Beamline Upgrades for T2K-II and Hyper-K

M. Friend

High Energy Accelerator Research Organization (KEK)

NBI2022
September 19, 2022

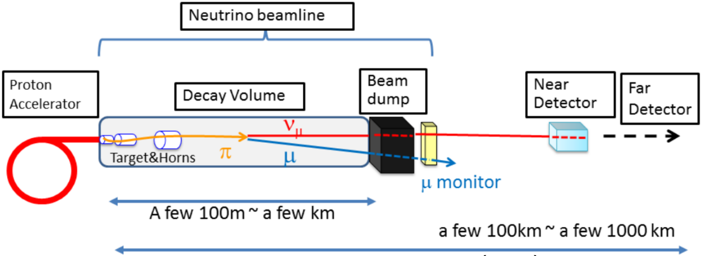
Outline

- Many upgrades underway at J-PARC this year !
- Many more future upgrades planned !
  - Many related talks at NBI2022
- General overview / highlights discussed here

J-PARC Neutrino Facility

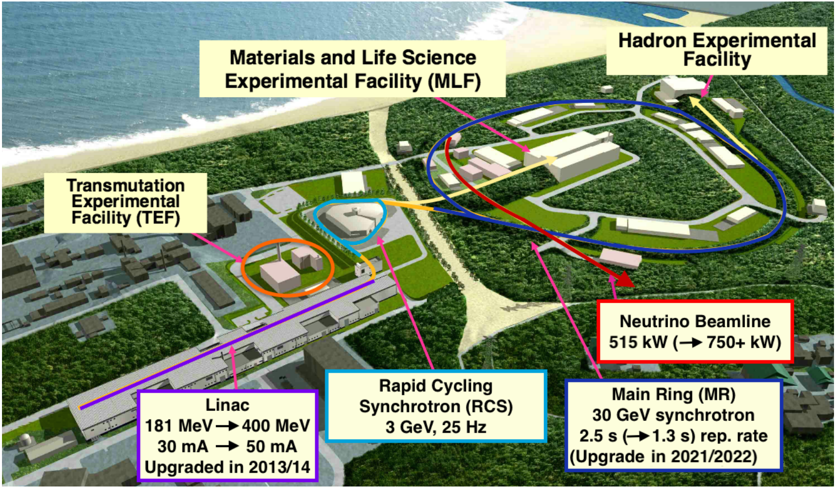
- Conventional high-intensity neutrino beam for the currently running T2K long-baseline neutrino oscillation experiment (2009$\sim$)
  - $+$ other auxiliary experiments
- Various upgrades underway for T2K and towards the Hyper-Kamiokande experiment, which is scheduled to start in 2027

Producing the J-PARC Neutrino Beam



- 30 GeV protons from J-PARC Main Ring (MR) accelerator hit a long 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
    - Change horn polarity to switch between primarily ν_μ's and $\bar{\nu}_\mu$'s
- 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
- Using a 2.5° off-axis beam allows for narrower ν energy spectrum

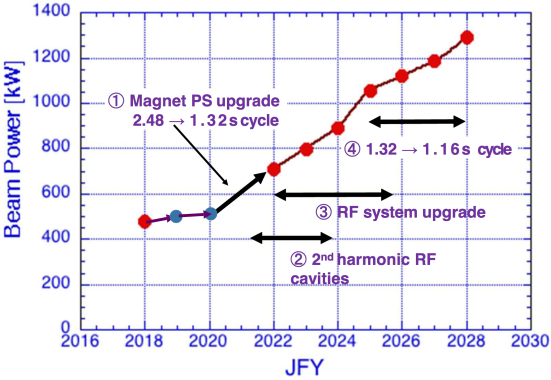
High-Power Proton Source – J-PARC

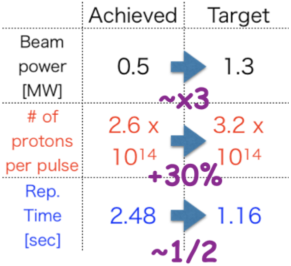


- Accelerates proton beam to 30 GeV by:
  - 400 MeV Linac (linear accelerator) → 3 GeV RCS (Rapid Cycling Synchrotron) → 30 GeV MR (Main Ring Synchrotron)

