J-PARC Neutrino Beam and Upgrades

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High Energy Accelerator Research Organization (KEK)

NuFACT2022
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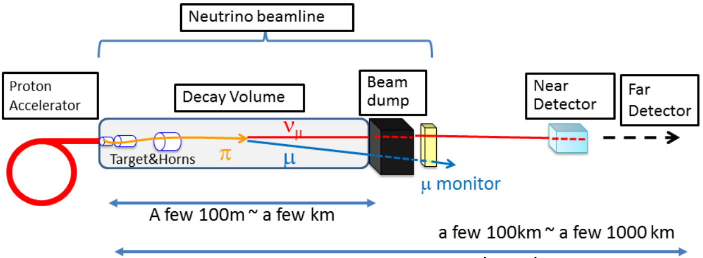
Outline

- Overview
- The J-PARC Accelerator and Upgrades to the J-PARC Accelerator
- The J-PARC Neutrino Facility and Upgrades to the J-PARC Neutrino Facility

J-PARC Neutrino Facility

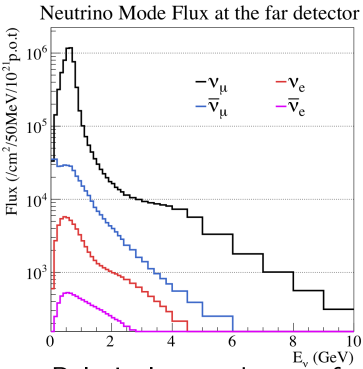
- Provides the neutrino beam for the currently running T2K long-baseline neutrino oscillation experiment (2009∼)
  - + other auxiliary experiments
- Will be upgraded for T2K and towards the Hyper-Kamiokande experiment, which is scheduled to start in 2027

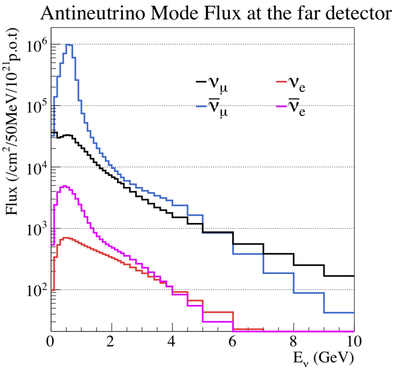
Producing the J-PARC Neutrino Beam



- 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 ~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

