J-PARC accelerator and neutrino beamline upgrade programme

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J-PARC accelerator and neutrino beamline upgrade programme

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Abstract. The 30 GeV proton beam from the J-PARC Main Ring (MR) accelerator is used to produce a world-class conventional neutrino beam – the neutrino source for the J-PARC long-baseline neutrino programme, including the current T2K experiment and proposed future experiments. Planned upgrades to increase the beam power of the MR from the current ~400 kW to the design power of 750 kW and beyond, to 1.3+ MW, are underway. These include hardware modifications, such as upgrades of the MR magnet power supplies, RF systems, and feedback systems, as well as a change of the MR beam betatron tune point. Upgrades to the neutrino beamline, such as to the proton beam monitoring, horns, and radioactive material handling, will also be required to accommodate the increased proton beam power. An overview of planned J-PARC MR and neutrino facility upgrades is given.

1. Introduction
The Japan Proton Accelerator Research Complex (J-PARC) neutrino programme consists of a series of experiments which first started taking data in 2010 and which have been proposed to continue until around 2036. First is the currently-running Tokai to Kamioka (T2K) Long-Baseline Neutrino Oscillation experiment [1], where the neutrino beam produced at J-PARC is detected in the Super Kamiokande (SK) [2] 50 kton water Cherenkov detector 295 km downstream of the neutrino production point. T2K is approved to take $7.8 \times 10^{21}$ Protons On Target (POT), which is expected to be achieved in 2021. A T2K extension, T2K Phase 2 [3], which would extend the T2K run to 2026 and $20 \times 10^{21}$ POT, was recently proposed and has received stage 1 approval by the J-PARC PAC. Finally, the Tokai to Hyper Kamiokande (T2HK) experiment [4] has also been proposed; T2HK would detect neutrinos from J-PARC in the planned Hyper Kamiokande detector as a far neutrino detector after its completion after 2026.

Increasing the proton beam power will proportionally increase the neutrino flux for these experiments. J-PARC Main Ring (MR) accelerator upgrades to increase the beam power and POT as much as possible are therefore highly advantageous.

Currently, the J-PARC MR accelerator has been running stably at ~420 kW, but a series of upgrades are planned to reach the design power of 750 kW and beyond, to 1.3+ MW, as shown in Fig. 1 and described in detail in Sec. 3. There are two ways of increasing the proton beam power: increasing the frequency or number of beam spills, or increasing the number of protons per beam spill. Both methods will be used in this case, as summarized in Table 1.
Figure 1. Anticipated MR beam power and POT accumulation plan by calendar year. The black dotted line shows the proposed T2K Phase 2 full statistics.

| Year               | Power (kW) | Protons/Spill (×10^{12}) | Spill Rate |
|--------------------|------------|---------------------------|------------|
| Current (2016)     | 425        | 220                       | 2.48 s     |
| With Tuning (2016∼2018) | 425→450   | 220→235                   | 2.48 s     |
| Upgraded (2018∼2023)| 700→1326  | 190→320                   | 1.30→1.16 s|
| Upgraded (2023∼)   | 1326       | 320                       | 1.16 s     |

Upgrades to the J-PARC neutrino beamline, especially for the cooling capacity of various beamline components, will also be necessary to accommodate the increased beam power, as discussed in Secs. 4.1 and 4.2. Horn upgrades, aimed at improving the neutrino flux purity and neutrino flux prediction, are also planned, as described in Sec. 4.2.1.

2. J-PARC MR and neutrino beamline

The J-PARC accelerator complex consists of a 400 MeV proton Linac, 3 GeV Rapid Cycling Synchrotron (RCS), and 30 GeV Main Ring Synchrotron accelerator as shown in Fig. 2.

The MR proton synchrotron consists of 3-fold symmetric straight and bending sections around a 1568-m circumference. As shown in Fig. 3, it has 3 116-m-long straight sections dedicated to: injection and beam collimators; slow extraction; and a fast extraction (FX) and RF system, where the fast extraction scheme is used to extract the beam into the neutrino primary beamline.

Each FX beam spill has an 8-bunch structure with 80 ns (3σ) bunch width and 581 ns bucket length. The beam repetition rate is currently 1 spill (8 bunches) each 2.48 s, with a plan to upgrade to 1.3 s in 2018 and to 1.16 s in 2020 as discussed in Sec. 3.
Figure 3. The J-PARC Main Ring Synchrotron.

