HIGH INTENSITY ASPECTS OF THE J-PARC FACILITY

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Abstract

Recent status of the high intensity operation of the J-PARC accelerators is presented. Improvements performed in the 2010 summer shutdown period and near future plan are also reported briefly.

INTRODUCTION

The J-PARC is a multi-purpose proton accelerator facility aiming at MW-class output beam power. The J-PARC accelerator comprises an H^- linac, a Rapid-Cycling Synchrotron (RCS), a slow-cycling Main Ring Synchrotron (MR) and related experimental facilities. The H^- beam from the linac is injected into the RCS by charge-exchange injection. The RCS provides a 3-GeV proton beam to neutron and muon targets in the Materials and Life Science Experimental Facility (MLF) at a repetition rate of 25 Hz. A part of the beam extracted from the RCS is injected into the MR. The MR accelerates the beam up to 30 GeV and delivers the beam to the hadron (HD) beam facility using a slow extraction (SX) system and to a neutrino (NU) beam line using a fast extraction (FX) system.

Figure 1 shows a panoramic view of the J-PARC site. Beam commissioning was initiated starting from the upstream accelerators, while the construction of the downstream accelerators and experimental facilities was still in progress. The components are colored in this figure to indicate the Japanese fiscal year (JFY) in which beam commissioning was initiated in the various parts of the facility.

Figure 1: Bird's eye view of the J-PARC site.

LINAC

The linac consists of an H^- ion source, RFQ, DTL and separated-type DTL. The beam energy is 181 MeV at present. The designed maximum peak current for the 181 MeV operation is 30 mA. The repetition is 25 Hz and pulse width maximum is 0.5 msec. An energy upgrade project has already been approved by the government and the energy will be increased to 400 MeV by installing a new accelerating structure, the Annular Coupled Structure linac (ACS) in the 2012 summer shutdown.

The linac beam commissioning was initiated in November 2006, and a 181 MeV beam was successfully accelerated in January 2007. Since then, the linac has been delivering beams for commissioning of the linac itself, the downstream accelerators and experimental facilities. Trip rates for the RFQ, however, unexpectedly increased in September 2008. This problem has limited the RCS beam power available for the MLF users to below 20 kW.

In March 2009, we added two ion pumps to the RFQ, one turbo molecular pump in the Low Energy Beam Transport (LEBT, the beam transport between the ion source and the RFQ), and an orifice was installed in the LEBT to reduce the gas flow from the ion source. We also performed further vacuum system improvements during the 2009 summer shutdown. The oil rotary pumps were replaced with oil-free scroll pumps. In addition, we replaced the old LEBT chamber with a new clean chamber containing a divider plate with an orifice for differential pumping. One cryopump was installed on the RFQ side and one 1500 L/s turbo molecular pump on the ion source side. In July, we performed in-situ baking for 10 days to accelerate degassing [1].

The vacuum system improvements reduced base pressure in the RFQ section to several x 10^{-7} Pa, a quarter of the pressure before the improvements. In addition, hydro-carbon components gradually decreased during rf conditioning.

In November 2009, based on the stable operation of the RFQ at 20 kW in October, we tried to increase the beam power for the MLF user operation by increasing the beam pulse length from 0.1 to 0.2 msec and peak beam current from 5 to 15 mA, thus obtaining a 6-fold increase from 20 up to 120 kW. We were able to deliver beam to MLF users without any incident. Since December 2009, the linac and the RFQ delivered the beam with a maximum pulse width of 0.5 msec, which is in accordance with the full design specifications. The results verified the restoration of the RFQ performance.

RCS

The RCS has three-fold symmetry and a circumference of 348 m. Each super-period consists of two 3-DOFO arc modules and a 3-DOFO dispersion-free straight section. The arc module has a missing bend cell, which makes a very high transition energy of 9 GeV, far beyond the extraction beam energy.

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After the improvement of the RFQ, the RCS has delivered the beam to the MLF users stably and at a beam power of 120 kW since November 2009.

Figure 2 shows experimental and simulated results of beam survival rate for various intensities and painting conditions. The data sets #1-5 are for cases without painting for beams equivalent in intensities from 60 to 300 kW, which correspond to the numbers of particles per pulse (ppp) ranging from 5.0 x 10^{12} to 2.5 x 10^{13}. The data sets #6 – 9 are for the 300 kW equivalent beam with various painting conditions as shown in Table 1. The red curves and closed circles are the results measured by DC current transformer (DCCT) and blue dotted-curves and open circles are the results of space-charge simulation [2]. In the no painting case, the particle loss greater than 7 % were observed around the injection energy for the case of the 300 kW equivalent beam (data #5). On the other hand, particle loss is reduced by the painting injection scheme. In the cases of data sets #7-9, the painting scheme is applied not only transverse but also longitudinal direction. The data sets #9 gives minimum beam loss in this study and it is about 1 % around the injection energy.

