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EQUIPMENT PROTECTION SYSTEM AGAINST UNEXPECTED ABNORMALITIES DURING HIGH-INTENSITY PROTON BEAM OPERATION AT J-PARC MR*

M. Yoshii†, Y. Morita, T. Kimura, K. Niki, E. Yanaoka, K. Ishii, M. Tomizawa, R. Muto, K. Miura
J-PARC/KEK, Tokai, Japan
R. Sagawa, Universal Engineering, Mito, Japan
M. Yoshinari, NAT, Tokai, Japan

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Abstract

The J-PARC MR synchrotron began high repetition operation with shortened accelerator cycles in 2022. FX has been supplying a 2×10^{14} proton per pulse (ppp) beam to the Neutrino Experimental Facility with a repetition rate of 1.36 seconds, and SX has been supplying a 0.6×10^{14} ppp beam to the Hadron Experimental Facility with a 4.24 seconds repetition. The amount of heat per accelerated proton beam pulse exceeds 1 MJ, and it is an important issue to avoid damage to the equipment caused by high-intense beam due to abnormalities during beam acceleration. Since the MR is operated in different extraction modes, i.e. FX and SX, the countermeasures are also different, and the adequate protection system also needs to be considered, respectively. Therefore, the countermeasures have been put in place, including a high-speed beam abort system and/or a fast sequential interlock between devices. This report summarizes the systems to protect equipment from abnormalities that unexpectedly occur during high-intensity proton beam acceleration.

INTRODUCTION

The Japan Accelerator Research Complex (J-PARC) is a high intensity proton accelerator facility, which consists of the 400MeV-Linac, 3 GeV Rapid Cycling Synchrotron (RCS) and 30 GeV Main Ring (MR). And the MR synchrotron delivers beam to two experimental facilities (NU and HD) with two different extraction modes. The fast extraction mode (FX-mode) is a single turn extraction with fast kicker magnets and in the slow extraction mode (SX-mode), the circulating beam is slowly extracted over a time period of about 2 seconds. The circulating proton beam current is reached to a 2×10^{14} proton per pulse (ppp) for the Neutrino Experimental Facility with a repetition rate of 1.36 seconds, and SX has been supplying a 0.6×10^{14} ppp for the Hadron Experimental Facility with a 4.24 seconds' repetition. The amount of heat per accelerated proton beam pulse exceeds 1 MJ. The device component composing of the accelerator is equipped with interlocks to protect itself. However, the interlock system that protects other (passive) components (e.g., production target, beam pipes, etc.) in the event of equipment malfunction was inadequately provided.

The MR synchrotron went into a long-term shutdown in 2021, and the main magnet power supplies were replaced in order to increase the beam power by shortening the operating cycle time. This paper summarizes and reports on the inter-device interlocking shutdown system after configuration of the MR synchrotron magnet power supply, which began operation in 2022.

† masahito.yoshii@kek.jp

J-PARC OPERATION CYCLE

The accelerator operation cycle is defined as two extraction modes of the MR synchrotron. One is the fast extraction (FX) mode that delivers the beam to the neutrino beam line using fast-kicker magnets, which extract the circulating beam pulse within a one-turn time period. This operation cycle is 1.36 seconds at present. The proton linac and the RCS operate 25 Hz, and 4 of 34 proton pulses are injected into the MR synchrotron for further acceleration and other remaining pulses are delivered to the Material and Life Science Facility.

In case of failure occurring in the MR devices or in the facilities where the MR beam is delivered, A so-called "MR-inhibit" process is carried out and the incidence of the beam directed at the MR is stopped. As a result, beam supply to MLF continues. In the MR, an abort process is performed for the circulating proton beam within the accelerator. There are three modes for this abort process from the perspective of equipment protection, which are used depending on the operating mode of the MR.

MR Abort (normal mode)

The fast extraction system has two functions to lead the circulating proton beam in the MR. One is to direct a beam to the neutrino beam line and the other is to the abort beam line of where beam dump is located opposite and outside of the MR ring. The extraction system performs an operation for MR abort at the end of each cycle.

Milisecond-Abort (ms-Abort)

This mode is used only in the Fast Extraction mode and circulating beam is immediately aborted at any timing from input (P1) to extraction (P3) when device failure happens. This system can abort the beam in case of an abnormality at any time from injection to extraction. To realize this beam abort system, the extraction equipment is energized in a pattern following the momentum of the beam.

SX Abort

The timing to abort the beam during the slow extraction mode is set so that the kicker magnet can fire when the beam extraction is completed. The purpose of this is to reduce as much as possible the risk of damage to the slow

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extraction device such as an electrostatic septum magnet (ESS) due to malfunction of the beam abort system during slow beam extraction.