Increasing the MR Proton Beam Power

- In 2020, J-PARC MR accelerator delivered $\sim 2.65 \times 10^{14}$ protons every 2.48 seconds = 515 kW
- Now increasing the beam power in 2 ways:
  - Upgrade PSs + RF to reduce the time between beam spills from 1 spill every 2.48s → 1.36s → 1.16s
  - Improve stability to increase the number of protons per spill from $\sim 2.65 \times 10^{14} \rightarrow 3.2 \times 10^{14}$ 515 kW → >700 kW → 1.3 MW





MR Upgrades Towards 1.3MW

JFY	2020	2021	2022	2023	2024	2025	2026	2027	2028
Event		Long Shutdown							
FX power [kW] SX power [kW]	515 55	- 60–70	>700 >80	800 >80	900 >80	>1000 >80	>1100 ~100	>1200 ~100	1300 ~100
Cycle time for Fast Extraction New Magnet PS	2.48s Mass Production Installation/Test		1.32s	1.32s	1.32s	1.32s	<1.32s	<1.32s	1.16s
RF system upgrade 2nd RF system upgrade									
Collimator system		Add.colli. (3.5kW)							
Injection system FX system	Kicker PS improvement Septa manufacture Test								
Beam Monitors (BPM circuits)									
SX: Diffuser/Bent crystal/VHF Local shield									

Prog. Theor. Exp. Phys. 2021, 033G01

2021/2022 Upgrade Work

MR Power Supply Upgrade

- New MR magnet power supplies with energy recovery with capacitor banks developed and tested
  - Allow for 1.36s repetition rate
- Installed in 2021
- Power supplies tested in-situ in April and May 2022
- MR beam commissioning with 3GeV DC-mode June 2022
  → commissioning with 30GeV 1.36s cycle in November 2022

Capacitor Banks for BM3

Future MR Upgrades

T. Yasui @NuFACT2022

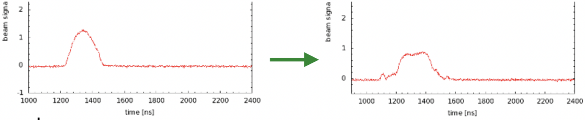
Higher RF voltages are necessary for faster cycling.

The LLRF system was replaced to the new system.

Fundamental cavity : for acceleration

2nd harmonic cavity : for suppressing peak current

New cavity

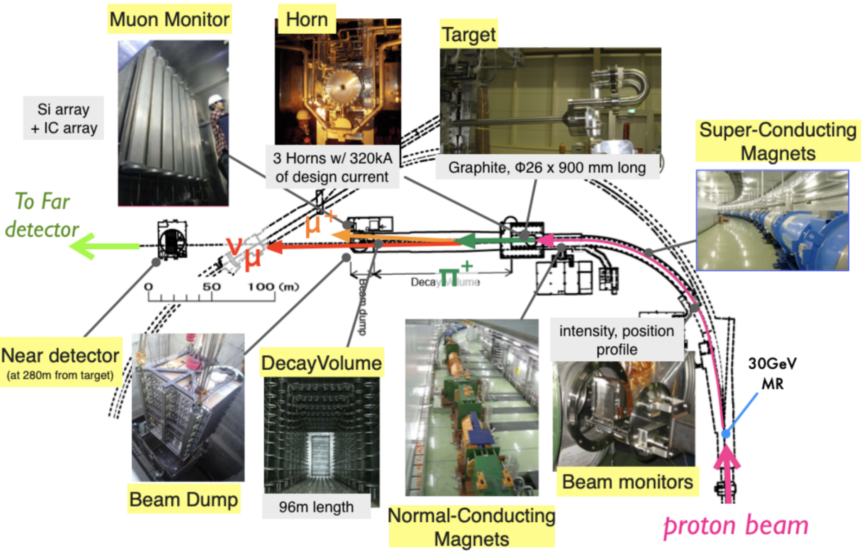


(simulation)