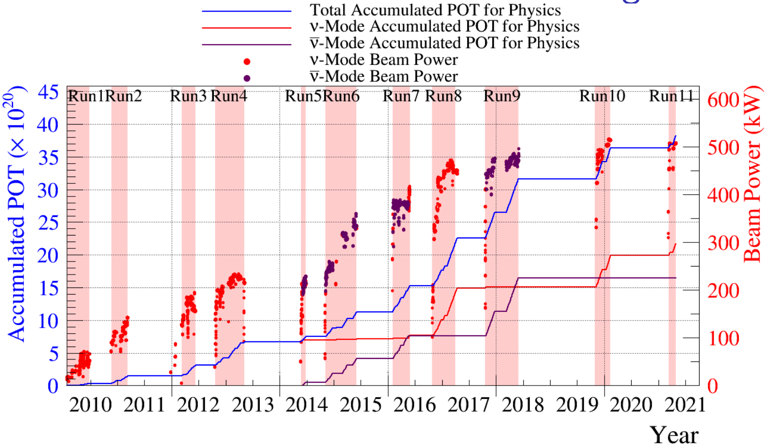
J-PARC Neutrino Flux





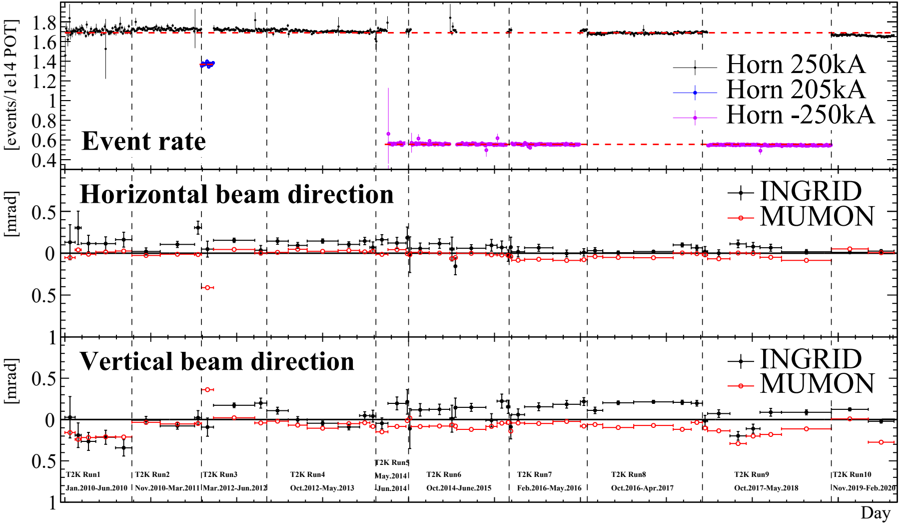
- Relatively pure beam of ν_μ or $\bar{\nu}_\mu$
  - 2$\sim$3% wrong-sign background at flux peak energy
  - $<$1% ν_e contamination at flux peak energy
- Must understand proton beam + all beamline components well to precisely predict flux
- Also constrain hadron interactions inside + outside the target
  - External NA61/SHINE experiment @CERN (in use + future measurements), EMPHATIC experiment @FNAL (future)

J-PARC Neutrino Beam Running Status



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

J-PARC Neutrino Beam Stability



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

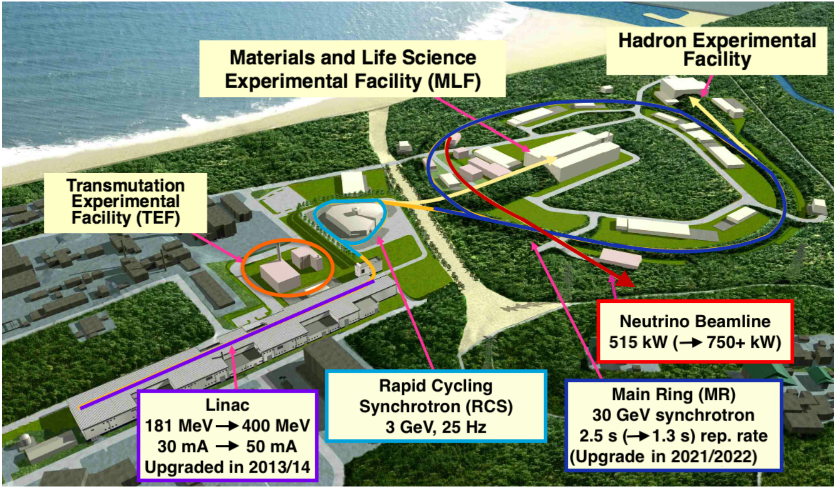
Upgrade Overview

J-PARC produces a conventional neutrino beam – how do we increase the number of neutrinos?

→ First step is to increase the number of protons

- Two ways to increase the proton beam power:
  1. Increase the frequency, number of beam spills
     - Increase beam repetition rate
     - (Maximize beam operation time..)
  2. Increase the number of protons per spill
     - Reduce beam instabilities and beam losses
- Of course, after increasing the proton beam power, all components in the neutrino extraction beamline must be able to handle the increased power
- – And – there are ways to increase the *effective* number of protons
  - i.e. improve the target to increase right-sign hadrons, increase the horn current for better right-sign hadron focusing
- **Major upgrades towards high intensity in 2021/2022!**

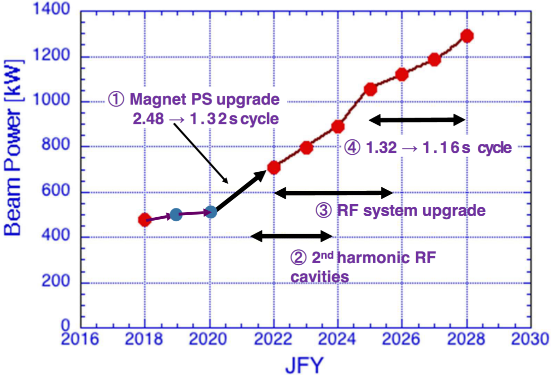
High-Power Proton Source – J-PARC



- 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



	Achieved	Target
Beam power [MW]	0.5	1.3
# of protons per pulse	2.6 x 10^{14}	3.2 x 10^{14}
Rep. Time [sec]	2.48	1.16

