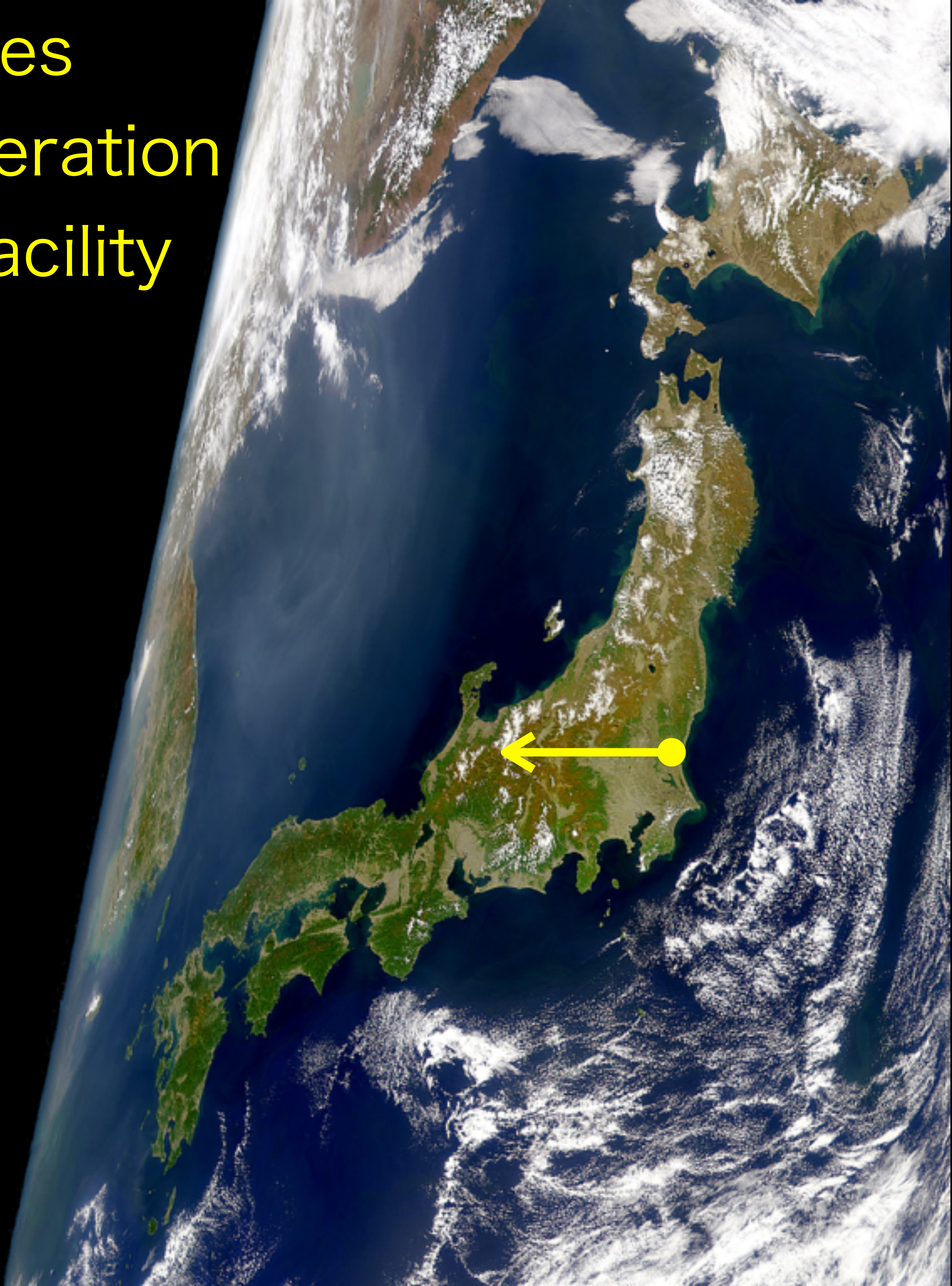
Technical challenges for higher intensity operation at J-PARC neutrino facility



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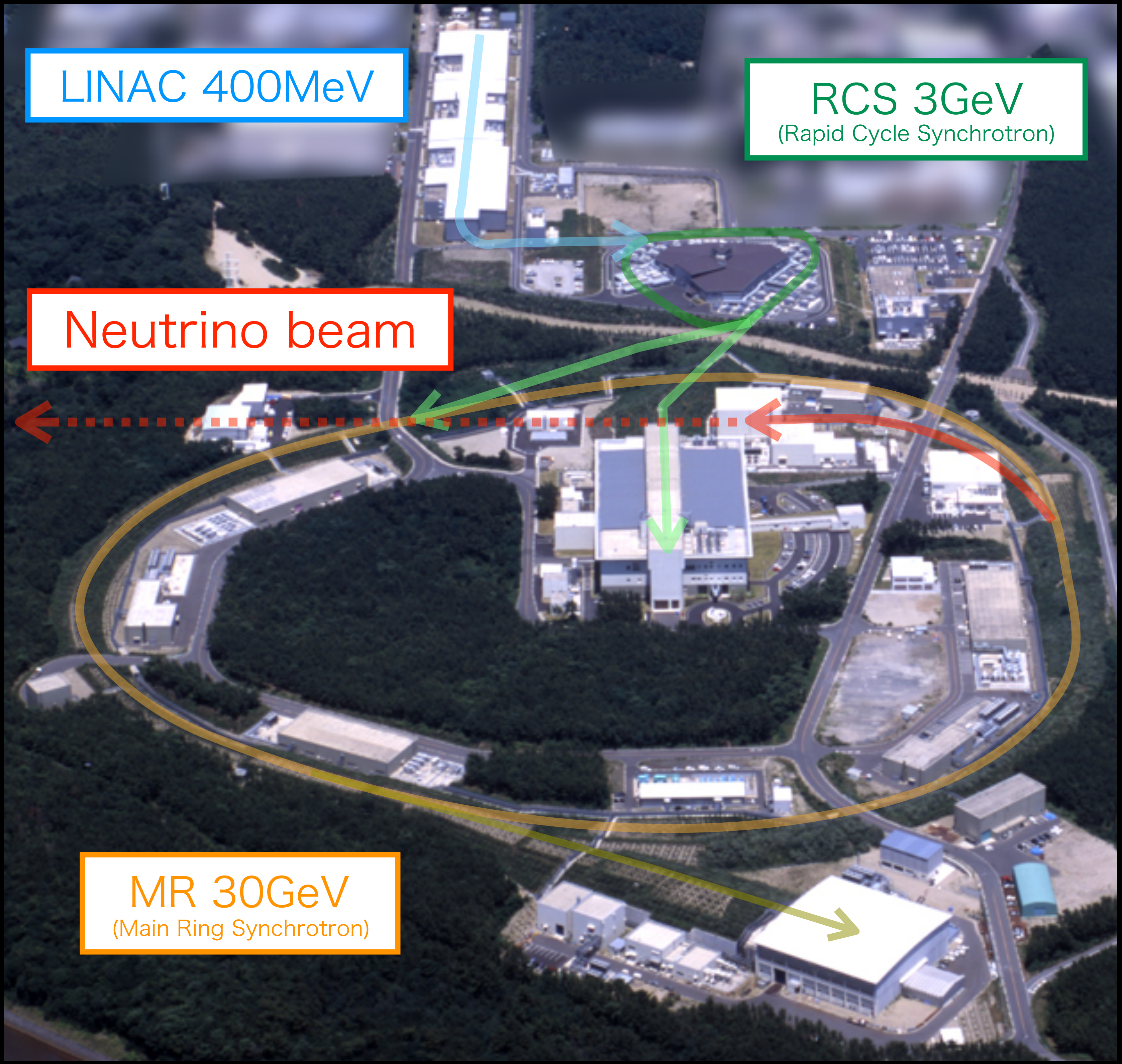
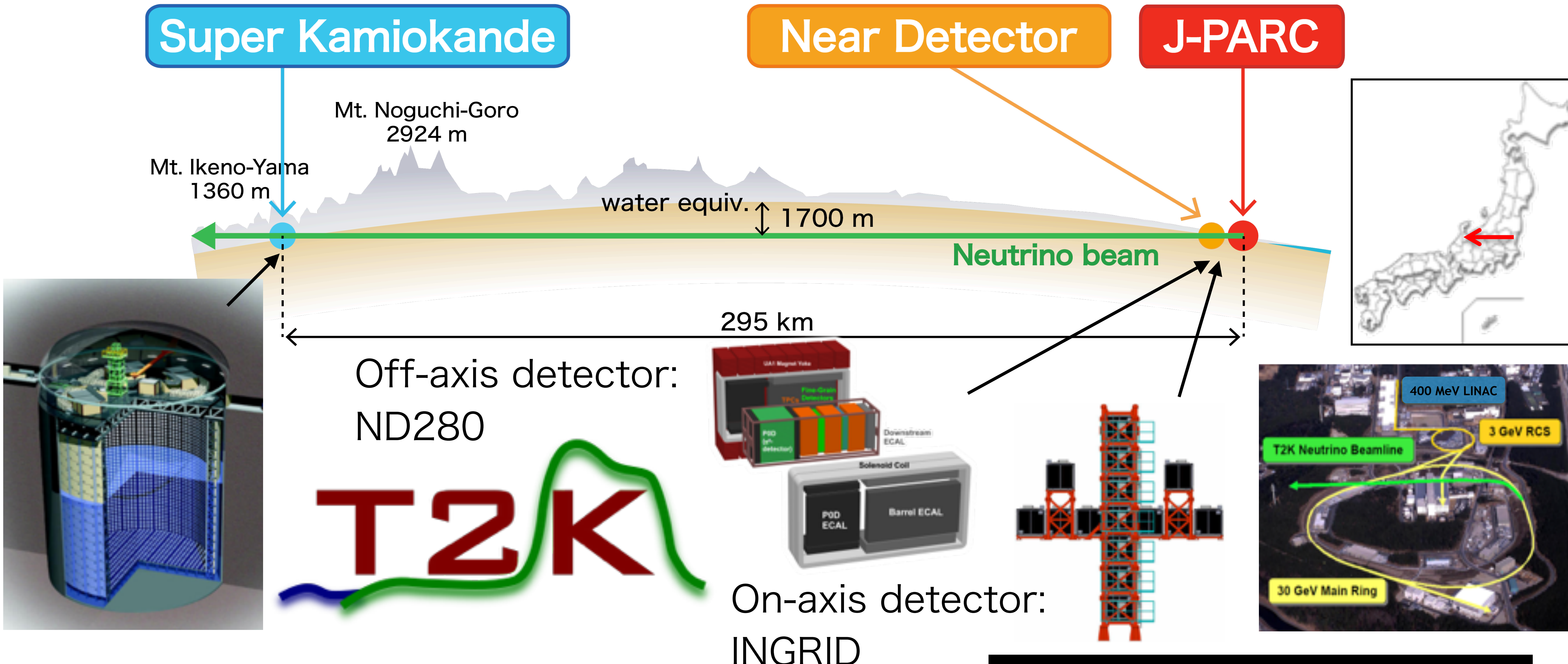
J-PARC Neutrino Experimental Facility

- Provide high intensity neutrino beam with 30GeV protons from J-PARC MR for the long-baseline neutrino oscillation experiment.
  - Operation from 2009
- J-PARC MR Original design
  - Beam power: 750 [kW] (3.3×10^{14} [p/pulse])
  - Repetition cycle: 2.1[s]
- Achieved MR performance:
  - Beam power: 490 [kW] (2.5×10^{14} [p/pulse])
  - Repetition cycle: 2.48[s]

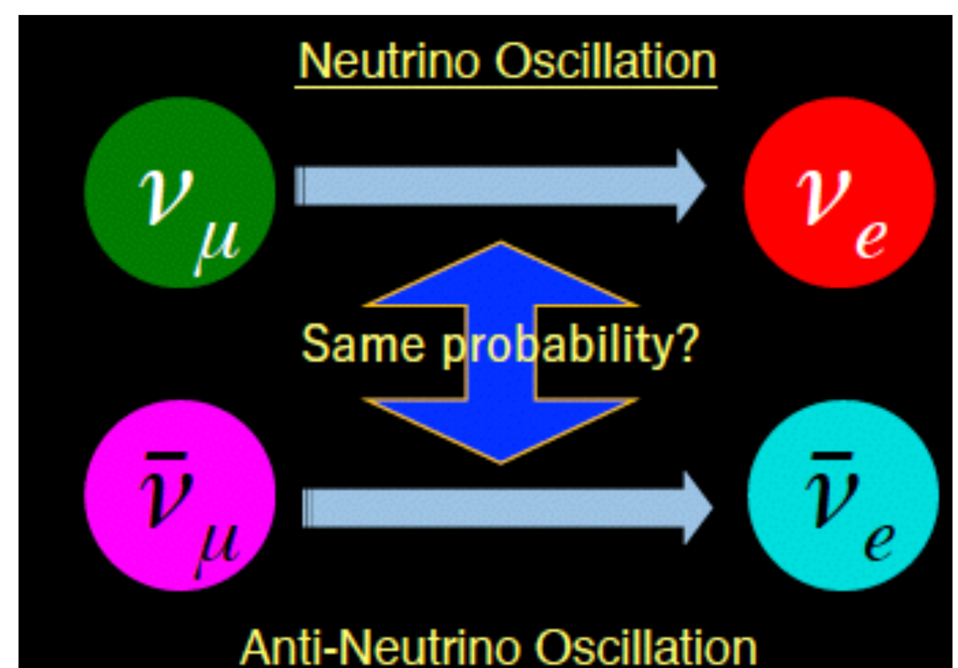


Long-baseline neutrino oscillation experiment: T2K



Physics goals

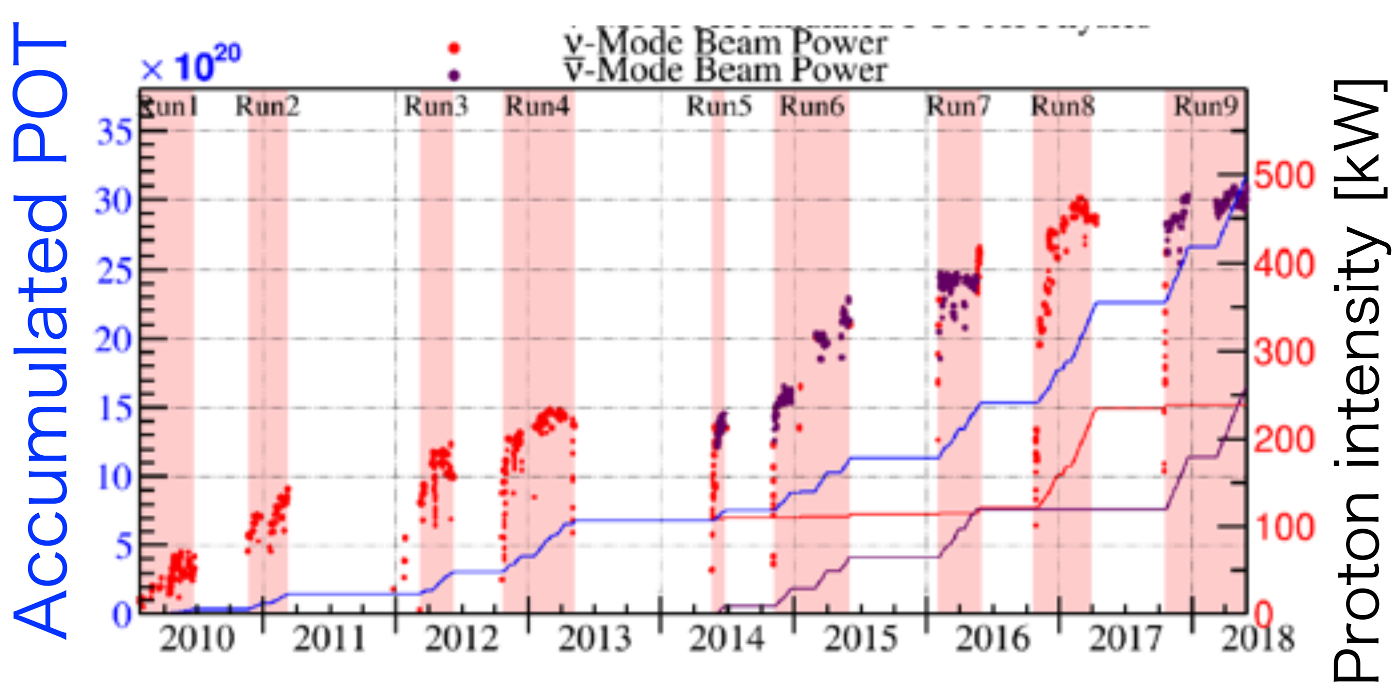
- Search for the new neutrino oscillation: $\nu_\mu \rightarrow \nu_e$ (~2013)
- **Search for CP violation in lepton sector (2014~)**

