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PULSE-BY-PULSE SWITCHING OF OPERATIONAL PARAMETERS IN J-PARC 3-GeV RCS

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Abstract

The J-PARC 3-GeV rapid cycling synchrotron (RCS) provides a high-power beam to both the materials and life science experimental facility (MLF) and the main ring synchrotron (MR) by switching the beam destination pulse by pulse. To meet different requirements from the MLF and the MR while keeping beam loss within permissible levels, the RCS has recently introduced a pulse-by-pulse switching of the operational parameters such as injection painting emittance, chromaticity and betatron tune. This paper reports such recent progress of the RCS beam commissioning and operation.

INTRODUCTION

The J-PARC 3-GeV rapid cycling synchrotron (RCS) is the world's highest class of a high-power pulsed proton driver aiming for a 1-MW beam power [1]. A 400-MeV H^- beam from the injector linac is multi-turn charge-exchange injected into the RCS through a carbon foil over a period of 0.5 ms. The RCS accelerates the injected protons up to 3 GeV with a repetition rate of 25 Hz. Most of the RCS beam pulses are delivered to the materials and life science experimental facility (MLF), while only four pulses every several second are injected to the following main ring synchrotron (MR) by switching the beam destination pulse by pulse. The requirements for the beam operations to the MLF and the MR are different. Thus, different parameter optimizations are required for the two operation modes.

Most of the key parameters in the RCS, such as injection bump field, RF voltage, steering field and sextupole field, can be switched pulse by pulse. They enable us to optimize transverse injection painting [2], longitudinal injection painting, closed orbit correction, and chromaticity manipulation for each beam destination. In addition, the power supplies of the quadrupole correctors were recently improved to realize a pulse-by-pulse switching of betatron tune.

In this paper, we present our recent efforts made to fulfill different requirements for the beam operations to the MLF and the MR while maintaining the compatibility between the two operation modes, by making the best use of the switchable parameters.

PARAMETER OPTIMIZATION FOR MLF

Most of the RCS beam pulses are transported to the MLF, so the machine activation of the RCS is mainly determined by the beam operation to the MLF. Thus, sufficient beam loss mitigation is essential in this operation mode. In addition, from the MLF, a wide-emittance beam with less charge density is required to mitigate a shockwave on the neutron target, which is essential to obtain a sufficient lifetime of the neutron target. Therefore, realizing a large transverse injection painting with a painting emittance of ε_{tp}~204π mm mrad (ε_{tp}^{rms}~35.4π mm mrad) is a key in this operation mode, where ε_{tp} and ε_{tp}^{rms} show the entire painting area normalized by $1/\beta\gamma=1/1.02$ at 400 MeV and its rms value respectively. This kind of large painting is useful for reducing a foil-scattering beam loss during injection as well as mitigating a major space-charge induced beam loss, and also for forming a wide-emittance beam.

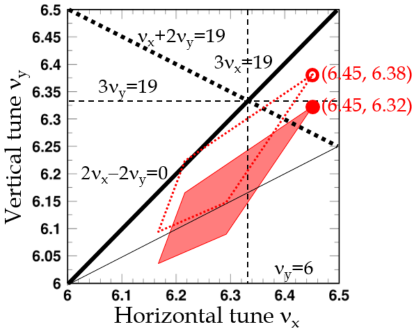

Figure 1: Tune diagram, where the necktie represents a schematic of the space-charge detuning at the end of injection for the case of the beam operation to the MLF.

Figure 1 shows the tune diagram near the operational point. As already reported in the IPAC'16 [3], major issues in realizing such a large transverse painting were the two resonances of $\nu_x+2\nu_y=19$ and $2\nu_x-2\nu_y=0$. They caused a shrinkage of the dynamic aperture and made a significant beam loss when the transverse painting area was enlarged to $\varepsilon_{tp}>100\pi$ mm mrad. But, by minimizing the effects of the resonances, the painting area was successfully expanded to $\varepsilon_{tp}=204\pi$ mm mrad, and we achieved a 1-MW beam acceleration (8.33×10^{13} particles per pulse: ppp) with a very low fractional beam loss estimated to be 0.25% [4]. This remaining beam loss amount is very small, but not negligible for machine activations, so we tried further beam loss mitigation.

