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PROGRESS OF BEAM POWER UPGRADE IN J-PARC MAIN RING

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Abstract

The J-PARC main ring is now in the middle of beam power upgrade. The beam power ramp-up has generally progressed as planned so far, and the routine beam power has now reached 830 kW in the fast extraction mode and 92 kW in the slow extraction mode. This paper reports on the present status and prospects of the MR beam power upgrade.

INTRODUCTION

The J-PARC main ring (MR) [1], which provides 30-GeV proton beams to the neutrino experimental facility (NU) by fast extraction (FX) and to the hadron experimental facility (HD) by slow extraction (SX), is now in the process of beam power ramp-up.

In the FX mode operation, a project to increase the beam power to more than 1 MW is in progress [2]; we are now increasing the beam power while reducing the operation cycle and increasing the beam intensity step by step in line with hardware upgrades, finally aiming to achieve 1.3 MW with a repetition cycle of 1.16 s and a beam intensity of 3.3×10^{14} ppp, as shown in Fig. 1. To realize faster repetition rates and accommodate higher beam intensities, MR upgraded the main magnet power supplies, RF system, injection and fast extraction devices, and collimators with about one-year long shutdown period from July 2021. With the hardware upgrades, the FX operation cycle has been shortened from 2.48 s to 1.36 s to date, and beam commissioning at this operation cycle is in progress in parallel to the user beam operation. Right after the high-repetition rate upgrade, various troubles occurred with the updated devices, but they were addressed each time, and several important milestones have been achieved; the beam power ramp-up has generally progressed as planned so far, and the routine beam power has now reached 830 kW, exceeding the original design performance of 750 kW, as shown in Fig. 2 (red).

Beam power upgrade in the SX mode operation has also proceeded towards over 100 kW [3]. With a repetition cycle shortened from 5.20 s to 4.24 s, a stable user operation at a beam power of 92 kW, breaking the previous record of 65 kW before the high-repetition rate upgrade, has been achieved to date, as shown in Fig. 2 (blue).

Beam studies for further beam power ramp-up have also progressed well in both the FX and SX operations. The most important issues in realizing high-power beam operations are reducing and localizing beam loss to maintain a sustainable hands-on maintenance environment. This paper reports on the present status and prospects of the MR beam power upgrade, including the recent efforts to beam loss issues.

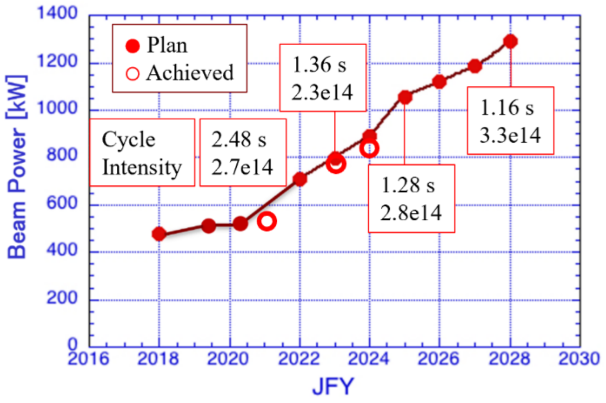

Figure 1: FX beam power projection through FY2028.

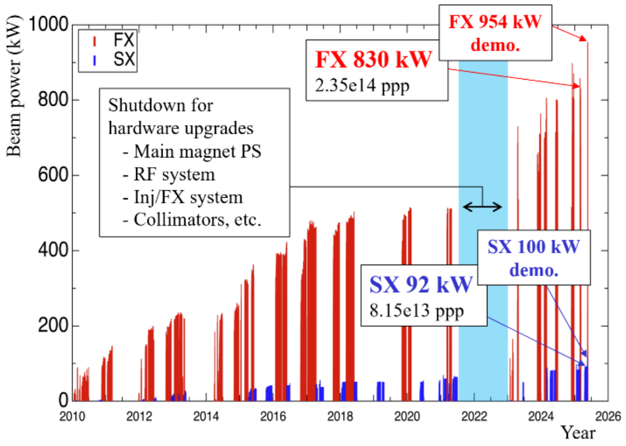

Figure 2: MR beam power achieved to date.

