Accelerator and Beamline Research and Technology Development for High-Power Neutrino Beam

大強度ニュートリノビームのための加速器とビームラインの研究・技術開発

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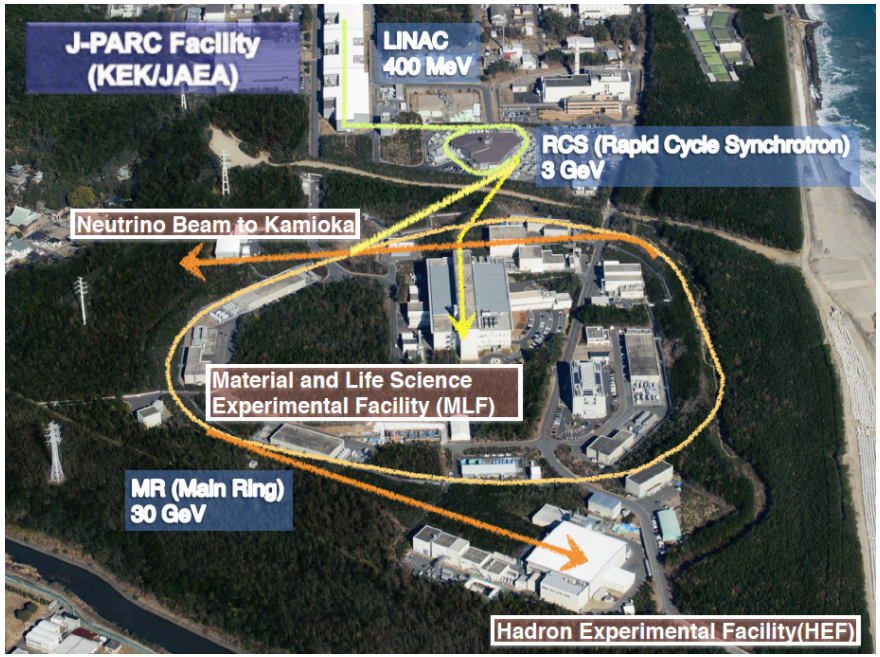
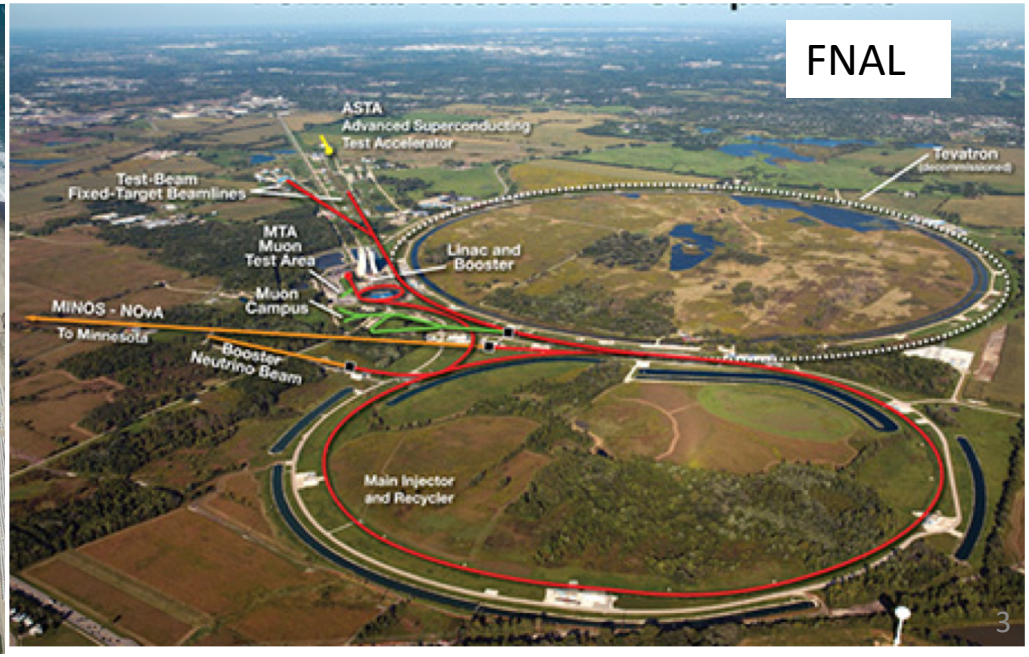
Overview

- Long Base-line Neutrino Oscillation experiment searching for the CP violation phenomena at lepton sector is one of the main topics in high energy physics.
- Both US and JP have on-going projects (T2K, NOvA) and future projects (HK, DUNE).
- The projects in US and JP are complementally for each other due to the difference of base-line length.
  - Unfold the matter-effect (mass-hierarchy) and CPV effects in Neutrino oscillation by combining the results from US & JP projects.
- The key components of LBL experiment are "High intensity neutrino beam" and "Huge neutrino detector".
- We are working together to realize "high intensity neutrino beam by >1MW proton driver"

Neutrino beam upgrade towards >1MW

- Accelerate more proton / pulse with minimizing beam loss in the accelerator ring and the extracted proton transport
  - To keep the residual radioactivity of equipment acceptable
  - To keep he radiation outside the shield below the regulation limit
- Increase the capacity of neutrino production facility.
  - Make equipment (target, horn, etc) robust
  - Handle the highly radio-activated equipment/waste

