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MALFUNCTION, CAUSE AND RECURRENCE PREVENTION MEASURES OF J-PARC SLOW EXTRACTION

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Abstract

The radiation leakage accident occurred at the J-PARC hadron experimental hall on May 23, 2013 was triggered by a target damage due to an unanticipated beam from the main ring (MR). An extremely short-pulsed beam was extracted from MR by malfunction of the quadrupole (EQ) power supply for a spill feedback. A simulation with the slow extraction process explains such a short beam pulse generation. The cause of the malfunction has been identified by an intensive investigation of the EQ power supply system performed after the accident. We will show the recurrence prevention measures.

INTRODUCTION

The slow extraction of the J-PARC MR uses the third integer resonance. The horizontal tune is ramped up to $Q_x = 67/3$ by changing quadrupoles (48-QFN family) located in the ARC section. Eight sextupole magnets (RSX1∼8) to excite a third integer resonance are also located in the ARC section, which are fed by two sets of power supply. Two electric septa (ESS1∼2), low (SMS11∼12) , medium (SMS21∼24) and high field magnetic septa (SMS31∼34) and four bump magnets (SBMP1∼4) are located in a 116 m long straight section connected to a high energy beam transfer line to the hadron experimental hall [1, 2]. A uniform time structure of the extracted beam (beam spill) is required for the experiments. To get a uniform beam spill, a spill feedback system has been introduced. The spill feedback system comprises two extraction quadrupoles (EQs) and ripple compensation quadrupole (RQ). The EQ forms a rectangular spill shape, and the RQ suppresses a spiky time structure due to the ripples of power supplies of the lattice bending and quadrupole magnets [3]. The current ripples of these power supplies are large and cause serious problems for experiments. In addition to the spill feedback system, a transverse RF is applied to the circulating beam during the slow extraction [4]. The 30 GeV beam power before the accident was 24 kW at an accelerating cycle of 6 sec. with a flat top of 2.93 sec. (3×10^{13} ppp). The extraction efficiency was 99.5% and typical spill duty factor is 45%. The accident occurred at 11:55 a.m., May 23, 2013. The 2/3 of circulating particles was extracted in a very short period of 5 ms by the malfunction of the EQ power supply (EQ P.S.). The gold target was partially evaporated by the short beam pulse. A radioactivity was leaked into the experimental hall from gaps around target area. In this paper, an analysis of the malfunction shot, investigation of the cause and preventive measures for the malfunction are reported.

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ANALYSIS OF MALFUNCTION SHOT

In the ordinary slow extraction operation, a DSP generates the EQ current pattern to obtain an uniform spill shape from the spill monitor signal (see upper part in Fig. 1). Green line shows the DSP current command and blue line is actually flowed EQ current. The DCCT signal (red line) decreases linearly, which indicates that the beam spill shape is flat. Light blue line shows the spill monitor signal. Grass green line shows a RQ current pattern to suppress the spiky spill. Lower part of Fig. 1 shows the malfunction shot. Despite of the DSP command to flow the EQ current (green line) over 0.3 sec., the EQ current did not respond, and the beam is not extracted. The DSP required further to flow the current for the EQ P.S.. At the timing corresponding to 159 A set value, the EQ current suddenly flowed following to the DSP set value. The EQ P.S. was

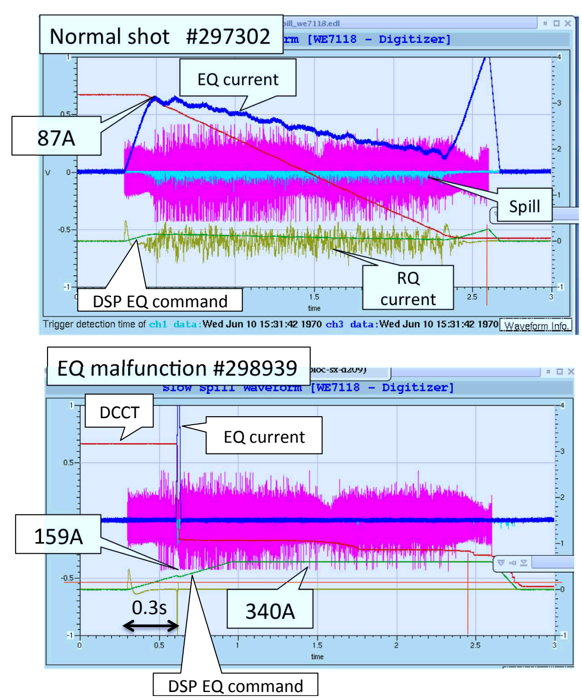

Figure 1: Spill control patterns of normal and malfunction shots.