FAST EXTRACTION MODE

The fast extraction (FX) system delivers the beam to the neutrino beam line using fast-kicker magnets, which extract all of the beam bunches within a one-turn time period. The operation cycle is 1.36 seconds and will be shorter in future. The circulating proton beam also increase to be 3.3×10^{14} proton per pulse (ppp) and the beam energy becomes 1.6 MJ, which is enough energy to melt metal beam pipes, cause vacuum leaks, and quench superconducting equipment. To protect devices from high intense proton beam incident, fast beam abort system, (so-called, "ms-Abort") has been adopted.

SLOW EXTRACTION MODE

In the slow beam extraction (SX) mode, the MR delivers the long pulse beam to the hadron experimental facility using the slow-extraction devices, which consist of two electrostatic septa (ESS1,2), followed by three septum magnets (SMS1-3), four bump magnets (SBMP1-4), eight sextupole magnets (RSX1-8) for exciting resonance, two high-speed response quadrupole magnets (Extraction Quadrupole and Ripple Quadrupole) for time structure feedback of extracted proton beam (spill).

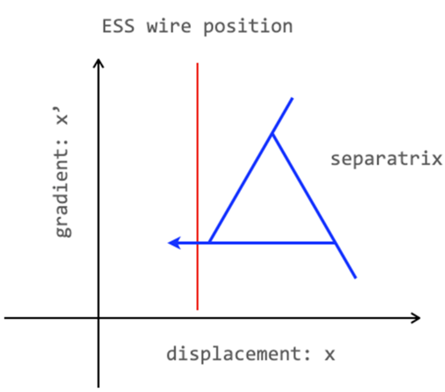

Figure 1: Horizontal Phase Space Map (x - x').

This extraction is done by a high-intensity proton beam that circulates while betatron oscillation, approaching the third integer resonance at Qx = 22.333, expanding its while controlling the beam size, and gradually carving out the beam from the outside. First, we accelerate the bunch proton beam to 30 GeV, turn off the accelerating RF voltage, eliminate the bunch structure of the circulating beam, and create a continuous beam. Slowly extracted 30 GeV proton beam from the MR has a uniform time structure, so-called spill structure and injected into a fixed Au target (T1) to produce secondary beams (Kaons, pions, antiprotons, etc) with 4.24 s repetition [1]. The spill length is typically 2 seconds long. Figure 1 shows the phase space at the electrostatic septum (ESS) position during beam extraction, where the horizontal axis is the horizontal displacement x of the beam, and the vertical axis is the horizontal gradient x'. When RSX1-8 excite third-order resonance, a triangular separatrix (stability limit) exists as shown in the figure. This means that in order to bring the tune close to an integer of ±1/3, the state will be almost the same once every three turns, and particles that are out of this stable region will be kicked out in the same direction every three turns and will end up on the third resonance line [2].

FAST SEQUENTIAL INTERLOCK

In June 2013, while supplying beams to the hadron facility at J-PARC MR, due to a malfunction of the EQ magnet power supply used for the spill control system, about two-thirds of the beam, that was slowly extracted over a two-second period, was extracted in a five-millisecond period. The short-pulsed proton beam hit the production target of the hadron beam line, causing a radiation accident in which part of the target was damaged and radioactive materials leaked out of the target [3]. We deeply investigated the cause of the accident and took steps to prevent it from happening again, and in addition to improve the interlock of the EQ magnet system, we also developed measures to quickly shut down the pair of quadrupole magnets which control the betatron tune. We took measures to suppress short pulse beams for the target caused by rapid horizontal tune movements [4].

Main Magnet Configuration

The MR synchrotron consists of 96 bending magnets and 216 quadrupole magnets. Before 2021, the bending magnets were configured with 16 units each and 6 units of magnet power supply, and the quadrupole magnet was configured to excite 6 types of the focusing quadrupole (QF) magnets and 5 types of the defocusing quadrupole (QD) magnets with different power supplies.

In 2021 for higher repetition operation, 6 bending magnet power supplies and 4 quadrupole magnet (QFN, QDN, QDR, QDT) power supplies have been replaced to new power supplies. And to maximize the reuse of existing power supply, the seven families of quadrupole magnets were rearranged according to the output rating of the existing power supplies [5].

Fast Sequential Interlock

At the initial stage, to avoid short pulse beams due the horizontal tune sudden movements, when an emergency stop is detected in the specific defocusing quadrupole (QD) magnet power supplies, countermeasures have been taken to stop the paired focusing quadrupole (QF) at high speed. As a result of the analysis of the entire family that governs the betatron oscillations in the direction, all bending magnet power supplies and five QD magnets (QDS, QDR, QDN, QDX and QDT) are tuned to an emergency stop and a short pulse beam is extracted to the hadron target. I found out that it is highly possible. Additionally, this analysis revealed that the increase in tune can be suppressed by stopping one specific focusing quadrupole magnet (QFN) rapidly in conjunction with the emergency stop signal of the relevant power supplies distributed in five different power supply buildings.