The successive beam test, conducted with a similar beam intensity of 7.70×10^{13} ppp (924 kW-eq. intensity) obtained from a 41-mA injection pulse, implied that the 3rd order random resonances of $3\nu_{x,y}=19$ contribute to the remaining beam loss. Actually, the beam loss was further reduced by half by modifying the betatron tune at

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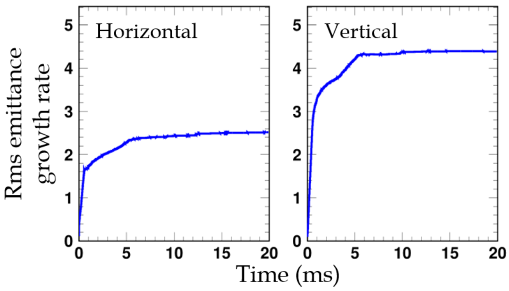

Figure 2: Time dependence of the rms emittance growth (normalized rms beam emittance/normalized rms painting emittance) calculated from injection to extraction.

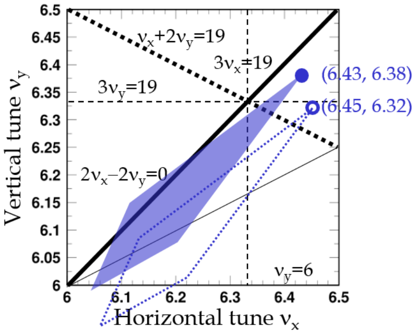

Figure 3: Tune diagram, where the necktie represents a schematic of the space-charge detuning at the end of injection for the case of the beam operation to the MR.

Table 1: Operational Parameter Sets Tested, Where IDs Show the Identification Number of Each Parameter Set

	ID1	ID2	ID3	ID4
Painting area ε_{tp}	51π mm mrad	51π mm mrad	51π mm mrad	51π mm mrad
Sextupole field	(A) in Fig. 4: Off	(B) in Fig. 4: Bipolar	(B) in Fig. 4: Bipolar	(B) in Fig. 4: Bipolar
Betatron tune	(a) in Fig. 6	(a) in Fig. 6	(b) in Fig. 6	(c) in Fig. 6

injection from (6.45, 6.38) to (6.45, 6.32) as shown in Fig. 1. This new operating point minimizes the effect of $3\nu_y=19$, and also keeps the less effect of $3\nu_x=19$.

The key parameters optimized for the beam operation to the MLF are summarized in Table 2 shown later.

PARAMETER OPTIMIZATION FOR MR

Contrary to the MLF case, a low-emittance beam with less beam halo is required from the MR, which is essential to mitigate beam loss at the MR. Consequently, a small injection painting with a painting emittance of ε_{tp}~51π mm mrad is required in this operation mode. What is more, dynamical tune and chromaticity manipulations are essential in this operation mode for mitigating additional emittance growth after injection. This beam test was conducted with a beam intensity of 5.84×10^{13} ppp. This beam intensity corresponds to the MR beam power of 452 kW for the present MR operation cycle of 2.48 sec, and 863 kW for a faster MR operation cycle of 1.3 sec which is realized in the future.

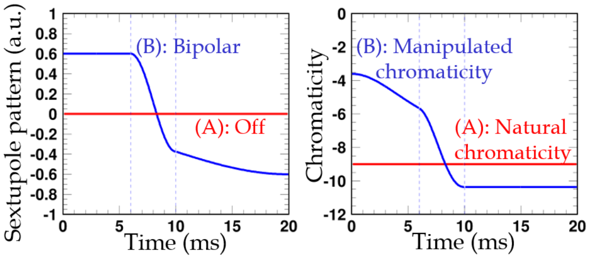

Figure 4: (Left) Sextupole field pattern. (Right) Corresponding time dependence of the chromaticity.