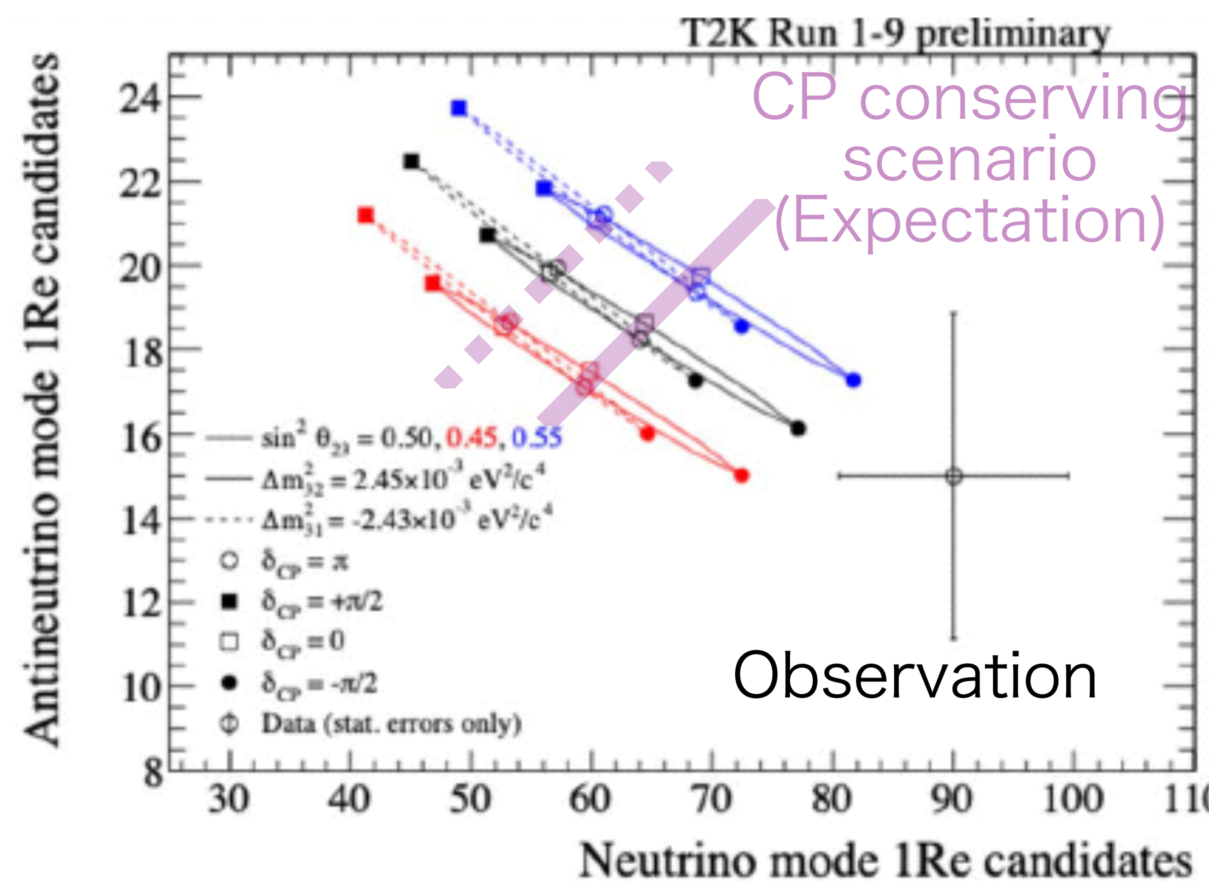


Current status of T2K

- Accumulate 3.16×10^{21} POT (40% of approved POT)
- Latest analysis results:
  - Excess of $\nu_\mu \to \nu_e$ observation for ν-beam data (1.51×10^{21}POT) w.r.t the expectation assuming NO CP violation.
  - Less $\bar{\nu}_\mu \to \bar{\nu}_e$ observation for $\bar{\nu}$-beam data (1.65×10^{21}POT)

  → >2 σ rejection of CP conserving scenario.
- **Hint of Large CP violation in lepton sector?**
  - Beam power upgrade & Near detector upgrade is on-going.

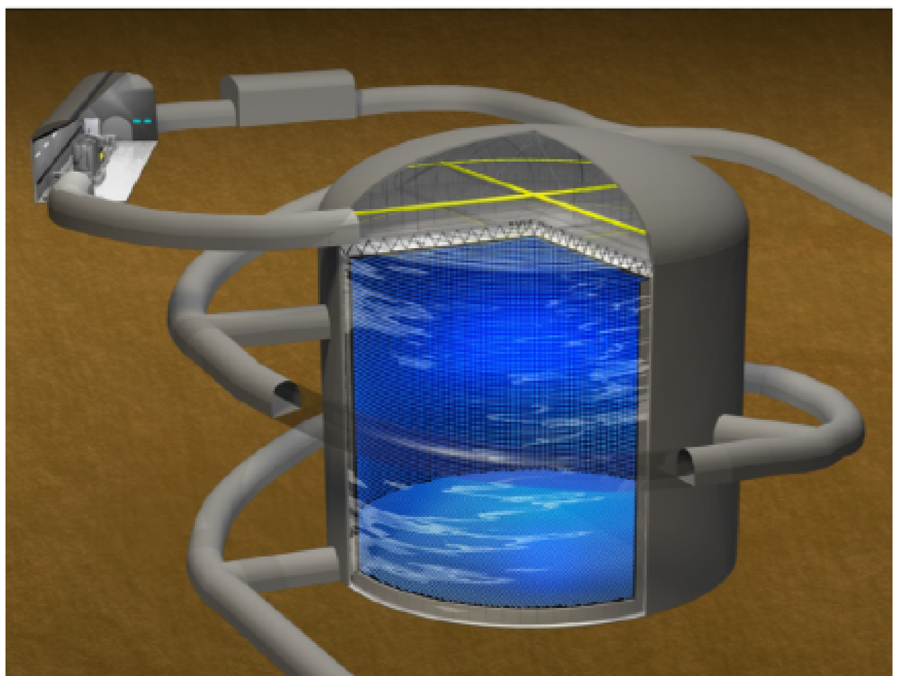




Next generation experiment: **Hyper-Kamiokande**

- Physics goal in LBL experiment: Discovery of CP violation in lepton sector
- Aiming to achieve >5σ significance by accumulating ~2000 $\nu_\mu \rightarrow \nu_e$ events and ~2000 events in ~10 years (2027~)

