STATUS AND FUTURE UPGRADE OF J-PARC ACCELERATORS

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Abstract

The linac energy reached to 400 MeV as a design value and also a beam current was upgraded to 50 mA by replacing a new ion source. At the 3 GeV synchrotron, a high power beam of 8.41×10^{13} protons per pulse was demonstrated, which was equivalent to 1 MW when the repetition would be 25 Hz. At the main ring, beam loss was reduced by suppression of transverse instabilities and so on. The beam power for both the neutrino experiment and hadron experimental facility is increasing to reduce beam loss. J-PARC accelerators each have their own upgrade plan to increase beam power. The progress and future plan of J-PARC accelerators are reported in this paper.

INTRODUCTION

The J-PARC facilities consist of a linac, a 3 GeV Rapid Cycling Synchrotron (RCS), a Main ring Synchrotron (MR) and three experimental facilities (Material and Life Science Facility; MLF, Hadron Experimental Facility; HD, and Neutrino Facility; NU). Construction of a Transmutation Experimental Facility (TEF) will be planned in phase-II in near future (seen in Fig. 1). The goal of the J-PARC project in phase-I is to deliver a 1MW beam power from the RCS and a 0.75 MW beam from the MR [1]. The linac started beam commissioning in 2006 at an energy of 181 MeV. To achieve the goal, a step-by-step approach has been taken; energy of the linac was upgrade from 181 MeV to 400 MeV, and then, peak current was upgrade from 30 mA to 50 mA. The linac energy was upgrade from 181 MeV to 400 MeV by adding new accelerator cavities (ACS, Annular-ring coupled Structure linac), and also the linac beam current was upgraded from 30 to 50 mA by replacing a new ion source and a radio frequency quadrupole linac [2]. The RCS was beam commissioned in 2007 [3] and started the user program in December 2008 with an output beam power of 4 kW. Since then, the output beam power has been steadily increasing by beam tuning and hardware improvements [4-6]. Figure 2 shows a history of the output beam power to the MLF from the RCS. The RCS has successfully achieved high intensity beam trials up to 540 kW equivalent beam in the case of 181 MeV beam injection from the linac (seen in Fig. 2). And also 550 kW equivalent beam power test was successfully with 400 MeV beam injection after linac upgrade. The study produced a beam intensity of 8.41×10^{13} protons during short time, an intensity equivalent to 1.01 MW operation on 10th January 2015 [7]. Beam power at the MLF for user operation has been increased to 500 kW. Figure 3 shows the history of the output beam power from the MR to the HD with slow extraction and to the NU with fast

extraction. There are two long interval in this figure, one is due to big earthquake and the other is due to the hadron hall incident. The MR beam power is increasing since Dec. 23, 2008 and it becomes 42 kW for the HD and 390 kW for NU in this year.
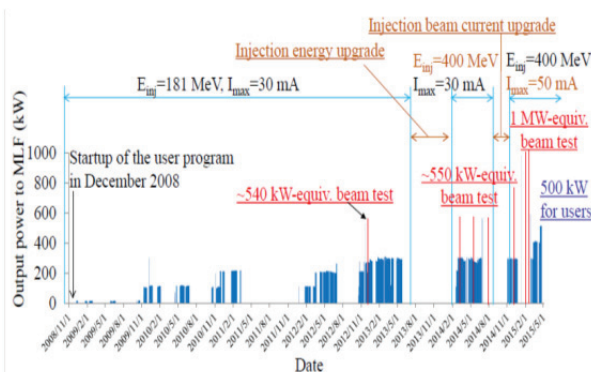

Figure 1: Layout of J-PARC facilities.

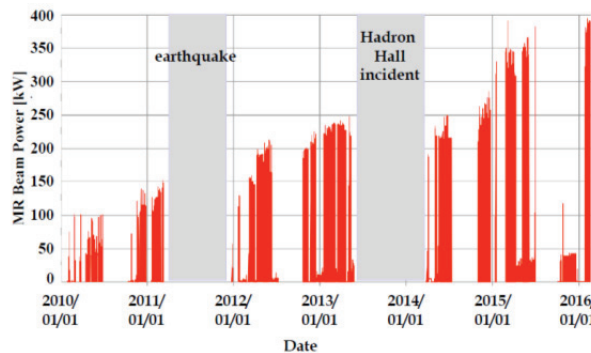Figure 2: History of the output beam power to the MLF from the RCS.