BEAM COMMISSIONING AND OPERATION

FX Operation

MR started the high-repetition rate FX operation for NU users in earnest in November 2023 via the initial machine and beam tunings. With the operation cycle of 1.36 s, beam power was gradually increased while carefully monitoring beam loss, and in December 2023, it reached a major milestone achieving 760 kW exceeding the original design performance of 750 kW. Detailed beam dynamics tuning continued thereafter for further beam power ramp-up, including precise optics tuning to establish the 3-fold symmetry of the MR lattice [4], tune manipulation at the early stage of acceleration to minimize the effect of resonance crossing, intra-bunch feedback to mitigate beam instabilities, linac and RCS tuning to reduce the injection beam emittance, and so on. In addition, large efforts were made for main magnet power supply tuning, such as reducing the output current ripples of the bending magnet power supplies by reducing noises in their current feedback

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circuits [5]. These continuous efforts in both beam dynamics tuning and hardware tuning steadily reduced beam loss and achieved an 800-kW stable beam operation in June 2024 within the permissible beam loss level; the beam loss was estimated to be 0.8% (0.6 kW) in the injection energy region and most of it was well localized at the collimator section, as shown in Figs. 3 and 4. Along with the progress in beam dynamics tuning, the routine beam power has further increased, now reaching 830 kW.

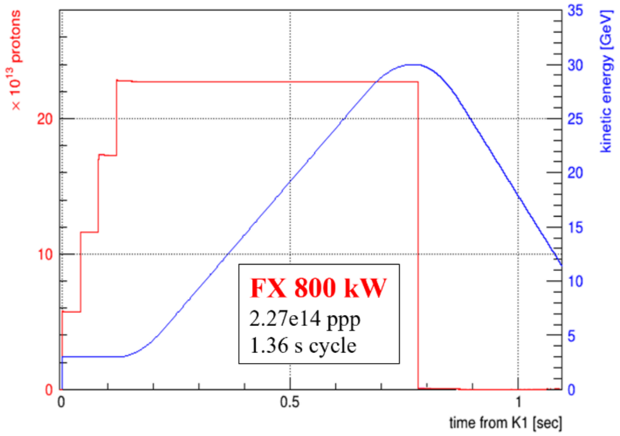

Figure 3: Circulating beam intensity during the 800-kW FX operation.

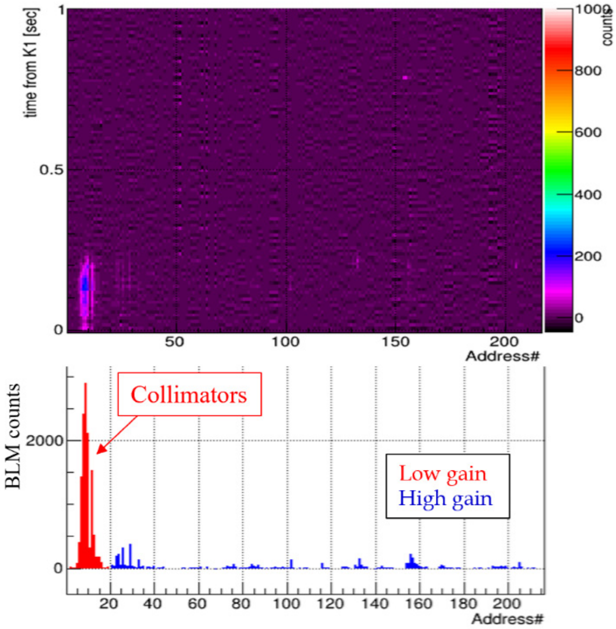

Figure 4: Beam loss monitor (BLM) counts along the ring during the 800-kW FX operation.