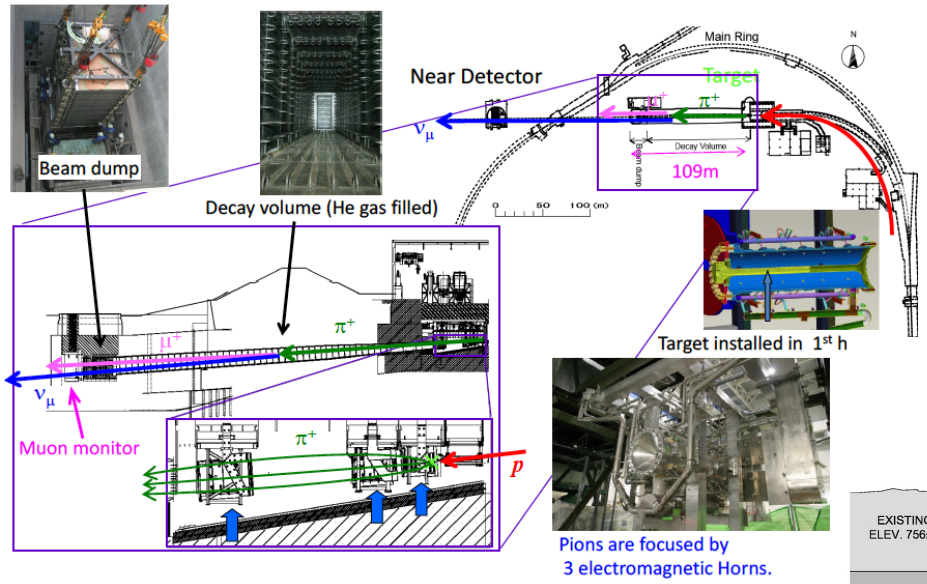


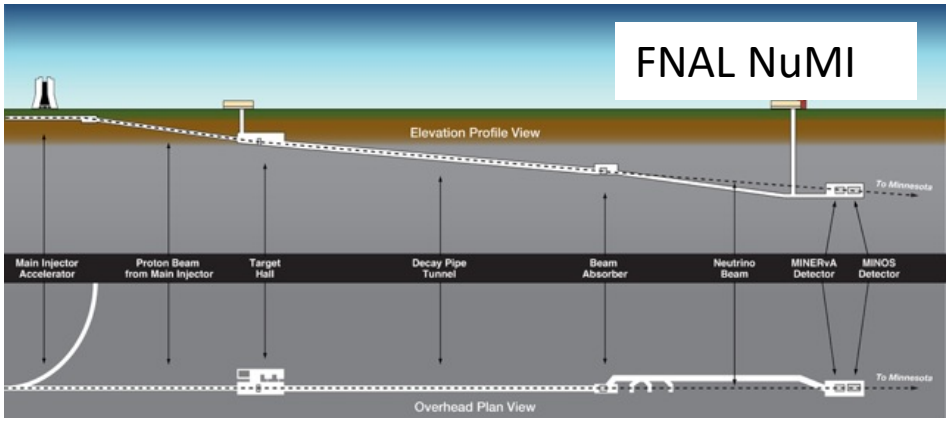


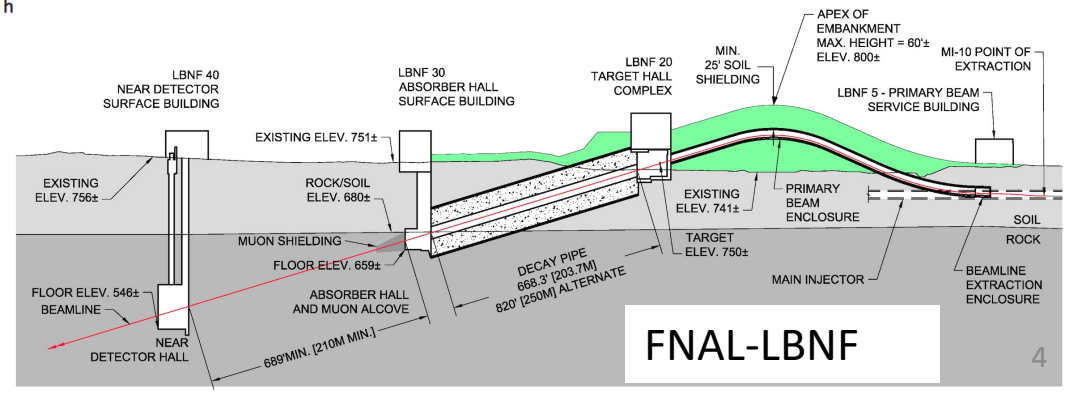
Common interest to increase the beam power

- Improvement of secondary beam-line.
  - Robustness of secondary components that are exposed by high-radiation, high heat-load environment.
  - Maintenance of highly activated equipment
  - Containment, treatment and safe disposal of activated air/coolant gas/water.
  - Better neutrino yield / proton.

J-PARC ν beam line: secondary line





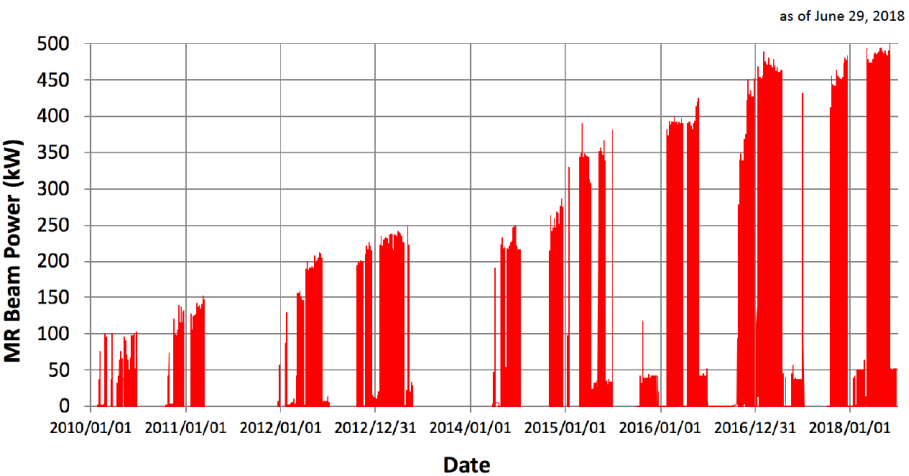


R&D items in this program

- To Reducing the beam-loss.
  - Better beam monitoring
    - Gated-IPM
    - high precision beam position measurement
  - Identification of cause of beam loss and correction:
    - Joint-Accelerator commissioning
    - Electron cloud studies
  - Reducing the interaction between beam and beam-instrument:
    - Laser beam manipulation
    - WSEM for extraction beam monitoring

J-PARC

Beam Power History of MR

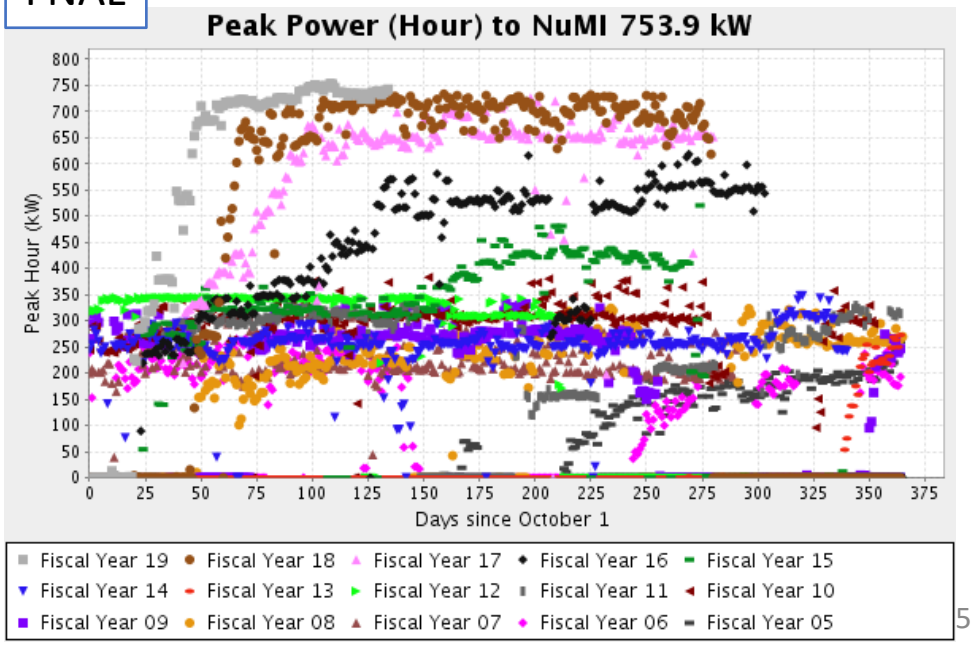


Delivered beam power in the spring of 2018 :