Figure 3: History of the output beam power from the MR.

STATUS OF ACCELERATORS

The linac energy was upgrade from 181 MeV to 400 MeV by adding new accelerator cavities (ACS, Annular-ring coupled Structure linac), and also the linac beam current was upgraded from 30 to 50 mA by replacing a new ion source and a radio frequency quadrupole linac. At the 3 GeV synchrotron, injection bump magnet power supply system was modified and the bump orbit was stabilized. A high power beam of 8.41×10^{13} protons per pulse was demonstrated at 3 GeV, which was equivalent to 1 MW when the repetition would be 25 Hz. After these upgrade and improvements, beam power at the Materials and Life science experimental Facility (MLF) for user operation was increased from 300 to 500 kW. At the main ring, beam loss was reduced by suppression of transverse instabilities and so on. The beam power for the neutrino experiment was increased to 395 kW, and the beam power was increased to 42 kW for hadron experiment as of December.

Linac

The linac was operated successfully with high availability for this one year and many of the past problems have been resolved. User operation was regularly held at 30 and 40 mA with reasonable number of trips. All specifications have been achieved. Figure 4 shows operation history of ion source beam current for this one year. This has demonstrated up to 60 mA beam current. Continuous operation of 1,100 hours at 33mA and 1,004 hours at 45mA were achieved without any significant issues.

Figure 4: Ion source beam current for this one year.

Linac beam studies have been continued to clarify problems, especially mitigation of beam losses. Beam losses could be reduced by increasing components aperture and by changing materials along the line.

RCS

Stable user operation has been performing with beam power of 500kW for the MLF and of 600kW equivalent beam for the MR. It is unfortunate that the routine output beam power form the RCS is now limited to 200kW for the MLF due to a trouble of the neutron production target.

The study produced a beam intensity of 8.41×10^{13} protons during short time, an intensity equivalent to 1.01 MW operation, however in that time, the beam losses observed for the 944 kW and 1010 kW equivalent beams (see in figure 5 (a)). These losses could be interpreted as longitudinal beam loss arising from a distortion of the rf bucket caused by the beam loading effect [8]. Such beam particles suffered from large momentum excursion and most of them were lost in the high dispersion area, not at the collimator section located in the dispersion-free section. This type of longitudinal beam loss had to be caused by beam loading compensation, but then the anode power supply in the rf system had no enough margin to complete sufficient beam loading compensation for such a high power beam. Since the anode power supplies were upgraded for summer maintenance period in 2015, the longitudinal beam loss was well mitigated as expected by sufficient beam loading compensation (see in Fig. 5 (b)).

Figure 5: Beam loss monitor signals at high dispersion area (a) before and (b) after rf power supply upgrade in the case of high power beam operation. Red line shows beam loss signal in the case of 8.41×10^{13} particles per pulse, and blue line is 7.86×10^{13} particles per pulse.

Since beam loss other than foil scattering beam loss has been well minimized, thus the next subject is to further reduce the foil scattering beam loss. To realize this loss reduction, beam commissioning has been performed. The detail is described in ref. [9]. Figure 6 shows an average number of foil hits per particle during beam injection for several kinds of beam injection conditions in the RCS. In the case of 500kW routine beam operation with ID3 in fig. 6, in that time the average number of foil hits was 12, the residual radiation level near the charge exchange foil was about 6.5 mSv/h on the chamber surface, which was sufficiently within the acceptable level. Since we could realize beam operation with ID4, the residual radiation level could be expected at the same level as the present value (~7.6 mSv/h on the chamber surface) even for the