Efforts to further beam power ramp-up are also steadily in progress. RF anode power supplies were upgraded during the last summer maintenance to accommodate heavier beam loading by higher beam intensities of > 900 kW. In addition, beam tuning for a new beam optics [6, 7], which is effective in mitigating the effects of systematic betatron resonances near the operating point, has also progressed, and its effectiveness for further beam loss reduction has recently been demonstrated. Through these efforts, in May 2025, 855-kW and 954-kW (Fig. 5) beam accelerations have successfully been demonstrated at beam losses of 0.8% (0.7 kW) and 1.6% (1.5 kW) respectively, albeit a single-shot operation. The beam loss for 855 kW is sufficient for the continuous operation, which is the same level as that of the previous 800-kW user operation. The beam loss for 954 kW is also passible, well below the collimator limit of 3.5 kW, but it needs to be reduced to less than 1% from the viewpoint of maintaining a sufficient hands-on maintenance environment. There are still several key parameters that have not yet been fully adjusted, and by fine-tuning them, we aim to further reduce the beam loss.

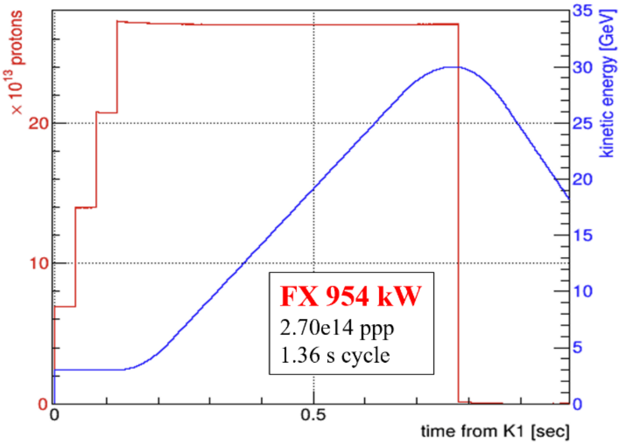

Figure 5: Circulating beam intensity during the 954-kW FX beam study.

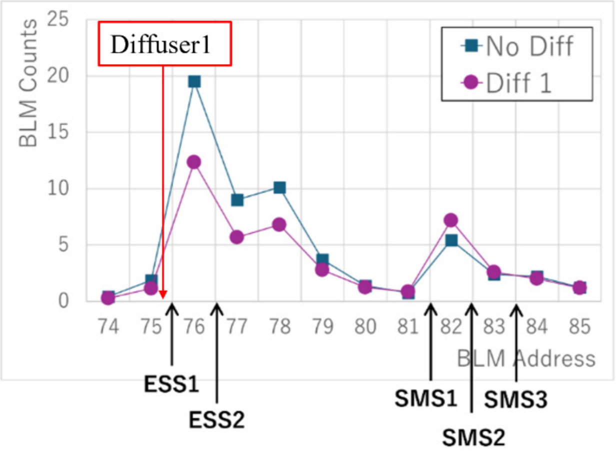

Figure 6: Beam loss monitor counts in the SX section during the 80-kW SX operation with and without the diffuser.

SX Operation

MR started the SX beam operation with a repetition cycle reduced from 5.20 s to 4.24 s in April 2024. Two-step de-bunching technique well mitigated beam instability during the de-bunching process at the flattop [8]; besides a beam diffuser installed upstream of the first electrostatic septum (ESS) successfully reduced the number of beam particles hitting the ESS ribbons, leading to significant beam loss reduction during SX [3], as shown in Fig. 6. Via such efforts, in June 2024, MR achieved a beam power of 80 kW with extremely high extraction efficiency of

99.65%, which broke the previous records (65 kW and 99.5%) before the high-repetition rate upgrade. In addition, the spill duty factor was also significantly improved from 61% to 83% through the optimization of the transverse RF knockout parameters and the spill feedback control based on the real-time beam rate measurements. The current ripple reduction of the main magnet power supplies, mentioned above, also contributed to the improvement of the spill duty factor.

After that, the routine beam power was further increased to 92 kW in April 2025. By introducing a second harmonic RF during injection and adjusting the phase offset between the fundamental and second harmonic RFs, the longitudinal beam distribution was well flattened. The reduction in charge density peak contributed significantly to both reducing beam loss during injection and suppressing beam instability during the de-bunching process at the flattop, resulting in the beam power upgrade.

