

# CURRENT STATUS OF SLOW EXTRACTION FROM 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 facility. A dynamic bump scheme under achromatic condition drastically reduces beam hit rate on the septa devices, and we have attained 51 kW SX operation at 5.2 s cycle with high slow extraction efficiency of 99.5%. A spill duty factor indicating a uniformity of the time structure of the extracted beam is typically 50%. The current SX performance and future plans for improvements will be presented.

## INTRODUCTION

Japan Proton Accelerator Research Complex (J-PARC) [1] is located at Tokai-mura, Ibaraki, Japan, and its Main Ring (MR) provides 30 GeV protons for various particle and nuclear physics experiments. The MR has two extraction modes, fast and slow, and slowly extracted protons are delivered to the hadron experimental facility. Figure 1 shows the schematic view of the MR and the layout of the straight section for slow extraction (SX). High power and flat time structure of the extracted beam are crucial for the efficient data acquisition in the physics experiments.

The SX in the MR utilizes third integer resonance of the horizontal betatron tune [2]. The horizontal tune is ramped up toward the third integer resonance of 67/3. The stable region of the phase space gradually decreases and particles in the unstable region increase their betatron oscillation amplitude along separatrices. When particles reach the septum ribbons of the electrostatic septum (ESS) [3] they are kicked and extracted. The straight section for the SX is dispersion-free, and we set the chromaticity close to zero during the extraction, thus the separatrices are independent on the momentum of the particles. In addition, a dynamic bump scheme [2] is adopted to minimize the change of the separatrix during the extraction. Due to above measures we accomplished very high extraction efficiency of 99.5%. The spill duty factor, which indicates the uniformity of the time structure of the spill, is defined as  $\langle I^2 \rangle / \langle I \rangle^2$ , where  $I$  is the beam intensity and  $\langle \rangle$  denotes the integration during the extraction, and typical value is about 50%.

In this paper the current operation status and the future prospects of the SX in J-PARC MR are presented.

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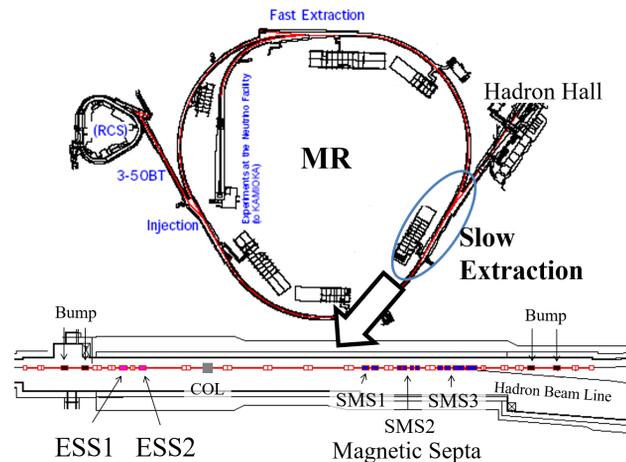


Figure 1: Schematic view of J-PARC MR and its straight section for the slow extraction. COL stands for collimator. SMS stands for magnetic septa for SX [4].

## CURRENT OPERATION STATUS OF SLOW EXTRACTION

The SX operation in the year 2019 started in February after the 6-month shutdown. The beam power for the user operation reached 51 kW, which corresponds to  $5.5 \times 10^{13}$  protons per pulse with the repetition rate of 5.2 s and the flat top length of 2.61 s. The current acceptable beam power of the hadron experimental facility is 57 kW and we almost reached the limit. The user operation was terminated in late April owing to the magnet trouble in the beam transport line from the RCS to the MR, and the total number of protons on target was  $3.5 \times 10^{19}$  in this run.

### Extraction Efficiency

The efficiency of the extraction is estimated by the signals of the beam loss monitors (BLM) [5] which are located at each quadrupole magnet. The estimated extraction efficiency was about 99.5%. Figure 2 shows the typical signals of the BLM for a cycle of the slow extraction with the signal of the DC current transformer (DCCT) which counts the number of particles in the ring. The time dependence of the beam loss is almost flat during the extraction, and the dynamic bump scheme plays principal role in making the beam loss flat and small.

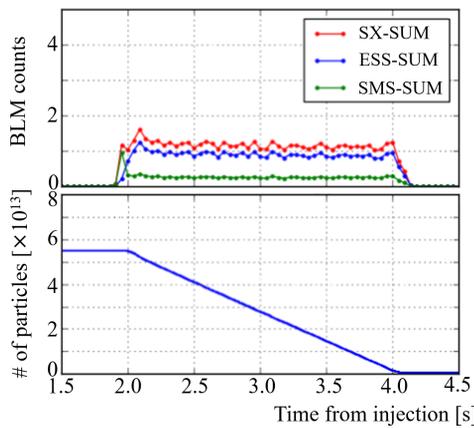


Figure 2: Typical monitor signals for a cycle of the SX. Upper panel shows the time dependence of the BLM signals integrated in all SX region (red), in the neighborhood of the ESS (blue) and the SMS (green). Lower panel shows the DCCT signal for the number of particles in the MR.