~x3

+30%

~1/2

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 2^{nd} 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

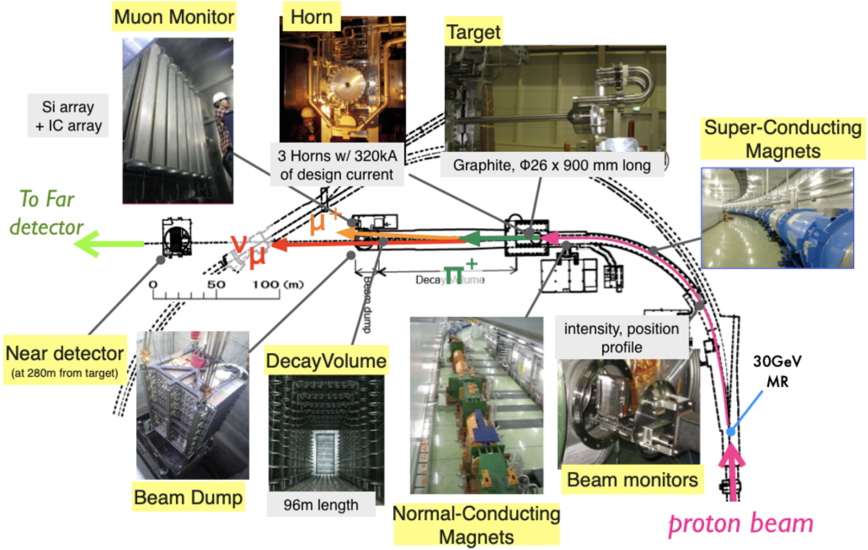
MR Power Supply Upgrade

- 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

(See talk by T. Yasui on 8/2)

J-PARC Neutrino Beamline



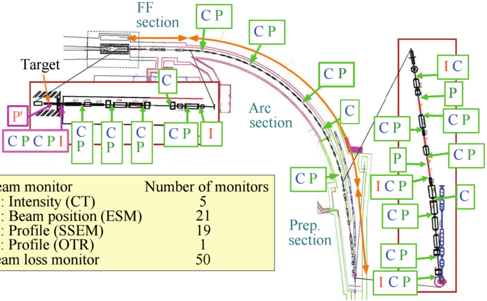
J-PARC Neutrino Primary Proton Beamline

Primary beamline includes:

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

Final Focusing NC magnets

Arc SC magnets



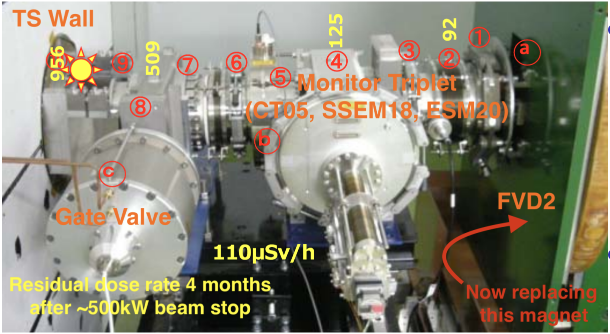
Beam monitor	Number of monitors
I : Intensity (CT)	5
C : Beam position (ESM)	21
P : Profile (SSEM)	19
P' : Profile (OTR)	1
Beam loss monitor	50

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
- Long-term upgrade: move to fully remote maintenance scheme

2021/2022 Upgrade Work

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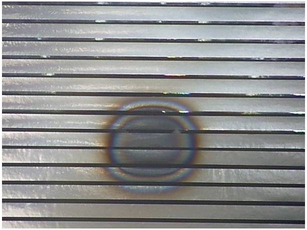
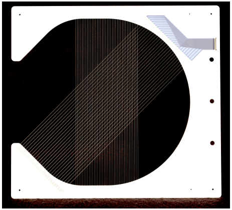
Proton Beam Profile Monitor Upgrades

- 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 joint R&D for lower loss monitor (WSEM) – 1 in use now
- Non-destructive profile monitor – Beam Induced Fluorescence Monitor (BIF) – developed, prototype installed, tested
  - Upgrading towards full working monitor now