	Cycle	Number of cavities		Voltage	
		Fundamental	2nd	Fundamental	2nd
2021	2.48 s	7	2	300 kV	110 kV
2023	1.36 s	9	2	510 kV	110 kV
2026	1.16 s	11	2	600 kV	110 kV

- + collimator upgrades, FX system upgrades
- + future upgrade to MR abort dump – see talk by C. Densham

J-PARC Neutrino Beamline



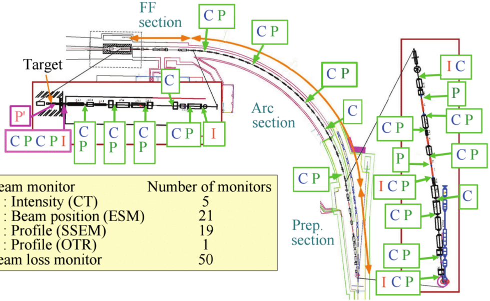
J-PARC Neutrino Primary Proton Beamline

Primary beamline includes:

- Series of normal- and super-conducting magnets
- Proton beam monitors

Final Focusing NC magnets

Arc SC magnets



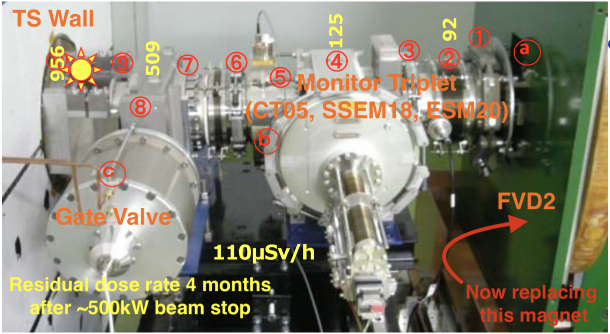
Beam monitor	Number of monitors
I : Intensity (CT)	5
C : Beam position (ESM)	21
P : Profile (SSEM)	19
P' : Profile (OTR)	1
Beam loss monitor	50

Beam Monitors along the primary beamline

2021/2022 Upgrade Work

Primary Beamline Maintenance Upgrade

- Residual radiation dose at most downstream end of primary proton beamline is high
  - Due to backscattering from the neutrino production target, beam window, etc
  - Residual dose reaches >1mSv/hr on contact weeks after beam stop, even at 500kW beam power
    - Proportional to integrated POT – will increase with higher beam powers, longer running time



- Make space for quick, hands-on maintenance by reducing length of most downstream bending magnet – new magnet installed summer 2021

See talk by Y. Fujii

2021/2022 Upgrade Work

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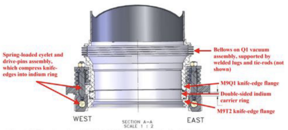
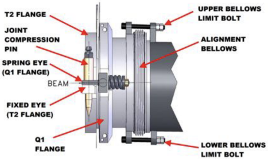
See talk by Y. Fujii

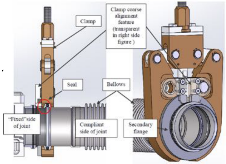
See talk
by Y. Fujii

Longer-Term Primary Beamline Maintenance Scheme Plan

- Quick, hands-on maintenance will not be sufficient for long-term, 1.3 MW HK running
    - Expect residual dose at 1 foot will reach 600 μSv/h after 1.3 MW $\times$40 months operation
- Now considering additional future upgrades towards fully remote maintenance scheme
    - Replace several flanges with remote operation flanges
        - Pillow seals are currently used at neutrino beamline Target Station, but difficult at primary beamline
        - Considering new remote flange technologies
    - Improved crane system
    - Other ideas ?
- Discussion with various remote-handling experts ongoing



