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IMPACT OF SLOW-EXTRACTED BEAM BY MAIN POWER SUPPLY TRIP IN J-PARC MAIN RING

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Abstract

J-PARC Main Ring delivers 30 GeV, 65 kW (7×10^{13} ppp) slow-extracted proton beams over 2 s to the hadron experimental facility to drive various nuclear and particle physics experiments. Unexpected behavior of the high-intensity beam caused by a trip of the power supply for the magnets or a beam instability could cause a serious machine damage. In the long shutdown after the 2021 run, the power supplies for the main magnets (bendings, quadrupoles and sextupoles) have been renewed or reused for a higher cycle operation toward the beam power ramp-up. The impact of the slow-extracted beam by the main power supply trip has been evaluated by the beam simulation. The simulation showed that a trip of the defocusing quadrupole or bending power supply could deliver a short-pulsed beam and damage the gold production target in the hadron hall. The mechanism forming the short-pulsed beam and the countermeasure will be reported in this paper.

INTRODUCTION

The J-PARC Main Ring (MR) supplies proton beams, accelerated from 3 GeV to 30 GeV over approximately 2 s using a slow extraction method based on the third-order resonance, to the hadron experimental facility for particle and nuclear physics experiments. Since the first successful slow extraction of a 30 GeV proton beam in January 2009, as of June 2021, the number of particles has reached 7×10^{13} ppp in a 5.2 s cycle, corresponding to a beam power of 65 kW [1]. In the operation of the high-intensity slow extraction in MR, avoiding damage the electrostatic septa (ESSs) or the production target due to an abnormal beam caused by a machine trip is a major challenge in addition to suppressing beam losses during the slow extraction and beam instability occurring in the debunching process [2]. However, in the MR slow extraction operation, immediate extraction to the abort dump by fast extraction is not adopted when a trip signal by the machine protection system (MPS) occurs. Thyratrons are used for the switches of the fast extraction kickers. If one of the five kickers malfunctions during slow extraction, the beam not to be fast-extracted could be circulated with a large transverse amplitude. As shown in Fig. 1, around the ESSs, the circulating orbit is close to the septum by the extraction bump magnets during the slow extraction, and a part of the beam with a large horizontal amplitude may hit the septum and damage it.

After the 2021 beam operation, the main power supplies

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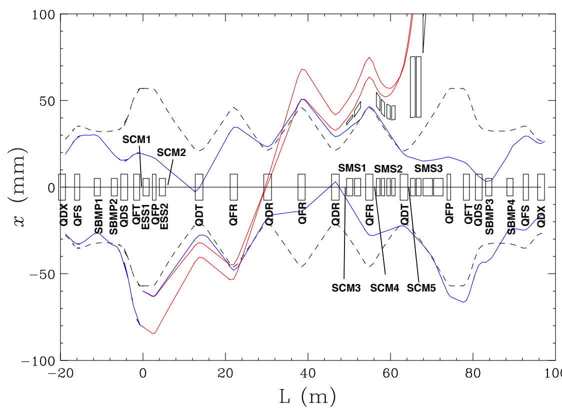

Figure 1: Beam envelops in the SX section.

consisting of 6 bending, 16 quadrupole, and 2 chromaticity correction magnets were renewed or reused for a higher cycle operation toward the beam power ramp-up. We evaluated the risk of one of the power supplies stopping during slow extraction. We proposed an additional interlock system avoiding the risk. Slow extraction operation at 30 GeV will start after this interlock implementation.

MACHINE TRIP RISKS AND PAST TROUBLES

In slow extraction operation, abnormal beams inducing machine damage are classified into two types. The first one is that beams are extracted in a shorter time than usual. A typical example of this type is the trip that triggered the radiation leak accident in the hadron experimental facility in 2013. Due to a malfunction in the current command control of the beam spill control quadrupole (EQ) power supply, a large amount of the beam reached the gold target within a short period of 5 ms and part of the gold target evaporated and diffused. A system to detect abnormal current deviations of the EQ power supply at a high speed (« 1ms) and stop the current as measures to prevent recurrence [3]. Furthermore, the SX abort system shown in Fig. 2 was introduced to stop slow extraction by various interlock signals and then sweep out the beam at the end of the slow extraction [4]. These measures have worked well and contributed to the subsequent beam intensity ramp-up.