1MW routine operation. RCS beam commissioning is making steady progress toward realizing the routine 1MW design beam operation.
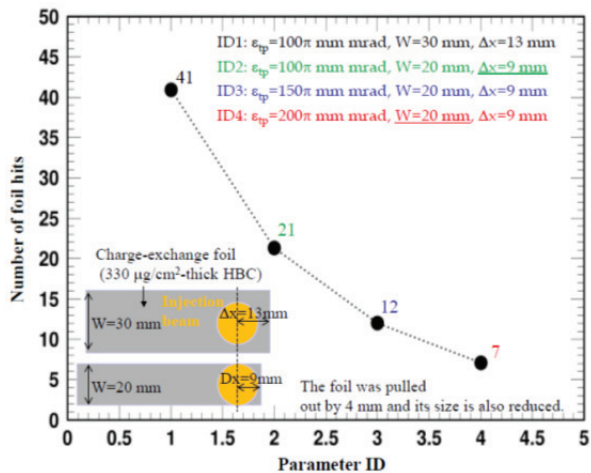

Figure 6: Average number of foil-hits per particle during beam injection for several kinds of beam injection conditions of the RCS.

MR

Typical operation status for fast extraction is summarized in Table 1. Beam power is 395 kW with 2.48 s repetition (injection; 0.14s, acceleration; 1.4s and recovery; 0.94s then total; 2.48s). Beam loss power in the ring is about 940W in total of injection and acceleration. These losses are localized at collimator area. The collimator aperture are 60-70 πmm-mrad for both horizontal and vertical. Residual radioactivity measured 4 hours after routine operation was about 2 mSv/h on surface of vacuum chamber in the fast extraction area. To reduce this loss new quadrupole magnets with larger aperture are under construction.

Beam loss at beam transport line (3-50BT) is less than 100W at the collimator whose limit is 2kW.

Table 1: Summary of the MR Operation Status for Fast Extraction

Beam power	395kW
Repetition	2.48s
Beam loss during injection period	191W
Beam loss in the beginning of acceleration	746W
Beam loss at beam transport line (3-50BT)	<100W

Slow extraction operation was resumed on April 9 in 2015 and user operation was started from April 24 since the hadron hall incident. Figure 7 shows the MR beam power to the HD for this one year. Beam power has been increased from 23 kW to 42 kW. Current hadron target has the beam power limit of 50 kW. Beam power of

42 kW has been achieved for HD user operation with extraction efficiency of 99.5 % and spill duty of 42 %. These values have been reached with fine tunings of extraction efficiency, faster cycling from 6s to 5.52 s, RF phase offset injection and additional transverse rf newly applied.
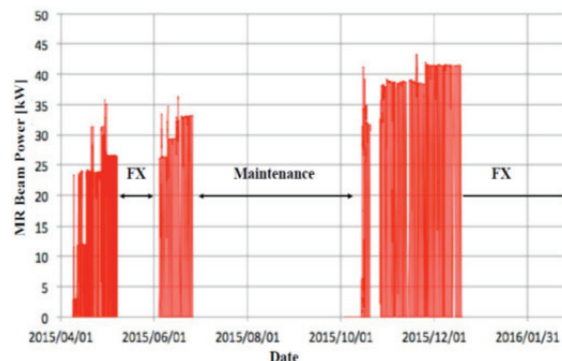
Figure 7: MR beam power to Hadron Facility for this one year.

UPGRADE OF ACCELERATORS

Beam power upgrade of the RCS and the MR will be planed and also construction of a Transmutation Experimental Facility (TEF) will be planned in phase-II in near future.

Linac

The linac is performing remarkably well and has demonstrated the capability to supply beam at the nominal level of performance (400 MeV, 50 mA, 500 μs at 25 Hz) and is hence ready to contribute to running the synchrotrons at their nominal power (1 MW for the RCS and 750 kW for the MR). To reach 1.5 MW beam power from the RCS, the plan is to increase by 20% both beam current and pulse length. This implies optimization of the LLRF for operating with some klystrons at 0.85 of saturated power. Otherwise only some minor cooling upgrade will be sufficient.