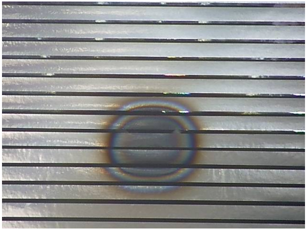




2021/2022 Upgrade Work

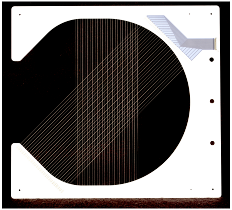
Proton Beam Profile Monitor Upgrades

- Proton beam profile is measured by series of foil-based SSEMs
  - Each monitor causes 0.005% beam loss – only use for beam tuning
  - Most downstream one is near the target – can be used continuously
- Concern with degradation of foils, increase of beam loss/component irradiation with increasing beam power
- US/Japan R&D for lower loss monitor (WSEM) – new installation
- Non-destructive profile monitor – Beam Induced Fluorescence Monitor (BIF) – developed, prototype installed, tested
  - Upgrading towards full working monitor now

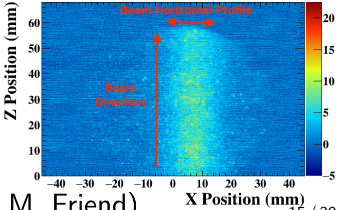


SSEM after $\sim 3.2 \times 10^{21}$ Incident Protons

New WSEM (FNAL)



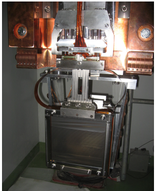
Beam profile measured by BIF @beam test



(see talk by M. Friend)

SSEM19 Exchange

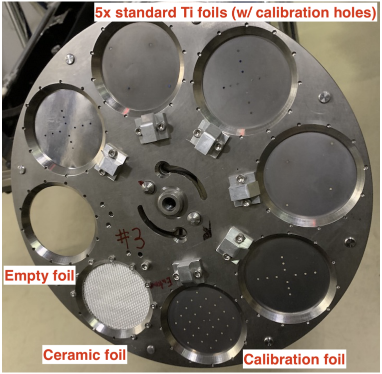
- SSEM19 sits at the bottom of monitor stack, between primary and secondary beamlines
  - Very difficult to access
  - Highly radioactive, so requires full remote handling
- Now developing procedure for SSEM19 exchange – first mockup tests done
  - Cables interfere with remote manipulator jig – need to improve
- Watch first mockup test on YouTube!
  - Mockup disconnection:
    https://www.youtube.com/watch?v=fA8R7n0eFDI
  - Mockup connection:
    https://www.youtube.com/watch?v=PG2Km-rdlB0
  - Mockup spent cable handling:
    https://www.youtube.com/watch?v=tgkIkr-AEtE
  - Mockup new cable handling:
    https://www.youtube.com/watch?v=a6atAl1LUTo



2021/2022 Upgrade Work

OTR Upgrades

- Optical Transition Radiation Monitor (OTR) measures proton beam position and profile directly upstream of the target
- Decrease in OTR light yield observed
  - Due to radiation-induced darkening of optical component (fiber taper)
  - Upgrading optical system to use easily-replaceable fiber taper now (York University + TRIUMF)



OTR target disk

- Upgrading Ti foils now
  - Add holes to all OTR target foils – can be used to cross check foil position by back-lighting
  - Upgrade to thinner foil for improved stress tolerance
  - New OTR disk will be installed in the beamline in late 2022
- Upgrading OTR readout for 1Hz operation, Windows $\rightarrow$ Linux now (ICL) (see talk by M. Friend)