Fast extraction ~ 485 kW (2.50 x10^{14} ppp)

504 kW (2.61 x10^{14} ppp) for 50 shots demonstration

FNAL

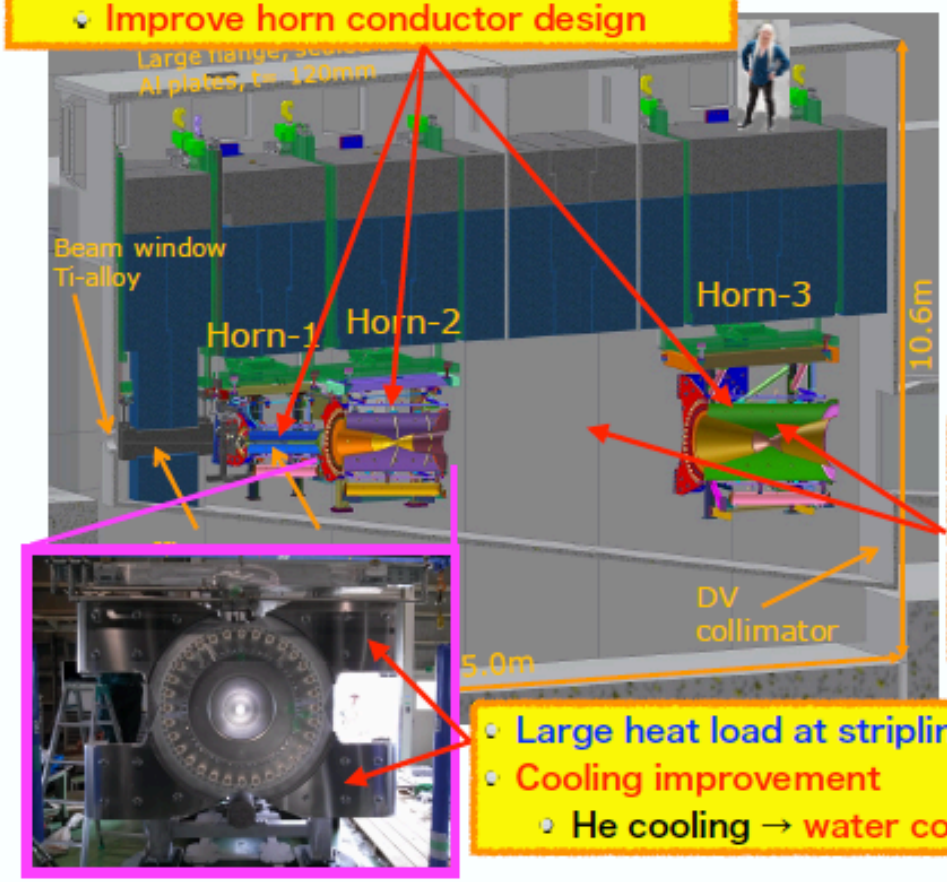


R&D items in this program

High Power Target Facility Issues

Challenges for high power beam!!

- Robustness of equipment in He Vessel
  - Improve horn conductor design



- Tritium production at cooling water for horns and He Vessel
  - Tritium treatment is key issue
- Hydrogen production by water radiolysis in horn cooling water

- Large heat load at striplines
- Cooling improvement
  - He cooling → water cooling

Summary of progress in JFY2018

- Beam dynamics studies for beam loss reduction
  - Joint machine study @ J-PARC in Jun./Jul. 2018
  - Joint machine study @ FNAL in Mar. 2019
    Comparison of data and simulation with common method at J-PARC and FNAL is very useful to build more precise accelerator model.
- Laser manipulation of H^- beams
  - Electro-optic modulator is produced: Key component to obtain required laser light for .
  - FNAL expert will stay at J-PARC in March for join development of two mirror non resonant laser cavity.
- Gated IPM (Ionization profile monitor)
  - Improvement of the developed IPM, and finalize the design of gated system by joint discussions between J-PARC and FNAL experts.
  - Production of a gated power supply and its control unit was finished and ready for installation.

Summary of progress in JFY2018 (cont'd)

- Extracted beam monitoring
  - Replace SSEM with another WSEM (wire secondary emission profile monitor) produced by joint R&D at the most downstream of J-PARC NU beam-line for practical use.
  - Development of the more practical mover system is in progress.
- High-Power Target Facility Issues
  - Preparation of the developed water-cooled strip line of the horn
  - Information exchange Tritium production and water radiolysis.
  - Trial installation of ion exchange resin to decompose H_2O_2 (radiolysis product)

- Plenary face-to-face meeting is scheduled in Mar. 19th ~ Mar. 20th, 2019 at FNAL.

Summary of plans in JFY2019

- Beam dynamics studies for beam loss reduction
  - Joint machine study
- Gated ionization profile monitor
  - Installation and tuning (¥640k).
  - Joint development of simulation and verification of actual data.
- Electron cloud studies: New
  - Detailed discussion by comparing independent measurements by J-PARC and FNAL.
  - Simulation model cross-checking using both FNAL and J-PARC experimental data.
- New signal acquisition system for high precision beam position measurement : New
  - Joint development of position monitor read out with fast and higher precision (¥3,300k)
- Laser manipulation of H- beams
  - Build IR laser system for 400MeV POP test-bench, and two mirror cavity system (¥9,661k)
- Extracted beam monitoring
  - Development of WSEM with low-z wire material (¥600k)
  - Development of OTR with new foil materials
- High-power target Facility issues
  - Current test of the developed water-cooled strip-line for horn (¥750k)
  - Measurement of the tritium production/desorption at beam environment. (¥500k)

