ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPMP008

# A CONSIDERATION ON THE TRANSFER FUNCTION BETWEEN RQ FIELD AND SLOW EXTRACTION SPILL IN THE MAIN RING OF J-PARC

K. Okamura†[1], Y. Arakaki[1], T. Kimura[1], S. Murasugi[1], R. Muto[1], Y. Shirakabe[1], M. Tomizawa[1], E. Yanaoka[1], KEK, Tsukuba 305-0801, Japan
[1]also at J-PARC Center, Japan

*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. Increasing the duty of beam spill is one of the important issues in the slow extraction system. In the MR, the spill feedback system utilizing a digital signal processor (DSP) combined with EQ and RQ magnet is used to smooth the spill, where EQ defines a rough outline of the slow extraction shape and RQ is used for the ripple cancelling. In this study, frequency domain characteristics between the current of RQ magnet and the beam spill was investigated by driving the RQ magnet with sinusoidal current, so that the transfer function from the current of RQ magnet to the spill signal is delivered.

## INTRODUCTION

The main ring of Japan Proton Accelerator Research Complex (J-PARC) [1], the main ring of which provides 30 GeV protons for various particle and nuclear physics experiments. The MR has two extraction modes, namely fast extraction and slow extraction. The former is used for neutrino experiments and the latter is used for hadron experiment. 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. Therefore, to know the behaviour of the spill is an important issue for the SX operation generally [2,3]

The SX in the MR utilizes third integer resonance of the horizontal betatron tune [4]. 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) [5], they are kicked and extracted.

The spill duty factor (SDF), which indicates the uniformity of the time structure of the spill, is defined as $\langle I2 \rangle/\langle I \rangle 2$, where $I$ is the beam intensity and ⟨⟩ denotes the integration during the extraction. The typical value of the SDF at J-PARC MR is about 50 % [6]. Such high SDF is attained adopting a transverse RF kicker system [7] and a spill feedback system [8], which correct the tune ripple using two types of dedicated quadrupole magnets.

To optimize the feedback gain, it is important to comprehend the transfer function from the current of correcting magnets to the spill of the extracted beam. A consideration delivered from the study by driving the magnet with sinusoidal current in the beam extraction experiment is described in this paper.

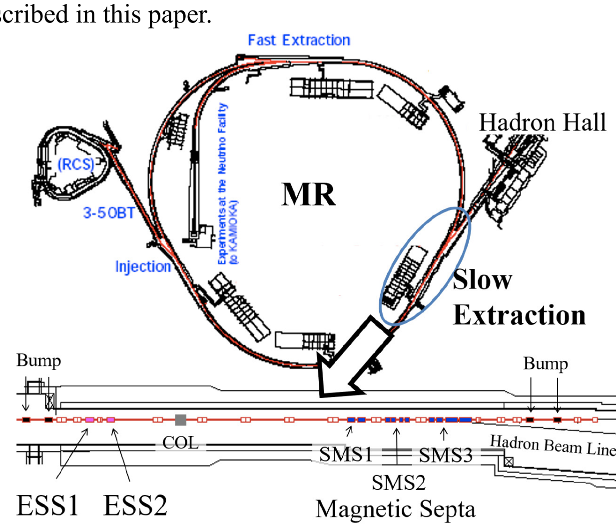


Figure 1: Schematic view of J-PARC MR and its straight section for the slow extraction. COS and SMS stand for collimator and magnetic septa for SX, respectively.

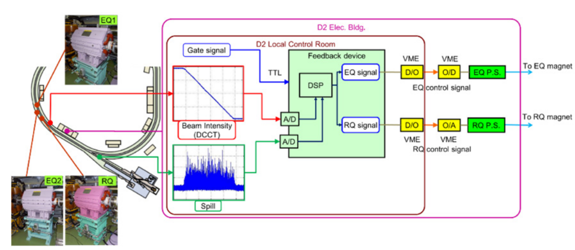

Figure 2: Schematic of the spill feedback system.