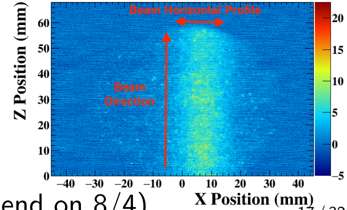


SSEM after $\sim 3.2 \times 10^{21}$ Incident Protons

New WSEM (FNAL)



Beam profile measured by BIF @beam test

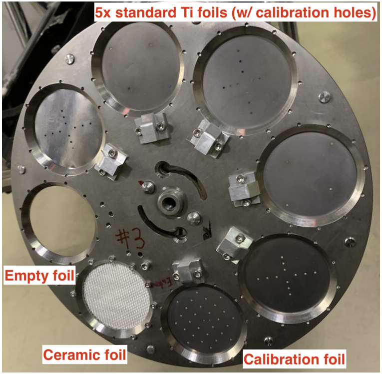


(see talk by M. Friend on 8/4)

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)



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 → Linux now (UCL) (see talk by M. Friend on 8/4)

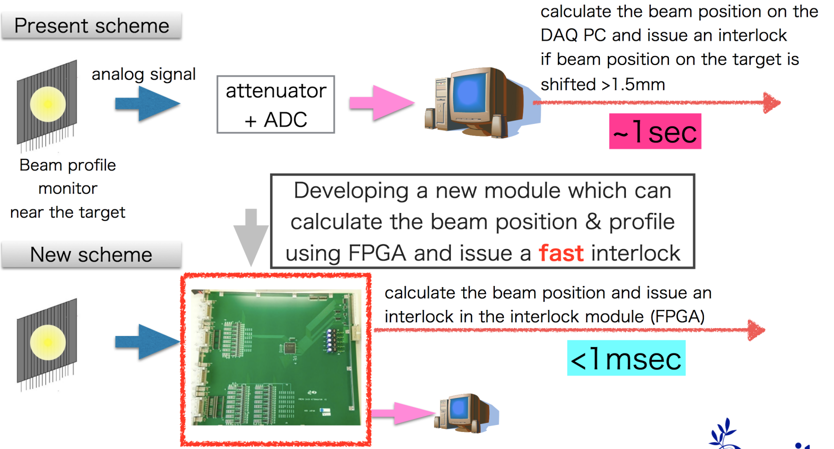
2021/2022 Upgrade Work

OTR Upgrades

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

DAQ, Beam Control, Interlock Upgrades

- DAQ for beam monitor readout upgraded for 1 Hz operation
- New interlock system for fast beam interlock under development

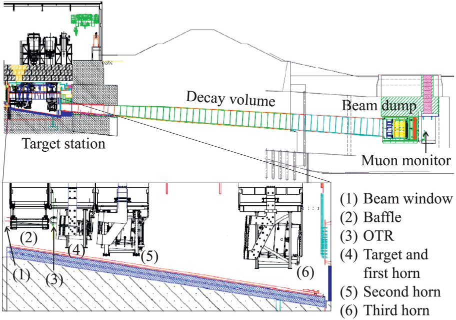


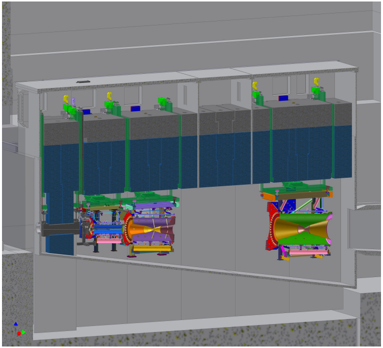
PAPILLON board : http://openit.kek.jp/project/beam_monitor_interlock/beam_monitor_interlock

Development: Okayama University, Tohoku University, KEK

Neutrino Secondary Beamline

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

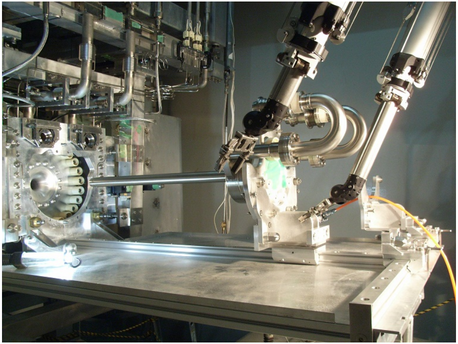




2021/2022 Upgrade Work

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
- New target (+ beam window) for 1.3MW also under development (RAL)