Another dangerous abnormal beam is that a high-density circulating beam hits the septum ribbons of the ESS for a short period of time. In the bump orbit commissioning in 2017, the coherent beam oscillation grew due to the horizontal beam instability, and broke the tungsten-rhenium (W/Re)

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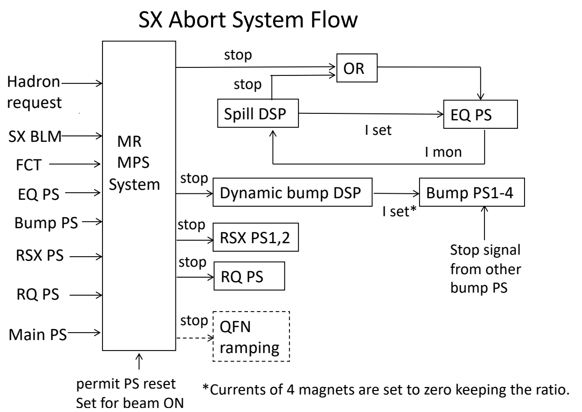

Figure 2: Slow extraction stop system flow (SX Abort).

alloy septum ribbons. It is speculated that this was due to the horizontal chromaticity set to a value that enhance the instability. In the February 2021 slow extraction operation, a malfunction of the vacuum circuit breaker (VCB) in the AC line stopped all seven power supplies of the quadrupole magnets located in the long straight sections and three power supplies for the chromaticity correction magnets. Dozens of upstream septum ribbons in the first ESS were broken, resulting in the operation stop. The analysis revealed that the circulating beams hit the septum ribbons for a short period of time, since the bump orbit was distorted and approached toward the septum due to the current decrease of the quarupole power supplies. As a countermeasure, the bump current fall time of 200 ms was shortened to 54 ms, which was limited by the capacity of the power supply. In order to maintain the closed orbit condition in the fall time, the four bump power supplies need to be lowered keeping the current ratio with the dynamic bump DSP [2]. After the ESS was replaced with a new one, the operation resumed, however, the VCB malfunctioned again. The ESS was avoided to be broken by this countermeasure. Subsequently, in order to shorten the response time from the VCB malfunction to stop the bump power supplies, the trip signal from the VCB has been directly connected to the SX abort system instead of via the quadrupole power supplies.

DEFOCUSING QUADRUPOLE OR DIPOLE POWER SUPPLY TRIP

If the trip of a defocusing quadrupole power supply occurs during slow extraction, the horizontal tune Q_x rises in a short time and approaches the third-order resonance line, which could result in the beam being extracted in a short time. After the 2013 incident, we introduced an interlock system, which stops the focusing quadrupole (QFN or QFX in the arcs) power supply, when the defocusing quadrupole (QDN or QDX in the arc) power supply trips. In the 2021 long shutdown for the upgrade of the main power supplies mentioned above, this type of issue was systematically examined for all quadrupole families. We have decided to stop the power supply of the focusing quadrupole QFN in the arc section when one of any defocusing quadrupole power supply stops. Conversely, if the focusing quadrupole power supply stops, Q_x will move away from the resonance line and the beam will not be extracted. We will demonstrate only the QDX1 power supply trip case. The QDX1 family consists of 13 defocusing quadrupole magnets. Figure 3 (a) shows the measured current waveforms (normalized) when an artificial trip of the power supply was generated, and then the QFN power supply was stopped through the interlock wire connected between their power supplies. Although there is significant noise in the current waveform, it was found that the QFN current begins to decrease at about 15 ms after the QDX1 stop timing. Figure 3 (b) shows the time variation of Q_x calculated by the beam optics code SAD [5] using the current waveforms. The horizontal and vertical tunes before the variation are 22.315 and 20.780, respectively. The Q_x increases by about 0.0145 in a 15 ms delay of the QFN current. This indicates that the beam could be extracted in 15 ms if the trip occurs during slow extraction. Figures 3 (c) and (d) show the current waveform and the time variation of Q_x when the delay is consciously adjusted to be enough short. In this case, the Q_x rise is not seen within the noise width.

We have found that the bending power supply trip increases Q_x similar to the defocusing quadrupole case. This is due to the sextupole field of the chromaticity correction magnets distributed in the arc section. The horizontal and vertical chromaticities Q'_x and Q'_y during slow extraction are corrected to approximately 0 and -3 (unnormalized), respectively. We will demonstrate the BM3 (one of 6 bending power supplies) power supply stop case. Figures 4 (a) through (c) show the normalized BM3 current, the constant QFN current and Q_x variations. The Q_x increases with the BM3 current decrease. Figures 4 (d) through (f) show the time variations when the QFN power supply was stopped with a short delay after the BM3 power supply trip. It is found that Q_x does not increase and then falls down.

EXTRACTED BEAM FRACTION BY TRIP

We evaluated the relationship between the delay time, from the defocusing quadrupole power supply or the bending

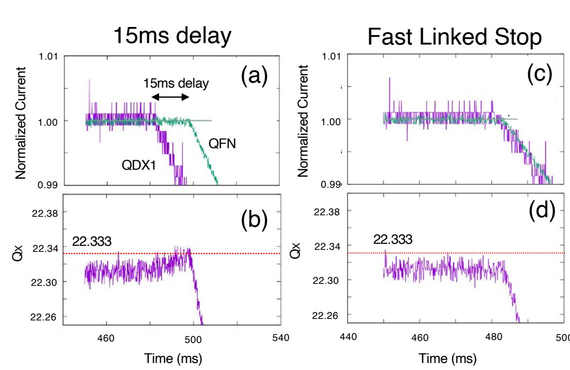

Figure 3: Current and Q_x variations in case QDX1 power supply is tripped and QFN one is stopped by the trip.