Protons from the MR are extracted by the fast extraction scheme to the neutrino primary beamline, which consists of a series of normal- and super-conducting magnets to bend the proton beam towards the SK far detector direction and focus the protons onto the neutrino production target. A series of proton beam monitors are used to ensure that the proton beam is well-controlled and that beamline equipment is continuously protected from potentially mis-steered beam. A secondary beamline, which consists of a 91.4 cm-long (1.9 interaction length) graphite target, a series of 3 electro-magnetic focusing horns, a 100-m-long water-cooled decay volume, a beam dump to stop hadrons and un-interacted protons, and a set of two muon monitors, is used to produce, focus, and monitor the hadron beam which becomes the neutrino beam as detailed below. The target, horns, decay volume, and beam dump are all kept under He in order to suppress tritium and nitrogen oxide production.

The J-PARC neutrino beam is generated by the interaction of 30 GeV protons from the MR incident on the long graphite target. Outgoing hadrons, mostly pions but also including other particles such as kaons and un-interacted protons, are focused by the horns and then allowed to decay in the decay volume. Pions, for example, decay into muons and muon neutrinos, producing a relatively pure muon-neutrino ($\nu_\mu$) beam. Predictions of hadron production inside the target are constrained by outside hadron production measurements, such as the NA61/SHINE experiment [5]. The horn polarity can be switched to control the polarity of the focused hadrons, allowing for the production of a relatively pure beam of either $\nu_\mu$’s or $\bar{\nu}_\mu$’s. The J-PARC neutrino beam takes advantage of an off-axis method to generate a neutrino beam with a relatively narrow peak energy: the off-axis angle of the SK far detector is 2.5° allowing for a neutrino beam energy peaked around 0.6 GeV. The neutrino flux predicted at the SK far detector in both $\nu$- and $\bar{\nu}$-mode is shown in Fig. 4.

3. MR upgrades towards 1.3 MW
A series of MR hardware upgrades and beam stability improvements are planned in order to reach the J-PARC target beam power of 1.3+ MW.

3.1. MR hardware upgrades
As discussed above, one way to increase the MR proton beam power is to increase the beam spill repetition rate. The present limiting factor in increasing the repetition rate is the ramping time of the MR magnet power supplies. All MR magnet power supplies are being upgraded for 1 Hz operation, where the budget for this upgrade has been approved from JFY2016. A prototype magnet power supply system has been fabricated, tested, and is working well: the ramp-time has been reduced to give a full repetition cycle under 1.3 s using power recovery by a capacitor bank, and the fractional current ripple is reduced to below $10^{-6}$, which is the fluctuation limit for stable operation. Infrastructure for installing these new power supplies is currently under
construction, with a plan to finish the full installation and turn on the beam with a beam spill repetition rate of 1.3 s following the annual J-PARC summer shutdown in 2018.

A new high-gradient RF cavity system has also been developed. The new RF cavities use a new type of magnetic alloy core (FT3L) which have an increased shunt impedance and allow for a field gradient increase of ~50%, as shown in Fig. 5. All of the old standard RF cavities (which used the magnetic alloy FT3M) have been gradually replaced with new ones, where five new RF cavities have been in use and working well since 2015 and four more were installed in 2016 (for a total of 9 new cavities). Two new additional cavities for tuning at the RF 2nd harmonic may be installed in 2017 (or previously uninstalled cavities may be refurbished and re-used for this purpose), such that the fully upgraded RF system should be ready and tested before the MR magnet power supply upgrade is completed in 2018.

Upgrades to the RF cavity power supplies planned to take place in 2019~2023 will allow for further gradual increase of the repetition rate, from one beam spill every 1.3 s down to 1 spill every 1.16 s.

3.2. MR stability improvements
The MR proton beam power can also be increased by increasing the number of protons per spill, which can be achieved by improving the beam stability and reducing beam losses in the MR.

The MR stability will be improved by running at a new betatron tune point, which, as shown in Fig. 6, avoids destabilizing betatron resonances more effectively than the previous tune. As
of early 2016, this new tune point has been successfully used to run continuous 425 kW beam, and stability at this tune has been established.

![Figure 6. Betatron tune resonance diagram for the J-PARC MR. The resonance diagram shows the tune points (colored points), tune spread (black regions), and betatron resonances (lines). The tune region should avoid resonances to enhance accelerator stability.](image)

Now that a new, more stable, betatron tune has been established, optimization of many RCS and MR parameters can proceed. The RCS beam parameters (such as the painting, tune, and chromaticity) for injection to the MR can be improved. The RF voltage pattern for the MR fundamental and 2nd harmonic will be tuned. The compensation kicker will be optimized for the new tune point. Collimator tuning will be done in order to optimize beam loss localization throughout the MR. All available octupole magnets can be used to optimally damp higher-order resonances (where currently only two magnets are being used). The trim quadrupole and trim sextupole patterns can also be tuned to damp higher-order terms. The beam optics at the extraction timing can be tuned for beam loss reduction. Instabilities can also be further damped by tuning the intra-bunch feedback and chromaticity settings.

