Upgraded J-PARC neutrino beamline & prospects for further increase of beam power

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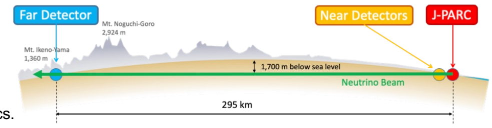
J-PARC accelerators for the T2K/Hyper-Kamiokande experiments

Japan Proton Accelerator Research Complex (J-PARC) is a JAEA and KEK joint project in Tokai, Japan.
- Multi-purpose and multidisciplinary facilities utilizing high-intensity proton beams.
    - Accelerator complex : 400 MeV proton linac, 3 GeV Rapid Cycling Synchrotron (RCS) and 30 GeV Main Ring (MR) synchrotron
    - Experimental facilities : Particle and nuclear and physics, materials and life science, and nuclear technology

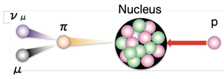
Neutrino programs - One of the flagship programs at J-PARC
- Tokai-to-Kamioka (T2K) experiment is operating from JFY2009 to present.
- Hyper-Kamiokade experiment aims to start data taking from JFY2027.

High-intensity beam is a key for the accelerator neutrino physics.
- Sensitivity on the long-baseline accelerator neutrino experiment is currently limited by statistics.

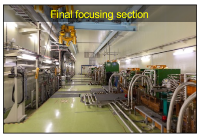


J-PARC Neutrino beamline

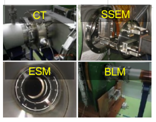
Neutrino beam generation
- Protons from the MR are extracted/guided to the carbon target
- Hadrons, mostly pions, are produced/focused by a target and horns
- Pions decay into muons and muon neutrinos in flight



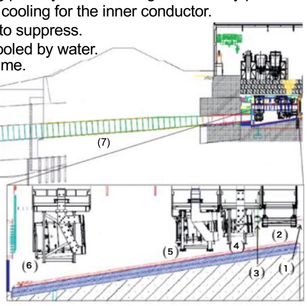
Primary beamline
- Preparation sec. : Normal-conducting magnets and collimators to prepare for a clean beam before the arc section.
- Arc sec. : 28 super-conducting combined function magnets (~150 m) to bend protons with 80˚ toward the Kamioka direction. (Dipole field : 2.6T, Quadrupole field : 1.86 T/m)
- Final focusing sec. : Normal-conducting magnets to shape the beam for the neutrino target.

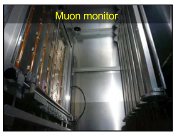


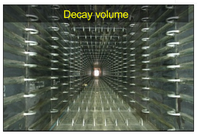
Series of proton beam monitors
- Intensity monitors
  - Current transformer (CT) x 5
- Beam loss monitors
  - Beam loss monitor (BLM) x 50
- Profile monitors
  - Electrostatic monitor (ESM) x 21
  - Segmented secondary emission monitor (SSEM) x 18
  - Wire secondary emission monitor (WSEM) x 2 since 2018

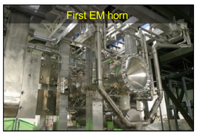


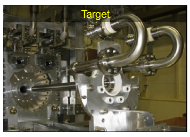
Secondary beamline
(1) Beam window : Separating from vacuum in the primary beamline. Made of 0.3 mm thickness of Ti-6Al-4V, cooled by He gas (0.8 g/s).
(2) Baffle : Collimator to protect downstream equipment. Made of Carbon block of 1.7 m x 0.3 m x 0.4 m with a hole of 30 mm diameter.
(3) OTR : Optical Transition Radiation (OTR) monitor in front of the target. Light emission from various foils read out by CCR through mirrors.
(4) Target : Made of graphite rod with 91.4 mm long & 26 mm diameter, cooled by He gas (32 g/s).
(4, 5, 6) EM horns : Focusing hadrons forward and switching polarity with ~2T magnetic field by pulsed current. Made of Aluminum alloy. Water cooling for the inner conductor.
(7) Decay volume : Volume waiting for decay under He gas to suppress. Tritium and nitrogen oxide production, cooled by water.
(8) Beam dump : Stopping hadrons at the end of decay volume. Made of graphite core & Aluminum cooling module.
(9) Muon monitor : Si PIN photodiode & Ion Chambers to monitor the beam in real time.









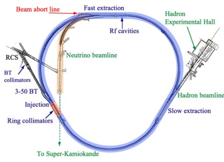


Original design power was 750 kW - To accept higher power, some equipment needed to be upgraded.
- Horn operation cycle and current
- Cooling capacities for the Beam window, Target, Horns, He vessel, Decay volume, and Beam dump
- Radiation measures such as quick handling system & shielding enhancement

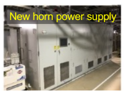
Upgrades in JFY2021/2022

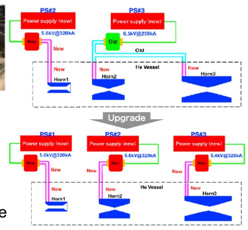
	Cycle time (sec)	Intensity (proton per pulse)	Power (kW)
Before upgrade	2.48	2.6×10^{14}	500
After upgrade	1.32	2.1×10^{14}	750
Goal	1.16	3.3×10^{14}	1300
	x2	x1.3	x2.6

Main ring (MR) upgrade
- Beam power upgrade aiming to 1.3 MW from 500 kW by faster cycle time & increased proton per pulse.
- Upgraded various devices during the MR long shutdown
  - Main magnet PS system, RF system, Injection/extraction devices, Collimator, Beam monitors, and so on.