The TEF used for 400 MeV beam with 25Hz from the linac. To realize this operation, a repetition of linac will be upgrade from 25Hz to 50Hz [10]. Figure 8 shows typical combinations of beam current waveforms and pulse-BM excitation pattern during parallel operation of both the RCS and the TEF. Required beam power of the TEF is 250 kW. Feeding the ADS with beam at 25 Hz requires pulsing the linac at 50 Hz, which is significantly more demanding. Beyond the LLRF optimization, additional developments are necessary for the ion source to reduce emittances and for the MEBT-1 scrapers to make them more resistant. Significant investments should also be made in the HVDC power supplies and in the cooling systems to double its capacity.

Preliminary investigations were conducted, using beam simulations based on 10% larger emittance at exit of the RFQ with 60 mA compared to 50 mA. Beam losses are identified at multiple locations (DTL entrance, ACS and arc) but their minimization to a tolerable level seems within reach. The possibility of the linac upgrade is summarized in Table 2.
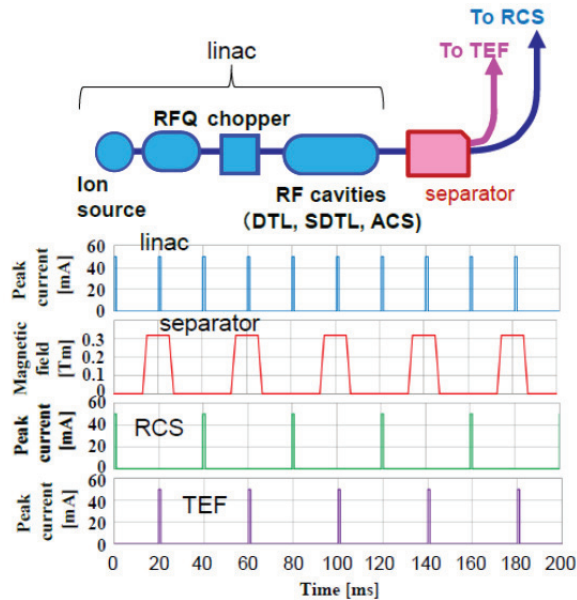

Figure 8: Typical combinations of beam current waveforms and pulse-BM excitation pattern during parallel operation of both the RCS and the TEF. (a): The LINAC operates at the repetition rate of 50 Hz. (b): The pulse-BM uses a 25 Hz excitation pattern with a trapezoidal waveform. (c): Thus, during the flat bottom of the excitation pattern, the LINAC beam passes through the pulse-BM and goes straight through the L3BT line. (d): During the flat top of the excitation pattern, the LINAC beam is deflected toward the LTBT beam line.

RCS

The RCS has successfully achieved high intensity beam trials up to 540 kW equivalent beam in the case of 181 MeV beam injection (seen in Fig. 2). This is corresponds to 1.6MW for 400MeV injection in terms of the Lasslett tune shift. The RCS beam power could reach 1.5 MW by injecting 60mA for 600 µs. This is high enough to present challenges on several fronts, yet still achievable. The primary issues have been identified as follows; 1) the anode current in the rf systems, 2) the 100µs longer pulse length of the shift bump and painting injection magnets, 3) the extraction kicker impedance [11], and 4) increased activation in the vicinity of the injection stripper foil. The scenario beyond 1MW operation in the RCS is summarized in table 3.

MR

The MR upgrade scenario and plan is shown in fig. 9. The basic upgrade plan of the MR is to increase the delivered power by the FX cycle up to 750 kW, by increasing the repetition rate from 2.48 s cycle to1.3 s cycle using new power supplies while keeping beam losses under control. The SX cycle should provide a 100 kW beam after 2019.

This reducing the magnet cycle length for the FX implies the renovation of the power converters of the 21 different magnet families. With the technology used for the existing power converters, this faster cycle would require a maximum power variation induced on the electrical grid of 140 MW, exceeding the maximum variation tolerated by the electrical power company. For this reason, the new power converters has been developed with full energy recovery based on capacitor banks. Production of the 1st power supply for one quadrupole magnet family has been started and its install is scheduled in this summer [12].