Table 1: Painting injection parameters: ε_{tp} is the transverse painting emittance, V_{2nd} is voltage ratio of the second harmonic and fundamental rf, $\Delta\phi$ is phase sweep of second harmonic rf voltage relative to the fundamental, $\Delta p/p$ is momentum offset, i.e., the rf frequency offset.

Data ID	**ε_{tp} [π mm-mrad]**	**V_{2nd} [%]**	**$\Delta\phi$ [deg]**	**$\Delta p/p$ [%]**
6	100	-	-	-
7	100	80	-80	-
8	100	80	-80	-0.1
9	100	80	-80	-0.2

On December 7, 2009, the RCS successfully demonstrated a beam delivery of larger than 300 kW at 25 Hz for one hour to the neutron production target. This was an important milestone for us. The laslett tune shift at the injection energy of 181 MeV for the 300 kW operation is equivalent to the value for an injection energy of 400 MeV and 1 MW operation, which is the RCS design goal. Therefore, the stable operation of the 300 kW beam shows that our design goal, 1 MW beam operation is reachable from the perspective of tune shift.

The 300 kW demonstration also showed that beam loss issues need to be solved before starting regular user operation. The following improvements are in progress : (1) Installation of the smaller foil (40 mm-> 15 mm in vertical) to reduce the number of foil hits during painting injection. (2) Installation of AC power supplies for sextupoles. Before 2010 summer shutdown, the sextupoles were driven by DC power supplies and chromaticity is corrected only at the injection energy. AC power supplies are necessary to reduce beam loss during acceleration.

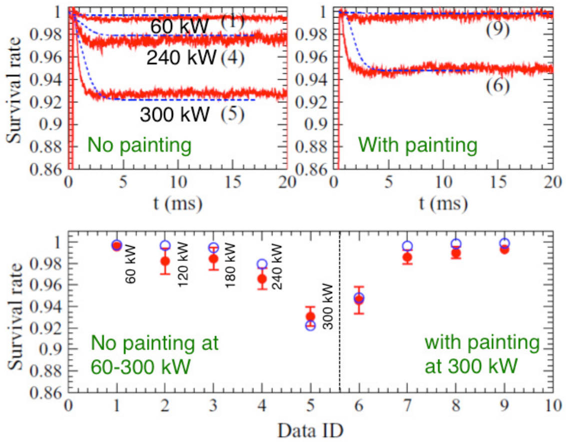

Figure 2: Experimental and simulated results for beam survival rate for various intensities and painting conditions.

MR

The layout of the MR and the experimental facilities is shown in Fig. 3. The MR has three-fold symmetry and its circumference is 1567.5 m. An arc section consists of eight 3-FODO arc modules. Each of the arc modules has a missing bend cell. The MR is the first large proton accelerator that adopts an imaginary transition energy lattice and therefore does not have a transition crossing between the injection and extraction energies. The three dispersion-free 116-m long straight sections, each of which consists of 3-FODO cells and matching sections to the arcs at the both ends, are dedicated to “injection and beam collimators”, “slow extraction”, and “rf cavities and fast extraction”.

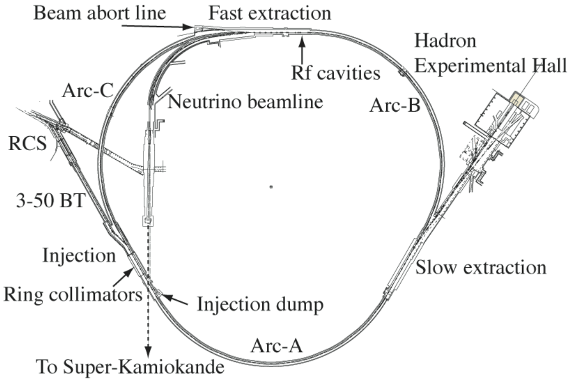

Figure 3: layout of MR and experimental facilities.

High Power Operation in Fast Extraction

The FX system is composed of five kicker magnets and six septum magnet systems. It is a bipolar system and can bend the extraction beam both inside (to the NU beamline) and outside (to abort beamline) of the ring. The beam extracted to the NU beam line is delivered to a graphite target of the T2K (Tokai-to-Kamioka) experiment, a long baseline neutrino oscillation experiment. The intense neutrino beam is sent to a large water Cherenkov detector, the Super-Kamiokande (SK), which is located 300 km away from the J-PARC site.