2021/2022 Upgrade Work

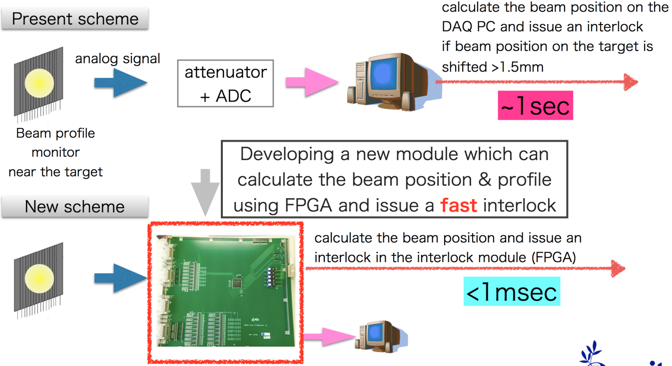
OTR Upgrades

- Test installation of new OTR disk on mock Horn 1 by OTR group members in May 2022

DAQ, Beam Control, Interlock Upgrades

- Readout electronics upgraded for 1 Hz beam operation
- New interlock system for fast beam interlock under development – see talk by S. Tairafune
- Improvements to beamline magnet interlock system underway – see talk by K. Nakayoshi

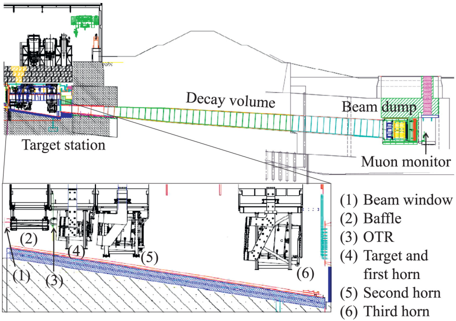
New 1 Hz profile monitor interlock system →

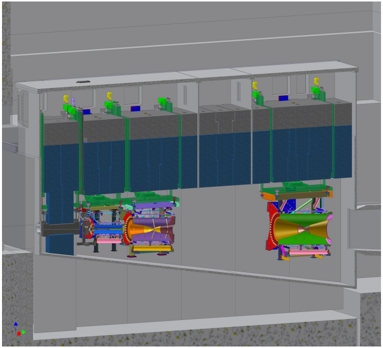


PAPILLON board : http://openit.kek.jp/project/beam_monitor_interlock/beam_monitor_interlock
Development: Okayama University, Tohoku University, KEK

Neutrino Secondary Beamline

- Neutrino production target and focusing horns for J-PARC neutrino beamline are kept in a gigantic He vessel, followed by 100-m-long He-filled decay volume
  - $\sim$1500 m^3 He vessel
  - He-filled to minimize production of tritium and NOx by interaction of high-energy particles with air

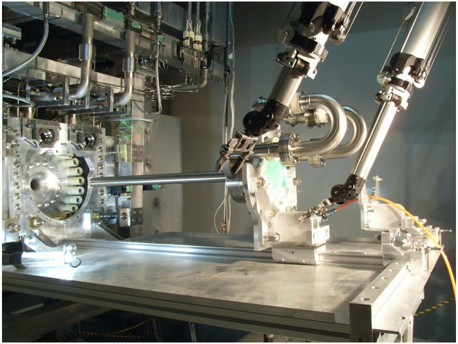




2021/2022 Upgrade Work

Neutrino Production Target

- J-PARC neutrino production target consists of a 91.4cm long (1.9 interaction length) monolithic carbon target installed in the 1st horn
- Cooled by He gas – increase of cooling capacity for higher power underway now – see talk by T. Nakadaira
- New target (+ beam window) for 1.3MW also under development (RAL) – see talk by M. Fitton



- Longer term studies to establish new target types to further maximize number of produced neutrinos are also ongoing
  - Possible to decrease forward-going wrong-sign component by new target design
  - Higher-density and/or hybrid materials, longer targets

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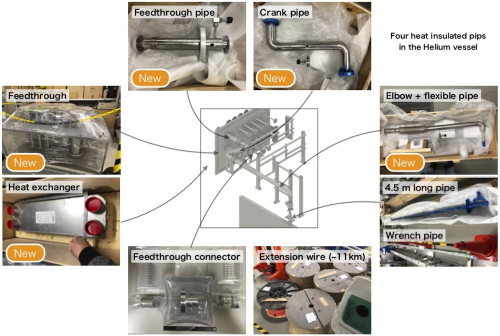
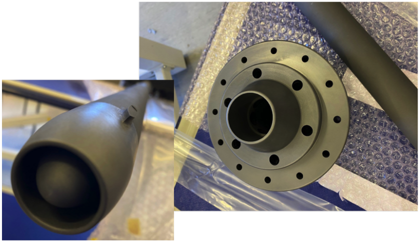
Target cooling upgrade



