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SLOW EXTRACTION OPERATION AT J-PARC MAIN RING

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Abstract

A high-intensity proton beam accelerated in the J-PARC main ring (MR) is slowly extracted by using the third integer resonance and delivered to the experimental hall. A critical issue in slow extraction (SX) is a beam loss caused during the extraction. A dynamic bump scheme under an achromatic condition provides extremely high extraction efficiency. We have encountered a beam instability in the debunch formation process, which is estimated to be triggered by a longitudinal microstructure of the beam. To suppress this instability, the beam to the MR has been injected into the RF bucket with a phase offset. A newly developed RF manipulation, 2-step voltage debunch, has successfully pushed up the beam power up to 64.6 kW keeping a high extraction efficiency of 99.5%. A drastic beam loss reduction has been demonstrated in the beam test using a diffuser installed upstream of the first electrostatic septum (ESS1). 8 GeV-bunched slow extraction tests for the neutrino-less muon to electron conversion search experiment (COMET Phase-I) have been successfully conducted.

INTRODUCTION

A high-intensity proton beam accelerated in the J-PARC main ring (MR) is slowly extracted by the third integer resonant extraction and provided 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 the slow extraction (SX) of a high intensity proton beam is an inevitable beam loss caused at an electrostatic septum (ESS). The slow extraction from the J-PARC MR has unique schemes to reduce the beam loss rate [1]. The first electrostatic septum (ESS1) is located in the section between adjacent focusing quadrupole magnets as shown in Fig. 1. The Courant-Snyder β_x function in this section is ~40 m, which is highest in the MR. In this condition, a large step size (spiral step) Δ at ESS1 can be chosen without causing any primary beam loss in other sections. The head-on hit rate of the beam on the septum in ESS1 can be reduced by the large Δ. The long straight sections in the MR are dispersion-free. If horizontal chromaticity is set to near zero during the extraction, the momentum dependence of the third-integer resonant separatrix can be neglected. When a bump orbit, which moves the circulating beam toward the septum of ESS1, is fixed during extraction, the outgoing arms from the separatrices can have different angles ($x' = dx/ds$) at ESS1 over the start and the end of extraction (fixed bump scheme). The angles of the bump orbit at ESS1 can be moved to overlap these arms during extraction (dynamic bump scheme). The dynamic bump scheme reduces the side hit rate on the ESS1 septum and reduces the beam losses also at ESS2 and the downstream magnetic septa.

In the actual beam tunings, the transverse septum position of the ESSs and the followed magnetic septa (SMS1 and SMS2) are finely tuned to minimize the beam loss iteratively with the dynamic bump orbit tuning. The beam loss is sensitive to horizontal chromaticity, which is searched to minimize the beam loss rate [1]. We have encountered a transverse beam instability occurring in a debunching process above 30 kW beam power. The mitigations we adopted have played an essential role to rise up the beam power as described in the next section. A current performance of 30 GeV-slow extraction operations, 8 GeV-slow extraction tests COMET Phase-I and future plans toward a higher beam power 30 GeV SX operation are also reported.

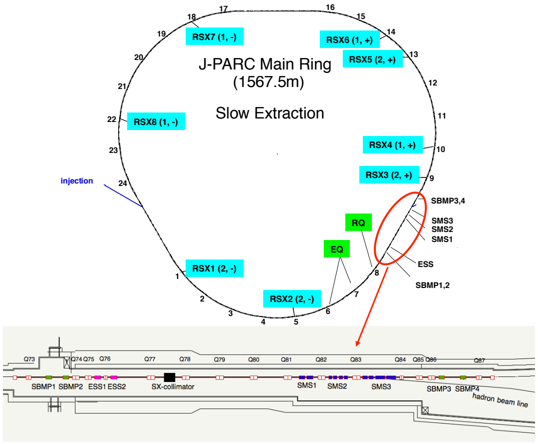

Figure 1: Layout of J-PARC slow extraction devices.