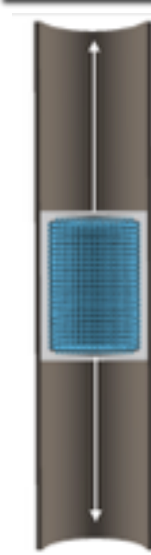
Hyper-Kamiokande



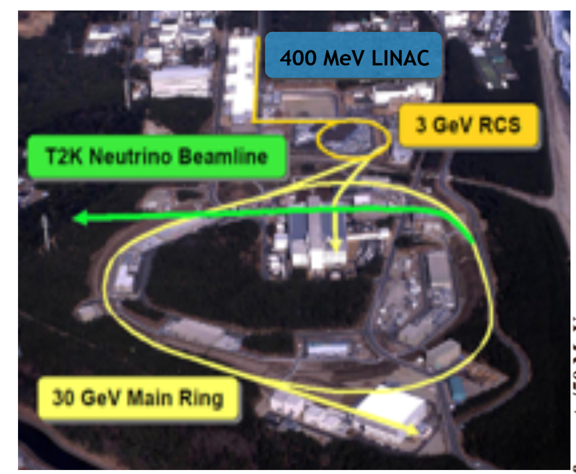
260kt

Cf: SK=50kt

New near-detector

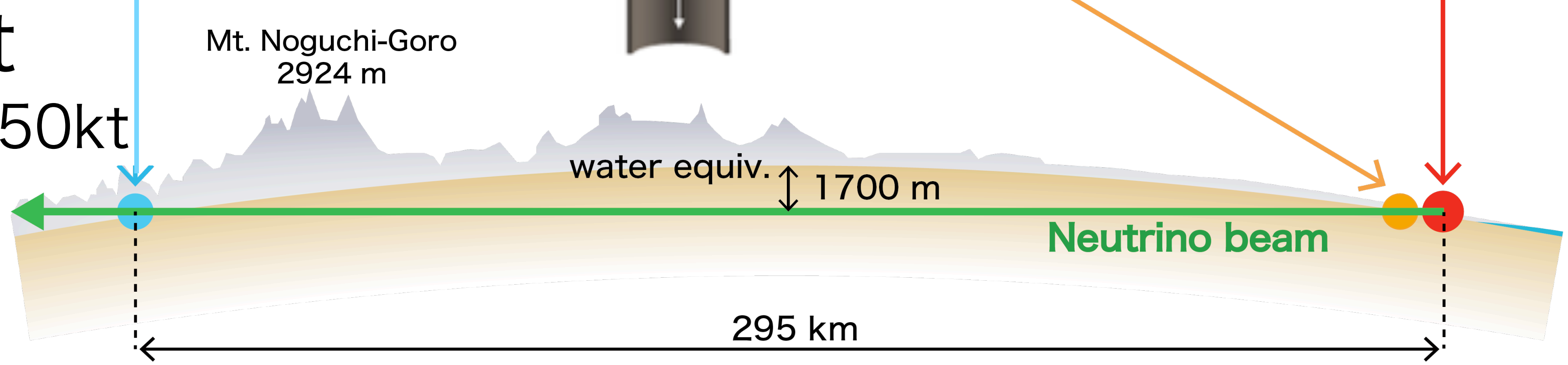


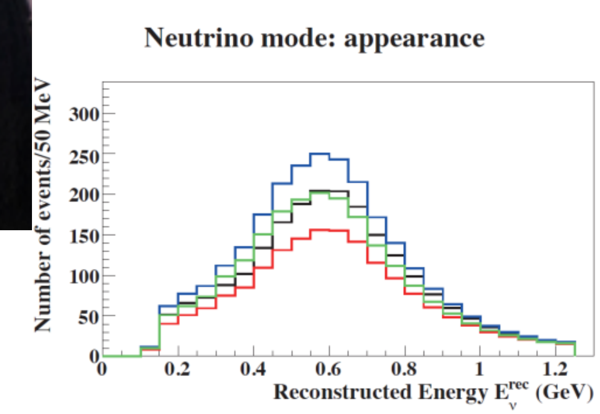
Beam power upgrade 750kW → 1.3MW

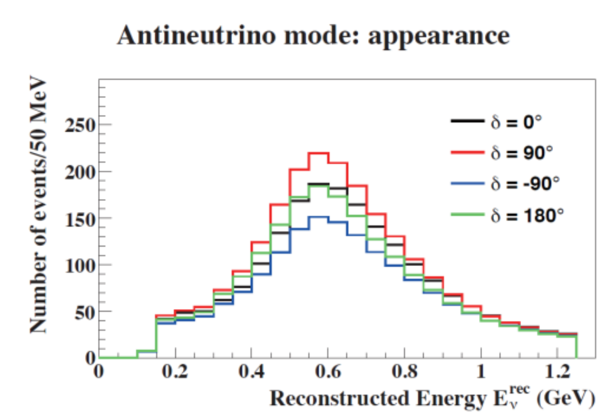


Near Detector

J-PARC







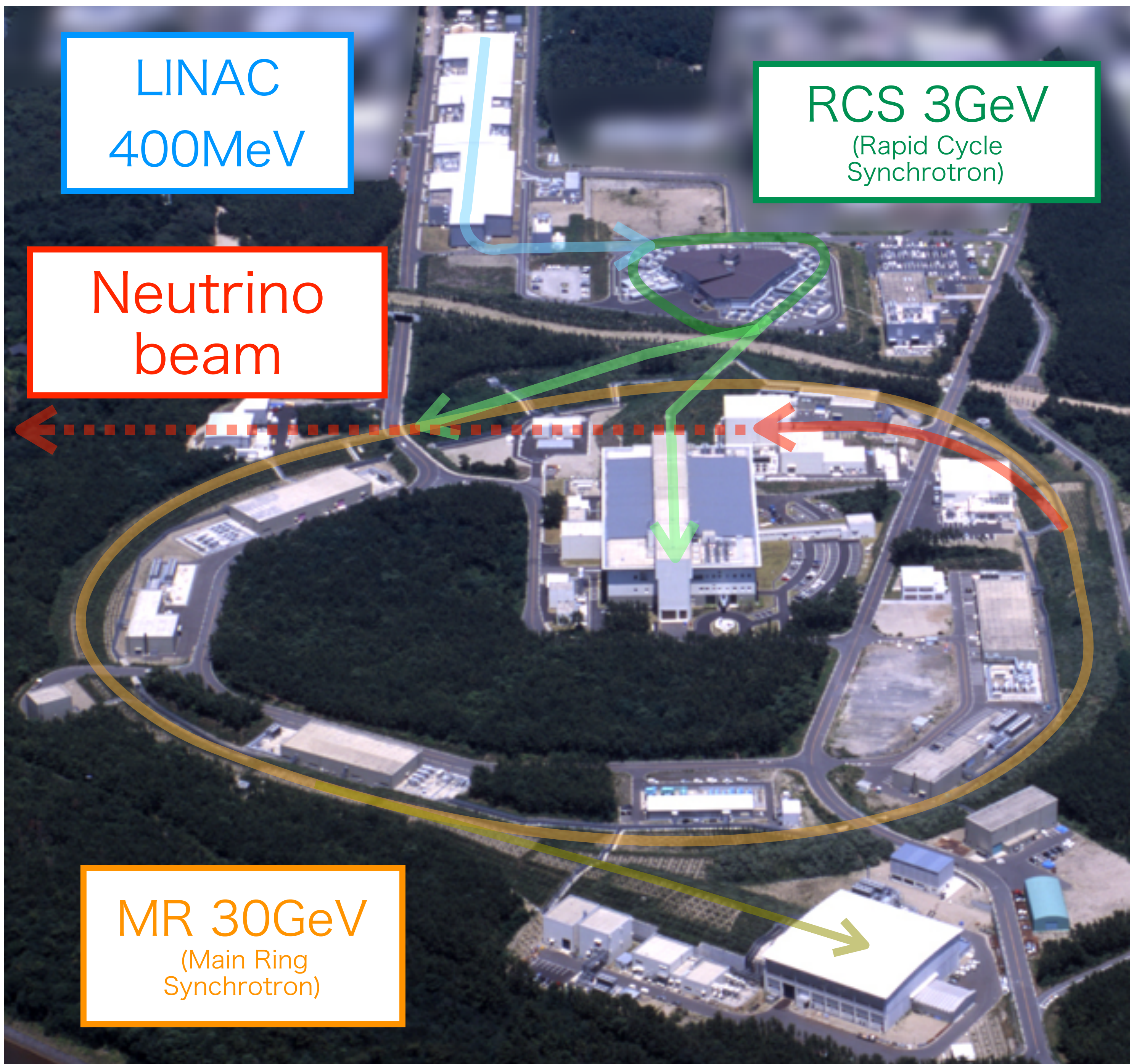
J-PARC MR status

- MR Beam power

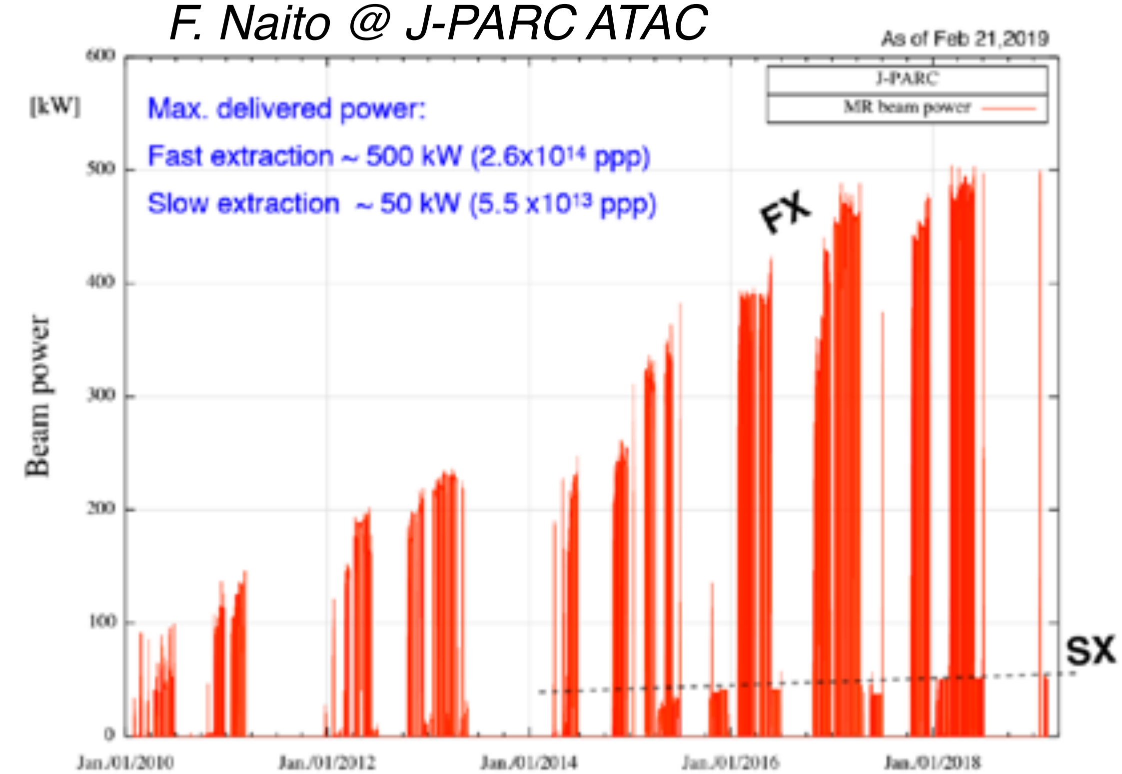
  ∝ (proton energy) × (protons/pulse) ÷ (repetition cycle)

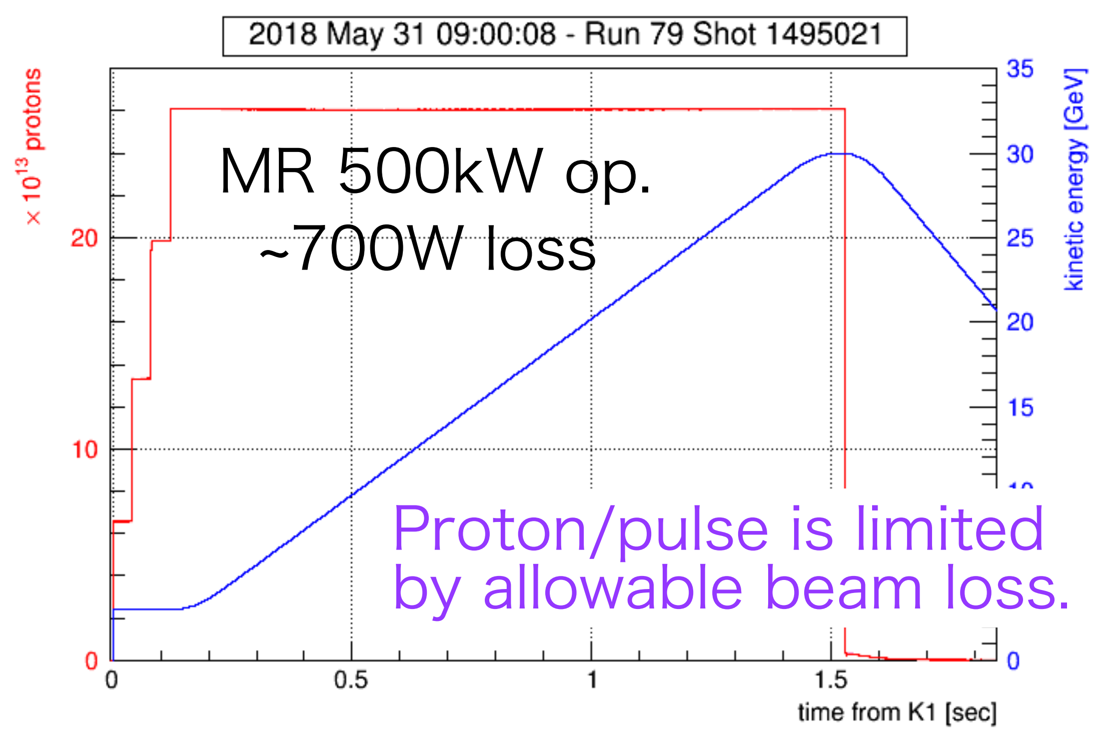
  = 30[GeV] = 2.6×10^{14} ppp = 2.48[s]

→ 500kW achieved



F. Naito @ J-PARC ATAC





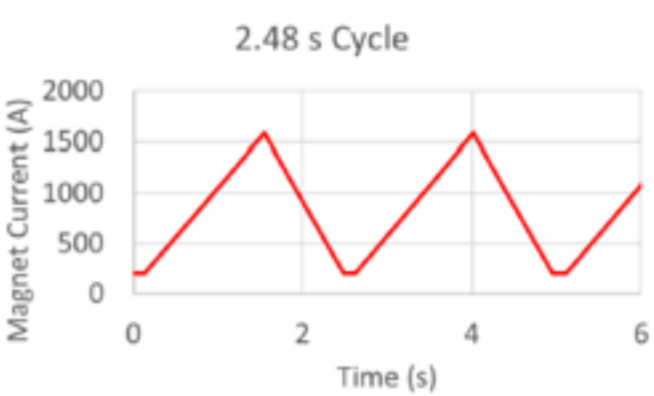
Proton/pulse is limited by allowable beam loss.

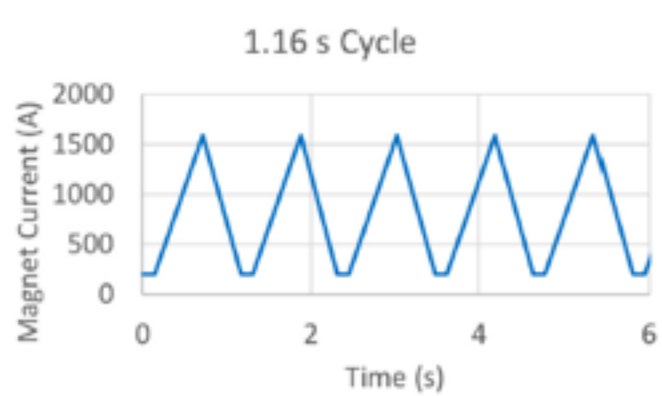
J-PARC MR upgrade plan

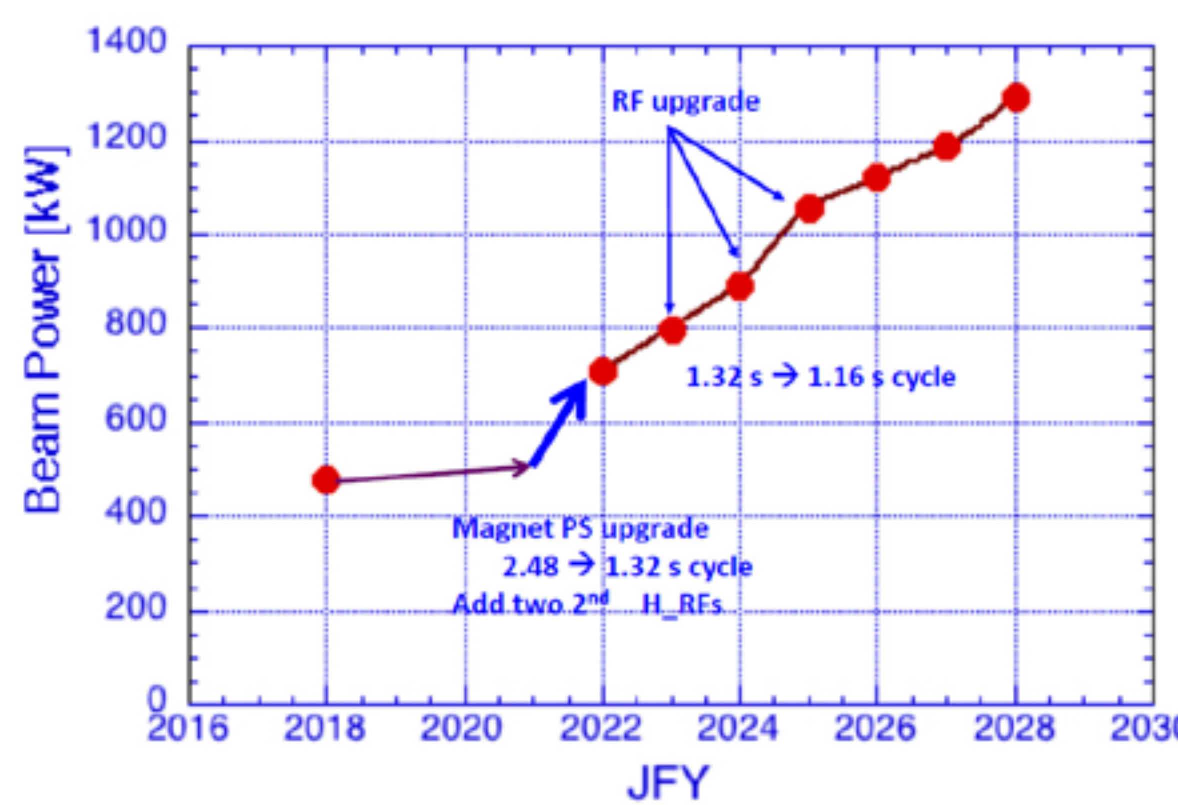
- Shorten repetition cycle
  + Increasing Protons/pulse
- Hardware upgrade in 2021.
  - Main magnet power supply
  - Reinforcement of RF.
  - Beam dump, etc

JFY	2017	2018	2019	2020	2021	2022	2023	2024
Event	New buildings		HD target		Long shutdown			
FX power [kW]	475	>480	>480	>480		>700	800	900
SX power [kW]	50	50	50	70		> 80	> 80	> 80
Cycle time of main magnet PS	2.48 s	2.48 s	2.48s	2.48s		1.32 s	<1.32s	<1.32s
New magnet PS	Mass production installation/test							
High gradient rf system								
2nd harmonic rf system	Manufacture, installation/test							
Ring collimators	Add.collimators (2 kW)				Add.colli. (3.5kW)			
Injection system	Kicker PS improvement, Septa manufacture /test							
FX system	Kicker PS improvement, FX septa manufacture /test							

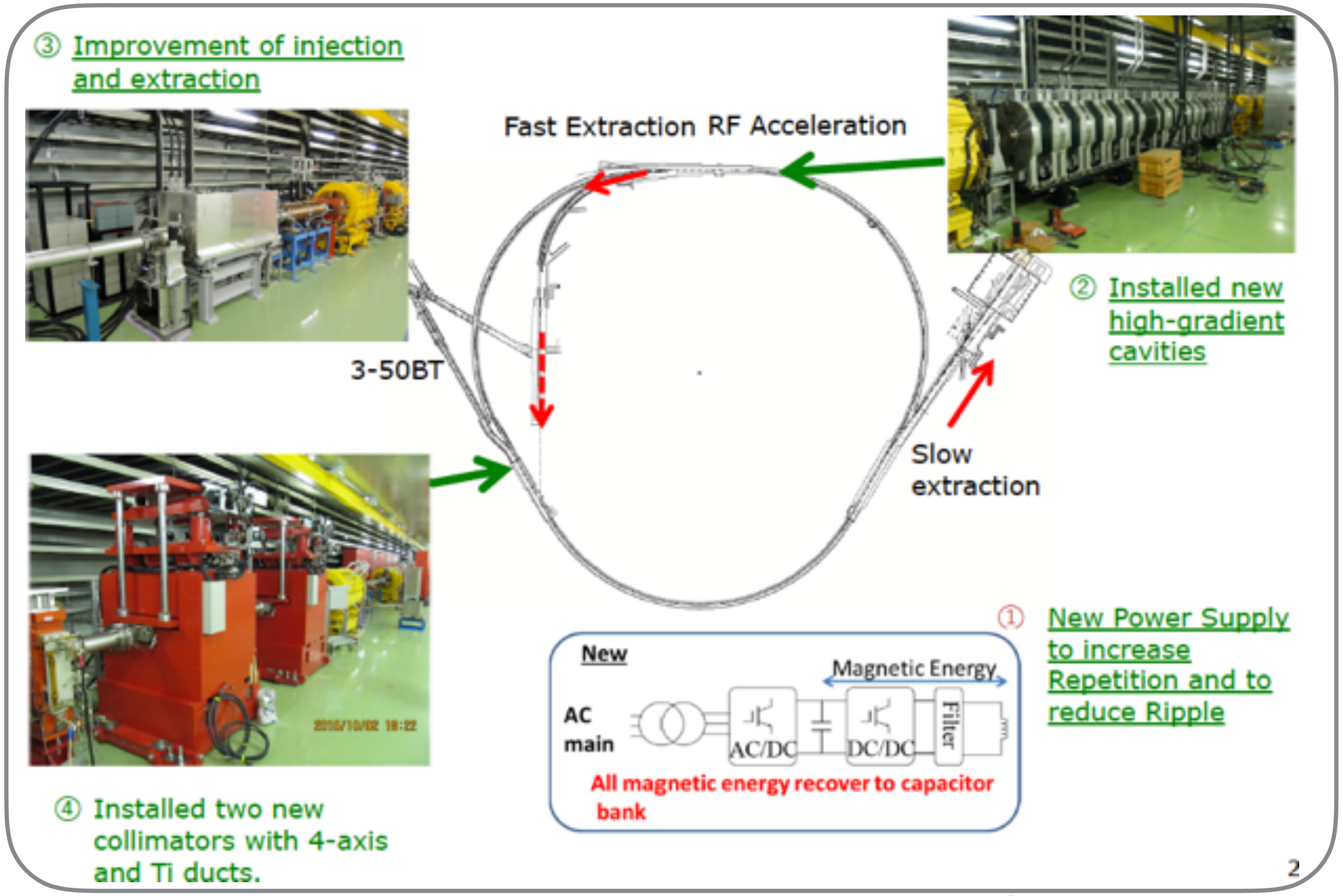
Beam Power	Cycle Time	Number of accelerated protons	Protons in each bunch	Equivalent beam power in RCS
500 kW	2.48 s	2.6×10^{14} ppp	3.3×10^{13} ppb	780 kW
750 kW	1.32 s	2.1×10^{14} ppp	2.6×10^{13} ppb	610 kW
1.3 MW	1.16 s	3.3×10^{14} ppp	4×10^{13} ppb	1 MW