Neutrino beamline upgrade
- During the MR long shutdown period, various devices in the neutrino beamline were upgraded, in addition to DAQ upgrade for the faster cycle.

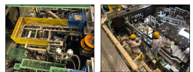




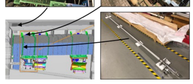
1) Upgrade of Horns for 1 Hz and 320 kA operation
- New horn power supply, transformer, strip-lines were upgraded
  - About 10% increase of right-sign neutrinos & 5~10% decrease of wrong-sign neutrinos compared to 250 kA operation.

2) Upgrade of cooling capacities
- Exchanged 1st and 2nd horns with higher cooling capacity by remote handling. (Target and OTR were also replaced with the 1st horn.)
- Exchanged the first heat exchanger for target to accommodate higher He gas pressure (0.16 → 0.4 MPaG) with increased flow rate.

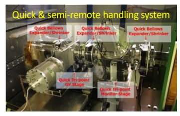
3) Upgrade of radioactive water disposal capacity
- Operation time per year was limited by the capacity to dilute radioactive water within the regulation for Tritium disposal.
- Increased capacity with the new disposal tanks (100 m³ → 500 m³).



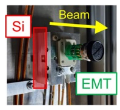
4) Upgrade of radiation shielding
- Reinforced radiation shield was required to go beyond 750 kW.
- Added concrete blocks in Target station & successfully completed facility inspection by the Nuclear Regulation Authority of Japanese government.

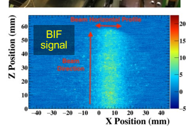


5) Upgrade of maintenance procedure for activated equipment
- Installed new shorter magnet to make space and installed quick handling systems at the most downstream part at the primary beamline.
  - High radiation due to backscattering there. Exposure can be mitigated.

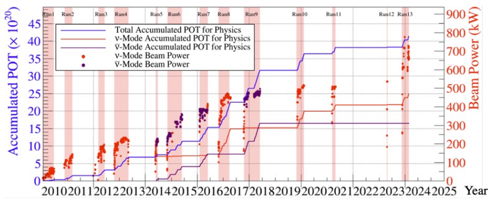


6) Upgrades of beam monitors
- Beam induced Fluorescence (BIF) monitor was developed.
  - Non-destructive and continuous beam monitor for high power operation.
  - Installed working prototype in 2019. Improving for continuous operation.
- Electron Multiplier Tube (EMT) for a muon monitor was developed.
  - Installed 7 EMTs with higher radiation tolerance. Confirmed stable operation. Muon profile was successfully measured. To be fully implemented



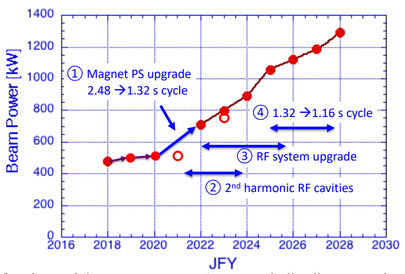


Operation status after the upgrade
- Beamline successfully ran stably at 710 kW in Dec 2023.
- Ran stably at ~760 kW for 38 minutes on Dec. 25, 2023.
- No issue found with any component during high power operation



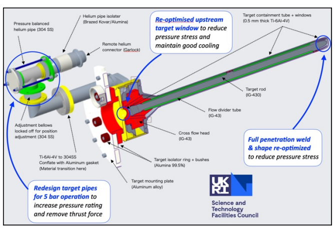
Prospects for further increase of beam power

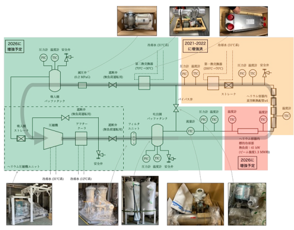
Prospects on the MR beam power



- As planned, beam power was increased after the upgrade
- While supplying the beams for the T2K experiment, further increase is expected after the RF system upgrade
  - Reaching ~1 MW in 2025
  - Reaching 1.3 MW in 2028 (in time for starting Hyper-K operation)

Prospects on the remaining upgrade in the neutrino beamline
- Upgrade of Cooling water system for He vessel, Decay volume & Beam dump toward 1.3 MW.
  - Pumps and other circulation systems will be replaced for higher flow rate.
- Upgrade of Target and Target He cooling system to accept >1 MW beam power.
  - Target will be exchanged to accept x2.5 higher He gas pressure.
  - Compressor and other circulation systems will be upgraded for increase cooling capacities.





- Maintenance plan in the Hyper-K era is under investigation.
  - Need to do replace monitors, beam window, OTR, target, horns after the beam exposure.

Summary

- Realizing a high intensity neutrino beam is a key for the T2K and Hyper-K experiments.
- Various upgrades of the neutrino beamline were successfully performed in the J-PARC MR long shutdown period.
- Reached a record beam power of about 760 kW (+40% of leaping compared to that before).
- While supplying the beam, aiming 1.3 MW beam power by the time when the Hyper-K starts.