Some relatively small-scale MR hardware improvements, such as widening beam apertures in regions where a large beam spot-size is causing halo scraping and beam losses, as well as upgrades to beam size, profile, and halo monitors for improved beam tuning and control, may also be done to help improve the MR stability.

### 3.3. MR high power trials

A high-power trial of the MR was carried out in 2015 (using the previous MR betatron tune point) with results shown in Table 2. A 1000-kW-equivalent beam power was achieved with a 2-bunch beam structure, although beam losses need to be reduced before continuous running with 8 bunches at that power can be achieved. The new MR betatron tune point and other improvements described above will be used to reduce the beam losses observed during this test.

| # of Bunches | Repetition | #P/Spill (10^{12} equiv) | Beam Power (kW) | Beam Loss (kW) | Notes       |
|--------------|------------|---------------------------|-----------------|----------------|-------------|
| 2            | 2.48       | 270                       | 132             | 0.42           | Measurement |
| 8            | 2.48       | 270                       | 530             | 1.7            | Estimation  |
| 8            | 1.3        | 270                       | 1000            | 3.2            | Estimation  |

Continuous beam at 420–425 kW with an 8-bunch beam structure was also demonstrated at the new MR tune point in 2016, as shown in Table 3. The MR ran stably at 420 kW for ~24 hours.
Table 3. MR high beam power demonstration at new betatron tune point for 8-bunch beam in 2016.

| Repetition Period (s) | #P/Spill (10^12) | Beam Power (kW) | Notes                           |
|----------------------|-----------------|-----------------|---------------------------------|
| 2.48                 | 220             | 425             | Intensity & Period Achieved     |
| 1.3                  | 220             | 800             | 8-Bunch Intensity Demonstrated  |
| 1.3                  | 270             | 1000            | 2-Bunch Intensity Demonstrated  |
| 1.16                 | 320             | 1326            | Planned                         |

4. Neutrino beamline upgrades towards 1.3 MW

The J-PARC neutrino beamline consists of a primary (proton) beamline and secondary beamline as described in Sec. 2. Plans for upgrades to the neutrino primary and secondary beamlines for 1.3+ MW beam power are detailed in Secs. 4.1 and 4.2 respectively.

4.1. Neutrino primary beamline upgrades

Major infrastructure or hardware upgrades to the J-PARC neutrino primary proton beamline shouldn’t be required to be able to handle the increased MR proton beam power, since all primary beamline magnets and power supplies were originally designed for high beam power at 40 GeV proton beam energy. There is some possibility that a magnet configuration change or an increase in beam-pipe aperture would be required in case of beam blow-up due to space-charge effects at high beam power, however so far no problem with the beamline configuration has been observed. The biggest issue foreseen in the neutrino primary beamline is the irradiation of down-stream beamline components by ionizing particles back-scattered from the beam window and production target. It will probably be necessary to develop a new remote maintenance scheme for the most down-stream beamline components, such that any required maintenance work can be carried out without risk to workers. Other unforeseen configuration changes may also be needed as the MR beam parameters are changed, and possible required upgrades will be kept in mind going forward.

Proton beam current, position, and loss monitors are distributed along the primary beamline, and all of these monitors are designed for high beam power. The readout for some of these monitors is done by a Flash Analog-to-Digital Converter (FADC) model that has a relatively long latency time – these FADCs must be replaced with low-latency FADCs for the faster ∼1 Hz beam spill repetition rate. This readout upgrade will be completed in 2018.

Segmented Secondary Emission Monitors (SSEMs) are also distributed along the neutrino primary beamline and measure the proton beam profile. These SSEMs each consist of 3 5-μm-thick Ti foils and cause 0.005% beam loss; most are therefore used for measuring the proton beam profile during beam tuning and are removed from the beamline during continuous beam. Since losses increase proportional to the increasing proton beam power, loss from these profile monitors may cause non-negligible activation of or damage to beamline components at high beam power. The most down-stream SSEM and an Optical Transition Radiation Monitor (also consisting of a Ti foil) are used to continuously measure the beam profile, position, and angle directly upstream of the target, and degradation of these two monitors after a high integrated number of incident protons is also a concern.