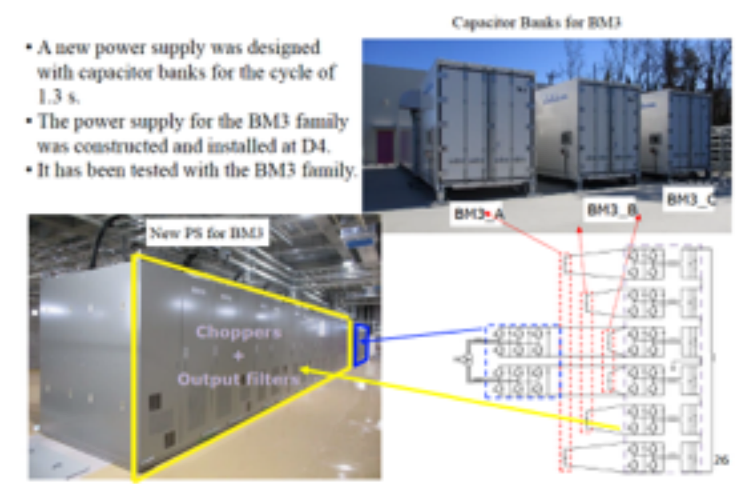


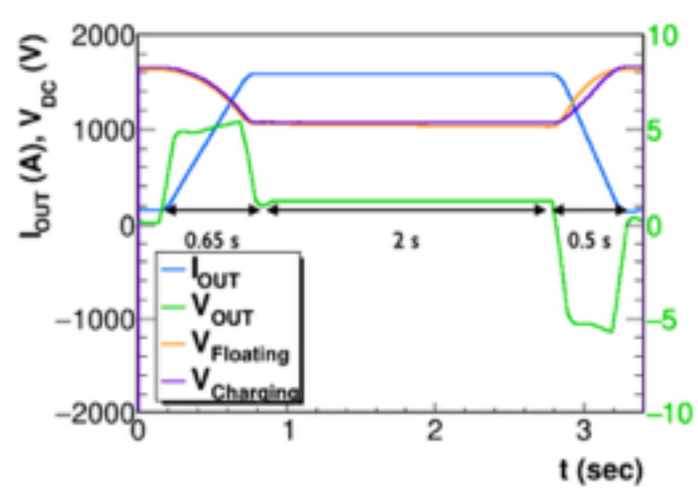
Accelerator upgrade status



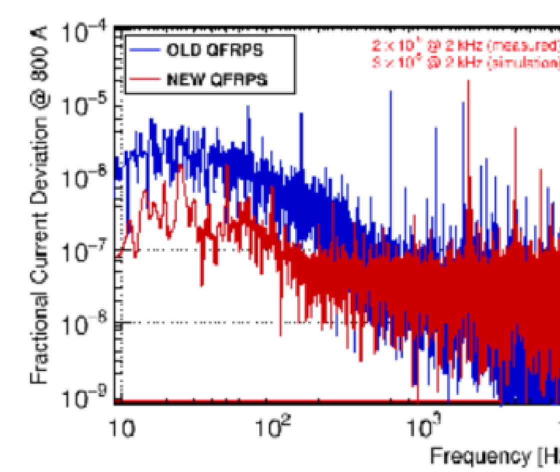
- New 2nd harmonic RF system for 1.32s operation was assembled

- New 2nd harmonic cavity with 4 accelerating gaps



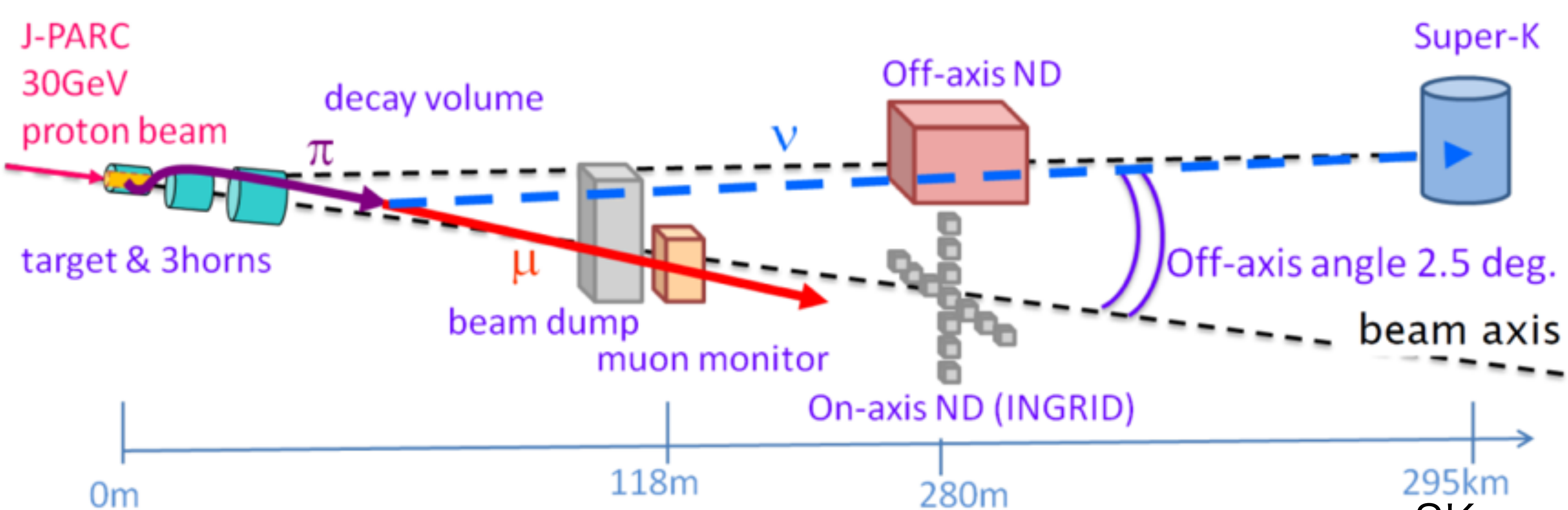


Output current ripple

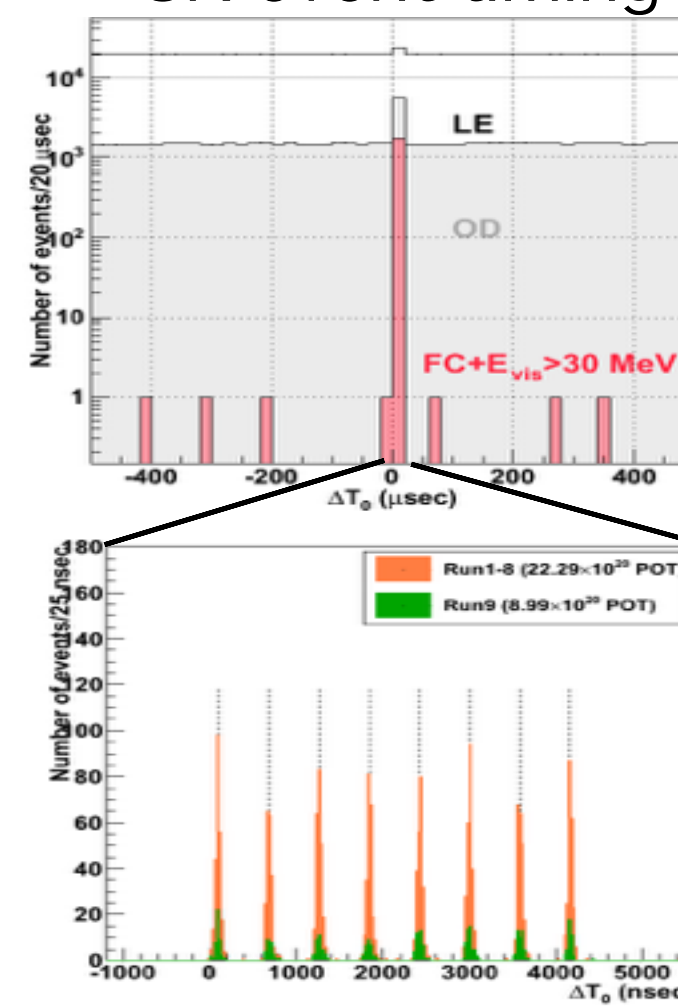


- One new power supply is tested and working as expected.

Challenges to the neutrino beam for LBL



SK event timing



- J-PARC neutrino beam: conventional neutrino beam
- Larger Heat load due to high intensity beam exposure.
- Using proton beam by **fast-extraction**.
  - Distinguish accelerator-origin neutrino by timing information.
  - Horn (pion focusing device) is pulsed magnet.

→ Instantaneous beam exposure for target, beam-window, and etc.

- Long-term experiment: $O(10^7)$ proton pulse / year × 10 years

Keeping same condition for ν-beam and ν̄-beam is important.

→ Long equipment lifetime is desired.

→ Understanding the radiation damage and fatigue behavior of the material is important.

Beam parameter MR-FX: Current and upgrade scenario

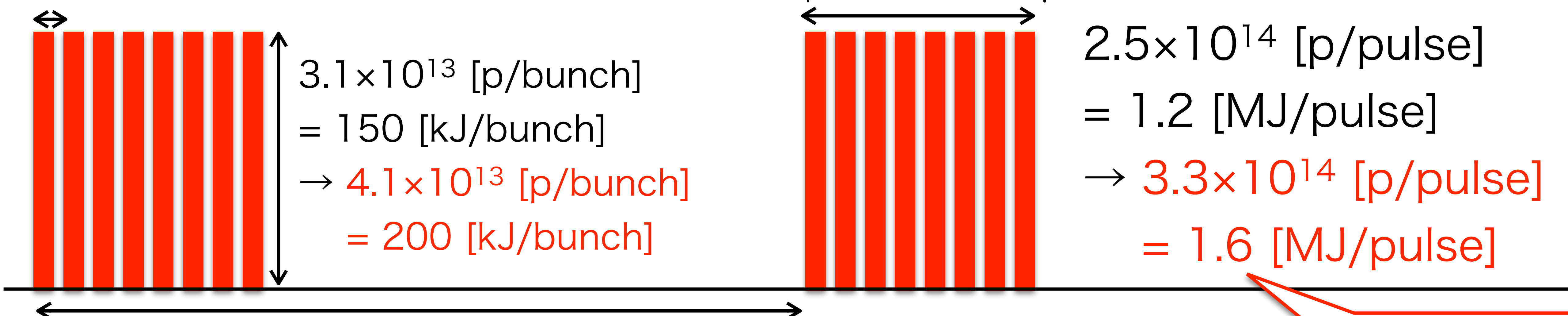
Table 1: Summary of the MR operation parameters for the current and proposed beam power.

Beam power	485 kW (achieved)	511 kW (demonstrated)	750 kW (proposed)	1.3 MW (proposed)
Beam energy	30 GeV	30 GeV	30 GeV	30 GeV
Beam intensity (ppp)	2.5×10^{14}	2.6×10^{14}	2.0×10^{14}	3.2×10^{14}
Repetition cycle	2.48 s	1 shot	1.32 s	1.16 s

- Time structure

Bunch width 20~40 ns (1 σ FW)
Bunch interval 581ns (RF=1.72MHz)

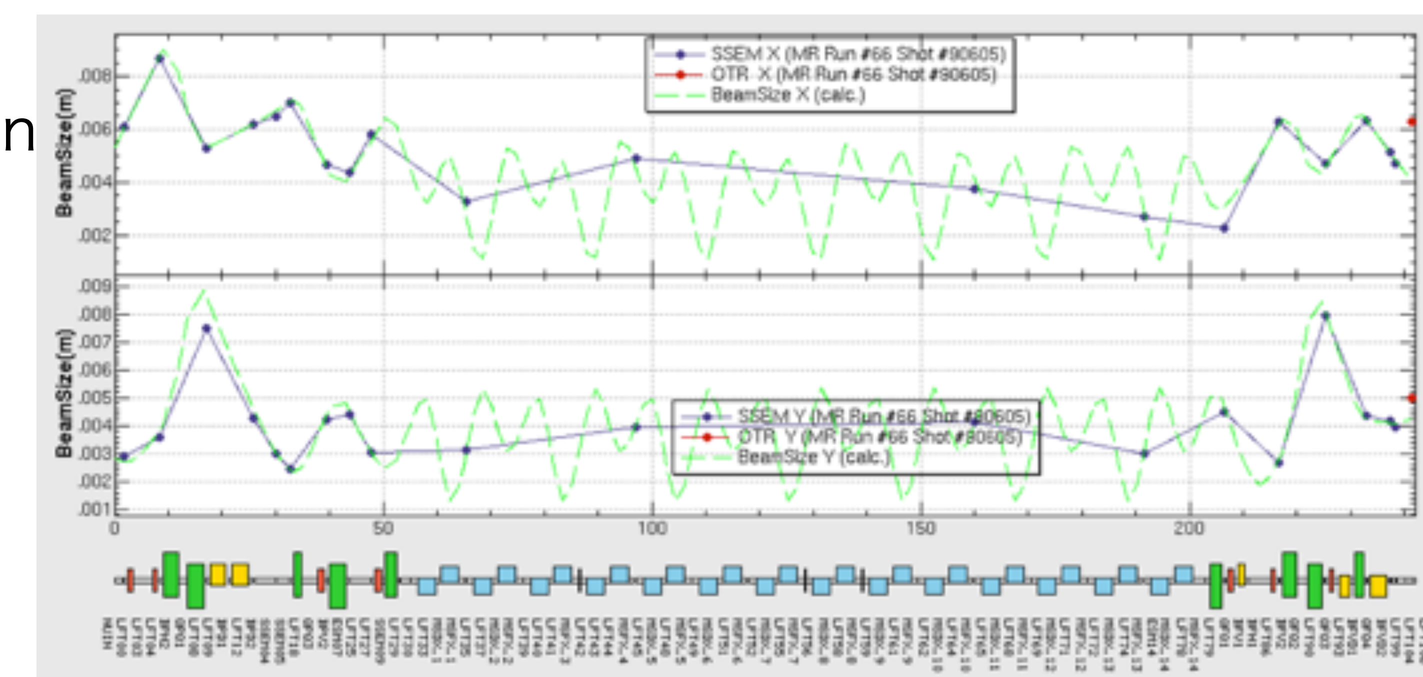
8 bunches / pulse
pulse width ~4.5μs



Same as original 750kW design

Cycle: 2.48s [0.40Hz] → 1.16s [0.86Hz]

Beam size at proton transport for extracted beam (Measurement and Fitted for 395kW beam)



Beam size (1 σ) at target is adjusted to 4mm×4mm.