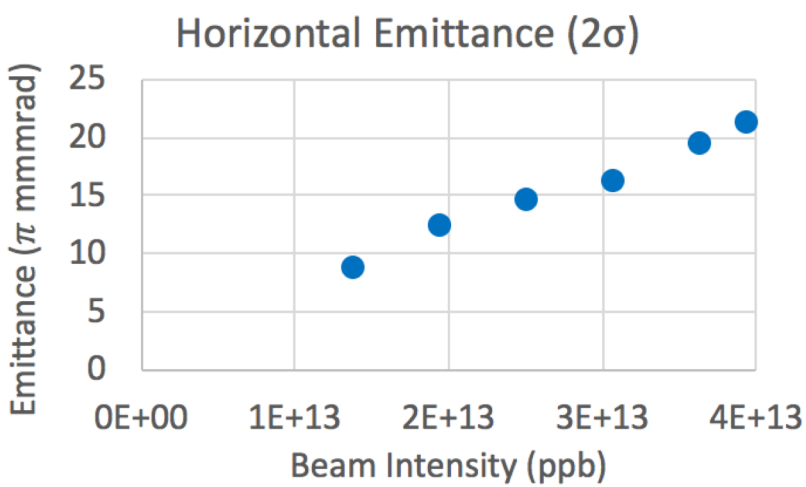
- Equipment and Supplies costs: Total ¥16,251 k
- Travel costs: Total ¥7,664 k
  - Plenary collaboration meeting at FNAL
  - NBI2019 (Neutrino beam instrumentation workshop) at FNAL.

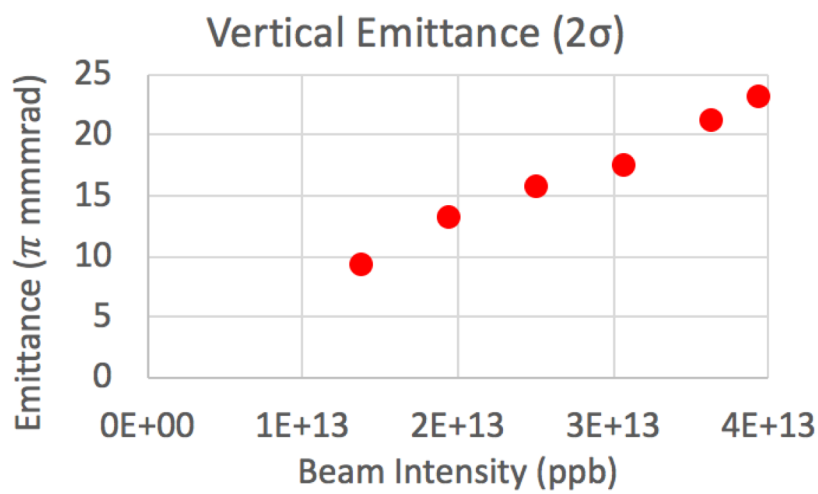
Detail of each R&D topics

Progress in JFY2018 for Beam Dynamics Studies for Beam Loss Reduction

Two Fermilab researchers visited J-PARC and participated in the beam studies from June 29th to July 4th 2018.

- The targets of the studies were to reduce the beam losses and to achieve higher intensity beams for all stages: linear accelerator (Linac), rapid cycling synchrotron (RCS) and main ring (MR).
- In Linac beam study, the beam current of 62 mA was achieved beyond the original target of 50 mA.
- In RCS beam study, a one-hour continuous beam delivery operation to the materials and life science facility with the beam power of 1 MW was achieved.
- In MR beam study, RCS parameters, such as tunes and chromaticity, were searched to reduce beam losses at the transfer beam line and MR.
- Beam Emittances was measured at the transfer beamline from RCS to MR for the optimized beam up to 4E+13 protons per bunch which is almost equivalent to the beam power of 1.3 MW with the planned cycling of 1.16 s.



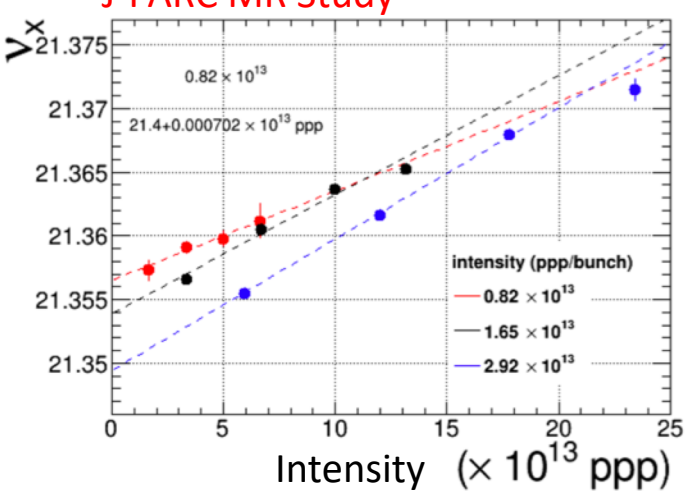


Plans in JFY2019 for Beam Dynamics Studies for Beam Loss Reduction

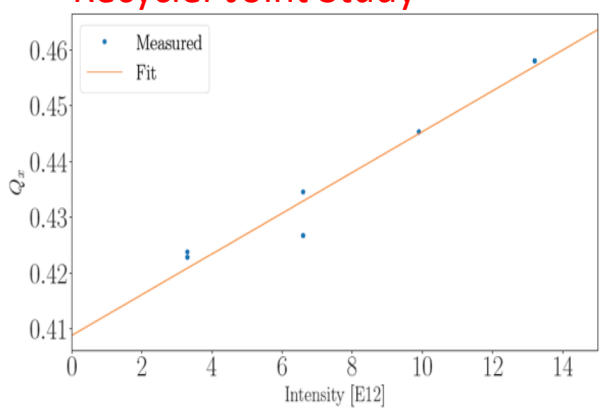
Joint beam studies were done in March 2018 at Fermilab for the following topics. We would like to continue each study.

1. Tune shift measurements with high intensity beams at FNAL Recycler
   - Horizontal tune shifts were observed depending on the number of injection bunched and the length of the bunches.
   - We would like to measure the vertical tune shifts.
   - Tune shift measured at J-PARC MR was compared with calculations with the effect of the impedances of the surrounding instruments such as vacuum chambers.
   - FNAL data are valuable for further understanding of the model calculation.