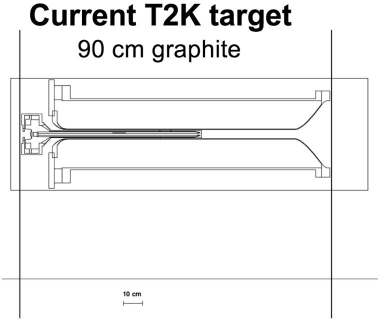


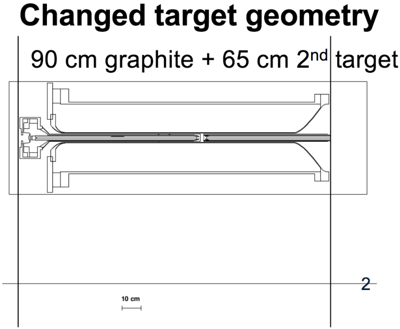
New prototype 1.3MW target

Neutrino Production Target Upgrade Ideas

- Longer term studies to establish new target types to further maximize number of produced neutrinos are also ongoing
  - Possible to increase pion yield and decrease forward-going wrong-sign component by new target design
  - Higher-density and/or hybrid materials, longer targets

One example new target idea – insert 2nd (higher density?) target into downstream end of Horn 1:



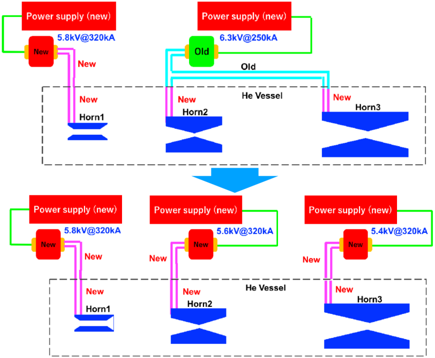


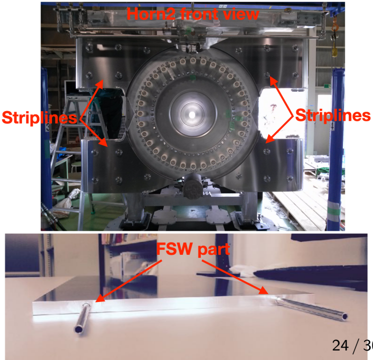
University of Glasgow, RAL

2021/2022 Upgrade Work

Horn Upgrades

- Upgraded 2 → 3 power supplies (+ new striplines, transformer) to increase horn current from ±250kA → ±320kA in 2022
  - ∼10% increase in right-sign neutrino flux, 5∼10% decrease in wrong sign neutrino flux
- Horn 2 striplines are particularly susceptible to impinging beam defocused by horn 1 – cooling upgrade essential
  - Upgraded, water cooled striplines installed in 2022
- Possible future improvements to horn focusing system??





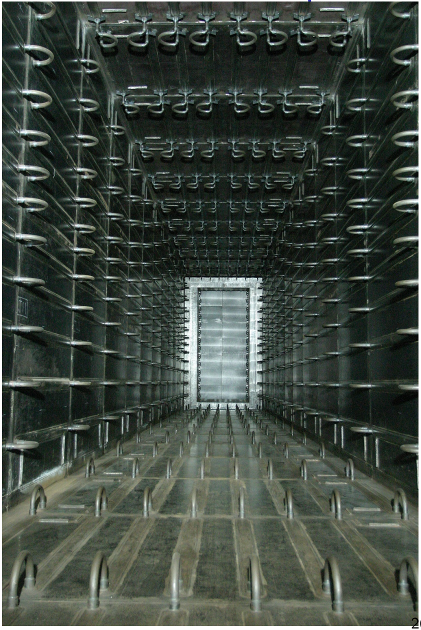
Horn Production, Testing, Installation

New Horn 2 during installation

- New Horns 1 and 2 were produced at University of Colorado and shipped to J-PARC – see talk by M. Reh
- Current/magnetic field excitation test of new Horns done
- New Horn 2 installed a few weeks ago
- New Horn 1 to be installed next month
    - New OTR disk also being installed with Horn 1

