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STATUS AND BEAM POWER RAMP-UP PLANS OF THE SLOW EXTRACTION OPERATION AT J-PARC MAIN RING

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Abstract

A 30 GeV proton beam accelerated in the J-PARC Main Ring (MR) is slowly extracted by the third integer resonant extraction and delivered to the hadron experimental hall. Slow extraction from the MR has a unique characteristics that can be used to obtain a low beam loss rate. The beam has a large step size and small angular spread at the first electrostatic septum (ESS), enabling a low hit rate of the beam. A dynamic bump scheme has been applied to reduce the beam loss. We have attained 51 kW operation at 5.2s cycle in the latest physics run. A suppression of instability during debunch process is also essential as well as low beam loss tunings. Plans toward a beam power ramp-up will be reported.

INTRODUCTION

A high-intensity proton beam accelerated in the J-PARC main ring (MR) is slowly extracted by the third integer resonant extraction and delivered to the hadron experimental hall to drive various nuclear and particle physics experiments. Most of the proposed experiments are best performed using a coasting beam without an RF structure and a uniform beam intensity during the extraction time. One of the critical issues in slow extraction (SX) of a high intensity proton beam is an inevitable beam loss caused by the extraction process at septum devices. Slow extraction from the J-PARC MR has unique characteristics that can be used to obtain a low beam loss rate as described in next section [1]. In the actual beam tunings, septa positions of the ESSs and the first and second magnetic septa (SMS1 and SMS2) must be finely adjusted to minimize the beam loss as well as the dynamic bump orbit tuning. The beam loss is sensitive to the horizontal chromaticity, which has a strong nonlinearity for momentum and is set to minimize the beam loss rate [1]. We encountered several high intensity issues. The horizontal and vertical chromaticities are set to negative values to suppress a transverse instability during injection, acceleration and debunching period. The horizontal chromaticity is set near zero just before extraction starts. At beam powers above 30 kW, we observed a transverse beam instability during debunching associated with a vacuum pressure rise. This instability increases the beam loss in SX. To suppress this instability, the beam from the RCS is injected into the RF bucket with a phase offset [2]. In this paper, J-PARC slow extraction schemes, a current status and future plans toward a higher beam power for 30 GeV slow extraction are reported. A preliminary result for a 8 GeV slow extraction test for the muon to electron conversion search experiment (COMET) will be also briefly presented.

J-PARC SLOW EXTRACTION SCHEME

Efficient Slow Extraction

The characteristics of slow extraction in the J-PARC MR can be summarized as follows [1]; (1) We have two ESSs. The first ESS (ESS1) is located in the section between adjacent focusing quadrupole magnets as shown in Fig. 1. This section has the highest β_x (40 m) in the ring. A large step size Δ at ESS1 can be achieved without causing any primary beam loss in other places, where the step size Δ is shown in Fig. 2. The large Δ reduces the hit rate of the beam on the septum of ESS. (2) The long straight section, where the ESSs are located, is dispersion-free. If the horizontal chromaticity is set to a small enough value during the extraction, the momentum dependence of the separatrix can be neglected. (3) When a bump orbit, which shifts the circulating beam toward the septum of the ESS1, is constant during extraction, the outgoing arm of the separatrix has different angles ($x' = dx/ds$) at the septum position at the start and end of extraction, as shown in the upper part of Fig. 2 (fixed bump scheme). On the other hand, this angular difference is sufficiently small if the orbit bump is changed during the extraction, as shown in the lower part of Fig. 2 (dynamic bump scheme). This scheme reduces the hit rate from the sides of the ESS and downstream septa.

Spill Regulations

The time structure of the extracted beam intensity (beam spill) is controlled by the following quadrupole magnets: two extraction-pattern quadrupole magnets (EQs) and one ripple-

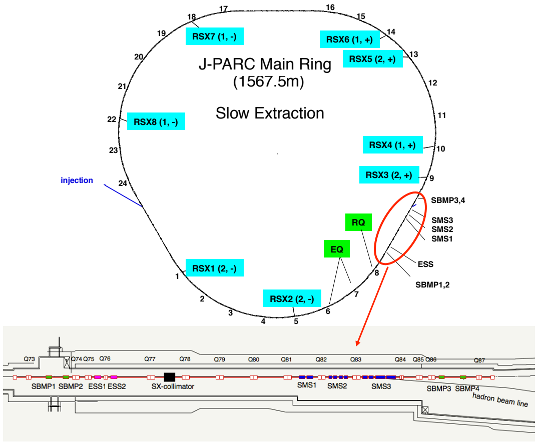

Figure 1: Layout of J-PARC slow extraction devices.