BEAM INSTABILITY AND MITIGATIONS

We have encountered a beam loss increase in the slow extraction at the beam powers above 30 GeV. This involves a vacuum pressure rise in the whole ring. An electron cloud has been detected by electron cloud monitors at the debunch formation process [2]. The horizontal and vertical coherent oscillations have been also observed at the same timing. A transverse beam size growth has been observed by a profile

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monitor located in the beam transport line to the beam dump. These observations shows a transverse instability related to an electron cloud is caused in the ring in the debunching.

A weak chromaticity correction could mitigate the instability. The horizontal and vertical chromaticities of −3.5 and −2.0 before acceleration are set to −5.0 and −7.1 at the flat top and keeping during the debunch formation process. Before the start of the slow extraction, the horizontal chromaticity is set near zero to make an achromatic condition. However this manipulation is not enough to suppress the observed instability.

Whenever this instability happens, a microstructure in the longitudinal beam distribution has been enhanced (see Fig. 2). We guess this transverse instability is triggered by a longitudinal coherent oscillation. A probable mechanism is that such a microstructure induces a vacuum pressure rise by e.g. a multipacting and brings electron clouds. The microstructure has broad frequency components up to ~300 MHz. Any coupling impedance source in the MR is not yet clearly identified.

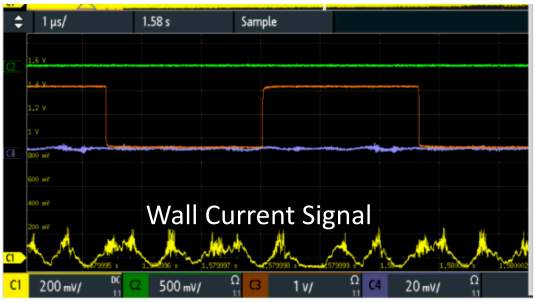


Figure 2: Microstructure observed by a wall current monitor.

In order to mitigate this instability, the beam bunch has been injected into the RF bucket with a phase offset of typically 50 to 60 deg as shown in Fig. 3 a) (phase offset injection) [3]. This manipulation spreads the longitudinal beam emittance and suppress the microstructure enhancement. The phase offset injection was very effective for a stable slow extraction operation up to 50 kW (5.4×10^{13} protons). However, a phase offset larger than 60 deg. which is necessary to suppress the instability above 50 kW, partially spilled the beam out of the RF bucket at the acceleration start timing.

A new technique, called 2-step voltage debunch, has been implemented to achieve the beam power higher than 50 kW since Dec. 2020. An RF voltage of 256 kV for acceleration is normally non-adiabatically set to zero at the flat top start for the debunching. In the 2-step voltage debunch, the 256 kV voltage is non-adiabatically reduced at a very low voltage, and then is set to zero after a half synchrotron period as shown in Fig. 3 b). This manipulation changes the longitudinal beam distribution and helps suppressing the microstructure growth. This technique pushed up the SX beam power to 64.6 kW (7×10^{13} protons).

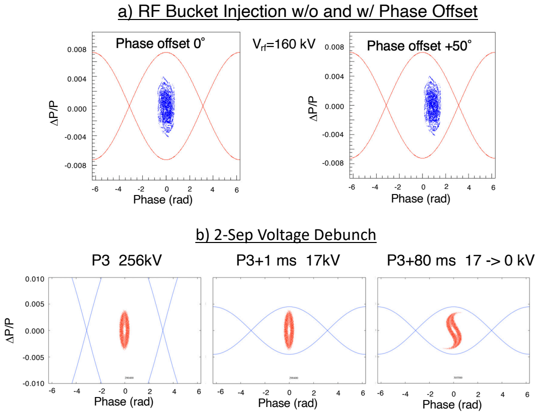


Figure 3: Phase offset injection and 2-step voltage debunch simulations.