He Vessel, Decay Volume, Beam Dump

- Helium vessel and decay volume are He-filled
  - To minimize production of tritium and NOx by interaction of high-energy hadrons with air
- 96-m-long decay volume
- Beam dump is graphite + iron blocks (∼5m) to stop hadrons
- Water-cooled by piping
- Water cooling capability will be upgraded by increasing the water flow

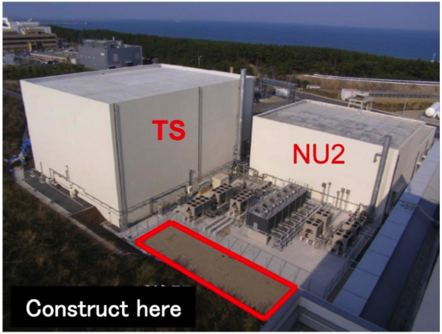


2021/2022 Upgrade Work

Radioactive Water Disposal

- Essential to properly handle radioactive water produced during neutrino beam production process – dilute + dispose
- New dilution tank to increase the water disposal capacity from 84 $m^3 \rightarrow 484\ m^3$ – construction finished early 2022
  - Capacity of the new tank will be enough for 1.3MW

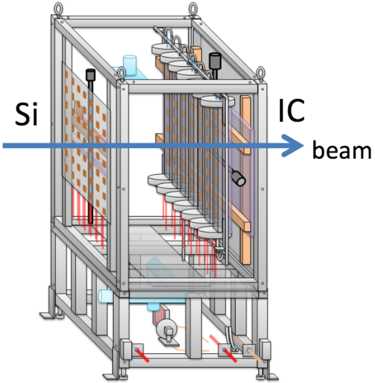
Before construction:



Fully constructed:

Muon Monitoring Upgrades

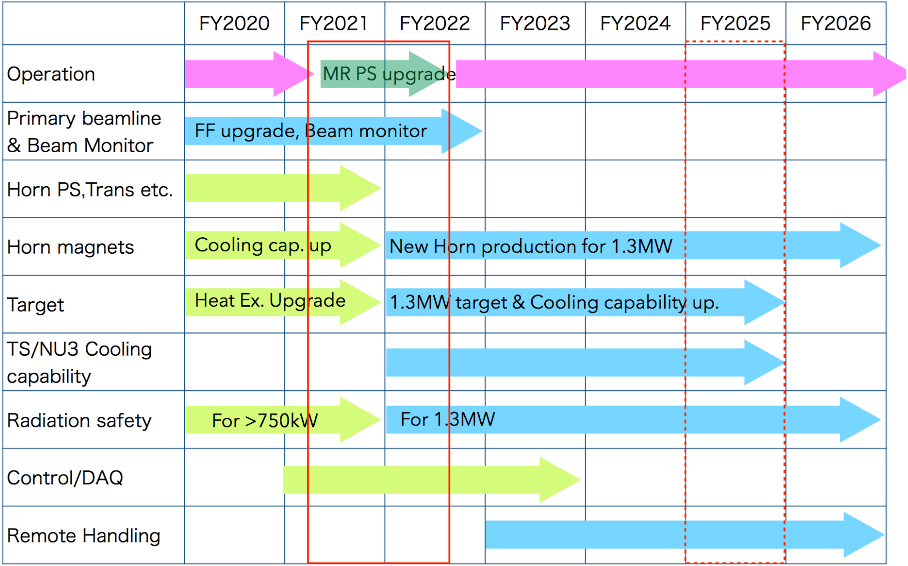
- Measure tertiary muon beam profile downstream of the decay volume, beam dump (>∼5 GeV muons)
    - Ensure alignment, healthiness of target, horns; proton beam position, angle at target; etc
- 2 redundant measurements of the muon beam profile, position using 7x7 arrays of sensors
    - Ionization chambers (IC)
    - Silicon photodiode sensors (Si)
- Now developing EMT (PMT w/out photocathode) as more robust sensor option
- Also developing MCT (MUMON CT) for muon sign measurement