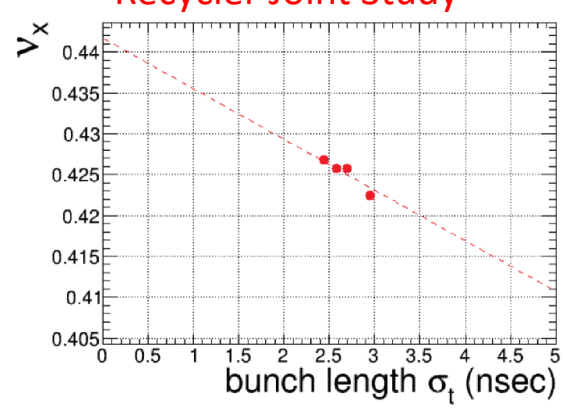
J-PARC MR Study



Recycler Joint Study

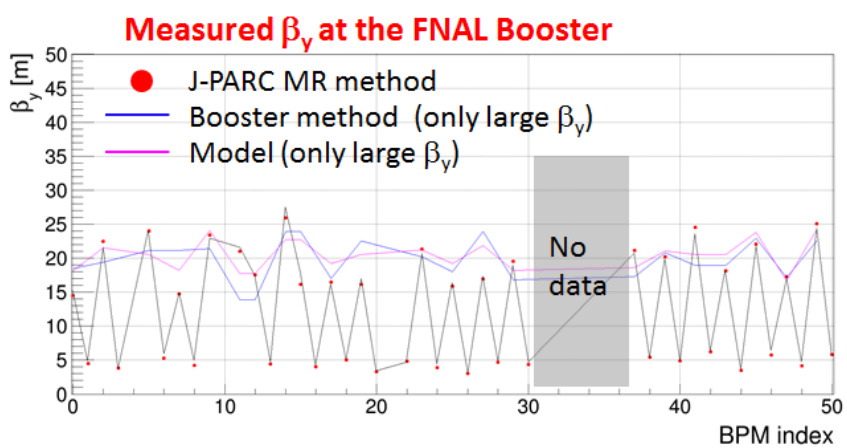


Recycler Joint Study

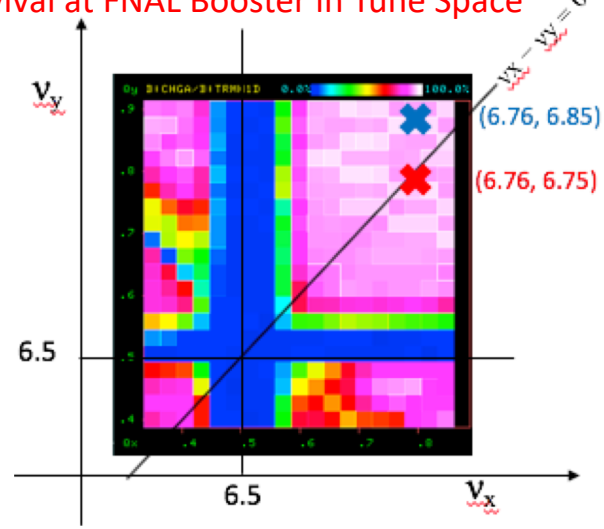


Plans in JFY2019 for Beam Dynamics Studies for Beam Loss Reduction

2. Beta function measurements at FNAL Booster
   - A method used at J-PARC MR for the beta function measurement has applied to the FNAL Booster. Amplitudes of the oscillations at the beam position monitors were measured when coherent oscillations were excited.
   - Measurements were done for the most of the monitors, however, some part of data were missing because of the data acquisition. We would like to take the data for the missing monitors.
   - The results should lead to the solution for the optics correction.
3. Coupling resonance study at FNAL Booster
   - The correction of the resonance νx−νy=0 was tried with the skew quadrupole magnets. Because we were not able to set the parameters of the 48 correction magnets independently, the parameter search for the beam loss reduction was limited.
   - We would like to continue the study after extending the corrector parameter options.



Beam Survival at FNAL Booster in Tune Space



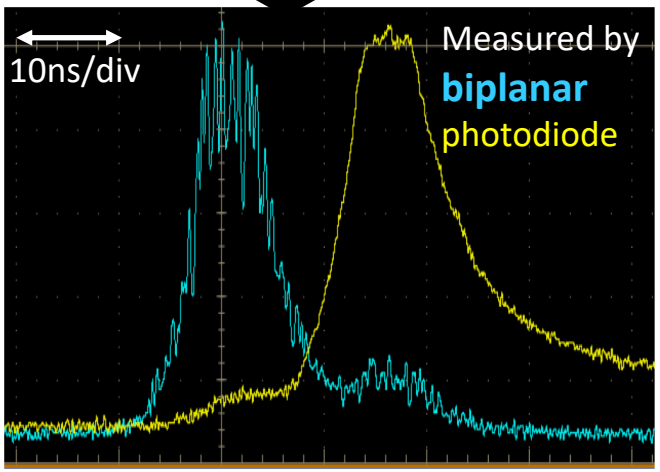
Laser manipulation of H^- beams: **JFY 2018 highlights and 2019 plans** -- P. K. Saha 2019/01/23

JFY 2018 highlights:

Development of a new Nd:YAG laser system (narrow pulse, narrow bandwidth, high repetition rate with ~mJ pulse energy.)

Present YAG laser issues: Temporal profile is very spiky and too broad (>10 ns).

A new Nd:YAG laser system is under development.
Specification: (<**100 ps, 10 mJ/pulse, 324 MHz**).



- The EOM, which overcomes the present laser issues has been **purchased by the US-Japan collaboration fund.**
- One set of fiber amp has also been prepared by another budget source.

Low energy seed Laser, (**EOM**) (0.1 nJ, <100 ps, 81 MHz) → Fiber Amps (~ 10 nJ?) → Lamp Amp [100 μJ] → Thin disk Amp [10 mJ]

In hand. To be assembled.

JFY 2019

Laser manipulation of H^- beams: JFY 2018 highlights cont'd

2. Development of two mirror non resonant laser cavity for H^- neutralization, laser profile monitors at 3 and 400 MeV energies.

→ common interests between J-PARC and FNAL.

D.E. Johnson will visit J-PARC in March, 2019 (2 weeks) for detail discussions and development of the two mirror cavity for the present and future multi-dimensional laser manipulations of the H^- beam at J-PARC and FNAL.

JFY 2019 plans:

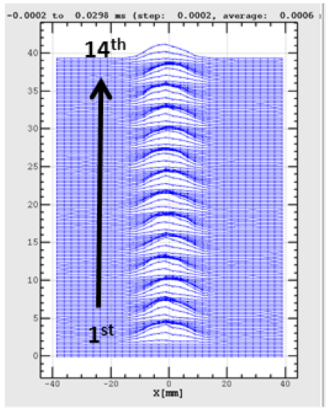
1. **Complete one full set of Nd:YAG laser system for the POP demonstration of 400 MeV H^- stripping by using only lasers.**
2. **Detail studies in the laser lab.**
3. **Preparations for laser installation in the accelerator tunnel** (2020 at the earliest)
4. 400 MeV H^- neutralization studies: 2020 late autumn expected.
5. POP demonstration of 400 MeV laser stripping: 2021 autumn.
6. **Development of a low power laser system and two-mirror cavity system for 3 MeV H^- neutralization and transverse and longitudinal laser profile monitors.**
7. **Development of a prototype multi-wire profile monitor system for the transverse beam profile measurement.**
8. Experimental studies at the test RFQ for 3 MeV H-: 2020 early autumn expected.

