HIGH-POWER BEAM OPERATION AT J-PARC

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Abstract

The Japan Proton Accelerator Research Complex (J-PARC) is a multipurpose high-power proton accelerator facility, comprising a 400 MeV linac, a 3 GeV rapid cycling synchrotron (RCS) and a 30 GeV main ring synchrotron (MR). RCS is now providing 500 kW beams to the materials and life science experimental facility (MLF) and its beam power will be increased step by step toward the design value of 1 MW. MR has been operated with the beam power of 500 kW at maximum for the long-baseline neutrino oscillation experiment (T2K). An upgrade plan of MR for the beam power of 1.3 MW for the T2K experiment is promoted with a faster cycling scheme.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a multipurpose high-power proton accelerator facility, comprising a 400 MeV linac, a 3 GeV rapid cycling synchrotron (RCS) and a 30 GeV main ring synchrotron (MR). RCS is now providing 500 kW beams to the materials and life science experimental facility (MLF) and its beam power will be increased step by step toward the design value of 1 MW [1, 2].

MR has two operation modes: slow extraction (SX) mode and fast extraction (FX) mode. For the SX operation the beam is extracted in about 2 s spill with the cycle time of 5.2 s. The beam spill is then delivered to the hadron hall to produce various secondary particles for the elementary particle and nuclear physics experiments. Proton beams with the power of 51 kW have been delivered for the SX operation [3].

For the FX operation the beam is extracted in one turn after the acceleration with the cycle time of 2.48 s. Proton beams with the power of 500 kW at maximum have been delivered to the long-baseline neutrino oscillation experiment (T2K). Figure 1 shows the beam power since 2010.

Significant experimental achievements have been reported including the first result on CP (charge-parity) violation search obtained from the T2K experiment [4]. The result indicates a potential discovery in the near future and further motivates MR to provide higher intensity beams.

The original design beam power of MR is 750 kW. The plan is to make the cycle time faster from 2.48 s to 1.32 s. New hardware is being made for the faster cycling, such as magnet power supplies, rf system, injection and extraction devices. Further upgrade plan is promoted for the beam power of 1.3 MW with the faster cycling of 1.16 s and intensity upgrade.

This paper describes the recent improvements and the future plan of the beam power upgrade.

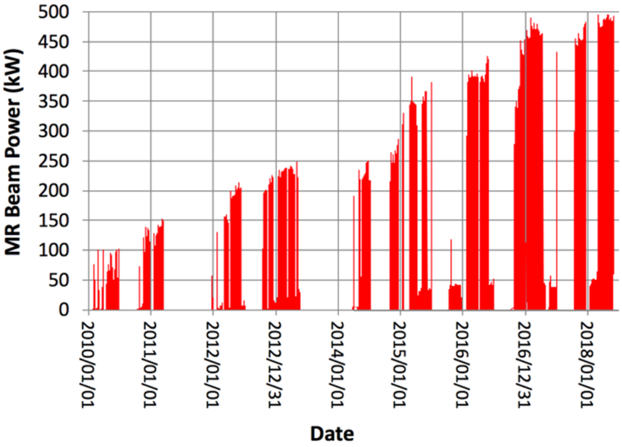

Figure 1: History of MR beam power.

OPERATION STATUS FOR THE FAST EXTRACTION

Eight bunches of beams are injected to MR in 4 times during the injection period of 0.13 s. The acceleration takes 1.4 s and the accelerated protons are then extracted. The recovery for the magnet currents takes 0.94 s and the total cycle is 2.48 s. The operation beam power was about 470 kW to 500 kW in the recent run of April and May of 2018. Figure 2 shows the beam intensity measured with DCCT as a function of the cycle time for a shot of beam power of 504 kW. The number of protons per bunch (ppb) was 3.3×10^{13} at the injection and the number of accelerated protons was 2.61×10^{14} ppp.

The beam loss was estimated to be 273 W during the injection period and 385 W during 0.12 s in the beginning of acceleration. The total beam loss was within the MR collimator capacity of 2 kW. The beam loss at 3-50BT was estimated to be 50 W. It was also within the 3-50BT collimator capacity of 2 kW.