### Strength of the Resonant Sextupoles

The change of the unstable particle's position in every three turn is called spiral step [6], and the larger spiral step corresponds to smaller beam loss at the ESS. The size of the spiral step is determined by the strength of third integer resonance driven by the resonant sextupole magnets (RSXs), thus the correlation between the strength of RSXs and the extraction efficiency was measured. Figure 3 shows the results.

In the past SX operations the strength of the RSXs were chosen for the maximum step size to be about 15 mm in SAD [7] simulation. We increased the RSX strength up to 1.13 times as large as the past setting and measured the extraction efficiency with readjusted dynamic bump orbit. The extraction efficiency was linearly improved with the RSX strength. The beam loss reduction rate at the  $\times 1.13$  RSX strength is  $(100 - 99.592)/(100 - 99.543) = 0.89$ , which is in good agreement with the naive prediction,  $1/1.13 = 0.88$ .

We chose the RSX strength for the 2019 operation to be 1.07 times as large as the past setting because too large step size possibly cause damage on the electrode of the electrostatic septum.

### Residual Radiation Dose with 50 kW SX Operation

Figure 4 shows residual radiation doses on the slow extraction devices after the delivery of  $2 \times 10^{19}$  protons on target with the beam power of 50 kW. The maximum residual dose at 1-foot distance after 1.4-day cooling is 2.1 mSv/h thanks to the high extraction efficiency. Figure 4 also contains beam loss rates estimated by the BLMs. The distribution of the residual radiation doses is roughly reproduced by the beam loss rates apart from the upstream of the SMS3, where the BLM is insensitive. Adding another BLM around the upstream of SMS3 is planned.

Figure 5 shows the accumulation of the residual radiation doses at the downstream edge of the electrostatic septum

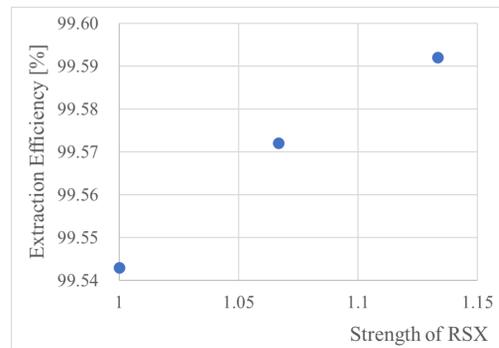


Figure 3: The correlation between the strength of the RSXs and the extraction efficiency. The strength of the RSXs is normalized at the value in the past SX operations.

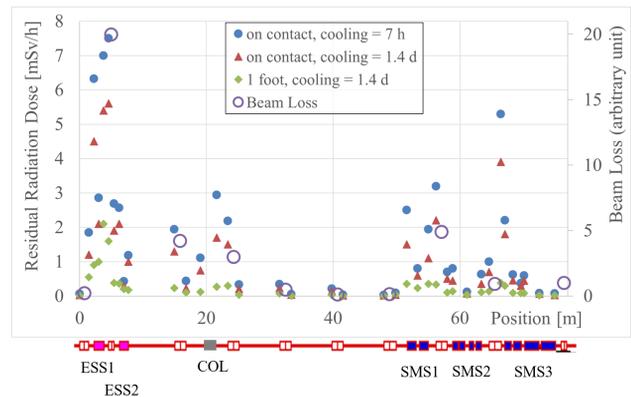


Figure 4: Residual radiation doses on slow extraction devices measured after 50 kW,  $2 \times 10^{19}$  protons-on-target slow extraction operation. Open circles are the beam loss rates estimated by the signals of the beam loss monitors.

and the upstream edge of the high-field magnetic septa. The residual radiation doses are almost saturated with  $1.5 \times 10^{19}$  protons on target.

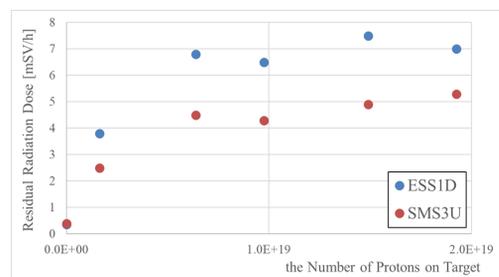


Figure 5: Accumulation of the residual radiation doses measured at the downstream edge of the electrostatic septum (ESS1D) and the upstream edge of the high-field magnetic septa (SMS3U).