↓

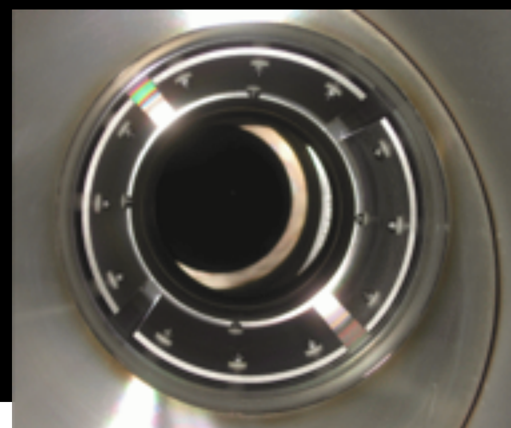
Peak proton density
3.3×10^{12}[p/pulse/mm^2]
Peak energy density
16 [kJ/mm^2/pulse]

J-PARC ν beam-line equipment

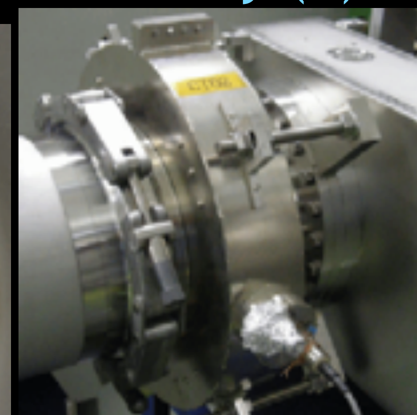
Beam monitors are install along the proton beam transport

Profile (19)

Position (21)



Intensity (5)

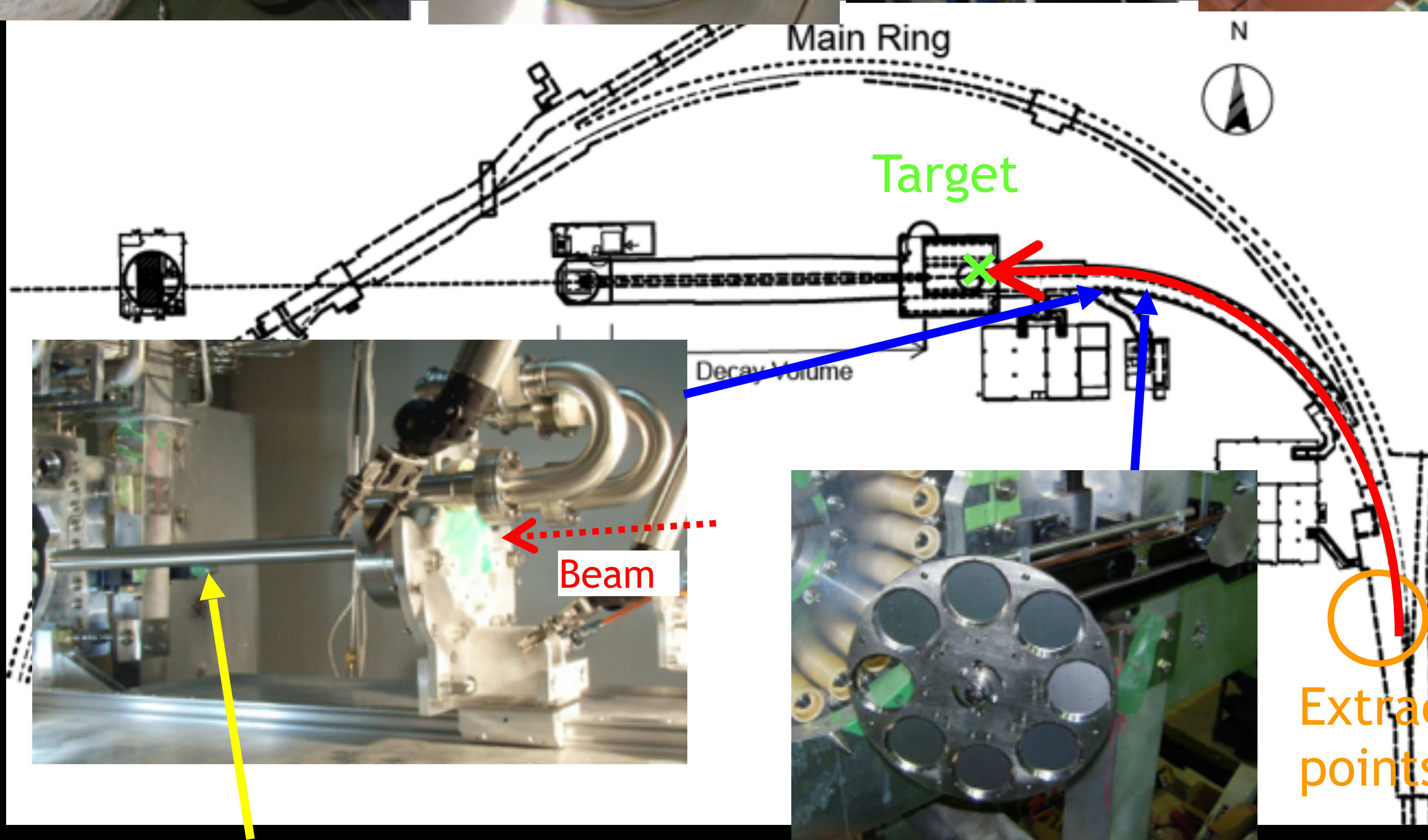


Beam loss (50)

Primary proton transport line

Super-conducting combined-function magnets

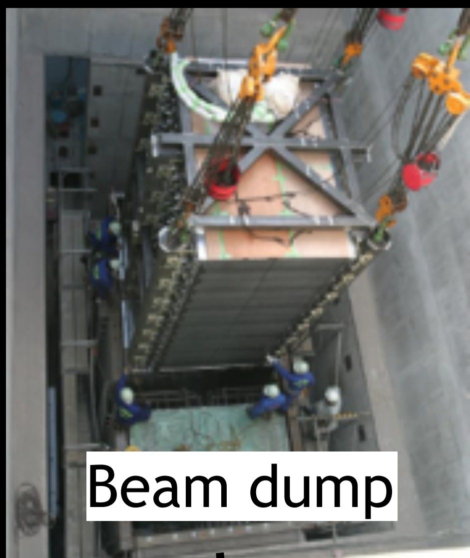
Normal-conducting magnets



Target :graphite rod
ϕ26mm,L=900mm

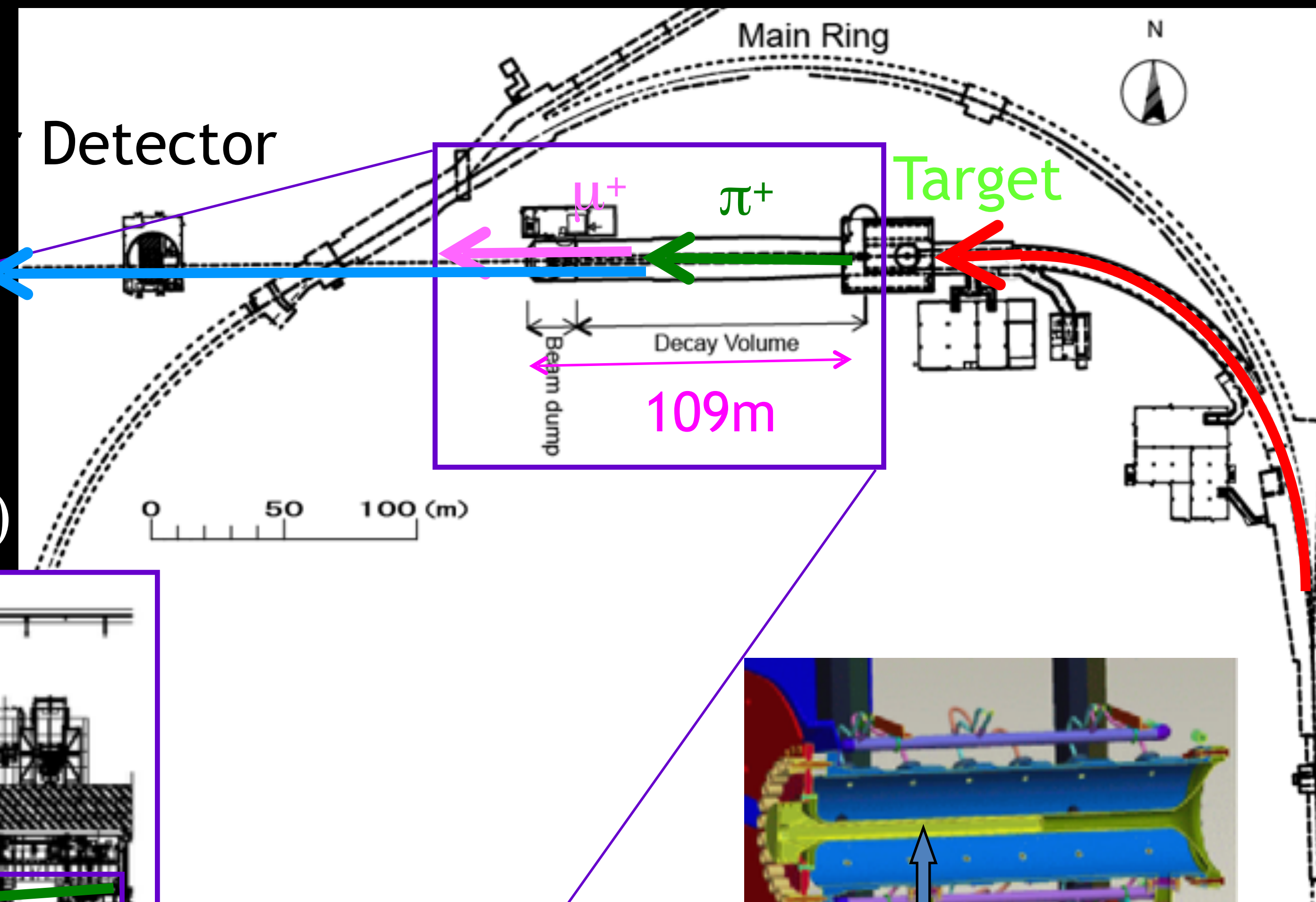
Optical Transition Radiation (OTR)
Profile monitor

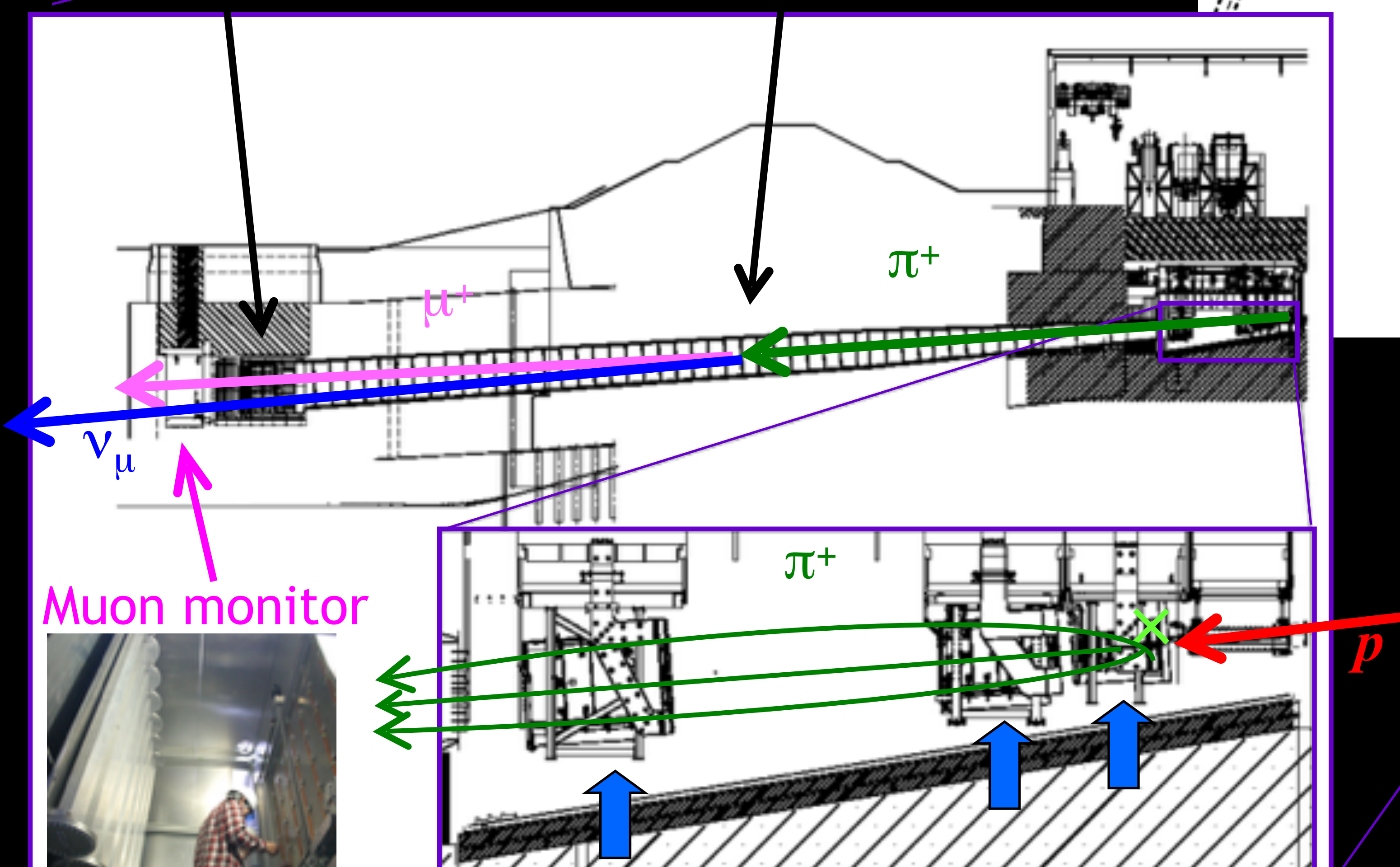
J-PARC ν beam-line equipment (cont'd)



Beam dump

Decay volume (He gas filled)