Furthermore, in May 2025, a 100-kW SX was successfully demonstrated at high extraction efficiency of 99.65% in a single-shot operation, as shown in Fig. 7. After making fine spill adjustment and confirming long-term stability, we will attempt continuous 100-kW operation.

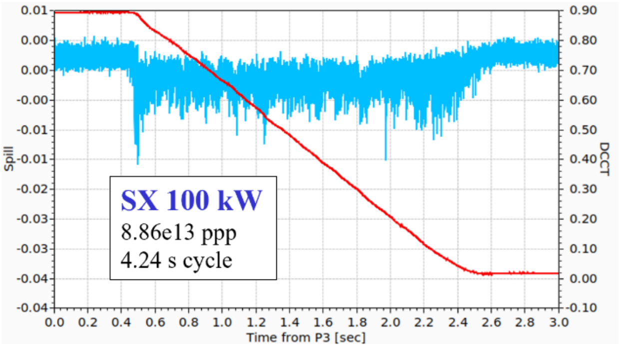

Figure 7: Beam spill structure during the 100-kW SX beam study.

FUTURE PLANS

FX Operation

After the next summer shutdown in 2025, we plan to further shorten the FX operation cycle from 1.36 s to 1.28 s. To realize this, main magnet power supply tunings have been underway since the last summer. The current patterns of the main magnet power supplies for the 1.28-s cycle are the same as those for the 1.36-s cycle from injection to extraction, only with a shorter fall time. Therefore, the beam dynamics of the 1.28-s cycle is the same as that of the 1.36-s cycle and the beam dynamics tuning so far can directly be applied to the 1.28-s cycle operation. Beam intensities of 855 kW and 954 kW well demonstrated with the new optics and the 1.36-s cycle correspond to 908 kW and 1013 kW for the 1.28-s cycle. We aim to achieve continuous beam operation at > 900 kW with the new optics and the shorter operation cycle of 1.28 s in FY2025.

To achieve the final goal of 1.3 MW, namely to realize the shorter operation cycle of 1.16 s, higher beam intensity of 3.3×10^{14} ppp and sufficient beam loss reduction, further hardware upgrades are planned after FY2025 for the RF system [9], main magnet power supplies, beam correction system [10, 11] and beam dump [12]. All the hardware upgrades required for 1.3 MW will be completed in FY2027, and then in FY2028 we are to aim to achieve 1.3 MW with the operation cycle of 1.16 s while continuing both hardware tuning and beam dynamics tuning.

SX Operation

The immediate goal in the SX mode is to achieve a beam power of 100 kW by FY2026. As mentioned above, beam tuning in the SX mode is progressing well, and the achievement of continuous 100-kW operation is now in sight. We aim for its early realization after this fall.

Efforts to further increase the beam power to beyond 100 kW are also underway. To further reduce beam loss during SX, the introduction of silicon bent crystals is under consideration [13], which is expected to more effectively reduce the number of beam particles hitting the ESS ribbons through the deflection of the beam. Beam instability mitigation is another important issue for beam power ramp-up. For this purpose, the introductions of a very high frequency (VHF) cavity and a new beam optics with a large slippage factor are being considered. Further improvement of the spill duty factor is also an important subject in the SX mode operation. To this end, the main magnet power supply tunings still continue to reduce the current ripples. In addition, the improvement of the spill feedback system is planned, in which the tune fluctuations are calculated directly from the current ripples of the main magnet power supplies and compensated in real-time. Through such efforts, we are aiming for further improvements of the beam performance in the SX mode operation.

SUMMARY

Beam power ramp-up is in progress steadily. So far, stable beam operations at 830 kW (FX) and 92 kW (SX) have been achieved as generally planned. Beam studies for further beam power ramp-up have also progressed well in both the FX and SX operations. The beam power will further be increased in stages aiming to achieve 1.3 MW (FX) by FY2028 and 100 kW (SX) by FY2026 in line with hardware upgrades and improvements as well as progress in beam dynamics and machine tunings.

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