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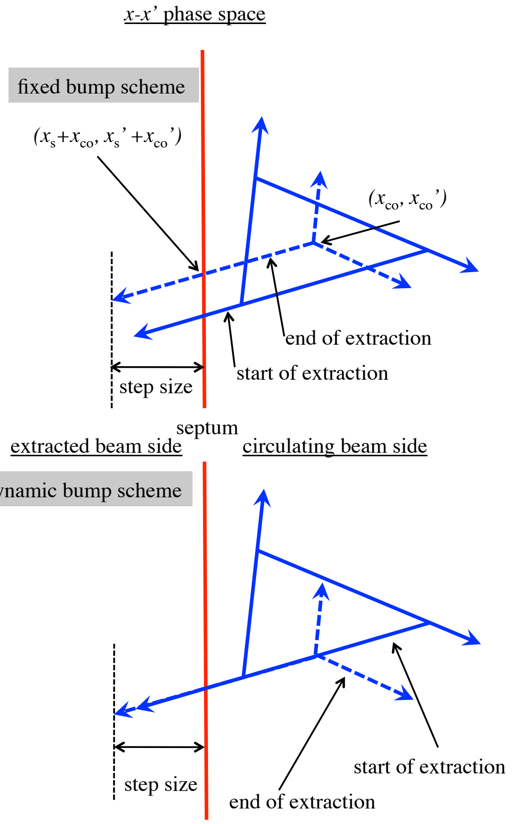

Figure 2: Fixed and dynamic bump scheme.

compensation quadrupole magnet (RQ). These quadrupole magnets are located in the arc section upstream of the LSS for slow extraction, as shown in Fig. 1. The EQs usually produce a beam spill with a flat shape by modulating the tune ramping speed. The RQ compensates for tune ripples originating in the main quadrupole and bending power supplies. A feedback control unit based on a Digital Signal Processor (DSP) has signal input ports for the gate logic, spill intensity and circulating beam intensity. The spill intensity monitor is a photomultiplier tube with a plastic scintillator placed near a 100-μm-thick aluminum foil separating the upstream and downstream vacuums of the hadron beam line. A typical EQ current is 50~100 A. A horizontal tune shift is 0.01 at 100 A. To improve the spill structure further, we have applied two transverse RF fields to the circulating beam during slow extraction [1]. The transverse RF fields are generated by two sets of horizontal strip-line kickers.

HIGH INTENSITY PHENOMENA AND MITIGATIONS

RF Beam Loading Compensation

The beam is debunched by turning off the RF voltage at the beginning of the flat top. The momentum shift (deceleration) during debunch process was observed in an early stage of the beam commissioning. The momentum shift was increased with the beam power up, and achieved to −1% level at 10 kW beam. This large momentum shift drastically increased the beam loss in the slow extraction. The momentum shift is mainly caused by the beam loading of the RF cavities. The beam loading of the RF cavities has been compensated by a feedforward technique [3]. At 51 kW beam power, the momentum shift is suppressed to −0.3% level.

Tunes, Chromaticity Adjust and Bunch by Bunch Feedback

In the beam commissioning for the beam power-up, a coherent transverse beam oscillation (beam instability) was observed. A week chromaticity correction mitigates the instability. However the chromatic tune spread induces a beam loss by betatron resonance. The chromaticities and tunes have been carefully chosen from the flat bottom to the flat top. The horizontal and vertical chromaticities are set to −3.5 and −2.0 at the before acceleration and then to −5.0 and −7.1 at the top energy, respectively. Before the start of the slow extraction, the horizontal chormaticity is set near zero to make an achromatic condition. Horizontal and vertical bunch by bunch feedback using strip line kickers has been introduced to suppress the instability during the flat bottom.