The T2K experiment started taking physics data in January 2010. The typical beam intensity delivered continuously to the T2K experiment was 50 ~ 70 kW until the end of June 2010. For a high power demonstration, a 100 kW beam has been delivered to the T2K experiment. Figure 4 shows the kinetic energy and circulating beam current measured by a DCCT in 100 kW operation. Two-bunch beam extracted from the RCS is injected into the MR three times. The acceleration time is 1.9 sec and the cycle time of the FX operation is 3.52 sec. The number of extracted particles is 7.5×10^{13} ppp in six bunches. The painting conditions of the RCS beam are horizontal painting of 150 π mm-mrad, V_{2nd} = 80%, $\Delta\phi$ = -100 deg. and $\Delta p/p$ = 0.2 %. At the present, the MR has no second harmonic rf system (We install one second harmonic rf system in the 2010 summer.). The applied rf voltage is 80 kV in the injection timing and increased from there to 160 kV in 100 ms. The aperture of the MR collimator is set to be 54 π mm-mrad for both the horizontal and vertical directions. Beam loss is almost localized on the collimator section during the injection time. The number of loss particles is about $\sim1.4\times10^{12}$, which is corresponding to ~190 W, while the design capability of the collimator is 450 W at the present.

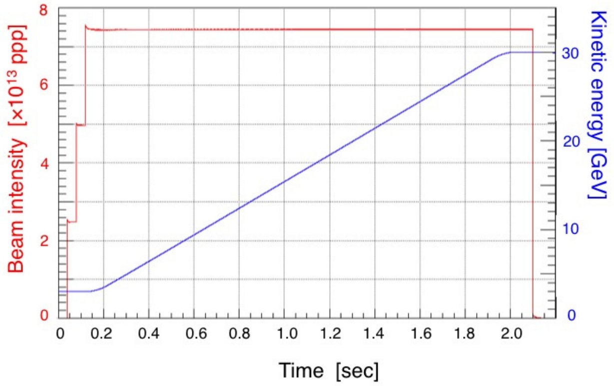

Figure 4: Intensity and kinetic energy of the 100 kW operation.

Figure 5 shows measured residual activation distribution in the 3-50 BT (beam transport line between the RCS and the MR) and the MR after three weeks continuous operation in June of 2010. In the June run, the MR delivered a 50-70 kW beam to the T2K experiment until end of the run at 7:00 am on June 26. The activation was measured by detectors "on contact" with the beam duct (red symbols in Fig. 5) and at the "one-foot distance" from the duct surface (blue symbols). The distribution of residual activation shows beam losses are mostly localized to the ring collimator section. However, there are two relatively hot areas in the arc sections, Arc-B and Arc-C. The peaks measured "on contact" in the Arc-B and Arc–C sections were ~1000 µSv/h and ~350 µSv/h, respectively. The positions correspond to peaks of dispersion function and the activation is caused by beam losses which occur just at the beginning of beam acceleration. They can be reduced by applying higher rf voltages during the acceleration start timing.

In the June run, the aperture of the 3-50 BT collimator was set relatively large, ~70 π mm-mrad, for both horizontal and vertical. The reason was that installation of an additional shield was scheduled to start in the beginning of July 2010. The activation in the 3-50 BT collimator area was therefore kept low level during the June run.

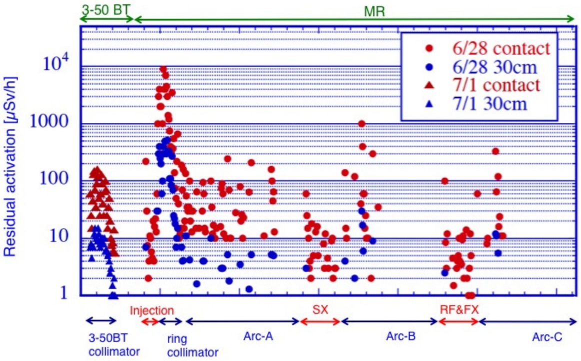

Figure 5: Residual activation after three weeks of beam delivery to the T2K experiment.

Slow Extraction

The SX system delivers the beam to the HD experimental facility. At present, three beam lines, KL, K1.8, K1.8BR are open for users of particle and nuclear physics experiments in the HD facility. So far, the maximum beam power of 2.8 kW has been delivered to HD facility.