- 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

2021/2022 Upgrade Work

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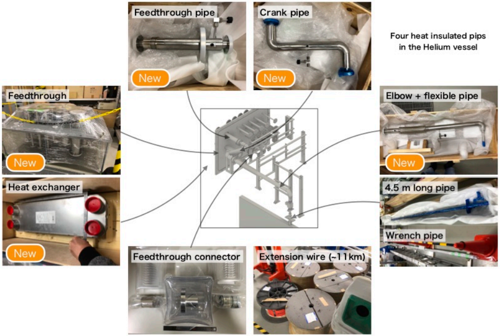
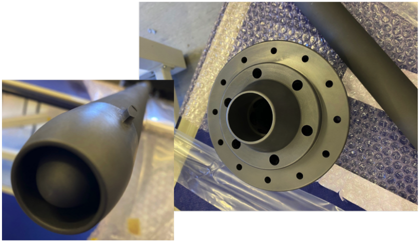
Target cooling upgrade





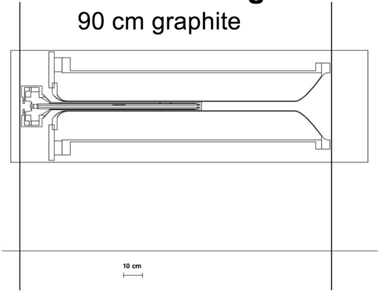
New prototype 1.3MW target

Neutrino Production Target Upgrade Ideas

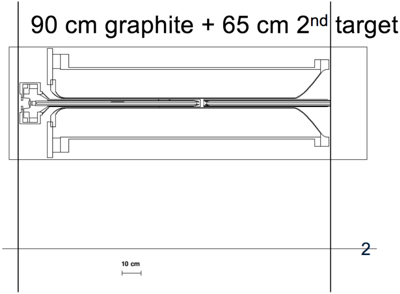
- Longer term studies to establish new target types to further maximize number of produced neutrinos are also ongoing
  - Possible to increase pion yield and decrease forward-going wrong-sign component by new target design
  - Higher-density and/or hybrid materials, longer targets

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

Current T2K target



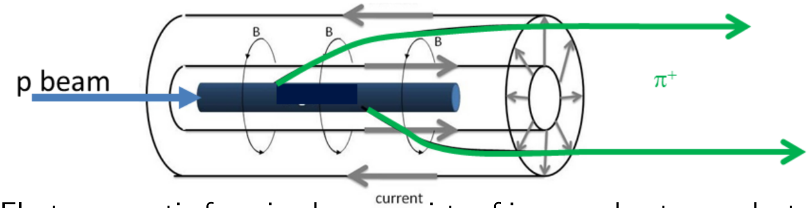
Changed target geometry



University of Glasgow, RAL

2021/2022 Upgrade Work

Electromagnetic Focusing Horns

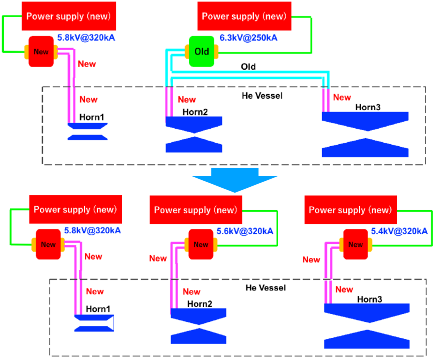


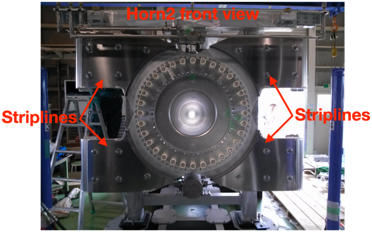
- Electromagnetic focusing horn consists of inner and outer conductor
  - Large magnetic field between conductors achieved by flowing high current down one conductor and back along the other
- Pions of the correct sign traveling between two conductors are focused
  - Sign of focused pions chosen based on direction of flowed current
- Horn conductors cooled by water spray between 2 conductors
- Current carrying striplines were cooled by He gas, being upgraded to water cooling now
- J-PARC neutrino beamline uses 3 horns which have been running at $\pm$250kA, upgraded to $\pm$320kA
  - 320kA horn test run underway now