CURRENT BEAM PERFORMANCES

The current cycle time of the SX operation is 5.2 s, in which the acceleration time and the flat top time is 1.4 s and 2.61 s respectively. The beam power in the physics run achieved at 64.6 kW (7×10^{13} p/pulse) in May, 2021. The instability in the debunch process has been well suppressed by a combination of the phase offset injection and the 2-step voltage debunch. In the latest SX operation, the phase offset was set at 50 deg. for a 165 kV RF bucket. The RF voltage was reduced from 256 kV to 23 kV at the flat top start, and then set at zero after 60 ms. The beam loss for the slow extraction was minimized by tuning the dynamic bump parameters and by tunings septa positions of ESS1, ESS2 and SMS1. Figure 4 a) to d) show the beam loss distribution around the SX area, the beam loss time structure during extraction in the SX area, the DCCT signal and the beam loss distribution in the whole ring. The beam loss distribution have a maximum at ESS1. The beam loss is flat during extraction. The red peaks in the MR collimator region and the SX area shown in Fig. 4 d) must be multiplied by 16 time comparing the blue peaks. The beam loss at the collimator region is mainly generated at the flat base and the beginning of the acceleration. The beam loss in the slow extraction is well localized around the SX area.

The beam spill time structure was measured by a spill monitor located in the beam line to the target. A spill feedback system, in which a DSP processes the spill monitor signal and control the fast response quadrupole (EQs and RQ) currents in real time, has been implemented to improve the spill time structure [4]. Transverse fields by two sets of horizontal strip line kickers have been applied to the circulating beam (transverse RFs) [5]. In the latest operation, the carrier frequencies corresponding to harmonics of the horizontal betatron frequency and its noise widths are 47.4719 MHz and 50 Hz for the D3 kicker, 0.239 MHz and 31.25 Hz for the D1 kicker, respectively. The spill feedback system and the transverse RFs pushed up the spill duty factor to 50−55% (ideal case 100%) [6]. Figure 4 e) shows a beam spill measured at 64.6 kW.

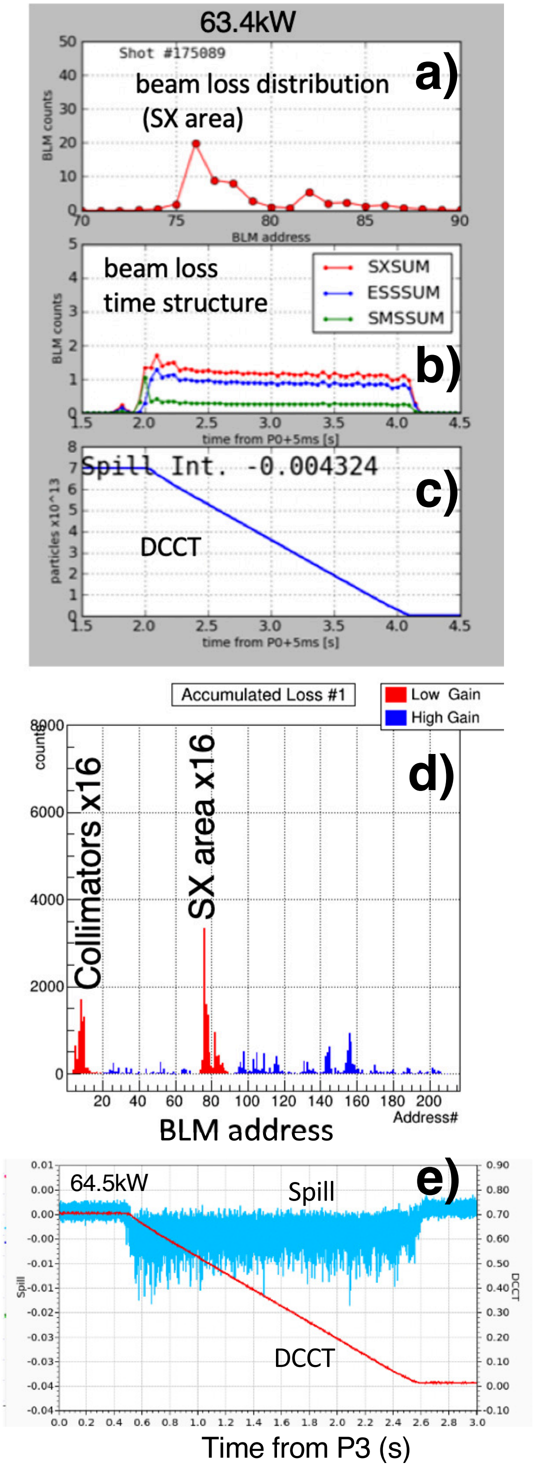
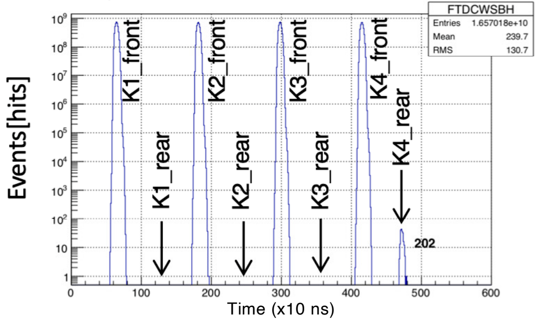