For the SX, we have four bump magnets, two electrostatic septa, ten magnetic septa in the straight section, which is connected to the HD beam line (a beam transfer line between the MR and the HD facility). Eight sextupoles to excite third integer resonance, $3\nu x=67$, are located in the arc sections. For the SX, the horizontal tune is gradually ramped up to the resonance line by changing one of the quadrupole families, QFN, which has 48 magnets and located in the arc sections [3]. A spill feedback system, which consists of two types of quadrupoles and a Digital Signal Processor (DSP) system, was installed during the 2009 summer shutdown. The beam spill signal is fed to the DSP system, which calculates the correcting current patterns sent to the feedback quadrupoles power supplies [4].

Figure 6 shows a typical beam intensity of the SX operation for the HD facility users. After the acceleration, beam is extracted for 2 sec. The overall cycle time for the slow extraction operation is 6 sec. The smooth decay curve for the stored beam denotes stable beam extraction. The extracted beam, however, has a spike-like time structure, arising from fluctuations of the betatron tune.

These fluctuations are due to current ripples coming from the main magnet power supplies. In order to improve the spill time structure, we adopted the trim coil short method of the quadrupoles [5]. We define the duty factor of the spill as

$$Duty = \left(\int_{T1}^{T2} I(t)dt \right)^2 \Big/ \int_{T1}^{T2} dt \int_{T1}^{T2} I(t)^2 dt \; , \qquad (1)$$

where *I(t)* is the beam spill intensity, *T1* and *T2* define the time gate width. The duty factor of the beam extracted using the spill feedback system and the trim coil short is calculated to be ~11 %, while without them is 1~3 %. For further improvement of the duty factor, spill ripple reduction using transverse rf noise [6], a feed forward system to cancel the spill ripple using the trim coils are studied and adopted in the 2010 autumn run.

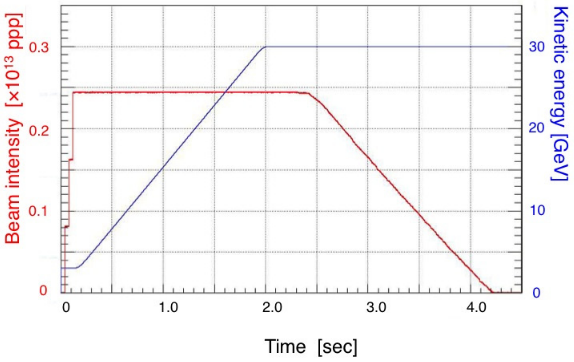

Figure 6: Intensity and kinetic energy profile of the SX operation for the HD facility users.

For the SX, one of the most critical issues is radio-activation of the components. A high extraction efficiency is required to avoid leaving residual activation which would make hands-on maintenance difficult. Using the DCCT and BLM signals, at present, the extraction efficiency is estimated to be 98.5 %. For higher extraction efficiency, a dynamic bump scheme will be adopted from the 2010 autumn run.

The residual activation in the SX section measured one week after five days of operation with a beam power 1~1.5 kW was less than 100 μSv/h on contact measurement. Our guideline is that the residual-activation maximum for the SX section should be less than ~1 mSv/h at a one foot distance.

New FX KickerMagnet System

In the 2010 summer shutdown period, all the five fast extraction kickers are replaced by newly developed ones. The old kickers have following two problems, slow rise time and a heating by the high power beam.

The rise time of the old kicker was 1.6 μs while a required rise time is less than 1 μs. That rise time limited the maximum number of circulating bunches to be six. The new kicker system has a rise time less than 1 μs. It makes possible operation with eight bunches, which is the originally designed bunch configuration.

A problem with the FX operation before the 2010 summer shutdown period was an orbit drift of the extracted beam. The orbit drift came from a kick angle drift of the extraction kickers due to heating of ferrite cores by the beam-induced field. The drift occurred during continuous operation with beam power greater than 50 kW. The horizontal orbit drift on the graphite target reached the limit tolerable, ~1 mm after 1~2 hours of continuous operation with a beam power of 65 kW. In order to reduce the beam coupling impedance, a damping resistor is attached between the coil conductors of the kicker and chamber ground. Beam induced wall current thus goes to the chamber ground via the resistor. This current opposes and cancels the magnetic fluxes in the ferrite cores. The estimated power loss in the new kicker is 210 W for 80 kW equivalent beam (1 x 10^{13} ppb x 6 bunches) while the estimated loss in the old kicker is 1.9 kW for the same intensity beam. In addition, water cooling channels were attached on the ferrite cores. This water cooling system is expected to reduce temperature rise to 20 % assuming a 1-kW power loss in the kicker.