Gated IPM (Ionization Profile Monitor)

Switching of operational HV of 30kV : DC to Pulse-mode

- Normal IPM
  - Measure all profiles for full interval: From Injection to Extraction -> Not always need to be measured
  - MCP particle detector -> Fast performance deterioration -> Need frequently replacement
- New Gated IPM
  - Measure profiles only for required timings (Gate)
  - Reduce unnecessary measurements -> reduce operational duty factor to <1/100
  - Need no MCP replacement virtually

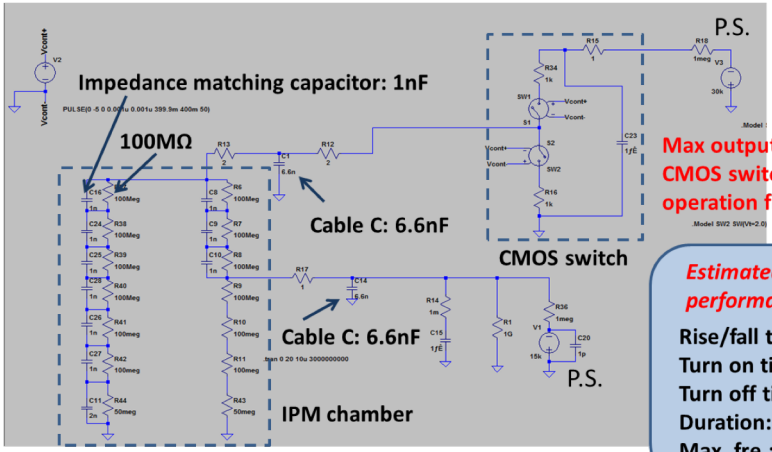
Photo of IPM



1st to 14th turn profile

- ***Progresses in FY2018***
  - Add capacitors between electrodes to improve pulse response for vertical type IPM
  - Final design of gated system was fixed after discussions with FNAL team
  - Production of a gated power supply and its control unit was finished and ready for installation
- ***Plans in FY2019***
  - Install and tunings
  - Start performance test -> Simulation works and discussions with FNAL
  - Electrodes modifications if needed, based on the first performance test
  - Procurement: A spare of CMOS HV switching device

The Final design of gated system



Max output current of PS and CMOS switch determine the operation frequency

Estimated Switching performance

Rise/fall time: 25μs
Turn on time: 100μs
Turn off time: 399.9ms
Duration: 400ms
Max. fre.: 2.5Hz

Final design:30kV switching module circuit

New projects started from FY2019

New signal acquisition system for high precision beam position measurement

Motivation

- MW class high power beam operation require "Fast" and "Precise" beam position measurement
  - Precise optics determination by BPM (Beam Position Monitor) -> Precise tuning of the optics
  - High-resolution and high-precision long waveform data -> fast data acquisition
  - On-line waveform monitoring system -> Instability monitoring, Anomaly detection system
  - Data storage system for large amount of data

⇒ **Common issue for high power accelerator facilities like J-PARC and FNAL**

⇓

New BPM system for high power accelerators

Development of new data acquisition system for next generation BPM system

- A new front end analog load with low signal distortion
  - 50 ohm matched load
  - Power divider
  - Selectable attenuator
- 16 bit high-precision ADC system
- High speed back end acquisition system

⇒ **Improve ENOB (effective number of bit) : Plus 2 bit**

⇒ **Improve Position precision: 1/3**

Collaboration plan in FY2019

- Discussions on the present performances of the BPM systems of J-PARC and FNAL
- Discussions on the next generation BPM system aiming for precise determination of the lattice parameters of high power synchrotrons
- Development of the front end analog load at J-PARC site -> performances test will be in both sites, J-PARC and FNAL, by using a high performance digitizer used in FNAL in JFY2020-21

New projects started from FY2019

Electron Cloud Studies

Motivation

- Electron cloud (EC) is a potential concern for both J-PARC and FNAL; it can drives the EC beam instability and limits the maximum beam power output
- J-PARC and FNAL have different EC detectors
- EC simulation works have been conducting with different codes at higher intensities however, there is a need to benchmark these codes

J-PARC & FNAL collaborate on simulations as well as discuss an experimental program to provide better confidence in the simulations

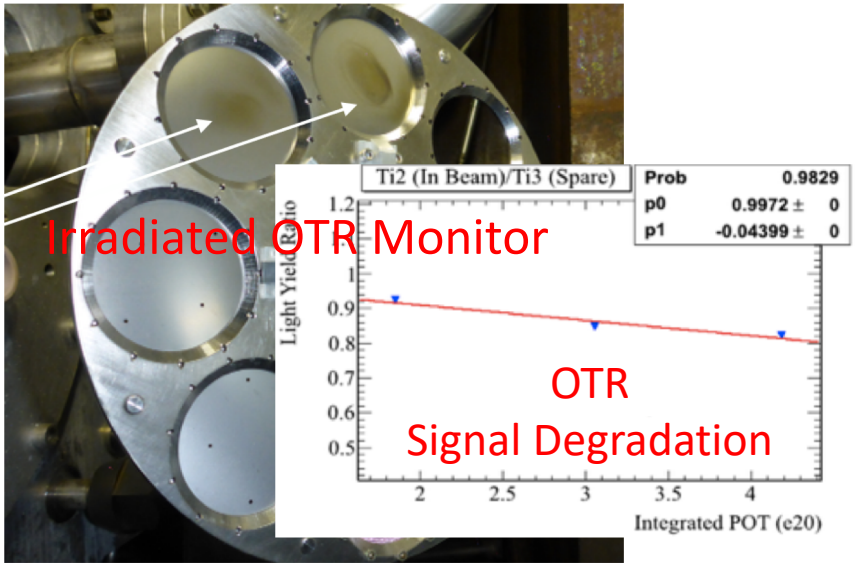
Collaboration plan in FY2019

- Discussions on the present performances of the EC detectors in J-PARC and FNAL
- Obtain experimental data set for simulation code cross-checking
- Mini-workshop -> Considerations on experimental and simulated results from both sites

Joint KEK-FNAL Beam Monitor R&D

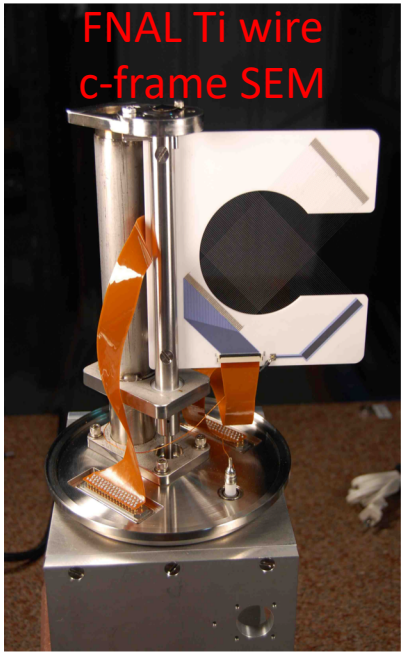
Monitors in the current T2K NU beamline:

- The proton beam profile must be monitored continuously. Essential for:
  - Protecting beamline equipment
  - Understanding proton beam parameters for flux prediction
- T2K uses SSEM19 and OTR to continuously monitor the beam profile at the target
- Have observed degradation of SSEM19 and OTR profile monitor foils

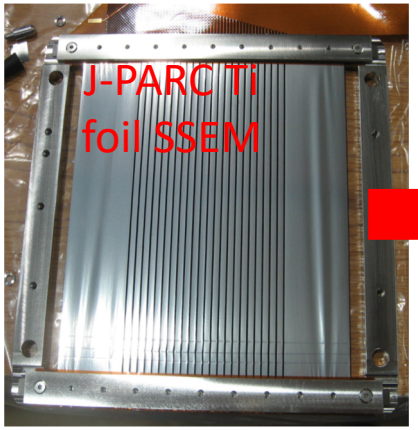


- Profile monitors may degrade very quickly with 1.3 MW proton beam power

Collaborative work on a new T2K NU beam profile monitor:

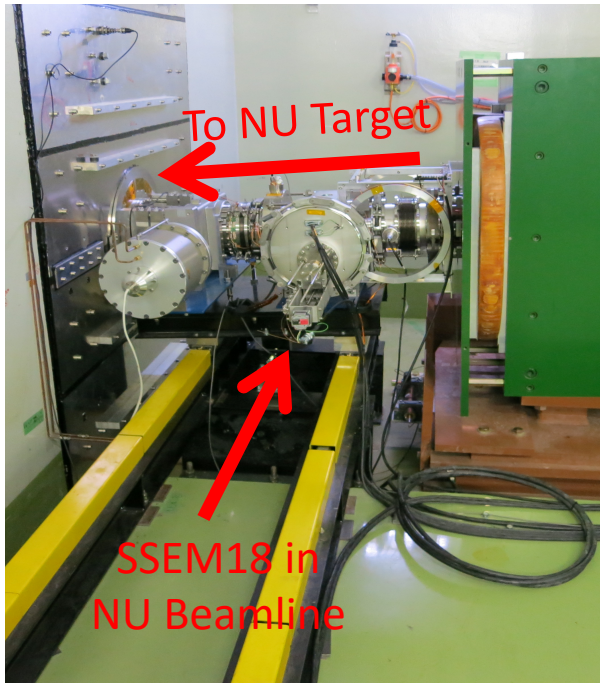


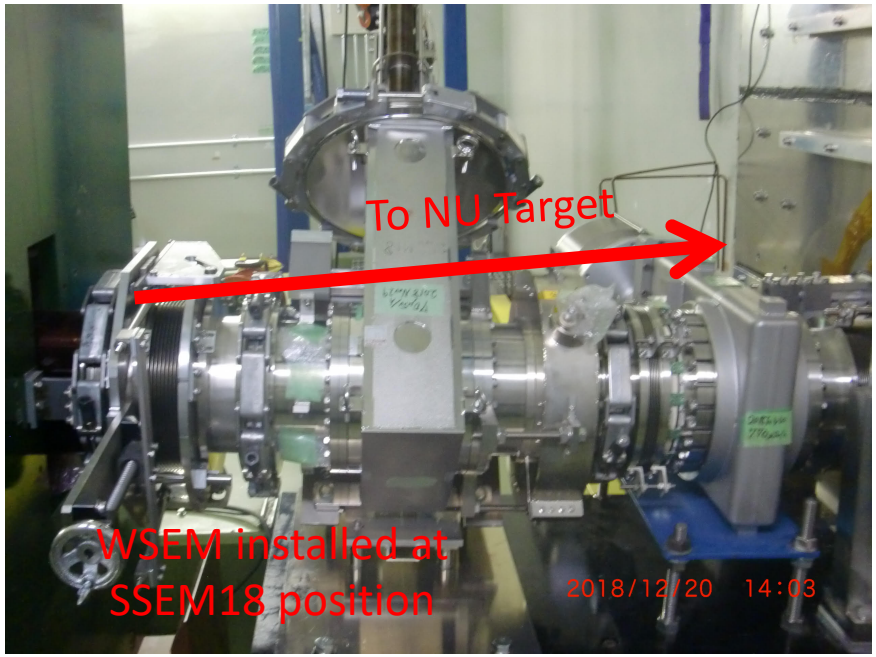
- Design more robust SSEMs using less material
  - Reduced beam loss/irradiation
  - (FNAL) C ribbons may be more robust than (T2K) Ti foils
- Collaborative work to modify FNAL SSEM design to fit T2K beam



Beam Monitor R&D Work Completed JFY2015~2017

- JFY2015: Designed and fabricated new WSEM monitor head
- JFY2016: Installed prototype for testing; took first beam data
- JFY2017: Designed improved mover; took additional beam data
- JFY2018: Built major component of improved mover; replaced J-PARC NU beamline downstream SSEM with WSEM

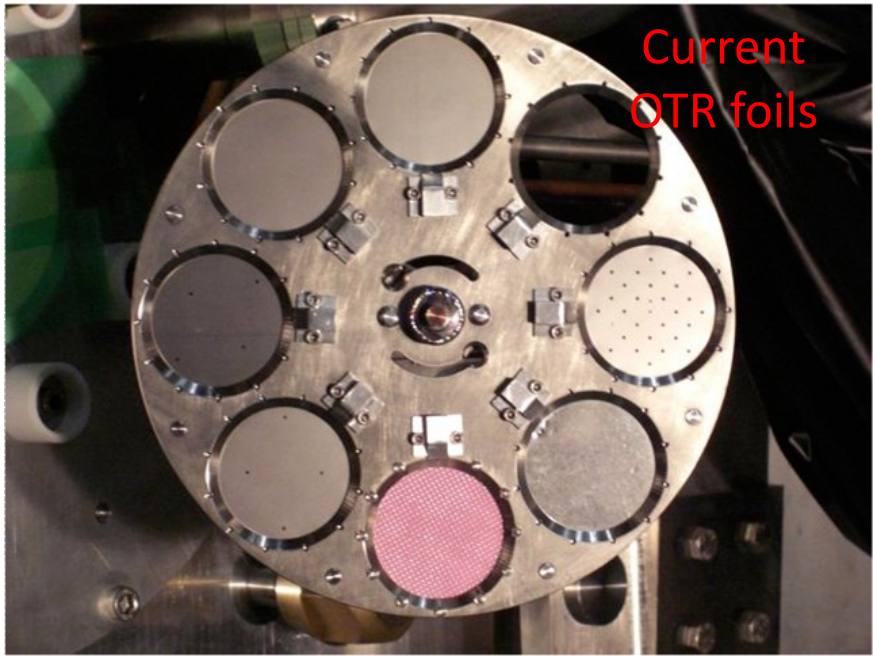




Plan for JFY2019~

- Further WSEM upgrades planned:
  - Improvements to installed WSEM mover and alignment
  - WSEM wire material studies – development of carbon wire WSEM for testing at J-PARC
    - Carbon-based wires should be more robust at higher beam powers