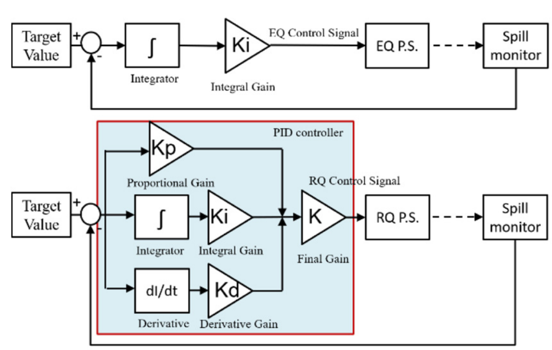


Figure 3: A block diagram of the feedback program.

## SPILL FEEDBACK SYSTEM

Figure 2 shows the block-diagram of the spill feedback system of the J-PARC MR. The feedback signal is obtained

† katsuya.okamura@j-parc.jp

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPMP008



from the optical signal that is emitted from a plastic scintillator, which is exposed by the secondary particles that is generated in events the main beam passes the vacuum septum. The optical signal is converted to the electrical signal by a photo multiplier tube, then is inputted to the feedback control system. At the front-end of the system, the signal is divided for EQ magnet, which defines the outline pattern of the extraction, and RQ magnet, which is used for the ripple cancelling. Figure 3 shows the block diagram of the feedback program, where only the integral control is used for the EQ magnet and the proportional, integral and the differential composite control (PID control) is used for the RQ magnet. Table1 shows the specifications of the EQ and RQ magnets. The EQ magnets has a steep field slope to form a general shape of the extraction by winding a large turn number of coils, whereas the RQ magnet has a less turn number of coils to attain a wide-band frequency response. Table 1 shows the specifications of EQ and RQ magnets.

Table 1: Specifications of EQ and RQ Magnets

| Item | EQ Magnet | RQ Magnet |
|---|---|---|
| Bore (mm) | 80 | 80 |
| Pole Length (m) | 0.62 | 0.62 |
| Turn Number | 22 | 6 |
| Number of magnet(s) | 2 | 1 |
| Field Slope (T/m) | 2.6 @301 A | 0.94 @400 A |
| Inductance (mH) | 8.8 | 0.65 |
| Frequency Range (Hz) | Dc – 1 k | 40 – 10k |
| ΔTune (/A) | 1.06E-4 | 1.43E-5 |

Figure 4 shows a typical DCCT signal of the beam current, EQ excitation current, RQ excitation Current, and the spill monitor signal. Figure 5 shows the frequency response of the power supply of the RQ magnet. The amplitude fit between +2 dB and -3 dB, although the phase shows a large shift until 180 degrees at 10 kHz.

## EXPERIMENT

### *Experimental Method*

Spill signals were acquired under driving RQ magnet with sinusoidal current, the frequency of which were from 20 Hz to 2 kHz.

### *Experimental Results*

**EQ driven with Feedback System** In the first experiment, the EQ magnet was driven utilizing the spill feedback system. A spill Monitor signal, a current waveform of the RQ magnet, and a current waveform of the EQ magnet at 150 Hz and 1 kHz are shown in Fig. 6.

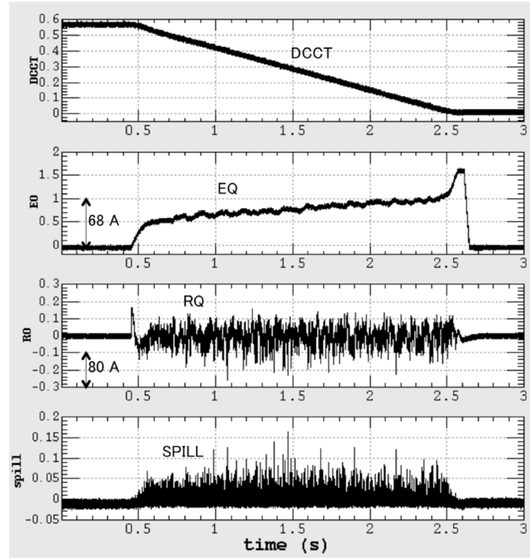


Figure 4: Typical DCCT, EQ magnet current, RQ magnet current, and SPILL signal in a SX operation.