Figure 4: Current performances of 30 GeV slow extraction.

BEAM TESTS FOR COMET

A planned muon to electron conversion search experiment (COMET Phase-I) needs 8 GeV bunched proton beam with a 1 MHz pulse structure in a long beam duration. In this experiment, the beam intensity ratio of inter-bunch to bunch, which is called extinction, should be less than 1×10^{-10}. In the ordinary 30 GeV operation, two bunches are accelerated by a 3 GeV rapid cycle synchrotron (RCS) and 4 batches are injected into the MR (harmonics 9) at the K1 to K4 timings every 40 ms. To derive the beam with a MHz structure, the RCS accelerates one bunch for the COMET experiment and 4 batches are injected into the MR. The four bunches are accelerated up to 8 GeV (revolution time of 5.26 µs) and they are slowly extracted keeping the bunch structure. An empty bucket in the RCS is produced by an RF chopper placed between the RFQ and the Drift Tube Linac (DTL). The residual beam intensity in the empty bucket is in 10^{-6} level at the ratio for the main beam bucket. To reduce the residual beams in the empty bucket, the MR injection kicker timing is shifted by roughly one bucket length. The timing is shifted forward when the main beam is in a forward bucket (front injection) and reversely shifted backward in a backward bucket (rear injection). By such a kicker timing shift, the residual beam in the empty bucket can not be deflected along the injection orbit and then lost in the MR.

a) Measurement in 2018



b) Measurement in 2021

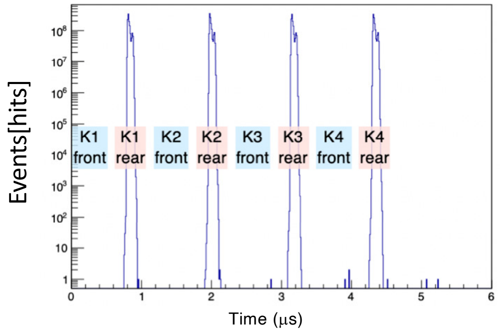


Figure 5: Time structures of extracted beams measured in 2018 and 2021.

The 8 GeV beam tests were conducted in 2018 and 2021. The acceleration pattern is swept in 2.48 s chosen in the COMET phase-I, and the repetition time of the MR is kept to 5.2 s, same as that of the 30 GeV operation avoiding a hard work to change the setting of the timing system. The particle number in the MR is $7.3 \sim 7.4 \times 10^{12}$ per pulse, which corresponds to 3.2 kW at a 2.48 s cycle nominal for the COMET phase-I. The beam loss around the slow extraction area was drastically improved in the 2021 test by a careful dynamic bump tuning and the septa position optimization. A tentative slow extraction efficiency is above 99%, which should be calibrated in a similar way as done at 30 GeV. The

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time structure has been also improved to be above 50% at the duty factor by the spill feedback tunings. The transverse RF used for the 30 GeV operation was not applied.