The beam loss distribution in the circumference is shown in Fig. 3. The beam loss is measured with beam loss monitors [5] located at all 216 main quadrupole magnets. The gains of the 24 loss monitors (#1 ~ #20 and #213 ~ #216) including the collimator area are set to low, and the others (#21 ~ #212) have higher gain about 8 times. The beam loss is reasonably localized in the collimator area of (#6 ~ #11). Details of the collimator operation are described in Ref. [6].

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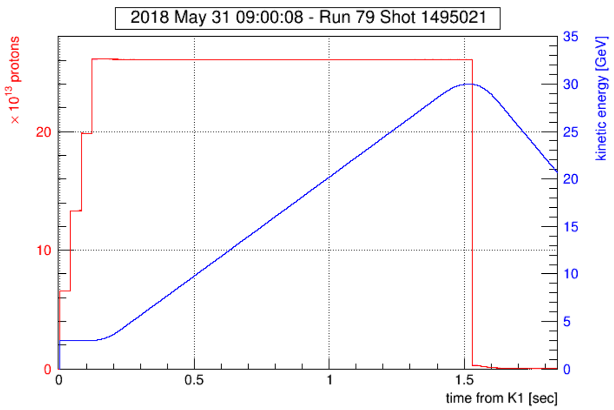

Figure 2: Beam intensity (shown in red) for a user-operation shot of the beam power of 504 kW as a function of the cycle time.

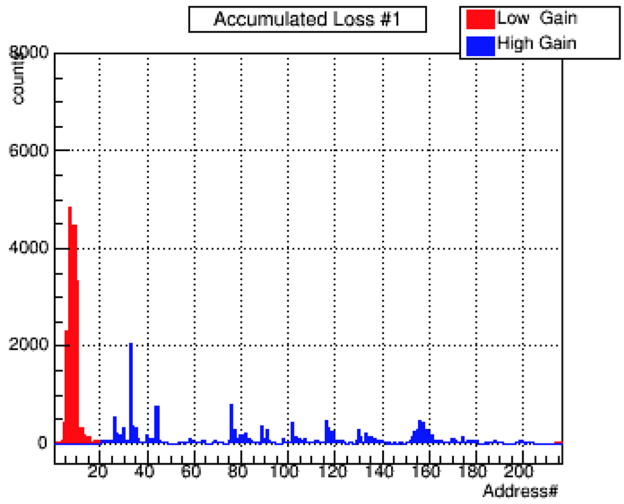

Figure 3: Beam loss distribution measured with beam loss monitors in the circumference as a function of MR address for a shot of the beam power of 504 kW.

RECENT IMPROVEMENTS

Optimization of the RCS Parameters

The large-emittance beam is preferred for the MLF target and for the minimization of the beam loss in RCS. For the transverse painting of the MLF beam, 200 π mmmrad is chosen. Because the aperture of MR is relatively smaller with respect to RCS, the parameters, such as the transverse paint, betatron tunes and chromaticity, should be optimized to make small-emittance beams. The RCS parameters for the MR beam are then different those from for MLF beam. The power supplies for the painting magnets and sextupole magnets for the chromaticity correction have been capable of switching patterns for MLF and MR beams. For the painting of the MR beam, we are able to set 50 π mmmrad.

The power supplies for the main dipole and quadrupole magnets, however, are not capable of switching patterns. We, therefore, were not able to switch the tune for MLF and MR beams. The correction quadrupole magnets (QDT) have been installed and used for the optics correction. The QDT magnets has recently been applied for switching tunes [7]. The tunes were then optimized to minimize the beam losses in both MR and RCS with QDT magnets.

RF Pattern

For the recent user operation, the fundamental rf of 155 kV and 2nd harmonic rf of 110 kV have been applied during injection period to improve the bunching factor and to reduce the space charge effects. The bunching factor was measured to be about 0.3 during injection period. In the beginning of acceleration, the fundamental rf voltage turned up to 310 kV in 60 ms and turned down to 256 kV at 0.4 s after the acceleration start until the acceleration end. The 2nd harmonic rf lasts 0.1 s in the beginning of acceleration and turned to 0 kV for the rest of acceleration.

Operation with the Working Point of (21.35, 21.43) and the Space Charge Tune Spread

The working point of MR used to be (22.40, 20.75) for the operation of less than 420 kW until 2016. For higher beam power operation, we started to apply the working point of (21.35, 21.43), because larger space charge tune spread may be afforded there from the structure resonances.