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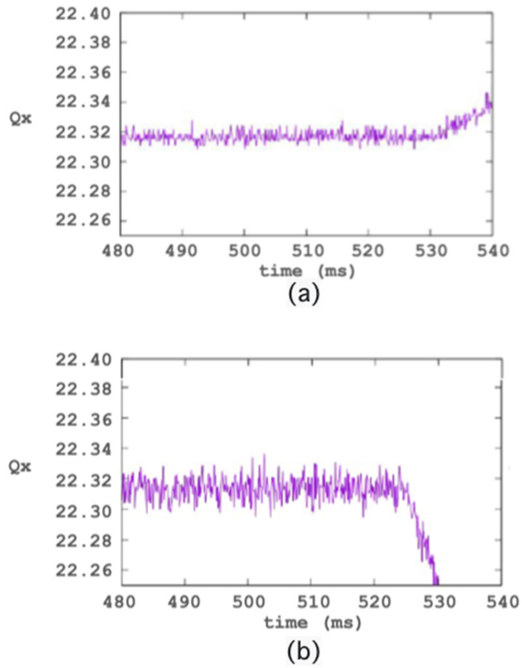

Figure 2: Horizontal tune behavior when the bending magnet (BM2) trips, (a) Qx increases by more than 0.02 in 10 ms, (b) in case of QFN stopped with BM2 trip.

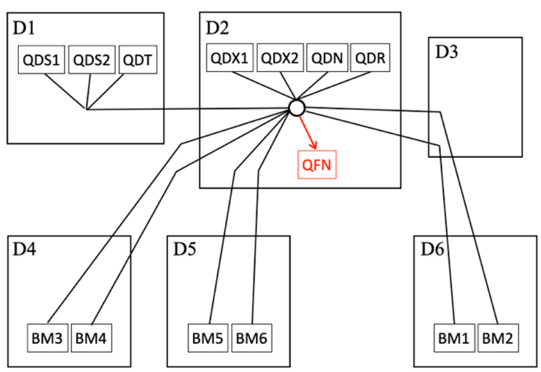

Figure 3: Fast sequential optical network for "Tomozure": Emergency stop signals for the 11 families (13 units) of power supplies distributed in five power supply buildings are sent to the D2 building and stop the QFN power supply.

Figures 2(a) &(b) show the calculation results of the time variation in horizontal tune (Qx) when each bending magnet makes an emergency stop (a). By sequentially interlocking the QFN quadrupole magnet power supply with the emergency stop signal of the bending magnet, the horizontal tune (Qx) decreases over time (b) and this indicates that the beam is not extracted.

The related 13 power supplies for the 11 magnet families are distributed in five power supply buildings. Therefore, as shown in Figure 3, we have created a so-called "Tomozure" network in which emergency stop signals are aggregated at each power supply building, sent to the #2 power supply building (D2), and the QFN focusing quadrupole magnet power supply is stopped in conjunction with each other.

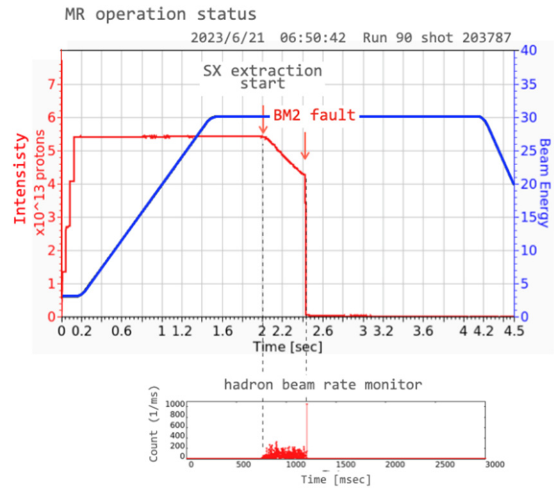

Figure 4: Example incident of "Tomozure" interlocking between QFN and BM2 power supplies.

A converter gate block signal and a high-speed protection signal are used as "Tomozure" fast sequential signals. As a result, interlocking stops can be achieved in a short time period of several tens of microseconds.

Figure 4 shows the circulating beam intensity and the beam energy in a cycle (upper) and the output waveform of the "beam rate monitor" taken out to the Hadron Experiment Hall (lower) when one bending magnet (BM2) power supply was stopped due to an interlock while a beam of about 50 kW was being taken out to the Hadron Experiment Hall. In this incident, the number of beam particles taken out from the beam rate monitor is about 6.4×10^{11} protons per pulse (ppp) (about 3 kJ), and the MR beam intensity graph shows that almost the total amount of residual beam when BM2 interlock occurs is 4.3×10^{13} ppp (equivalent to 39 kW/200 kJ) was not taken out to the hadron beamline due to the operation of the inter-device interlocking shutdown system.

SUMMARY

The high-speed interlock systems applied in the J-PARC MR in order to minimize damage to the components of the accelerator facility caused by intense beams, which is the fate of high intensity accelerators. J-PARC MR has two operation modes, each of which requires an appropriate interlock. The "ms-abord" system in FX mode and the "Tomozure" in SX mode, are the essential.

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