The extinction of the slow-extracted beam has been measured by an extinction monitor in an secondary beam line in the hadron experimental hall. Figure 5 a) shows a bunch structure of the secondary beam measured in the 2018 test [7]. Any residual beam has not been observed in the inter-bunch of the K1-K3 timings, however, the residual beam was seen in an empty bucket at the K4 timing. Though the residual beams injected at the K1 through K3 timings can be also circulated similar to that at the K4 timing, they can be lost by the kicker field at the followed K2 to K4 timings. The residual beam injected at the K4 timing can not be lost since the kicker field is not excited after the K4 timing. Figure 5 b) shows a bunched time structure measured in May, 2021 [8]. The beam was injected into the backward bucket and the kicker timing was shifted backward by 600 ns. Any peak seen for the front injection was not seen in the rear injection. A few events in random timing locations have been identified as accidental events in the extinction monitors by data analysis. The extinction rejecting such accidental events is less than 1×10^{-10}. In the 2021 test, two correction kickers were successfully applied to suppress a horizontal emittance growth by an undesirable reflection in the kicker transmission line.

FUTURE PLANS

Beam Loss Reductions

The power supplies for bending and quadrupole families in the MR will be replaced to shorten a cycle time from 2.48 to 1.3 s for a planned neutrino experiment program toward a 750 kW operation. This replacement will shorten a cycle time for the slow extraction from 5.2 s to 4.2 s finally. This means that the SX beam power can be pushed up by 1.23 times for the same proton number per pulse.

The beam loss reduction using a diffuser has been successfully demonstrated in CERN SPS [9]. Further beam loss reduction schemes are planned toward a higher intensity J-PARC SX operation. Two diffusers have been installed upstream of ESS1 as shown in Fig. 6. A multiple scattering in the diffusers reduces a head-on hit rate on the ESS1 septum. The beam loss reduction effect is sensitive to an angular spread of the beam coming into the diffusers. The dynamic bump which reduces the angular spread very well fits to the diffuser scheme. Further, we have a plan to boost up the effect by two diffusers combination. The sizes of the diffuse0 and the diffuser1 made of tantalum, have been optimized by a FLUKA simulation, 0.2 mm (W)×0.5 mm (L) and 0.1 mm (W)×2 mm (L), respectively [10]. A preliminary beam test using the diffuser0 has been conducted in 2021. Figure 6 shows the beam loss comparison with and without the diffuser0. The beam loss in all SX area except for the diffser0 has been definitely reduced, especially becomes 1/2.7 at ESS1 of a maximum beam loss point. In the next beam test, a combination effect by the two diffusers, a high beam intensity effect, a long term stability will be examined. To put them to practical use, the diffiser0 will be covered with a radiation shield.

A septum shadowing using a bent Si crystal would be a promising candidate as the diffusers [11]. Beams going through the crystal are deflected by a channeling effect and make a separation at the first ESS.

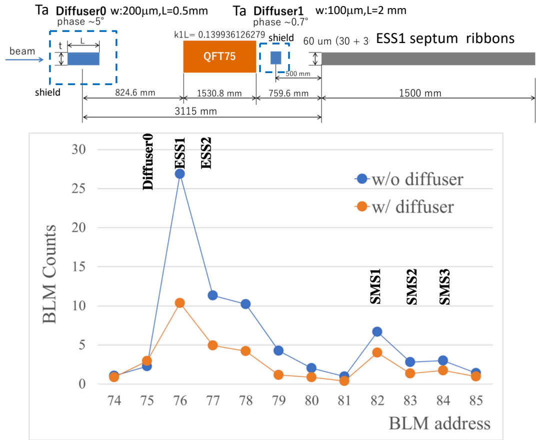

Figure 6: Diffusers configuration and beam loss distributions measured for w/ and w/o diffuser0.