Muon monitor

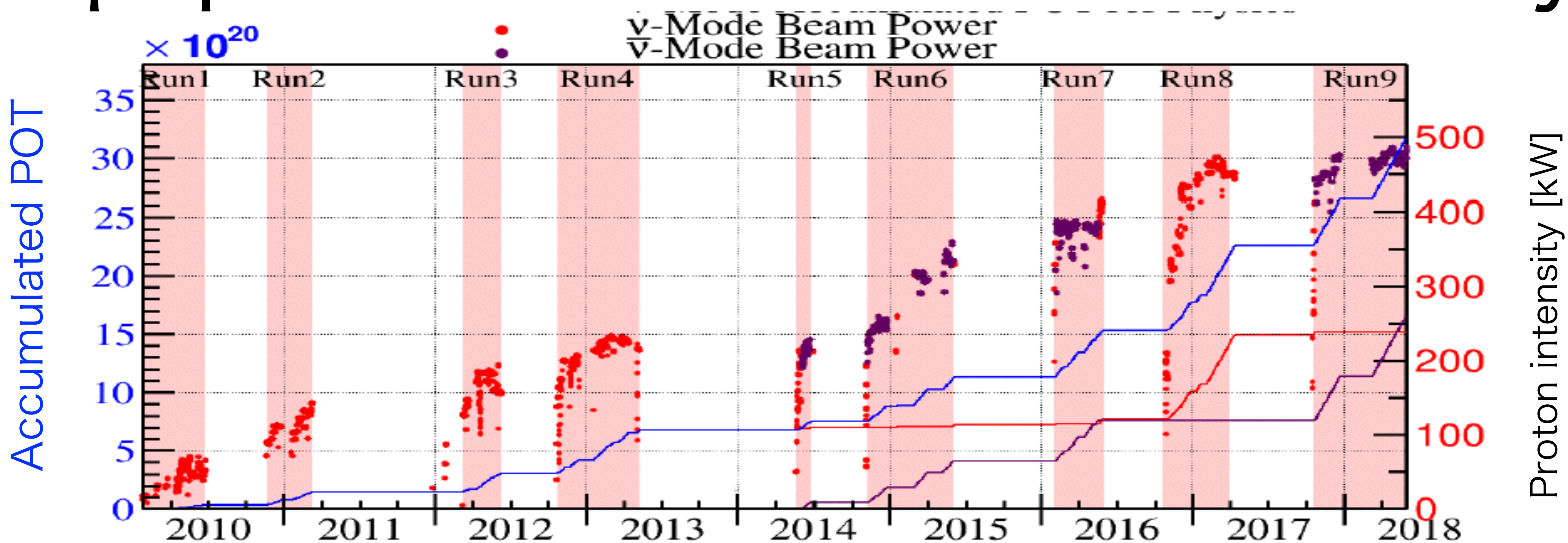
Target installed in 1st horn.

Pions are focused by 3 electromagnetic Horns.

Equipment exposed to proton beam

- Beam intersecting devices.
  - Beam profile monitors
    - Segmented Secondary Emission Monitor
    - Wire Secondary Emission Monitor
    - Optical Transition-Radiation profile monitor
  - Beam window: boundary between the proton transport (vacuum) and target area (He, 1atm)
  - Baffle (collimator at target/horn)
  - Target
  - Beam dump
- For the high intensity beam facility, failure mode and effect analysis on unexpected machine status is important for the safety / stable operation.
- At J-PARC neutrino facility, the following equipments can be exposed to direct proton beam hit in case of equipment trouble (the malfunction of the extraction kicker, etc.)
  - Beam plug (beam stopper for personal protection system)
  - Proton beam duct and Collimator (protection for SC magnets)
  - Beam position/intensity monitor and its beam ducts.
  - Gate valves intersecting the proton transport vacuum sections.

Equipment maintenance history



Target-1 → Target-2

OTR-1 → OTR-1

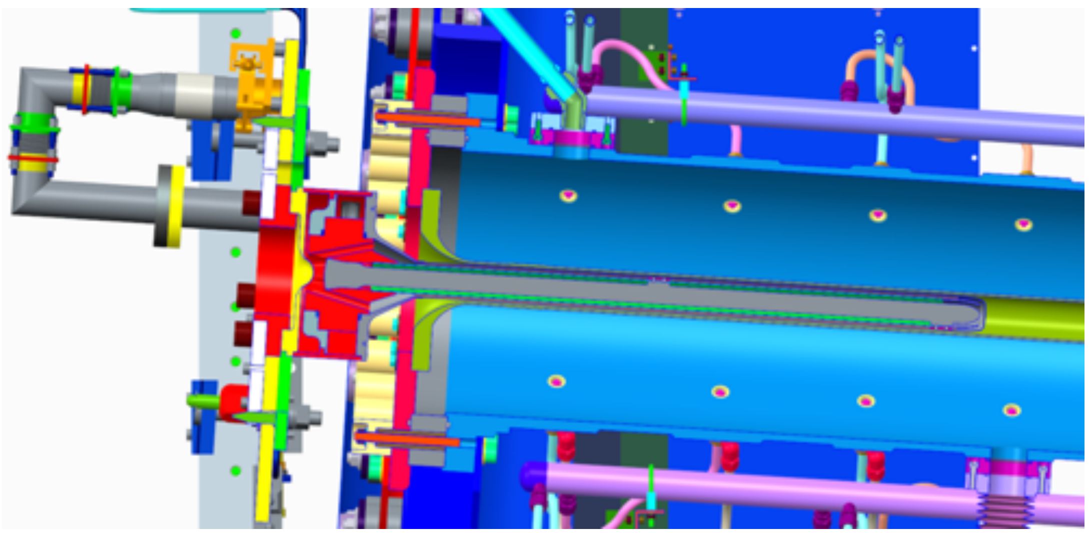
Horn ver.1 → Horn ver.2

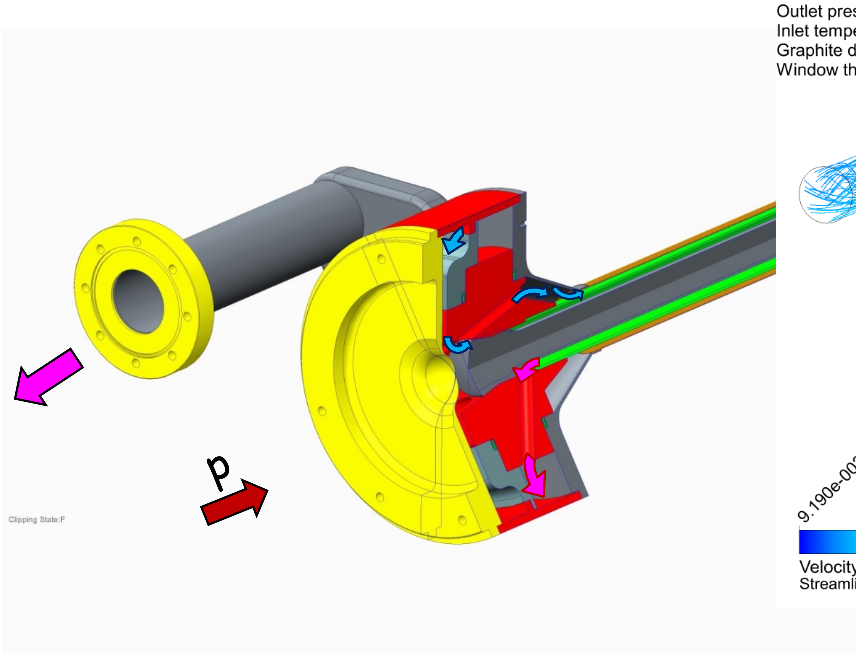
Beam window-1 → BW-2

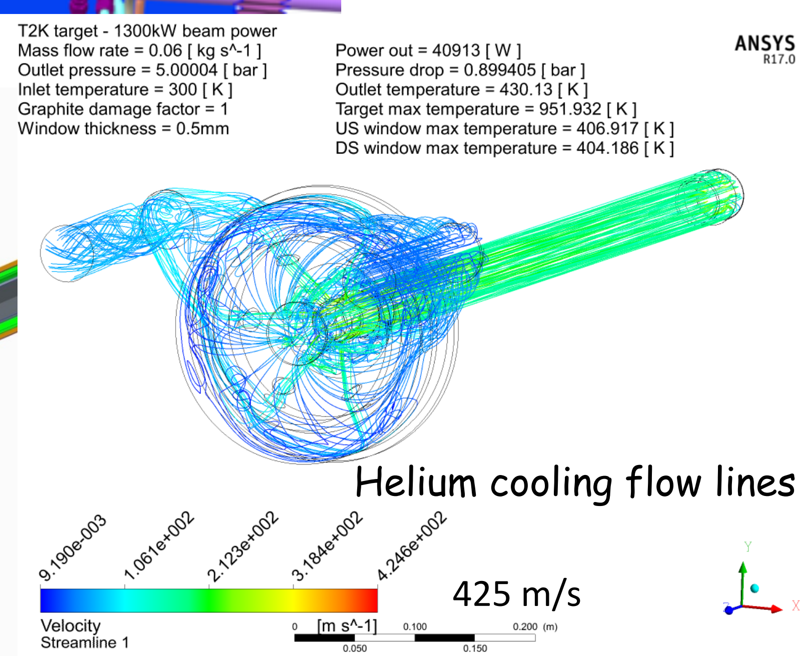
SSEM 19 foil

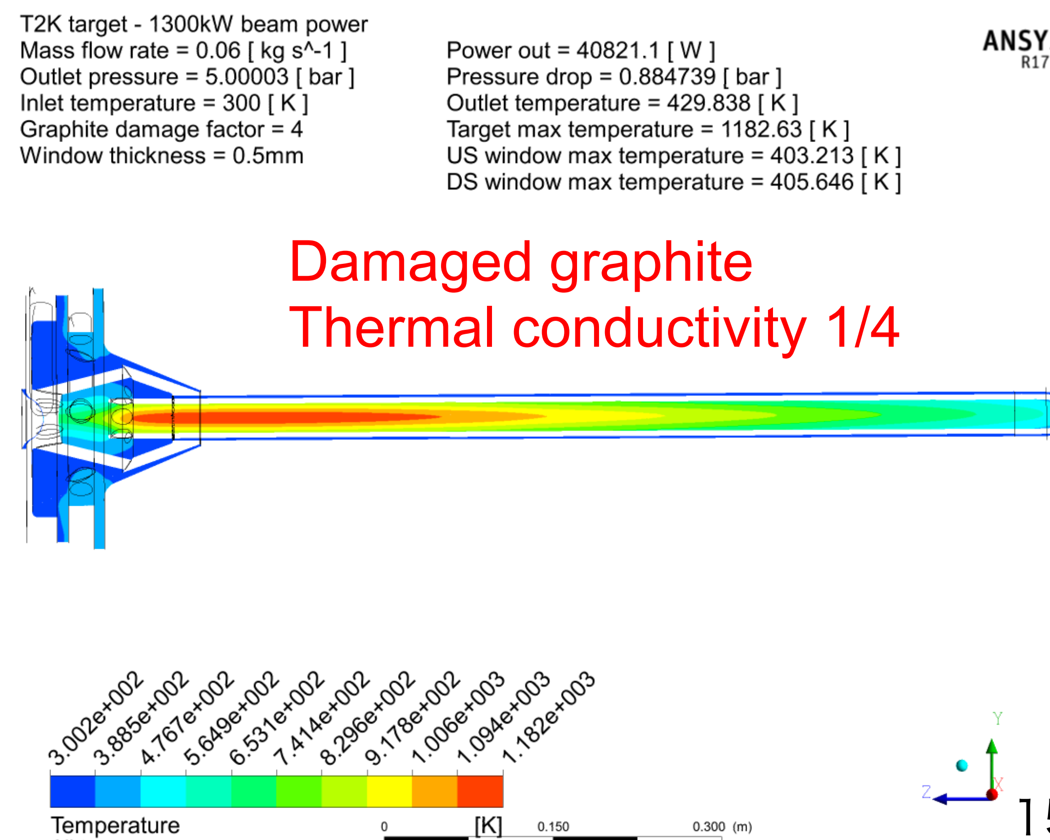
Target

- Current target is designed for 3.3×10^{14} p/pulse.
- Heat load: ~23kW (for 750kW) → ~41kW (for 1.3MW)
- He gas cooling will be reinforced. (0.3MPa→0.5MPa)
- Ti case design is updated for higher He pressure.