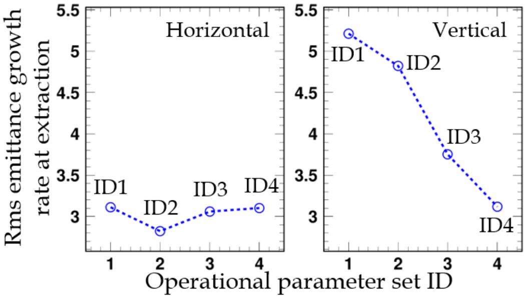

Figure 5: Rms emittance growth at extraction (normalized rms beam emittance/normalized rms painting emittance) measured with the parameter sets of ID1-4 in Table 1.

Figure 2 shows a time dependence of the rms emittance growth calculated from injection to extraction with a small painting emittance of ε_{tp}=51π mm mrad (ε_{tp}^{rms}=5.5π mm mrad), where the operational parameters other than the painting emittance were set to the optimized ones for the beam operation to the MLF. As shown in the figure, a significant emittance growth occurs for the first 6 ms especially on the vertical plane. This emittance growth is manly caused by the vertical stopband of $\nu_y=6$. The small painting applied for this operation mode generates a large space-charge detuning in the low energy region, so a part of beam particles reaches $\nu_y=6$ as shown by a dashed necktie in Fig. 3. On this integer, all-order systematic resonances are excited, so they lead to a large emittance growth on the vertical plane. In other words, this emittance growth can be mitigated by manipulating the tune and the chromaticity so that the beam separates from $\nu_y=6$. Based on this strategy, we performed step-by-step parameter optimizations from ID1 to ID4 in Table 1, where the parameter set of ID1 corresponds to the original one making the large emittance growth in Fig. 2.

To start with, we tested the parameter set of ID2, where a chromaticity manipulation was introduced. The blue curves (B) in Fig. 4 show the applied sextupole field pattern and the corresponding time dependence of the chromaticity. As shown in the figure, the chromaticity was adjusted to be small for the first 6 ms with a dc sextupole field. This manipulation shrinks the chromatic tune spread. That is, it reduces the number of particles

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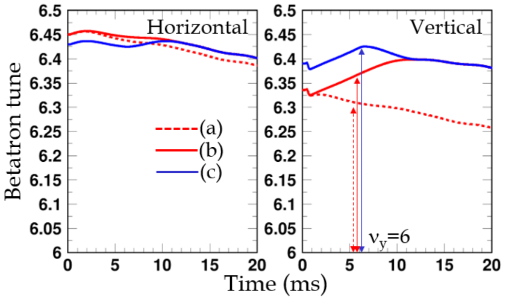

Figure 6: Betatron tunes from injection to extraction.

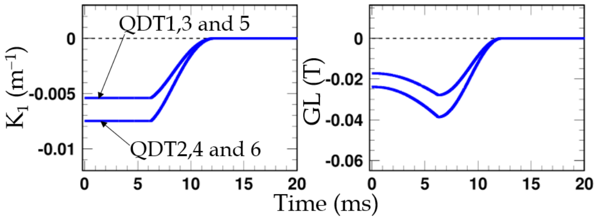

Figure 7: QDT field patterns required for the tune change.

crossing ν_y=6, leading to emittance growth mitigation for this period. After that, the sextupole field gradually fell down to zero, and then it was excited in the opposite polarity. By this latter manipulation, the chromaticity after 10 ms was increased by 15% over the natural value. This large negative chromaticity was utilized for damping a beam instability [5]. In the RCS, the extraction pulse kickers are the most dominant impedance source, causing a horizontal beam instability after 10 ms depending on the operational parameters [6, 7]. In particular, the small painting and the small chromaticity, required for the beam operation to the MR, strongly enhance the beam instability. This bipolar sextupole field pattern simultaneously achieved a suppression of the beam instability after the middle stage of acceleration as well as a mitigation of the emittance growth at the early stage of acceleration. By this effort, the extraction beam emittance was successfully reduced from ID1 to ID2 in Fig. 5.