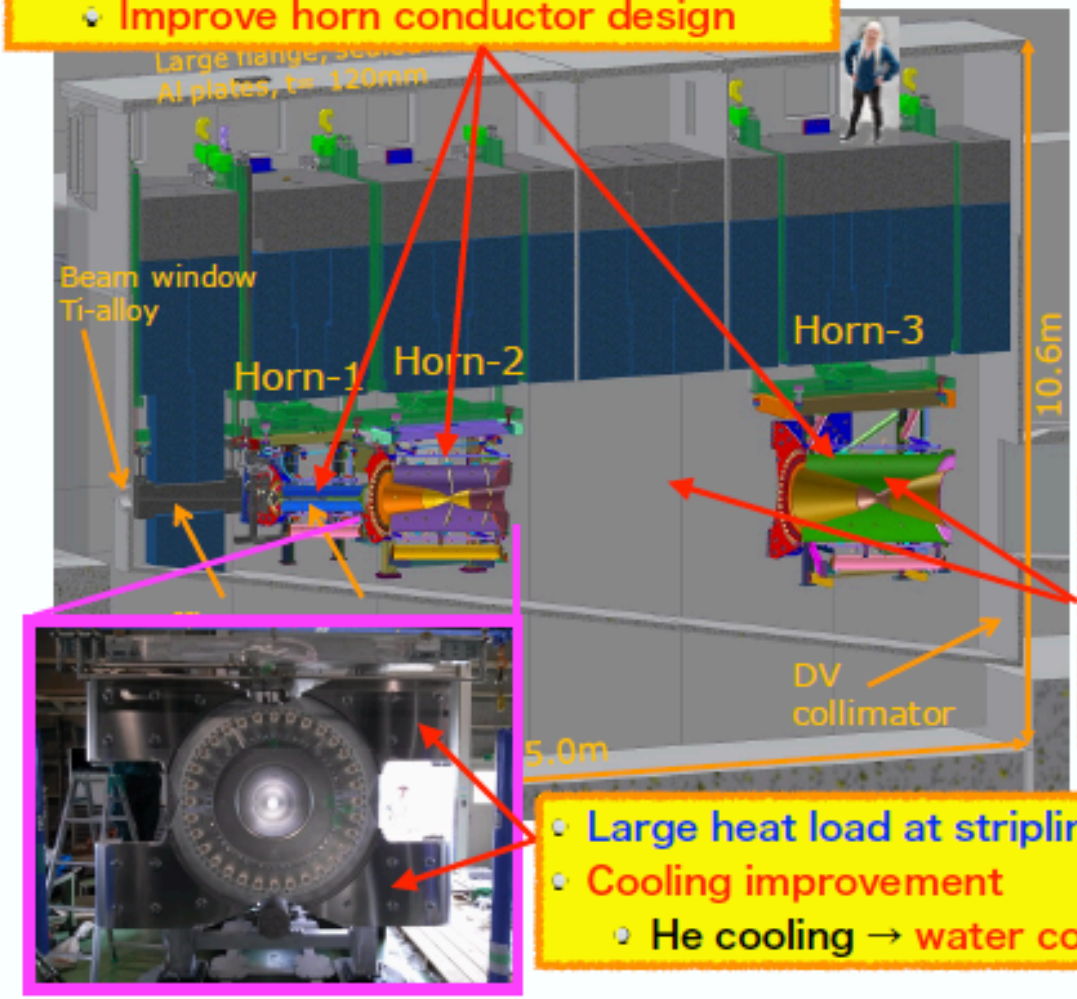
- OTR foil materials studies:
  - Current OTR foil material and thickness may exceed material stress limits at high beam power
  - Thinner foils or a lower-Z material may be necessary
  - Studies to understand new material properties and develop new foils and disk planned



High Power Target Facility Issues

Challenges for high power beam!!

- Robustness of equipment in He Vessel
  - Improve horn conductor design



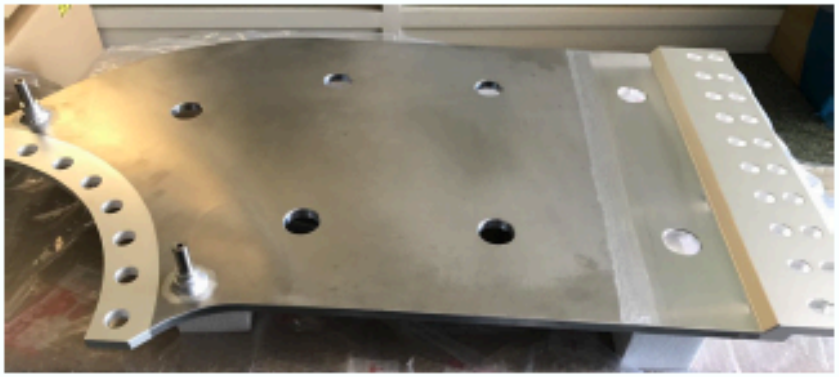
- Tritium production at cooling water for horns and He Vessel
  - Tritium treatment is key issue
- Hydrogen production by water radiolysis in horn cooling water

- Large heat load at striplines
- Cooling improvement
  - He cooling → water cooling

Accomplishment in FY2018

Water-cooled stripline

Current testing with horn1 under preparation



Tritium issue

- Detailed discussion on tritium production at secondary beamline
  - Understanding of production points was advanced through discussions

Water radiolysis issue

- Advanced ion exchanger system for H_2O_2 tolerance
  - H_2O_2 reduces lifetime of ion exchange resins
  - Add ion exchange resins to decompose H_2O_2
  - Proof-of-principle test to be done in FY2019

Ion exchanger including H_2O_2-tolerant resins

FY2019 Plan

- Development of water cooled striplines (KEK&CU)
  - Current testing of mockup stripline with horn1
- He Vessel issues (KEK&FNAL)
  - Exchange knowledge and expertise on Tritium treatment
  - R&D on tritium production measurements
  - Proof-of-principle test of H_2O_2-tolerant ion exchanger system
- Design study for strengthened horn conductors (KEK&CU)
  - To to be continued to increase lifetime of horns for high rep. rate/ high current operation