The tune spread was estimated for the beam power of 500 kW using the particle tracking simulation program SCTR [8], which takes the space charge effects into account. The number of ppb was set to 3.2×10^{13} for the cycle time of 2.48 s. The particle distributions for the input of the simulation were reproduced based on the measurements. The transverse 2σ emittance was 15π mmmrad and $19\,\pi$ mmmrad for horizontal and vertical respectively. The bunching factor was set to 0.3. Figure 4 shows the distribution of the tunes of macro particles with the simulation. The operation tune was set to (21.35, 21.43). The tune spread was estimated to be 0.4. There are some resonances of concern, such as a half integer resonance $2\nu_y = 43$ and third order resonances.

The tune shifts depending on the number of injection bunches were observed to be about 0.02 during the injection period [9]. The tunes were then shifted from the working point of the best operation. We have corrected the tune shift and reduced the beam loss accordingly.

Instability Suppression

The chromaticity pattern in the cycle time was optimized to minimize the beam loss. To suppress instabilities, the chromaticity is kept to be negative, typically −7 during injection. If the chromaticity is too small in negative value, instabilities may be observed causing beam losses. If the chromaticity is too large in negative value, we may observe beam losses those are probably due to chromatic tune spread. The optimization is iterated after the change of the beam intensity and parameters of following feedback systems.

To suppress transverse oscillations, the intra-bunch feedback system is applied during injection and in the beginning of acceleration [10]. The system consists of stripline BPM's which have wide frequency response, a signal processing circuit and stripline kickers with the bandwidth of 100 kHz ~ 100 MHz. BPM signals are sampled at the rate of 64th harmonic of the RF frequency. The signal processing circuit extracts the betatron oscillation signals on each slice and feedbacks kick signals for each slice. The system has been applied effectively during injection and up to 0.12 s after the acceleration start.

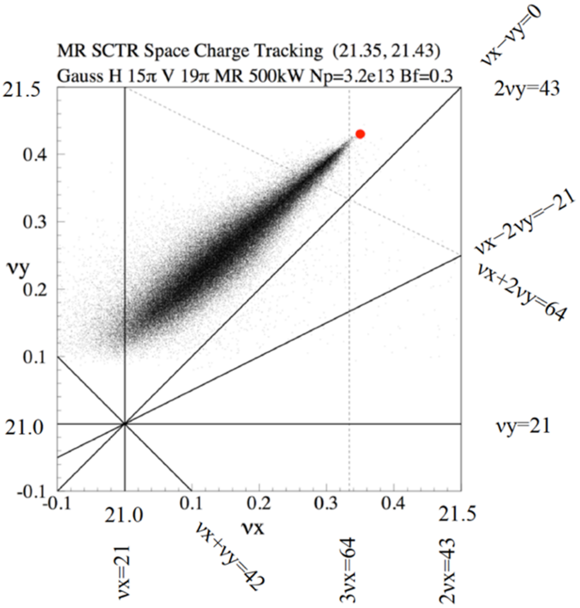

Figure 4: Space charge tune spread and resonances of concern.

Optics Measurement and Correction

We have recovered the effective physical aperture by corrections of the optics and closed orbit distortion (COD). The stripline kickers and the power amplifiers of the intra-bunch feedback system are used for beta measurement during injection and up to 0.37 s after the acceleration start. The kickers are to excite the betatron oscillation. The amplitudes of the oscillation are then measured with all the BPM's. The square root of beta should be scaled to the oscillation amplitude. The dispersion function is derived from the COD for the momentum deviation of $|\delta| < 1.3\%$. The betatron tune during injection and acceleration is measured from the frequency of the betatron oscillation that is induced by the kickers. The results of beta, dispersion and tune are corrected to what we intend to set by adjusting the currents of 11 quadrupole magnet families.

Half Integer Resonance Correction

The FX septum magnets make undesirable quadrupole fields for circulating beams with the leak fields. They were measured for all 8 FX septum magnets. The sum of the strength K1 corresponded to 3% of a main quadrupole magnet. Correction currents for the trim coils of three quadrupole magnets near the FX septum magnets were calculated. The correction has been applied and optics were measured at (21.35, 21.45) near the half integer resonance of $2\nu_y = 43$. Improvement of the beta modulation was then observed with the correction.