Next, we tested the parameter set of ID3, where the betatron tune after injection was modified from (a) to (b) in Fig. 6 by adjusting the main quadrupole field patterns. This tune manipulation provides a larger separation from ν_y=6, by which the extraction beam emittance was well reduced from ID2 to ID3 in Fig. 5, as expected.

Finally, we tried the parameter set of ID4. For further emittance growth mitigation, a more active tune manipulation including a tune change at injection is required. But, for minimizing beam loss in the beam operation to the MLF, the tune at injection has to be maintained at (6.45, 6.32), as mentioned in the last section. To solve this conflict, we introduced 6 sets of quadrupole correctors (QDT1-6), that is, tried to switch the tune by activating the QDTs only when the beam is shot to the MR. To realize such a pulse-by-pulse switching operation of the QDTs, the power supplies were improved in the last summer maintenance period. Figure 7 shows the QDT field patterns required for the tune change. By adding the QDT field patterns, the tune was switched from (b) to (c) in Fig. 6 for the beam operation to the MR. This additional tune change by the QDTs provides a larger separation from ν_y=6, by which the extraction beam emittance was further reduced from ID3 to ID4 in Fig. 5, as expected.

Table 2: Operational Parameters Optimized for the Beam Operations to the MLF and the MR

	For MLF	For MR
Painting area ε_{tp}	204π mm mrad	51π mm mrad
Sextupole field	(A) in Fig. 4: Off	(B) in Fig. 4: Bipolar
Betatron tune	(b) in Fig. 6 (6.45, 6.32) at injection	(c) in Fig. 6 (6.43, 6.38) at injection

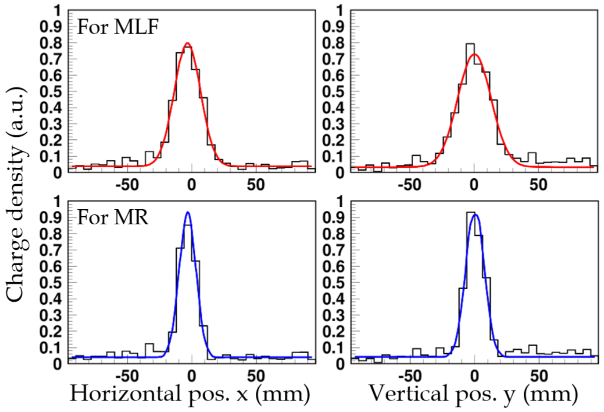

Figure 8: Beam profiles measured at extraction.

By these series of parameter optimizations from ID1 to ID4, the vertical emittance growth was successfully mitigated almost by half. This emittance growth mitigation is ascribed to the reduction of the resonance cross to ν_y=6, as shown in Fig. 3.

EXTRACTION BEAM PROFILES

The key parameters optimized for the beam operations to the MLF and the MR are summarized in Table 2. By introducing the pulse-by-pulse switching of painting emittance, chromaticity and betatron tune, a wide-emittance beam to the MLF and a narrow-emittance beam to the MR were achieved as requested, as shown in Fig. 8.

SUMMARY

The RCS has recently initiated a pulse-by-pulse switching of painting emittance, chromaticity and betatron tune. By this effort, we successfully met different requirements from the MLF and the MR while keeping beam loss within acceptable levels.

Before the next summer maintenance, we will conduct a beam test with the design injection beam current of 50 mA, in which the feasibility of the design 1-MW beam operation to the MLF and also its compatibility with the beam operation to the MR will be inspected again with the new operational parameters optimized this time.

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