See talk by M. Friend

Neutrino Beamline Upgrade Schedule

Overall schedule of beamline upgrade



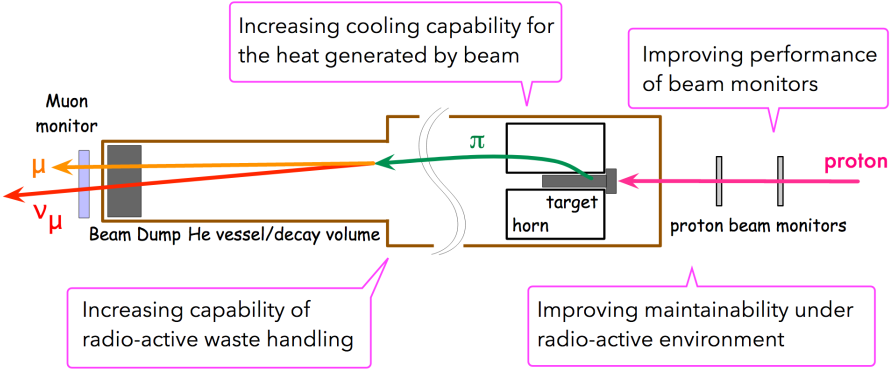
Conclusion

- J-PARC MR power supply upgrade for 1.36 s repetition rate ($>$700 kW) is happening now
  - Further RF upgrades towards 1.16 s repetition rate (towards 1.3 MW) coming before 2027
- Many upgrades to the J-PARC neutrino extraction beamline underway now in order to accept the higher power proton beam
- Additional upgrades to come before 2027
  - Primary beamline + monitor stack remote handling
  - Instrumentation upgrades (proton beam profile monitoring, muon monitoring)
  - Interlock upgrades
  - 1.3MW target

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

Backup Slides

Neutrino Beamline Upgrades Towards 1.3MW



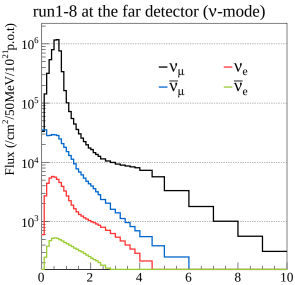
+ Accepting high repetition rate (~1Hz) beam

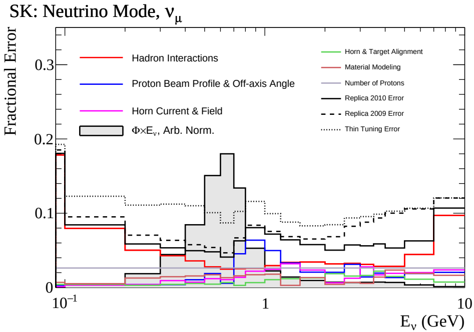
$\rightarrow$ Upgrade DAQ + control system

Technical Design Report : arXiv:1908.05141

Neutrino Flux Errors

Example predicted T2K flux and errors :





- Essential to not just produce a world-class neutrino beam, but also to precisely understand the neutrino flux
- The ν flux is predicted by simulations which take into account
  - Measured proton beam current, position, angle, profile
  - Measured neutrino beam angle
  - Measured Horn field, alignment
  - Hadron interactions inside + outside the production target
    - External constraints by NA61/SHINE experiment @CERN (in use + future measurements), EMPHATIC experiment @FNAL (future)