RF Phase Offset

We encountered the beam loss increase in the slow extraction around 30 kW beam power [2]. This involves a vacuum pressure rise in the whole ring. The electron cloud has been observed during the debunch timing. The wall current monitor or the fast CT during the debunch process shows an indication that longitudinal coupled bunch instability occurred The high frequency components (30−50 MHz) in the beam was seen by the wall current monitor or the FCT. We guess the beam loss increase is caused by a transverse beam instability accompanied electron cloud triggered by longitudinal beam instability which makes a frequency modulation causing multipactering and vacuum pressure rise [2, 4]. In order to mitigate this phenomena, the beam bunch is injected in the RF bucket with a phase offset of 50 to 55 deg [2]. This phase offset injection spreads longitudinal beam emittance and suppress the instability. This phase offset injection is essential for present high power SX operation. We have confirmed the instability for 7.6×10^{13} protons can be suppressed at 60 deg. phase offset.

PRESENT BEAM PERFORMANCES

In the SX startup in April 2018, the first ESS had a serious trouble that several septum ribbons were broken by an accidental hit of the circulating beam, and one of them touched on the high voltage electrode. The SX operation restarted one month later temporarily by moving the second ESS to the first ESS position. In 2017's summer shutdown, an ESS with a titanium vacuum vessel has been installed at the first ESS position and the second ESS has been returned to the original position. The SX operation (RUN78) after the installation has been conducted from January to February in 2018. The beam intensity gradually increased from 10 kW

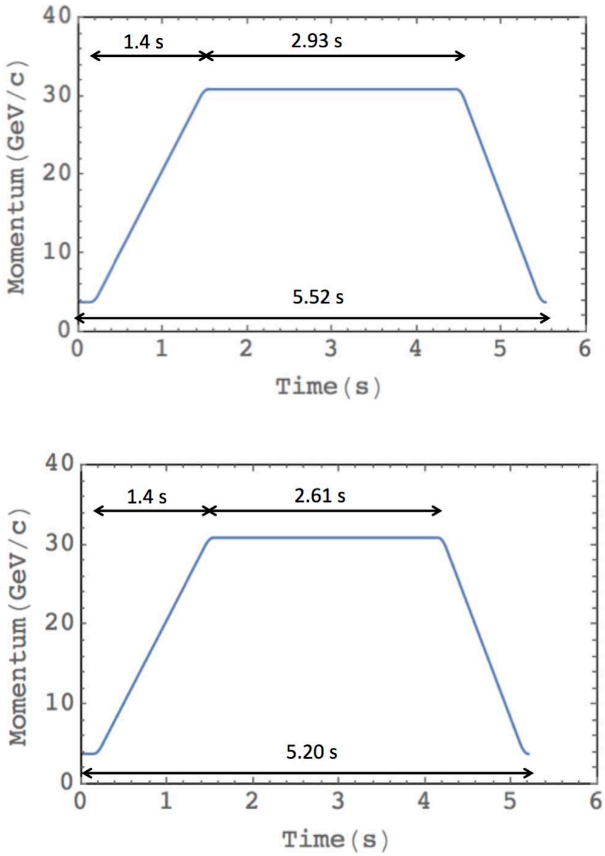

Figure 3: Acceleration patterns.

suppressing a vacuum pressure rise and a spark of the ESSs. In the RUN78, cycle period of the MR has been changed from 5.52 to 5.20 s as shown in Fig. 3 by shortening the flat top by 0.32 s keeping the beam extraction time of 2 s. This increased the beam power by 6%. Finally, the proton number per pulse has been increased to 5.5×10^{13} ppp corresponding to 51 kW, which is a maximum beam power limited by the target capacity. Figure 4 (a) and (b) show distribution and time structure of the beam loss around the SX area at 51 kW operation, (c) and (d) are DCCT signal and the beam loss distribution in the whole ring. A very high slow extraction efficiency of 99.5% was stably kept also at 51 kW operation. The beam power in RUN79 (June,2018) is 51 kW, which is same as that of RUN78.