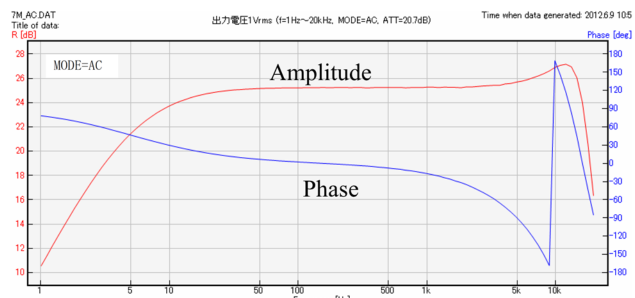


Figure 5: Frequency response of the RQ power supply.

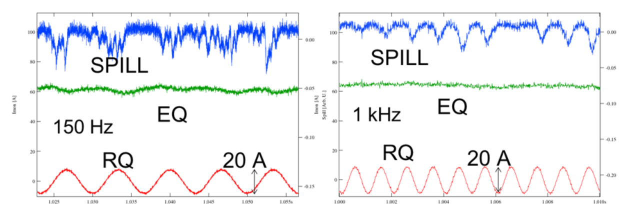


Figure 6: A spill Monitor signal, a current waveform of the RQ magnet, and a current waveform of the EQ magnet at 150 Hz (left) and1 kHz (right).

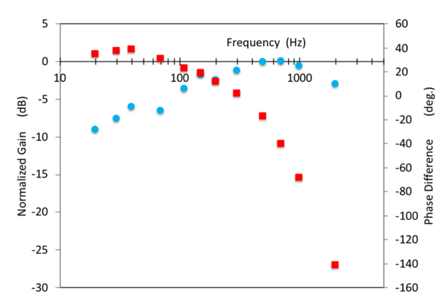


Figure 7: Frequency domain characteristics between the RQ current and the spill signal, where the gain is normalized at 700 Hz.

Time domain signal is converted to frequency domain signal by FFT processing. Figure 7 shows gain from the RQ current to the spill signal and the phase difference as a

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPMP008

function of frequency. Figure 7 shows that the conversion gain slightly increases up to 700 Hz, then falls. This is because of the EQ magnet, which cancels the tune modulation excited by the RQ magnet in low frequency range (Figure 6). Therefore, we conducted the experiment with fixed pattern operation of EQ magnet. Figure 8 and Figure 9 show the spill monitor and RQ magnet current and gain and phase characteristics with fixed pattern operation of EQ magnet, respectively. Figure 9 shows a kind of low pass filter characteristics.

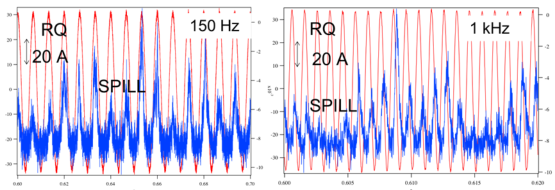


Figure 8: A spill Monitor signal and a current waveform of the RQ magnet with fixed pattern operation of EQ magnet at 150 Hz (left) and1 kHz (right).

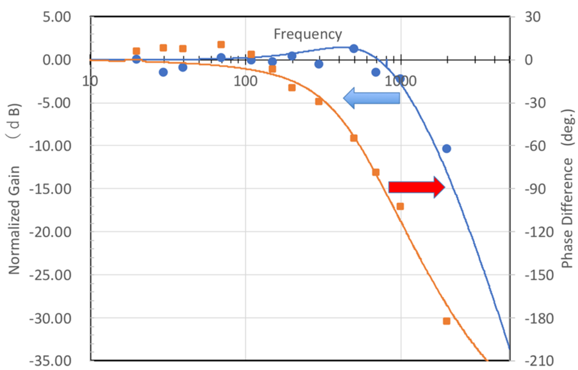


Figure 9: Frequency domain characteristics between the RQ current and the spill signal with fixed pattern operation of EQ magnet, where the gain is normalized at 20 Hz.