Third Order Resonance Corrections with Trim Coils of Sextupole Magnets

Third order resonances of $\nu_x + 2\nu_y = 64$ and $3\nu_x = 64$ have been corrected with trim coils of four sextupole magnets. The current setting of trim coils of two sextupole magnets was optimized to recover the beam survival for low intensity beams when the tune was set (21.24, 21.38) on the 3rd order resonance of $\nu_x + 2\nu_y = 64$. The amplitude of the resonance strength $G_{1,2,64}$ expressed by Eq. (1) was then measured to be 0.076.

$$G_{1,2,64} = \frac{\sqrt{2}}{8\pi}\beta_x^{1/2}\beta_y k_2 \exp[i(\phi_x + 2\phi_y)] \qquad (1)$$

The same procedure was repeated when the tune was set (21.33, 21.41) on the 3rd order resonance of $3\nu_x = 64$. The amplitude of the resonance strength $G_{3,0,64}$ expressed by Eq. (2) was also measured to be 0.055.

$$G_{3,0,64} = \frac{\sqrt{2}}{24\pi}\beta_x^{3/2} k_2 \exp[i(3\phi_x)] \qquad (2)$$

Trim coils of four sextupole magnets were used to correct both of $\nu_x + 2\nu_y = 64$ and $3\nu_x = 64$. A solution was solved for a simultaneous equation to reproduce the two resonance strengths of $G_{1,2,64}$ and $G_{3,0,64}$ in the complex planes. It was applied for the high intensity operation and the beam loss was improved. Further optimization was performed with high intensity beams to reduce the beam losses.

Longitudinal Coupled Bunch Instability

Longitudinal dipole oscillations have been observed during acceleration for the beam power of 480 kW or more (Fig. 5). The node analysis indicated that the beam loading of rf cavities was a possible cause [11]. A feedback system to damp the oscillation is being made and tested with low-power beams. The application to high-power beams are in preparation.

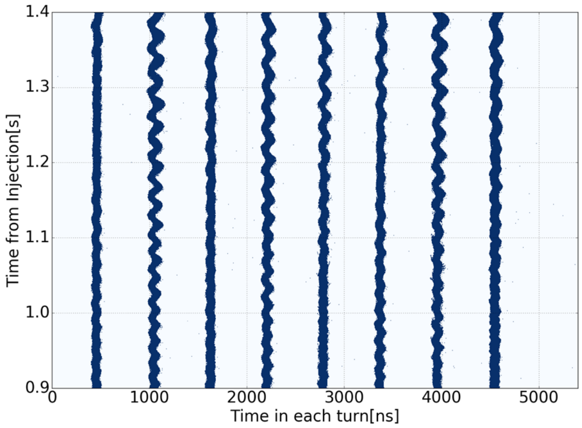

Figure 5: Wave form with the wall current monitor for the beam of 480 kW.

UPGRADE PLAN

Concepts

We plan to make the cycle time faster from 2.48 s to 1.32 s to achieve the original design beam power of 750 kW. The required number of accelerated protons is 2.1×10^{14} ppp which we have already achieved. Further upgrade has been promoted to the beam power of 1.3 MW for the CP violation search in the neutrino oscillation processes. The plan is to make the cycle time faster to 1.16 s and the number of the accelerated protons is to be increased to 3.3×10^{14} ppp. Because the accelerated protons of 2.6×10^{14} ppp has been achieved, about 30% of the intensity upgrade is required.

Hardware Upgrade Plan

For the faster cycling of 1.32 s, the magnet power supplies, rf system, injection and extraction devices are being upgraded. The upgrade will be done by JFY 2021.

The electric power supplier does not allow a large power variation of more than 100 MVA that is estimated with the present scheme of main magnet power supplies. Therefore, the energy recovery scheme has been chosen with bank capacitors [12]. Three new buildings were constructed for the power supplies. A new bending magnet power supply was installed in one of the building and being tested.

The rf cavities are also being upgraded for the faster cycling [13]. For the new target of 1.3 MW, the rf anode current power supplies should be upgraded for the beam loading compensation.

Additional collimators are being considered to upgrade for the total power capability of 3.5 kW [6]. The kicker magnets for injection and extraction are being improved and the septum magnets for injection [14] and extraction [15] are upgraded for the faster cycling.