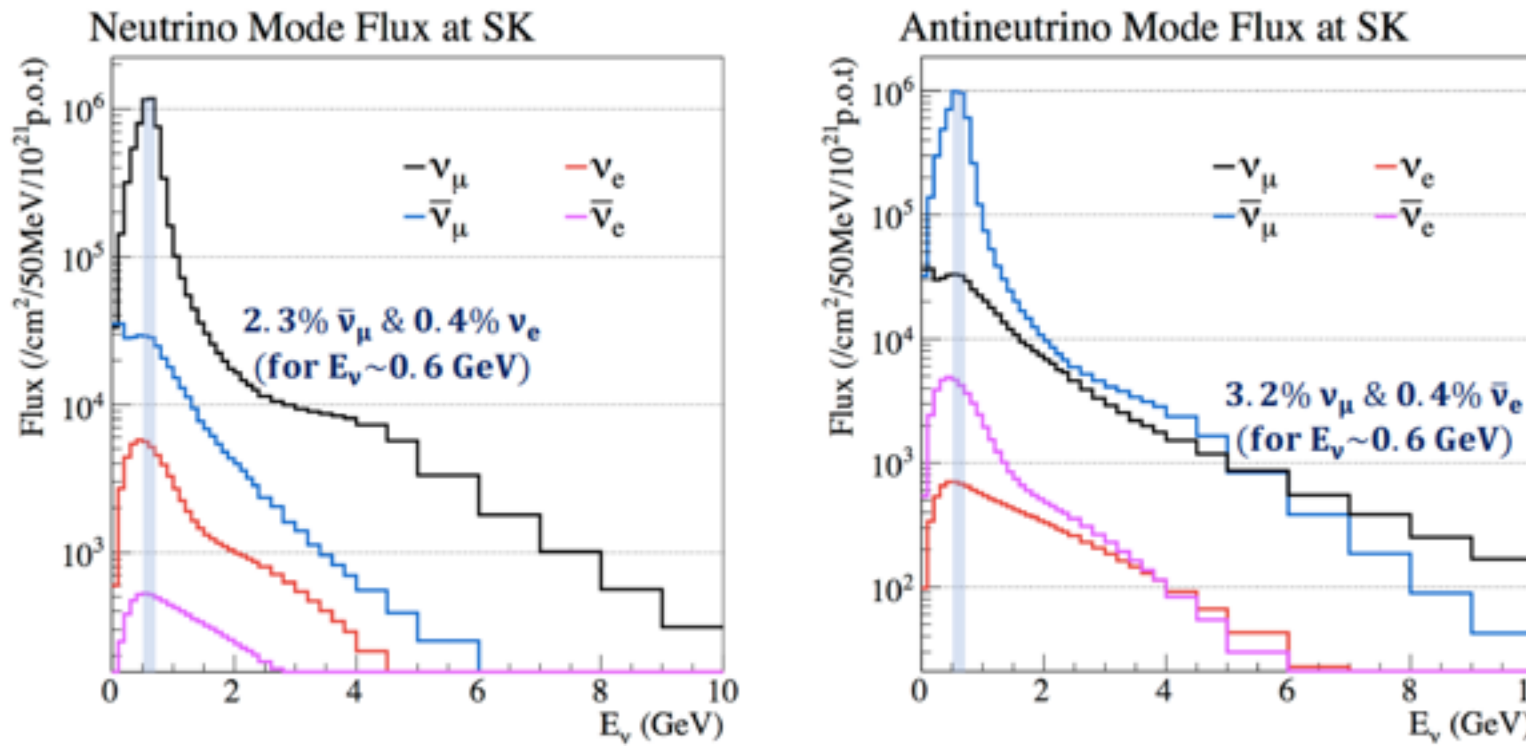




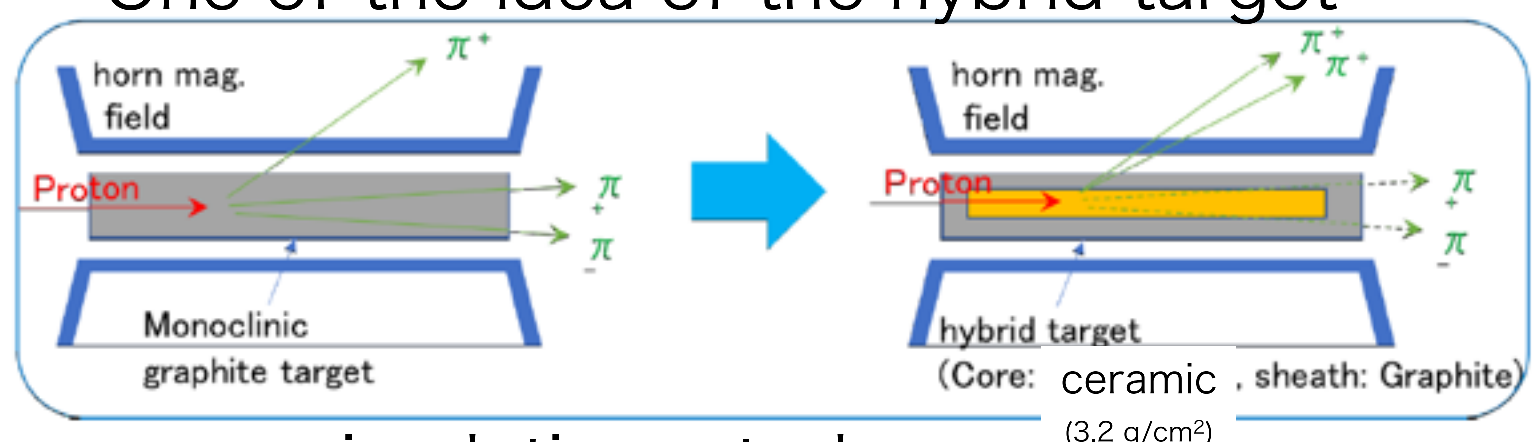
Possible future target upgrade

- For CPV search, higher “purity” of neutrino beam will be improve the sensitivity.
- We are investigating the possibility to use higher density material for the target material to improve yield and/or purity.
  - Candidate is thermal shock resistant ceramics: SiAlON, SiC.
- It is necessary to evaluate the resistance against the instantaneous impact shock due to beam exposure (and the radiation resistance.)
  - At least relative comparison with the isotropic graphite, etc.

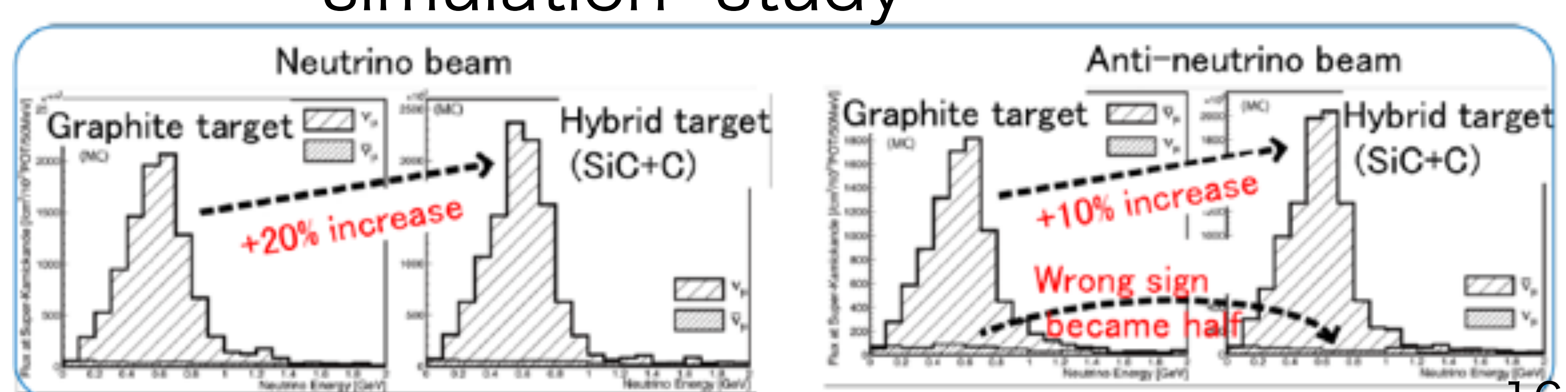
Current J-PARC neutrino flux



One of the idea of the hybrid target

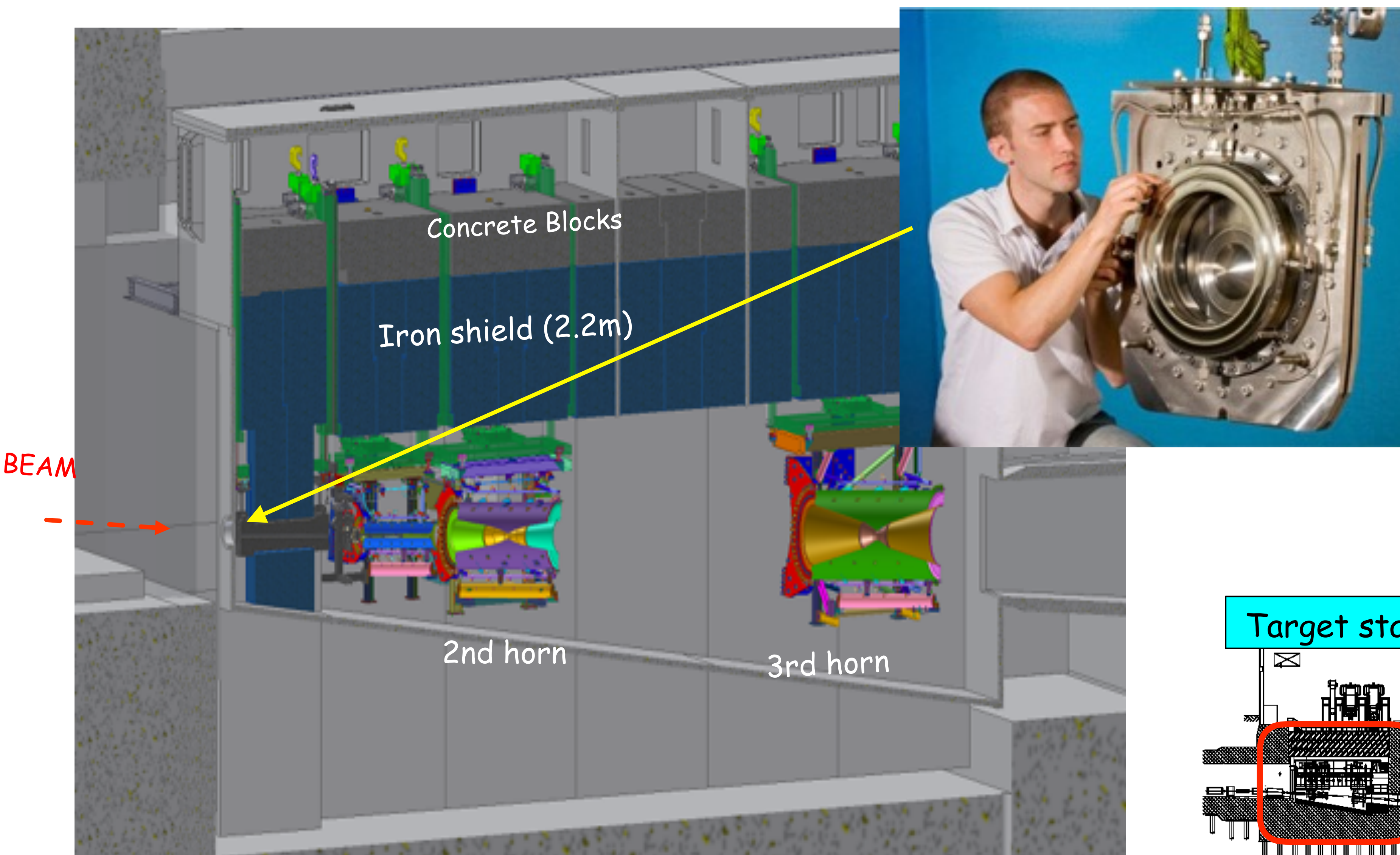


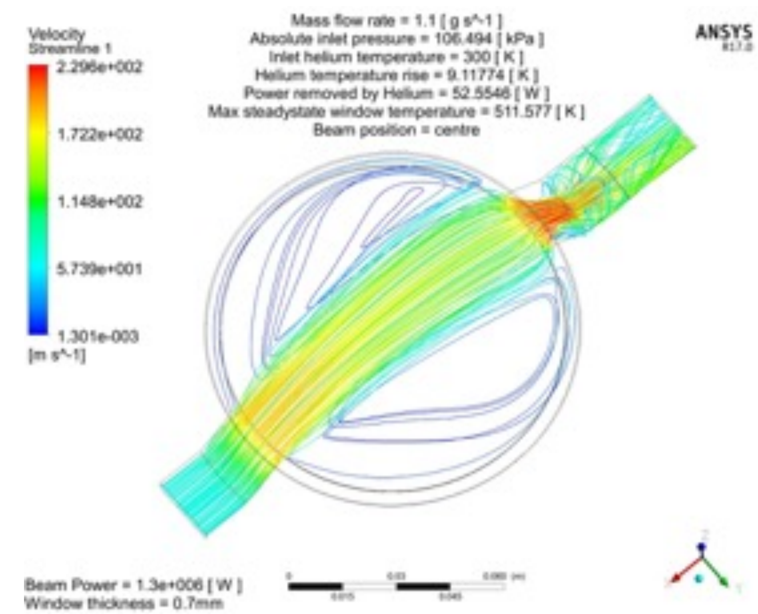
simulation study



Beam window

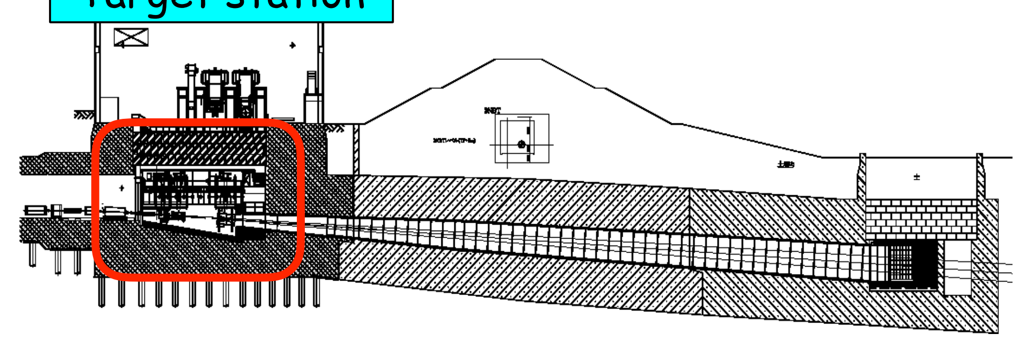
- Separating vacuum and Helium (w/ high humidity)
- Co-centric 2 Ti-6Al-4V Ti hemisphere shape w/ 2mm gap for Helium gas flow for cooling.
- Exposure of 2.4×10^{21} protons/year
  → Expected ~2 dpa/year for 1.3MW beam.





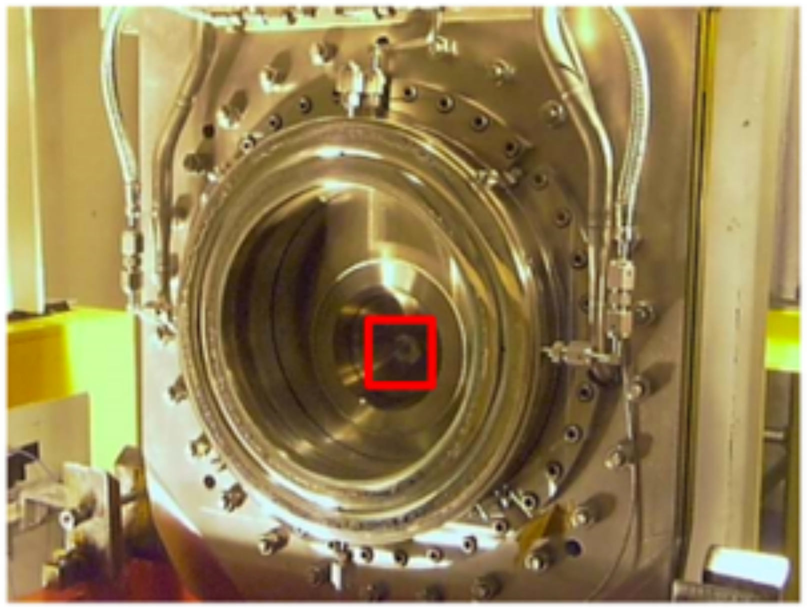
- Helium flow lines
- 1.3 MW beam (steady state/CW simulation)

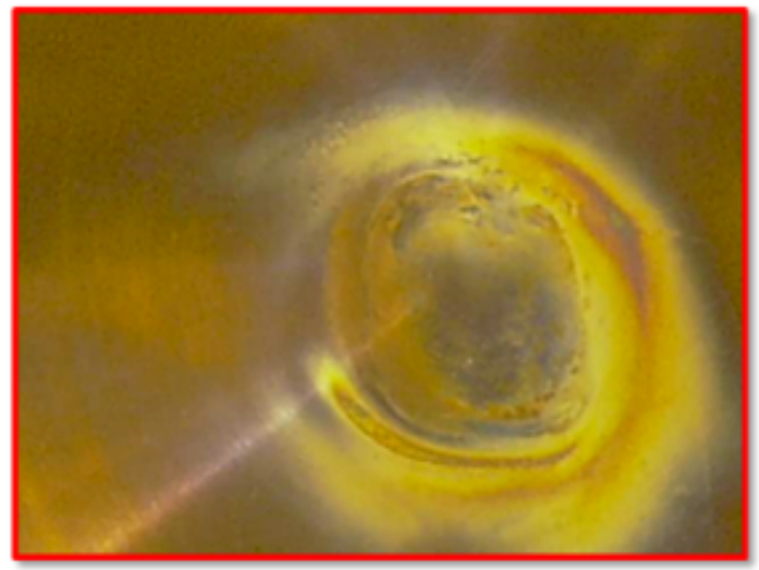
Target station



Beam window (Cont'd)

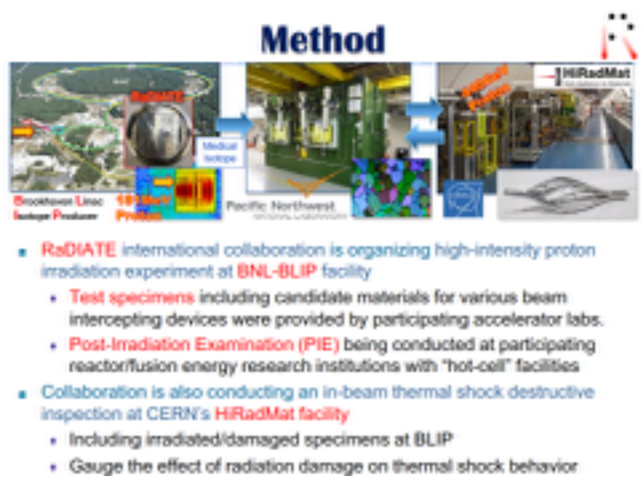
- First beam window survived for $2.2{\times}20^{21}$ exposure.
- "Beam spot" has been observed by visual inspection.