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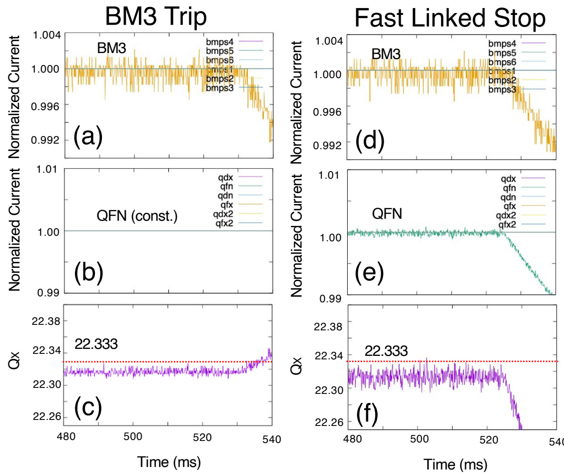

Figure 4: Current and Q_x variations in case BM3 power supply is tripped and QFN one is stopped by the trip.

power supply trip to the start of the QFN power supply stop, and the amount of extracted beam. The current decay pattern of the power supply depends on the load inductance and resistance and also the power supply output circuit. However, we ignore the influence of the power supply output circuit to obtain the decay pattern. The pattern obtained by this approximation decays faster than the measured waveform. Figure 5 shows the time variation of Q_x when the QFN power supply decay starts at 0.1 ms and 1 ms after the QDX2 trip. The Q_x variations under the decay curves are calculated by SAD. The tune variations dQ_x are 0.00014 and 0.00138 for delays of 0.1 ms and 1 ms, respectively. We approximate the phase space distribution of the beam before extraction with a Gaussian distribution (cut off at 3σ). The tune during extraction is expressed as the distance dQ_x from the resonance, the dQ_x is -0.02 at the start of extraction.

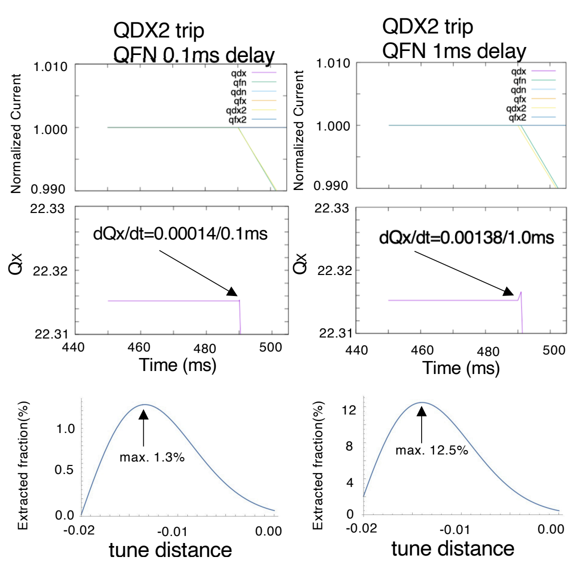

Figure 5: Current, Q_x variations and extracted beam fractions in case QDX2 power supply is tripped and QFN one is stopped by the trip.

The amount of extracted beam fraction changes depending on dQ_x at the trip timing shown in Fig. 5 (c). The maximum amount of extracted beam fraction can be obtained from the curves, which is 1.3% and 12.5% with a delay of 0.1 ms and 1 ms, respectively. A delay of ~0.1 ms is preferable from the target damage. According to this criteria, a fast interlock system (so called fast-linked stop) to output the trip signal and to stop the QFN power supply has been designed. The communication between them is carried out via optical fibers using the MPS system or directly.

CONCLUSION

A defocusing quadrupole or bending power supply trip during slow extraction could damage the production target by a short-pulsed beam due to the Q_x increase. The SX abort system does not work in this case. The fast beam abort using the kickers is not utilized in SX operation for a harmful thyratron pre-firing. The countermeasure is to stop the power supply of the focusing quadrupole family QFN in the arcs at the trip. The measured response time to stop the QFN power supply using the ready-made interlock system using PLCs is 15 ms, which is too slow from the permitted extracted beam fraction. A fast-linked stop system with a 0.1 ms order time response has been designed and soon implemented. The horizontal chromaticity Q'_x is set near zero during slow extraction to obtain a high extraction efficiency. A trip of the vertical correction sextupole power supply increases Q'_x. A risk to induce transverse instability by the trip is being evaluated.

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