Simulation Studies for the Upgrade Plan

Transverse profiles of beams from RCS have been measured with multi-ribbon profile monitors (MRPM) at 3-50BT for the intensity of up to 3.5×10^{13} ppb. Based on the measurement, both horizontal and vertical profiles for the simulations were set to be Gaussian distributions with 2σ emittances of 16 π mmmrad for beams of 3×10^{13} ppb which was 470 kW equivalent with the cycle of 2.48 s. Emittances of 2σ for both horizontal and vertical distributions were set to be 24 π mmmrad for beams of 4×10^{13} ppb which is 1.3 MW equivalent with the cycle of 1.16 s.

The beam survivals for both intensities were estimated with the space charge simulation program SCTR. The simulation result was compared with the measurement for the beam intensity of 470 kW equivalent as in Fig. 6. The simulation result of 470 kW equivalent beam with magnet errors are in good agreement with the measurement. The simulation indicated that the beam of 1.3 MW equivalent would be lost more than 5%, which would not be acceptable for the operation.

The simulation study indicated that the present working point of (21.35, 20.45) was affected by the structure resonances of $\nu_x - 2\nu_y = -21$ and $2\nu_x - 2\nu_y = 0$. Figure 7 shows footprints of 1000 turns of ten test particles for the horizontal and vertical actions of the betatron motions with SCTR. Values of 2Jx+Jy of some test particles were approximately invariants, which indicated the coupling resonance of $\nu_x - 2\nu_y = -21$. Values of Jx+Jy of some other test particles were approximately invariants, which indicated the coupling resonance of $2\nu_x - 2\nu_y = 0$. Because the aperture of MR is limited with the collimator of typically 60 π mmmrad, any coupling of horizontal and vertical motions would result in beam losses. We would then search for a working point which not affected by the structure resonances.

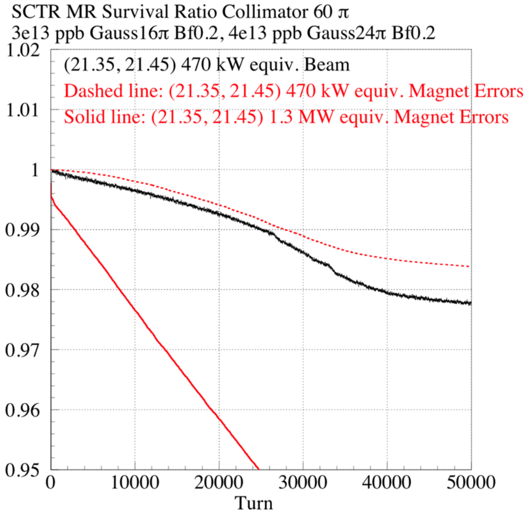

Figure 6: The measured beam survival for 1-batch beam of 470 kW equivalent (black line), simulation results of 470 kW equivalent beam (red dashed line) and simulation results of 1.3 MW equivalent beam (red solid line) for the working point of (21.35, 20.45). Simulation results with magnetic field errors and magnet alignment errors are shown.

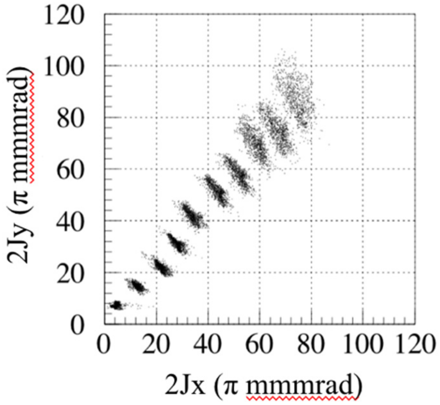

Figure 7: Simulation results of footprints of 1000 turns of ten test particles for the horizontal and vertical actions with SCTR.

Possibilities are being explored with the operation at the working point of (21.40, 20.45), because no low order structure resonances are close to the point (Fig. 8). There is a 4th order structure resonance of $4\nu_y = 81$. It, however, should be corrected with the octupole magnets. There is also a 6th order structure resonance $2\nu_x - 4\nu_y = -39$. The effect to the beam survival, however, seemed to be small from the simulation. The simulation results are shown in Fig. 9. The simulation without magnet errors indicated that the beam of 1.3 MW equivalent would be lost about 2%, which would be acceptable for the operation. Because the simulation result with the magnet errors indicated worse survival, corrections of non-structure resonances, such as $\nu_x - \nu_y = 1$, should be necessary for the reduction of beam losses.