Upgrade of Collimator Capacity

Beam loss capacity of the both 3-50 BT collimator and ring collimator sections is 0.45 kW. The capacity should be increased for an operation with the designed MW-class beam. During the 2010 summer shutdown, additional iron shields in the collimator section of 3-50 BT were installed. Figure 7 shows the 3-50 BT collimator section with newly installed gated-shape iron shields. The thickness of the shield is 0.72 m on top and 0.25 m for both sides. The shields are mounted and slide on a linear motion guide system to make maintenance work easily. The loss capacity of the 3-50 BT collimators is increased from 0.45 kW to 2 kW by the additional shields.

Figure 7: The 3-50 BT collimator section with the newly installed gate-shaped iron shields.

We are also planning to increase the shield of ring collimator section in the 2011 and 2012 summer shutdown periods. Finally, the loss capacity of the ring collimator section will be increased to 4 kW.

Improvement of Magnet Power Supplies

For increasing beam intensity, operation with a higher repetition rate of magnet power supplies is studied in the 2010 summer shutdown period. By reducing regeneration condensers of the bending magnet power supplies, the MR repetition time is shortened from 3.52 to 3.2 sec. The run in autumn of 2010, the MR will be operated with 3.2-sec cycle for the FX.

In order to reduce the current ripple, a newly designed trap-filter for reducing a rectification ripple of 600 Hz is adopted to the power supply of the QFN. The effect of the new filter on the spill ripple will be tested in the October run. If the effectiveness is confirmed using the beam, we will adopt the filters to the other power supplies.

Impedance Reduction of rf System

We have met impedance reduction problem in the Magnetic Alloy (MA) loaded rf cavities in the MR [7]. The reduction is relating with corrosion of cutting surface of the MA cores. The cooling water of the rf system is serially connected with the cooling water of the magnet system. Although the cause is now under investigation, it is supposed that there are some correlations between contamination of cupper in the cooling water and the impedance reduction. To recover the impedance, the cutting surfaces of the damaged cores are re-polished. Additionally, an R&D is in progress to coat the cutting surface by silicon rubber. In the long term, we are planning to separate the cooling water system from the magnets.

ENERGY UPGRADE OF LINAC

The linac was originally designed to accelerate the H^- beam up to 400 MeV for the RCS injection. At the present, however, the linac energy is limited to 181 MeV as a compromise due to constraints of construction budget. In the original design, the energy is increased from 181 MeV to 400 MeV by adding the ACS linac, to the existing system.

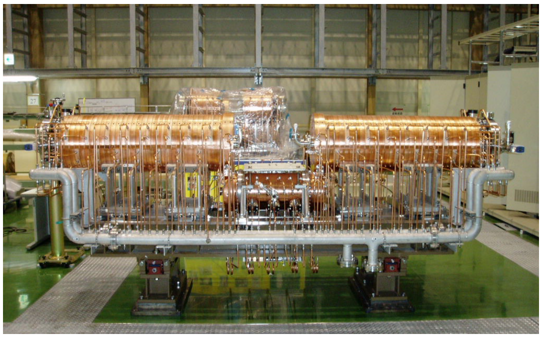

Figure 8: The lowest energy ACS accelerating module.

In the JFY 2008, the funding for the energy upgrade was approved by the government in the supplementary budget. Mass production of the major components of the ACS system has been started in March 2009 [8]. The ACS system has 21 accelerating modules, two bunchers and two debunchers. Figure 8 shows the fabricated lowest-energy accelerating module. Installation of all the ACS cavities is scheduled in the 2012 summer shutdown period. Beam commissioning of the 400 MeV linac will be started in autumn/winter of 2012.

SUMMARY

The J-PARC accelerator has started high power beam delivery to the experimental facilities. For the MLF users, 120-kW routine operation is continued and 300-kW operation for 1 hour was successfully demonstrated. For the T2K experiment, 50 - 70 kW beam was delivered by the FX. The beam delivery of 100 kW was also demonstrated. For the HD users, a beam of 2.6 kW in maximum was delivered by the SX.

During the 2010 summer shutdown, we have made various improvements of accelerator components. For the RCS, the smaller charge-exchanging foil and the AC power supplies of the sextupole was installed. For the MR, all the five FX kickers were replaced by newly developed ones having the shorter rise time less than 1 μsec. The beam loss capacity of 3-50 BT collimator section was increased from 0.45 kW to 2 kW by installing the additional iron shields.

After the 2010 summer shutdown, the J-PARC accelerators will resume beam delivery to the experimental facilities in October. The RCS will increase the beam intensity for the MLF to 160 kW in December 2010 and 200 kW in January 2011. The MR will deliver the beam intensity to the T2K greater than 100 kW. For the SX, the dynamic bump system will be adopted for achieving the extraction efficiency higher than 99 %. The continuous operation greater than 5 kW for the HD users and demonstration of 10 kW will be tried.

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