### *Transfer Function*

The solid lines in Fig. 9 are drawn using the transfer function of Eq. (1).

$$H(S) = \left(\frac{1}{1+T_{DMAG}*S}\right) * \left(\frac{1+T_L*S}{1+\alpha*T_L*S}\right) * \left(\frac{\omega_C^2}{S^2+\frac{\omega_C*S}{Q}+\omega_C^2}\right). \qquad (1)$$

In Eq. (1), first term means a first order low-pass frequency response of the RQ magnet, second term means phase lead response, which indicates increment response from $1/T_L$ to $1/\alpha T_D$ ($\alpha$<1), and third term means second order low-pass characteristics, which has a gain peak corresponding to the Q value at the resonance frequency and a steep slope. Figure 8 compares the experimental result and the calculation using Eq. (1), where $T_{DMAG}$:80 us, $T_L$: 455 us, $\alpha$: 0.29, $\omega_C$: 0.245 rad/sec, and Q: 0.6.

## SUMMARY

- To investigate the optimization of spill feedback system, we have studied how affect the RQ current on the beam spill by driving the RQ magnet with a sinusoidal current of various frequency.
- With the spill feedback operation of EQ magnet, it cancels the tune modulation caused by the RQ magnet in low frequency.
- With the fixed pattern operation of EQ magnet, the test result shows a kind of low pass filter characteristics.
- Fitting of the transfer function was attempted by the product of three function, which consists of first order low pass filter of the RQ magnet response, phase lead response, and second order low pass filter response.

## REFERENCES

[1] Joint *Project* Team of JAERI and KEK, "The Joint Project for High-Intensity Proton Accelerators", KEK Report 99-4, 1999 and JAERI-Tech 99-056, 1999.

[2] P. Singh, P. Forck, P. Boutachkv, S. Sorge, and H. Welker, "Slow Extraction Spill Characterization from Micro to Millisecond Scale", in *Proc. IPAC'18*, Vancouver, BC, Canada, Apr.-May 2018, pp. 2095-2098. Doi:10.18429/JACow-IPAC2018-WEPKA007

[3] S. Sorge, P. Forck, and R. Singh, "Measurement and Simulations of the Spill Quality of Slowly Extracted Beams from the SIS-18 Synchrotron" in *Proc. IPAC'18*, Vancouver, BC, Canada, Apr.-May 2018, pp. 924-926. Doi:10.18429/JA-Cow-IPAC2018-TUPAF081

[4] M. Tomizawa et al., "Slow extraction from the J-PARC main ring using a dynamic bump", *Nucl. Instr. Meth. A*, vol. 902 pp. 51-61, 2018. doi:10.1016/j.nima.2018.06.004

[5] Y. Arakaki et al., "Electrostatic Septum for 50 GeV Proton-Synchrotron in J-PARC", in *Proc. IPAC'10*, Kyoto, Japan, May 2010, paper THPEB010, pp. 3900–3902.

[6] R. Muto et al., "Current Status of Slow Extraction from J-PARC Main Ring", presented at *IPAC'19*, Melbourne, Australia, May 2019, paper WEPM007, this conference.

[7] A. Schnase et al., "Application of Digital Narrow Band Noise to J-PARC Main Ring", in *Proc. IPAC'10*, Kyoto, Japan, May2010, paper TUPEA051, pp. 1446–1448.

[8] A. Kiyomichi et al., "Beam spill control for the J-PARC slow extraction", in *Proc. IPAC'10*, Kyoto, Japan, May 2010, paper THPEB022, pp. 3933–3935.