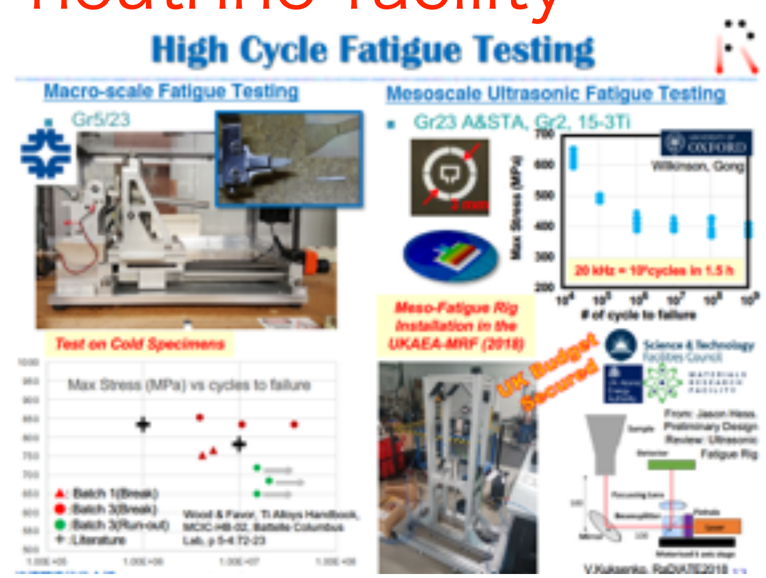


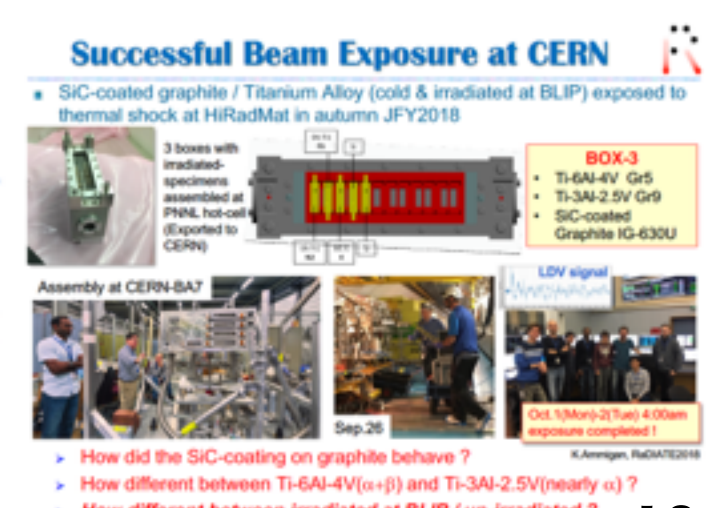


Note: These pictures were taken through thick lead glass under the lighting with sodium lumps.

- Intensive study for the properties of irradiated Ti-Alloy including the thermal shock studies at HiradMat is in progress by RaDIATE collaboration.
→ Crucial information for J-PARC neutrino facility





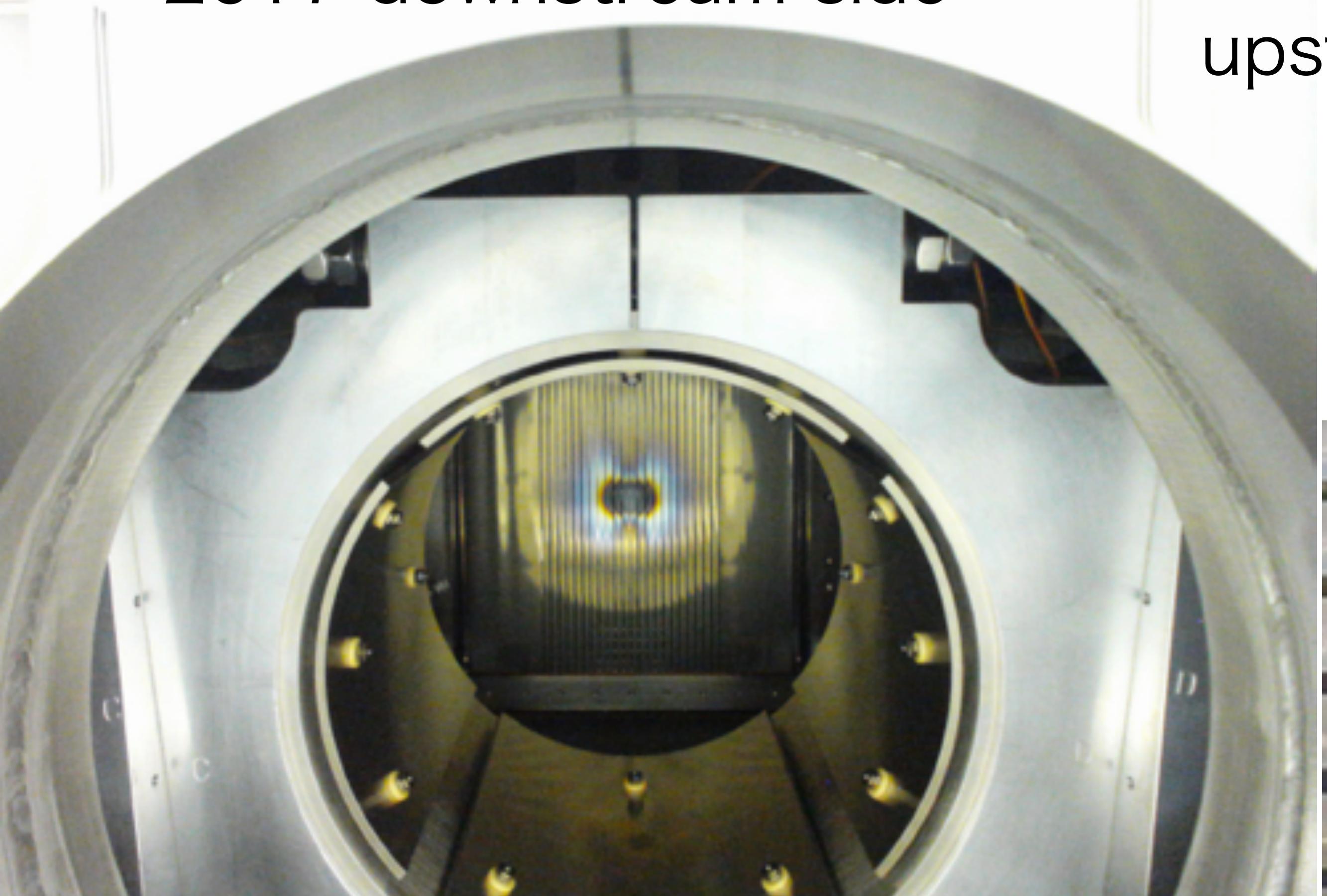


courtesy: T. Ishida

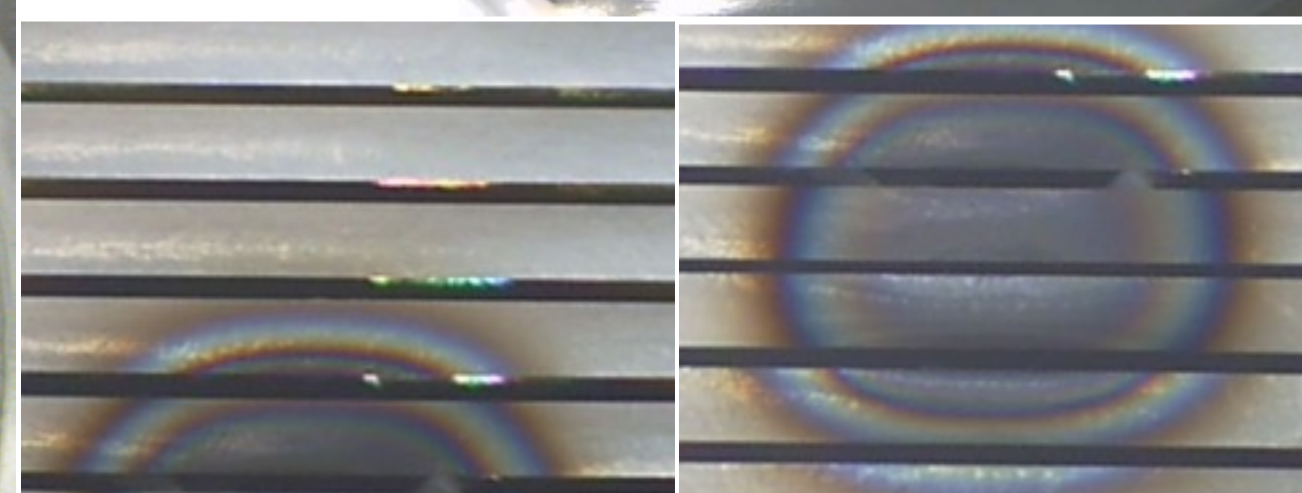
Secondary emission monitor

- Most downstream SSEM has been exposed to almost all beam pulse so far. (~3.2×10^{21} POT)
  - Other SSEMs are used only beam tuning beam spill.
- Beam sport on Ti-foil has been clearly observed by visual inspection.
- It is useful that if we can estimate lifetime of the monitor, because this SSEM measurement plays crucial role to guarantee the stability of the neutrino beam.

2017 downstream side



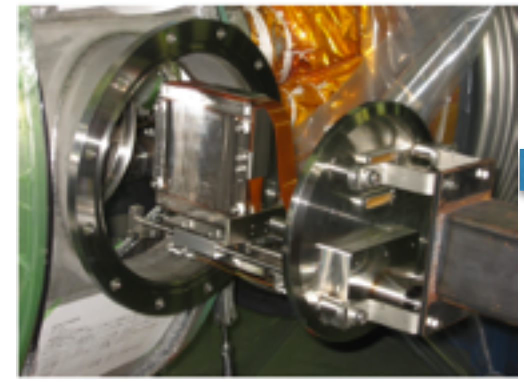
2018 upstream side



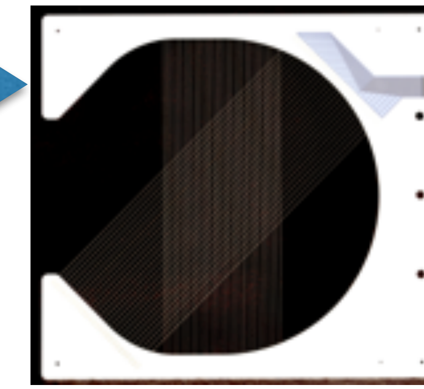
Beam monitor (cont'd)

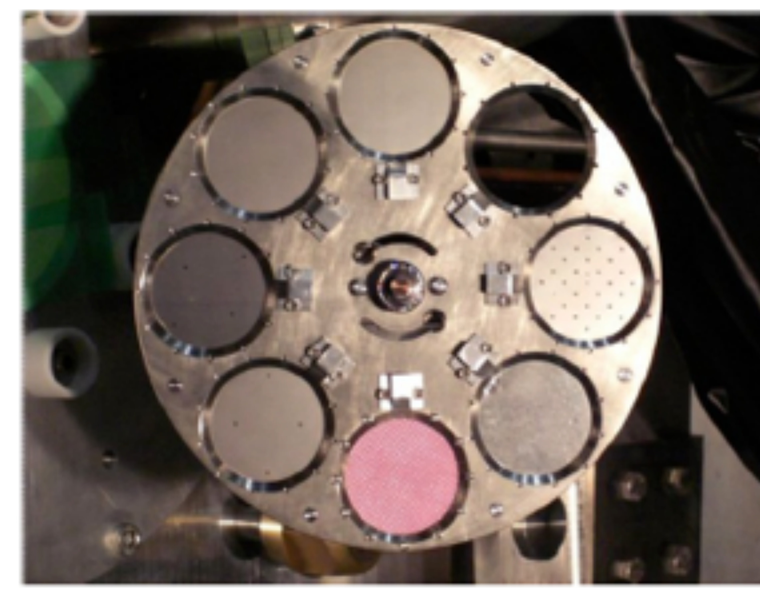
- We have replaced two SSEM with Wire-SEM.
  - It is under consideration to use low-z wire material (carbon) to reduce beam loss.
- Optical transition radiation monitors
  - 50μm Ti-15V-3Cr-3Sn-3Al foil is continuously exposed to proton beam.
- Non-destructive beam profile monitor by beam-induced fluorescence (BIF) monitor is under development.
  → Anti-reflection coating for the inner surface of beam duct can withstand (unexpected) beam hit?

SSEM

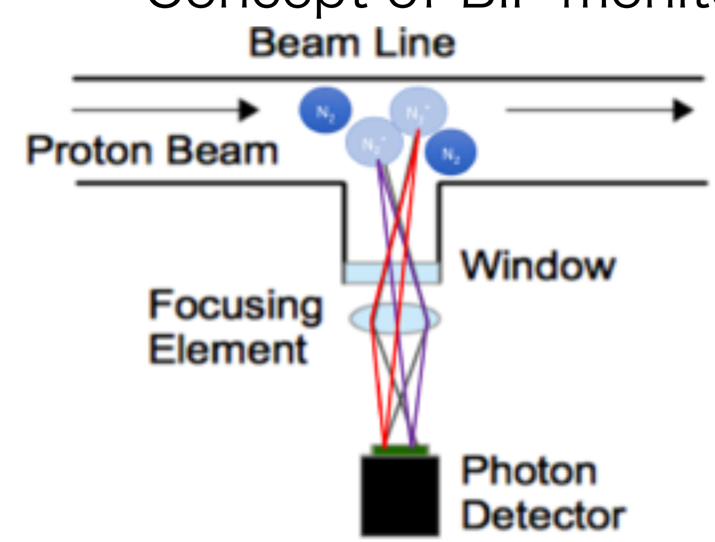


WSEM





Concept of BIF monitor



Summary

- J-PARC is providing the high intensity neutrino beam for the long-baseline neutrino oscillation experiment.
- Latest results of T2K experiment shows the interesting hint for CP violation in lepton sector. It strongly motivate the upgrade of T2K and realization of next generation experiment: Hyper-K.
- The J-PARC MR accelerator will be upgraded in 2021 to exceed 750kW design power, and further MR+neutrino facility upgrade aiming 1.3MW is planed.
- Notable feature of LBL ν program is the long-term (~10 years) experiment using fast-extraction high-intensity proton beam.
- For the improvement of the equipment that is exposed to beam, the information on the robustness against the instantaneous shock, and the fatigue properties after irradiation is desired.