### Spill Structure and Tuning of Transverse RF frequency

The time structure of the extracted beam spill was regulated by the spill feedback system [8] with fast-response

quadrupole magnets. In order to improve the time structure further, we applied transverse RF field on the circulation beam [9] using two strip-line kicker systems [10]. The center frequencies of the signals on those strip-line kickers are 47.47 MHz and 254 kHz, with the noise width of 100 Hz and 31.25 kHz, respectively. In the 2019 SX operation we scan the parameters of the transverse RF to maximize the spill duty factor. We decreased the center frequency of 47.47 MHz signal by 200 Hz and changed the noise width for the 254 kHz signal from 62.5 kHz to 31.25 kHz. In addition, the power of 254 kHz signal increased from 6 dBm to 9 dBm. The spill duty factor was slightly improved from 54% to 57%. Figure 6 shows a typical spill monitor signal and the comparison of the FFT results between before and after the parameter change. Amplitudes reduction can be seen in the region from 200 Hz to 1500 Hz.

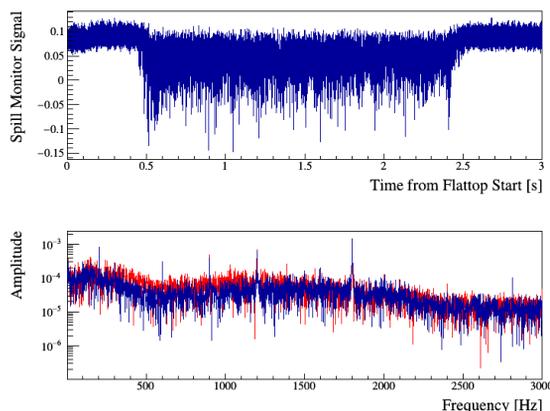


Figure 6: Typical spill monitor signal and FFT of the spill signals. Upper panel shows the signal of spill monitor located at the beam transport line between the MR and the hadron experimental facility. The bin width is 10 kHz. Lower panel shows the comparison of the FFT results. Red line shows the result before the adjustment of the transverse RF parameters and blue is with adjusted parameters.

The length of the extraction spill was about 2.05 s. In the previous run the spill length had to be adjusted once or twice per week owing to the signal deterioration of the spill monitor, which is made of a plastic scintillator and a photo multiplier. In the 2019 run the automatic spill length adjustment controlled by the integration of the spill monitor signals was implemented and the spill length became stable. Figure 7 shows the trend graphs of the spill length in the past and present SX operations.

## FUTURE PROSPECTS

The acceptable beam power of the hadron experimental facility will increase to around 100 kW in the summer of 2019, and the beam power upgrade of the slow extraction is strongly required for the physics experiments. One of the crucial issues for the further beam power upgrade is the reduction of the beam loss at ESS, where the largest beam

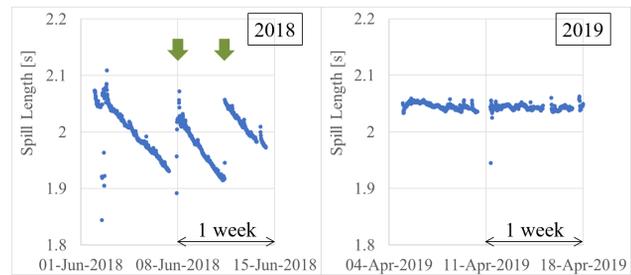


Figure 7: Trend graphs of the spill length during user operations in June, 2018 and April, 2019. Arrows in the left panel indicate the manual readjustment of the spill length.

loss occurs as seen in Fig. 4. We are developing two devices to cope with this issue. One is the new ESS using carbon nanotube wires as septa [11]. Another is a diffuser at the upstream of the ESS [12].

Another crucial issue for the beam power upgrade is the beam instability. In the course of the beam power increase up to 50 kW, we have observed beam instabilities during the debunching process after the acceleration. The instabilities were accompanied by the observation of electron clouds and vacuum pressure rises in the whole ring [13], and the large beam loss occurred during the extraction. In order to mitigate the beam instability, we injected the bunches in the RF buckets with phase offset of  $50^\circ$ . For further mitigation of the instability, we are now considering the phase jump before the debunching or other RF manipulation to obtain larger longitudinal emittance. The design of VHF cavities to spread the longitudinal emittance uniformly are also underway.

As for the spill structure, power supplies of the main magnets will be replaced in the year 2022 [14], which is expected to bring about drastic improvement of the flatness of the spill. In addition, a ripple canceler system [15] is being developed by main magnet group. An implementation of the spill feedback on the output level of the transverse RF signal generator is also in preparation.

## CONCLUSION

The SX operation was carried out in the J-PARC MR from February to April, 2019. The total number of protons on target was  $3.5 \times 10^{19}$ . The beam power was 51 kW, which almost reaches the current acceptable beam power of the hadron experimental facility. The extraction efficiency was about 99.5%, which is due to the dynamic bump scheme under the achromatic condition. The spill duty factor for the time structure of the extracted beam was about 50% with spill feedback system and transverse RF system. Plans for the further improvement of both the beam power and the spill structure are underway.

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