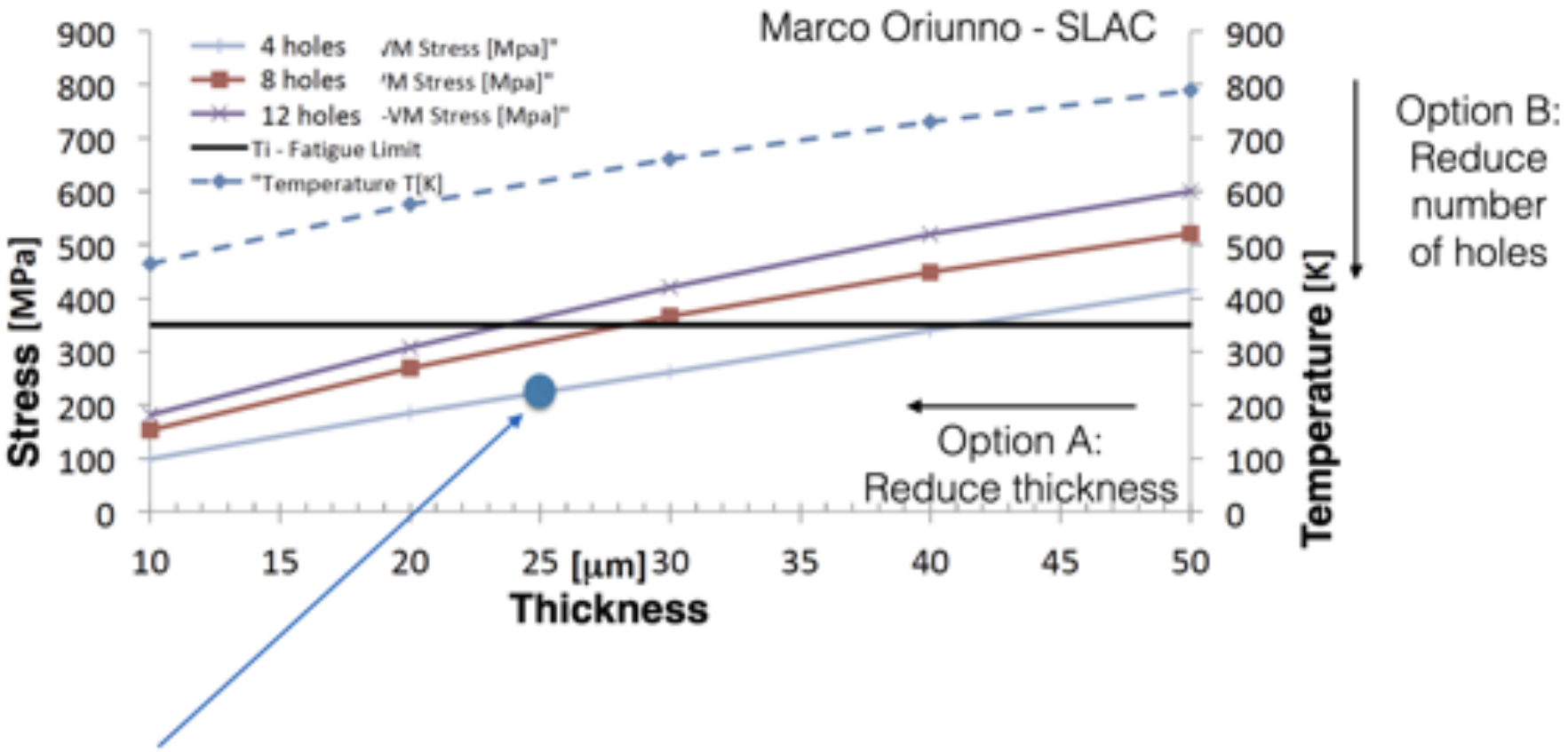
Options for OTR Foils in MW Beam

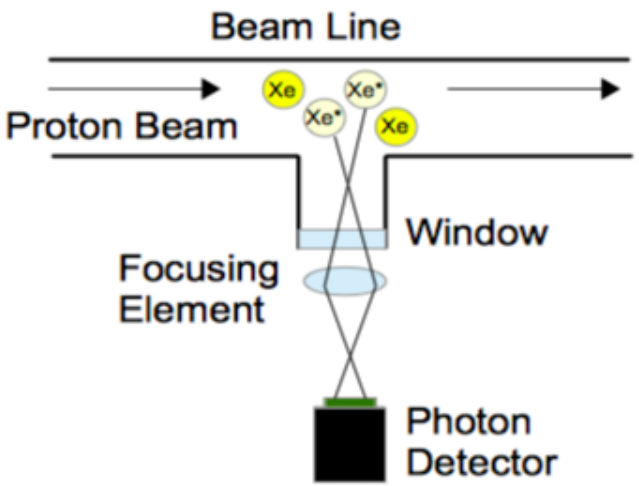


- Simply reducing the number of holes or the thickness of the foil is probably not enough. Likely need to do both.
- Vendors are being sought.

NBI2019 (G. Santucci)

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



S. Cao *et al.*, Proceedings of IBIC2019, 2019
M. Friend *et al.*, Proceedings of IBIC2020, 2020