The septa of the ESSs are made of a W/Re alloy with a large average atomic number [12]. If the septum of ESS1 can be made of a material with a low atomic number, the radioactivity around can be reduced. We have started a feasibility research using carbon-Nano Tube (CNT) wires developed by Hitachi Zosen (Hitz) as the septum material. In a high voltage test by a single CNT wire, we have achieved an electric field of 20 MV/m on the wire surface [13].

Instability Mitigations

Mitigations for the instability occurring in the debunch process are crucial to rise up the beam intensity.

The RF voltage and its RF-off timing in the 2-step voltage debunch technique will be optimized. As its advanced technique, a multi-step voltage debunch will be also studied.

A beam coupling impedance reduction in the MR is important. A major longitudinal impedance source triggering the instability has not been clearly identified. However, a RF cavity impedance is supposed to be a candidate. The impedance measurement for newly installed cavities is underway. An impedance reduction way for the RF cavities are also discussed.

Phase and amplitude modulations by VHF cavities increase the longitudinal beam emittance uniformly are a promising way suppressing the instability. The VHF cavities have been already designed [14]. A funding to build them can be an issue.

If absolute value of a slippage factor $|\eta|$ is enlarged during the debunch timing, a longitudinal microstructure is suppressed as expected from the well known longitudinal Keil-Schnell criterion. The MR ring has an imaginary transition γ_t. The η is -0.00192 at 30 GeV. The η can be changed by tuning the field strength of four quadrupole families in the arc sections keeping horizontal and vertical tunes and an achromatic condition in the long straight sections. The slippage change optics will be tried in the next beam test.

Beam Spill Improvements

The replaced bending and quadrupole power supplies in 2021− 2022 have one order less ripple than the present ripples, order of 10^{-4}. The improvement for the spill time structure will be expected from the next beam operation.

The two transverse RF fields have been applied to the beam at fixed frequencies and noise widths in the current operation. A feedback to the transverse RF fields from the spill signal will be planned. A voltage programable attenuator added in the low level line in the exciters can be controlled by the spill feedback DSP. A time response of the extracted beam by the DSP command has been tested.

A ripple canceler, processes the total horizontal tune shift by FPGAs from the measured current ripples for the bending and quadrupole power supplies, set the current to cancel the processed total horizontal tune shift to the RQ magnet [15]. The beam test showed the performance similar to that of the current feedback system in the condition without the transverse RF.

The transverse RF frequencies corresponding to two different harmonics of the betatron oscillation frequency is applied to the circulating beam by the two strip line kickers to improve the spill structure. Multi-harmonic frequencies more than the current two frequencies will be applied in a test to improve the spill time structure [16].

CONCLUSIONS

The 30GeV-slow extracted beam has been stablely delivered to the hadron experimental hall for various high energy and nuclear physics experiments. The current SX beam power have achieved to 64.6 kW, which corresponds to $7{\times}10^{13}$ protons per pulse. An extremely high slow extraction efficiency of 99.5% is maintained also at the current operation. The beam instability occurring in the debunch formation process is crucial. The mitigations of the phase offset injection into the MR RF bucket and the 2-step voltage debunch technique have played an essential role to push up the beam power. The time structure of the extracted beam has been improved by a spill feedback to the fast response quadrupoles and applying transverse RF fields to the circulating beam.

The 8 GeV-bunched slow extraction tests have been successfully conducted for the planned μ-e conversion experiment (COMET). The extinction measured for the extracted beam is $< 1 \times 10^{-10}$, which satisfies the requirement from the COMET Phase-I. The slow extraction efficiency and the spill time structure have been rather improved in the 8 GeV slow extraction test conducted in 2021.

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