R&D for two new types of beam profile monitors is currently ongoing. One new beam profile monitor will use ∼25-μm-diameter wires rather than foils to measure secondary emission induced by the beam – the greatly reduced amount of material in the beam should reduce the beam loss due to this profile monitor to ∼0.0002%. The other new monitor will measure fluorescence induced by proton beam interactions with gas injected into the beamline; this monitor is non-destructive and can therefore be used for continuous beam profile monitoring.
4.2. Neutrino secondary beamline upgrades

As shown in Table 4, all of the major J-PARC neutrino secondary beamline infrastructure (i.e. the shielding, decay volume, and hadron absorber) was designed for 3–4 MW proton beam power. However, upgrades to improve the cooling capacity of several components, radiation containment, and irradiated cooling water disposal will be required for running a 1+ MW proton beam on target. The secondary beamline upgrade schedule is shown in Fig. 7.

| Component | Limiting Factor       | Current Acceptable Value | Upgraded Acceptable Value |
|-----------|------------------------|--------------------------|---------------------------|
| Target    | Thermal Shock          | $3.3 \times 10^{14}$ ppp  | $3.3 \times 10^{14}$ ppp  |
|           | Cooling Capacity       | 0.75 MW                  | >1.5 MW                   |
| Horn      | Conductor Cooling      | 2 MW                     | 2 MW                      |
|           | Stripline Cooling      | 0.54 MW                  | >1.25 MW                  |
|           | Hydrogen Production    | 1 MW                     | >1 MW                     |
|           | Operation              | 2.48 s & 250 kA          | 1 s & 320 kA              |
| He Vessel | Thermal Stress         | 4 MW                     | 4 MW                      |
|           | Cooling Capacity       | 0.75 MW                  | >1.5 MW                   |
| Decay     | Thermal Stress         | 4 MW                     | 4 MW                      |
| Volume    | Cooling Capacity       | 0.75 MW                  | >1.5 MW                   |
| Beam Dump | Thermal Stress         | 3 MW                     | 3 MW                      |
|           | Cooling Capacity       | 0.75 MW                  | >1.5 MW                   |
| Radiation | Radioactive Air Disposal | 1 MW                     | >1 MW                     |
|           | Radioactive Water      | 0.5 MW | 0.75→1.3 or 2 MW |

Figure 7. Schedule for secondary beamline upgrades.

4.2.1. Horn upgrades

The J-PARC neutrino beamline utilizes a three-horn configuration. Each of the three electromagnetic focusing horns consists of a pair of coaxial conductors, and a large magnetic field is induced between the two conductors by passing a high current over them. Pions of the correct sign traveling between the two conductors are focused, where the sign of the focused pions can be chosen based on the horn current polarity. The horns are cooled by...
spray water, and beam power limits based on the horn cooling capacity, horn stripline cooling, and activation/disposal of the horn cooling water must be considered, as shown in Table 4.

The J-PARC horns are currently run at 250 kA, but an upgrade to run them at 320 kA is planned. This will be achieved by moving from two to three power supplies for the three horns. This upgrade to 320 kA will yield a predicted 10% increase in right-sign neutrino flux (e.g. $\nu$’s in a $\nu$-mode beam) at the far detector and a 5-10% reduction of wrong-sign neutrinos (e.g. $\bar{\nu}$’s in a $\nu$-mode beam) around the peak energy, as shown in Fig. 8. This upgrade should be completed in 2018.

![Figure 8](image)

**Figure 8.** Projected neutrino- (left) and anti-neutrino- (right) mode fluxes for 250 kA and 320 kA horn current.

Muon monitors are used to measure the secondary muon profile downstream of the beam dump ($<$~5 GeV) by two redundant measurements using two 7x7 arrays of sensors: ionization chambers (IC) and silicon photodiode (Si) sensors. Some muon monitor upgrade ideas include changing the IC gas type from the presently used Ar gas to a lighter noble gas such as He or Ne. Si sensor degradation with exposure has also been observed, and diamond and silicon-carbide sensors are being tested as possibly more robust alternatives. Other possible rad-hard sensors, such as electron-multiplier tubes, are also being considered.

5. Conclusion

The J-PARC long-baseline neutrino programme uses a neutrino beam generated by the high-power, high-quality proton beam from the J-PARC MR accelerator.

An increase of the MR proton beam power from the current 420 kW to the design 750 kW and beyond, to 1.3+ MW will be achieved by increasing both the the beam spill repetition rate and the number of protons per beam spill. A series of hardware upgrades, in particular an upgrade of the MR magnet power supplies in order to increase the beam spill repetition rate, will be required. Increased stability of the MR beam by optimization at a new betatron tune point and other upgrades will allow for an increased number of protons per beam spill.

Some relatively straightforward hardware upgrades, especially enhanced cooling of secondary beamline components, will be necessary for the J-PARC neutrino beamline to accept the MR beam at increased beam power. Increased horn current will also allow for an enhancement of the right-sign neutrino flux and a reduction of the wrong-sign flux.

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