Figure 5 shows the extracted beam spill monitored at the beam transport line to the hadron hall. The typical duty factor indicating the time structure of the spill is 50% of ideal case. The time structure of the beam spill was regulated by a feedback due to fast-response quadrupole magnet RQ. Transverse RF fields with frequencies corresponding to the horizontal betatron frequency and with a noise width are applied to the circulating beam by the strip-line kickers to improve the spill duty factor. The RF fields quickly push the beam to the resonance by increasing the betatron amplitude. An RF of 47.47 MHz with a flat noise spectrum of 0.2 kHz was applied in RUN79. A transverse RF of 0.2525 MHz with a 0.0625 MHz noise width is also applied by another set of strip-line kicker. The extraction efficiency has slightly worsened from 99.52% to 99.46% by transverse RF tuning to improve the spill duty in this run. The correction coils of the main quadrupole and bending magnets are shorted during the slow extraction by semiconductor switches. This suppresses large spill spikes sometimes occur. Figure 5 shows the time structure and the FFT spectra of the spill signal. 600, 900, 1200 and 1800 Hz sharp peaks have been seen as well as a broad peak below 200 Hz.

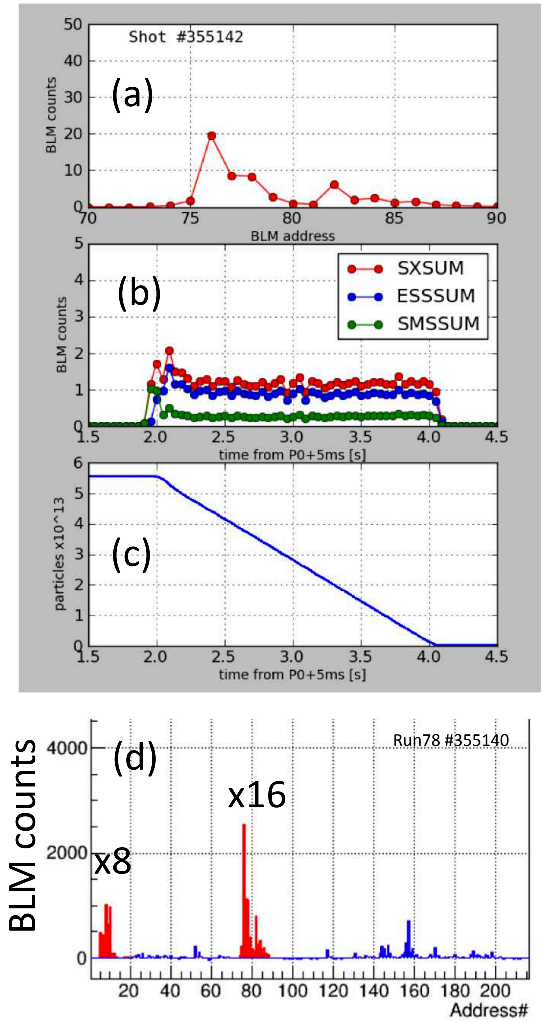

Figure 4: Beam loss distributions, beam loss time structure and DCCT.

Figure 6 shows residual radioactivity surveyed at 6.5 h after the beam was stopped. 51 kW beam was applied over 1 week by slow extraction operation until the beam was stopped. The maximum dose was just upstream of the ESS1, and was 6.5 mSv/h on the surface. The survey result can be understood in light of the achieved small beam loss rate. At the end of RUN78, a trial at a higher beam power has been conducted. We have succeeded in the slow extraction at 62.8 kW (6.8 × 10^{13} ppp). The slow extraction efficiency was 99.47%, which was slightly worsen than that of the 51 kW one at RUN78. In this test, the RF phase offset is 50 deg., which is same as the 51 kW one.