2021/2022 Upgrade Work

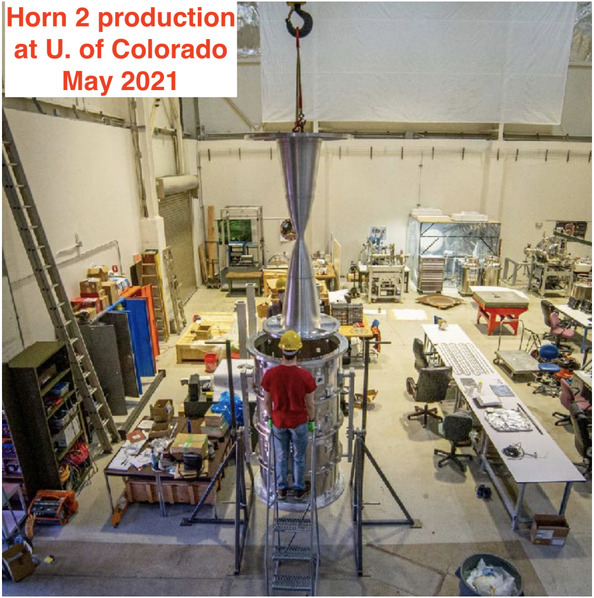
Horn Upgrades

- Upgrading 2 $\rightarrow$ 3 power supplies (+ new striplines, transformer) to increase horn current from $\pm$250kA $\rightarrow$ $\pm$320kA now
  - $\sim$10% increase in right-sign neutrino flux, 5$\sim$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 to be installed in 2022





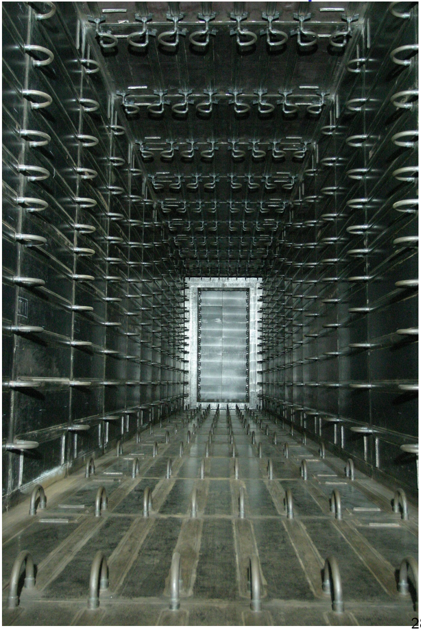
Horn Production, Testing, Installation



- New Horns 1 and 2 were produced at University of Colorado and have been shipped to J-PARC
- Current/magnetic field excitation test of Horn 2 is being done this week – almost ready to install
- New horns 1 and 2 are being installed in 2022
    - 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 ($\sim$5m) to stop hadrons
- Water-cooled by piping
- Water cooling capability will be upgraded by increasing the water flow

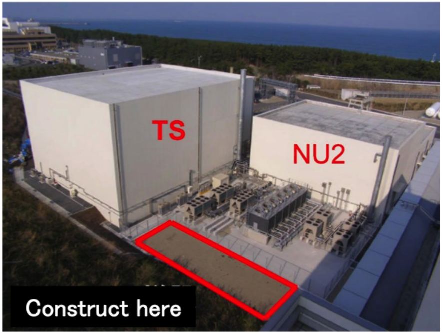


2021/2022 Upgrade Work

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

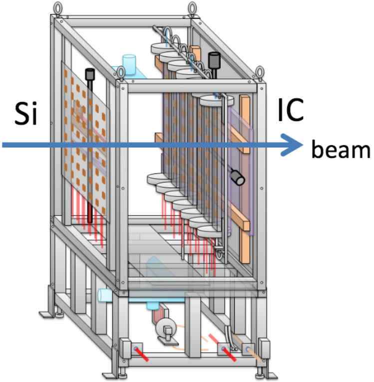
Before construction:



Fully constructed:

Muon Monitoring Upgrades

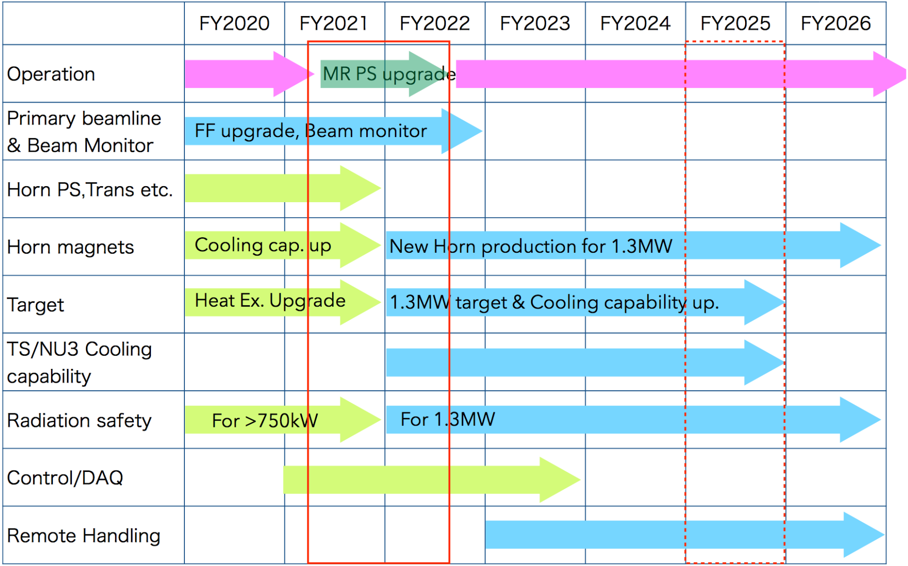
- Measure tertiary muon beam profile downstream of the decay volume, beam dump (>∼5 GeV muons)
  - Ensure alignment, healthiness of target, horns; proton beam position, angle at target; etc
- 2 redundant measurements of the muon beam profile, position using 7x7 arrays of sensors
  - Ionization chambers (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 T. Honjo on 8/4)

Neutrino Beamline Upgrade Schedule

Overall schedule of beamline upgrade



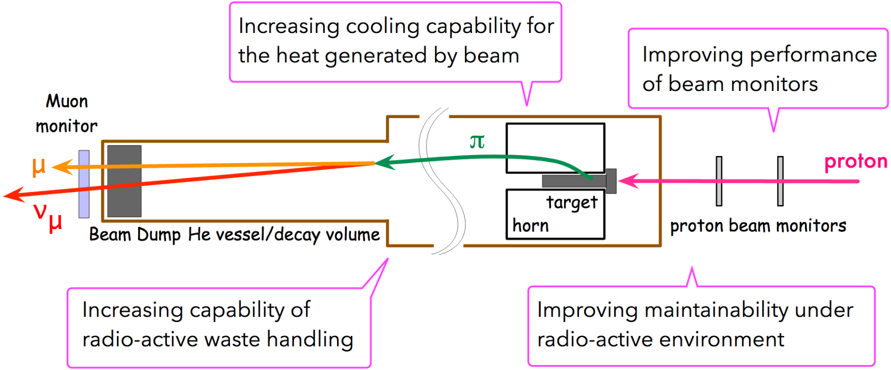
Conclusion

- 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 soon
- Many, many upgrades to the J-PARC neutrino extraction beamline underway now in order to accept the higher power proton beam

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

Backup Slides

Neutrino Beamline Upgrades Towards 1.3MW

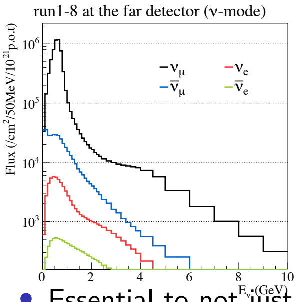


+ Accepting high repetition rate (~1Hz) beam

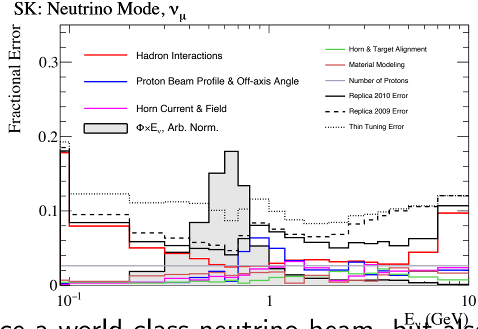
→ Upgrade DAQ + control system

Technical Design Report : arXiv:1908.05141

Example predicted T2K flux and errors :



Neutrino Flux 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)
- Beamline designed with this in mind