Table 2: Summary of Possibility of Linac Upgrade

Peak current [mA]	Pulse length [ms]	RCS beam power [MW]	TEF beam power [kW]*	Ion source	Chopper : ON/OFF	RFQ DTL SDTL ACS	High power RF	Low level RF	Beam loss	Utility (Cooling water)
50	0.5	1.0	133/250	◎	◎/◎	◎	○	○	◎	○
60	0.5	1.2	160/(300)	◎	△/◎	○	△	○	○	○
50	0.6	1.2	160/(300)	◎	△/◎	○	△	○	○	○
60	0.6	1.44	(320/360)	△	△/◎	○	△	○	○	○
60	0.7	1.7	(226/425)	△	×/◎	△	△	○	○	○
70	0.7	2.0	(226/500)	△	×/◎	△	×	○	△	○
100	0.5	2.0	(226/500)	×	×/◎	×	×	×	×	○

*Beam power of TEF with chopper ON/OFF. ** Required maximum beam power of TEF is 250 kW.

◎ No issues with present system or configuration. ○ No big issues but needs studies and may require minor modifications. △ Issues but within reach, needs significant modifications. × Hard to reach, require major modifications.

Table 3: Summary of Scenario Beyond 1 MW Operation in the RCS

Injection Energy [MeV]	Peak current [mA]	Pulse length [ms]	Particle per pulse (x10^{13})	Beam power [MW]	Space charge limits	Injection pulse magnets	FR system	Foil	Beam Instability
400	50	0.5	8.33	1.0	◎	◎	○	○	◎
400	60	0.5	10.0	1.2	◎	○	△	○	○
400	50	0.6	10.0	1.2	◎	○	△	○	○
400	60	0.6	12.0	1.44	○	○	×	△	△
400	60	0.7	14.0	1.7	△	○	×	×	×
400	70	0.7	16.3	2.0	△	○	×	×	×
400	100	0.5	16.3	2.0	△	◎	×	×	×

◎ No issues with present system or configuration. ○ No big issues but needs studies and may require minor modifications. △ Issues but within reach, needs significant modifications. × Hard to reach, require major modifications.

Several upgrades and improvements are required for the shorter 1.3 second cycle period. A new injection septum magnet and power supply have been built and installation is planned for this summer [13]. For the extraction septa and kickers, extensive replacements are planned for the fast extraction system. New magnets and new power supplies are being built and tested [14]. Installation of second harmonic rf cavities with higher field gradient using magnetic alloy cores, FT3L than present ones are planed [15].

Figure 9: MR upgrade scenario and plan.

CONCLUSION

The J-PARC accelerators have now approached their design intensities. The RCS has demonstrated 1 MW equivalent beam to the MLF and operated above 500 kW. The performance of 395 kW beam power from the MR for the T2K neutrino experiment and 42 kW of slow extracted beam for hadron science was also achieved.

J-PARC accelerators each have their own upgrade plan to increase beam power.

- The basic upgrade plan of the MR is to increase the delivered power by the FX cycle up to 750 kW, by increasing the repetition rate from 2.48 s cycle to 1.3 s. The SX cycle should provide a 100 kW beam after 2019.
- The RCS reaches 1.5 MW beam power by increasing 20% both beam current and pulse length of the linac.
- A repetition of linac will be upgrade from 25Hz to 50Hz to deliver a beam with 25Hz to the TEF.
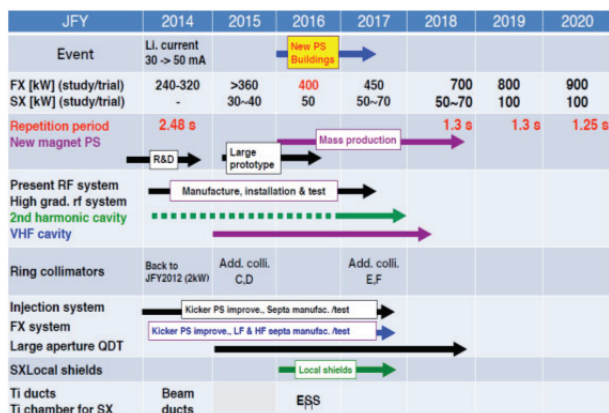
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