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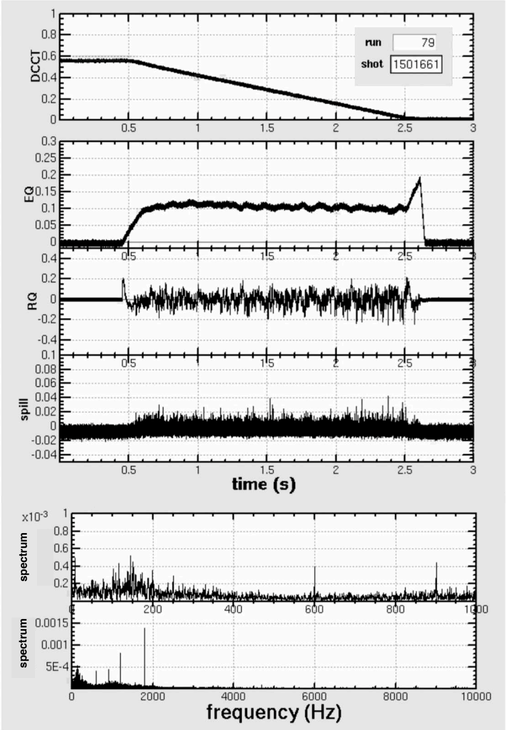

Figure 5: DCCT, EQ, RQ currents, time structure and frequency spectrum of the beam spill.

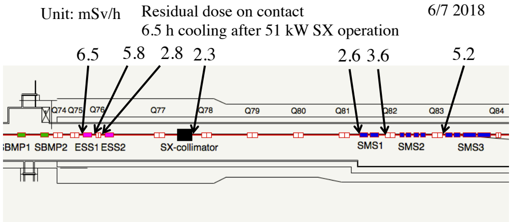

Figure 6: Residual dose measured after 51 kW SX operation.

8 GEV SLOW EXTRACTION

Planned muon to electron conversion search experiment (COMET) needs 8 GeV bunched proton beam with a 1 MHz pulse structure. In this experiment, ratio of residual beam intensity inter-bunch to the main bunch intensity, which is expressed as extinction, should be less than 10^{-9}. In RUN78, we have succeeded in slow extraction of 8 GeV protons with 7.3×10^{12} ppp required for COMET phase I, and the extinction obtained from time structure of secondary pions generated from the target is less than the required value.

BEAM STOP SYSTEM

After the target melting incident inducing a radioactive materials leakage in 2013, a slow extraction stop system (SX abort system) has been introduced. The EQ power supply was modified to turn off the output current within 1 ms from an interlock signal, which keeps away the horizontal tune from the resonance and immediately stops the slow extraction. The currents of the resonant sextupole and the bump magnets are also stopped by the interlock signal. The four bump currents are proportionally decreased to zero within 150 ms to keep the closed orbit. The beam remained in the ring after the beam stop circulates till the end of the flat top, and kicked out by the kickers and delivered to the abort dump. The SX abort occurs by interlocks of such as extracted beam rate, beam loss in the slow extraction devices or the hadron beam lines, which can protect the septa devices and the target. Figure 7 shows a real example of the SX abort by the beam loss increase at the ESS. The SX abort system is indispensable to protect the septa devices and the target in the present high power operation.

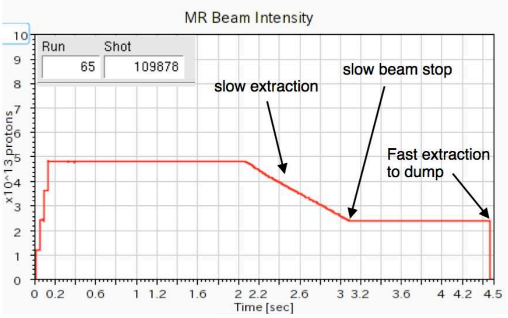

Figure 7: Slow extraction stop by the beam loss at ESS.

FUTURE PLANS

Main Power Supply Upgrade

The bending and main quadrupole power supplies of the MR will be replaced to rise a repetition rate from 0.40 Hz to 0.77 Hz and the beam power for a neutrino oscillation program within several years [5]. The repetition time for the slow extraction can be reduced to 3.7 s with a flat top of 2.4 s to keep the present beam on time of 2 s. The preparation time before the start of slow extraction will be shorten by 0.23 s saving the bump rise time. 100 kW operation will be achieved at this repetition period, if 7.7×10^{13} ppp can be extracted slowly. This proton number would be achievable without a serious hard work from the high power tests mentioned above.