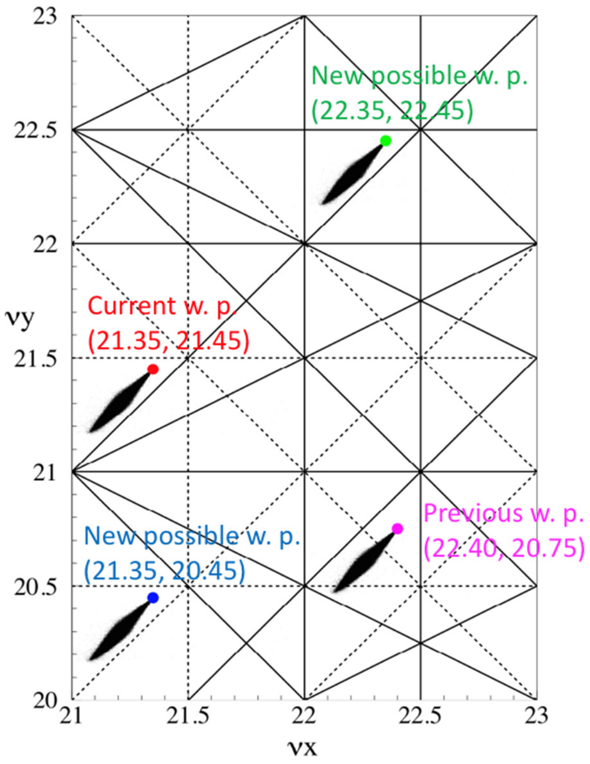

Figure 8: Structure resonances of up to third order (solid lines) and non-structure resonances of half integer and linear coupling resonances (dashed lines). Space charge tune spread shown for the working points of (22.40, 20.75), (21.35, 21.45), (21.35, 20.45) and (22.35, 22.45) for the beam power of 380 kW.

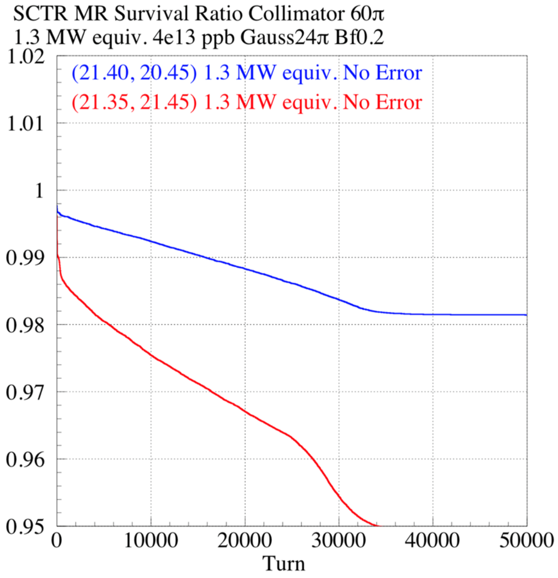

Figure 9: Simulation results of the beam survivals of 1.3 MW equivalent beam for the working point of (21.35, 21.45) (red line) and simulation results for the working point of (21.40, 20.45) (blue line). Simulation results without magnetic field errors and magnet alignment errors are shown.

SUMMARY

J-PARC is a high-power proton accelerator facility increasing the beam power step by step toward the design values. MR has recently delivered beams of the power of up to 500 kW with 2.6×10^{14} ppp and the cycle time of 2.48 s for the neutrino oscillation experiment. The beam loss was observed to be 700 W mostly localized at the collimator section. Recent improvements include the 2nd harmonic rf operation to reduce the space charge effect with a larger bunching factor and corrections of resonances near the operation setting of the betatron tune. We plan to achieve the target beam power of 750 kW by making the cycle time faster to 1.32 s with new power supplies of main magnets, rf upgrade and improvement of injection and extraction devices. Further upgrade plan is promoted for the beam power of 1.3 MW with the faster cycling of 1.16 s and intensity upgrade.

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