Instability Suppression During Debunch

The beam instability during the debunch process is one of the key issue toward a higher beam power slow extraction. A mitigation of the longitudinal phase space localization is effective to suppress this instability as described above. A phase jump technique to stay the beam on an unstable fix point (USFP) of the separatrix can be effective since the momentum spreads with duration on the USFP. Optimization of the RF voltage and the duration on the USFP by the simulation is underway. We have a plan to introduce a VHF cavity to spread the longitudinal emittance uniformly, which is also effective to suppress the instability. The design of the cavity is underway by the RF group.

Titanium ESS

A titanium vacuum vessel is superior than a stainless one from the residual radiation point of view. The first ESS has been already replaced from the stainless one to the titanium one and utilized for the slow extraction operation. The yoke straining the septum ribbons is also made of titanium. We have a plan to replace the second ESS from stainless to titanium one. Though a high voltage test for the titanium ESS2 is now in progress, 110 kV higher than nominal voltage at a gap of 25 mm has been already achieved without any trouble.

Carbon Nanotube ESS

1 mm wide and 30 μm thick tungsten ribbons (including 26% rhenium) have been strained on the yoke at every 3 mm pitch as the septum of the present ESS. Septum material with a low density such as carbon nanotubes (CNT) is preferable to reduce the secondary particle generation rate in the same beam hit rate on the septum. Recently 30 $\sim$ 90 μm thick CNT wires and 30 μm thick 1 mm wide CNT ribbons have been developed for the ESS septum. Stainless brackets was clamped to each end of the CNT wires and ribbons. Preliminary tensile test showed the wires and the ribbons were resistant for a stress of 361 MPa and 200 MPa, respectively. We have a plan to strain the CNT wires on a short yoke and supply a high voltage in vacuum, which is financially supported by Grants-in-Aid for Scientific Research in Japan and the U.S.-Japan Science and Technology Cooperation Program.

Scatterer

A scatterer (diffusers) can be put upstream of the ESS. If the scatterer material and its geometry is a good condition, the beam hitting on the scatterer spatially diffuses by multiple scattering and the beam hit rate at the downstream ESS is reduced. Total beam loss in the scatterer and the ESS can be reduced. In the recent simulation, in case a 50 μm thick and 1 mm wide tungsten ribbon is put at 350 mm upstream of the present ESS, total beam loss is reduced by 36% in the MARS simulation [6]. In other case, the present ESS septum length is shortened from 1.5 m to 1.0 m, and in the upstream 0.5 m space, 30 μm thick and 1 mm wide titanium ribbons are strained every 9 mm pitch as the scatterer, which results in a 50% loss reduction by preliminary MARS simulation. We have a plan to introduce a real scatterer after a further simulation study.

Stretcher

The MR provides 30 GeV high-intensity protons to the neutrino experimental facility (NU) by fast extraction as well as to the hadron experimental facility (HD) by slow extraction. A stretcher ring (SR) has been proposed to ensure that the integrated proton number on target from the slow extraction is sufficient [7]. A beam accelerated at 30 GeV in the MR is transferred to the SR and is slowly extracted over several seconds. While the slow-extraction procedure is performed, a beam can be accelerated in the MR and delivered to the NU. The arc sections of the SR consist of superconducting combined-function magnets and separated-function magnets (a hybrid lattice configuration). A 30 GeV beam transfer line from the MR to the SR uses superconducting combined magnets with dipole and quadrupole functions. The transferred beam is injected into an arc section of the SR. The POT (integrated proton number on target) from the slow extraction using the SR scheme triples while the POT at the NU remains the same as that of the present scheme.

CONCLUSIONS

The J-PARC slow extraction has a unique scheme using a dynamic bump under achromatic condition to derive a high extraction efficiency. The beam instability caused during a debunch process is a critical issue for beam power ramp-up. Phase offset injection for a RF bucket has mitigated the instability well at present operation. We have attained 51 kW operation at 5.2 s keeping a high extraction efficiency of 99.5%. This is a major milestone for the J-PARC accelerator complex. A spiky spill time structure has been improved by implementing the spill feedback using a fast response quadrupole and applying the transverse RF fields. A 8 GeV beam has successfully slow-extracted in the beam test for COMET phase I experiment. Measured extinction shows a promising result. Upgrade plans with the slow extraction have been discussed.

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