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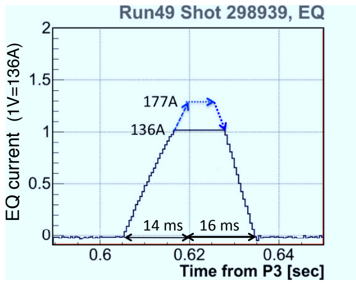

Figure 2: EQ current pattern at malfunction shot. Dotted line shows speculation by the test.

tripped by the over voltage. Tracking error indicating the deviation between the set value and the actual output current was detected in the EQ P.S.. At the same time, the RQ power supply was tripped by the over current so as to compensate the rapid beam intensity increase. The 2/3 of the circulating beam was extracted in 5 msec. by the rapid EQ current increase.

Figure 2 shows the EQ current at the malfunction shot. The recorded current was saturated at 136 A. From the response for a 159 A step command test performed after the accident, the maximum current achieved to 177 A by overshoot and repeating the hunching. A PLC detected the over voltage and dropped the output current after 14 msec. from the start of the current increase. The horizontal tune pattern can be derived from this EQ current pattern incuding the estimation and a scheduled QFN current pattern. The tune was estimated to be moved from 22.313 to 22.327 by 0.014. The extracted beam time profile is simulated by using the horizontal tune pattern. The circulated beam is assumed to be Gaussian distribution with the emittance of 0.8π mm·mrad cut at 3σ. Upper part of Fig. 3 shows a horizontal tune pattern and lower part shows actual beam spill obtained from time derivative of the recorded DCCT signal and the simulated one. The simulation reproduces an

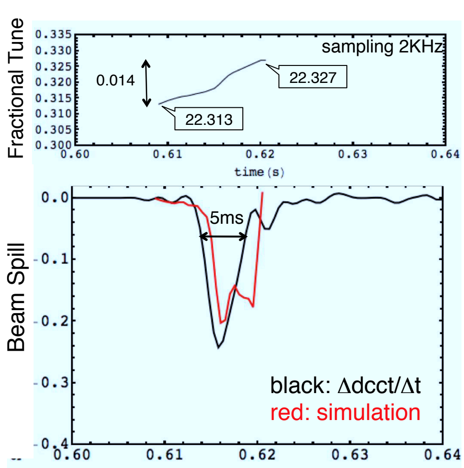

Figure 3: Horizontal tune pattern and beam spill at the malfunction shot.

actual beam spill. An extracted particle fraction can be derived from the simulation as a function of the tune distance from the third integer resonance line. The extracted particle fraction by the simulation is 67%, which is consistent with actually extracted particle fraction at the malfunction shot. A quick stop of the EQ current increase after the trip detection reduces the short-pulsed beam fraction.

CAUSE OF MALFUNCTION

Figure 4 shows a block diagram for the current control of the EQ P.S.. A digital signal from the DSP is converted to an optical signal and the optical signal is converted back to a digital signal by a VME board. The digital signal is transmitted to a digital interface (IF) board with photo-couplers. The digital signal from the photo-couplers is converted to an analog signal by a DAC and fed into FET gates to generate the output current. The 5 V necessary for the digital IF board is supplied from a DC power supply board.

To investigate the cause of the malfunction, the EQ P.S. was continuously operated at a sawtooth current pattern of 6 sec. cycle after the accident over 3 months. The trips of the EQ P.S. rarely happened also in the test. Trips by the over voltage were just 4 times of 774600 cycles. From the rare trip events, we observed an abnormal behavior of the digital signals sent to the DA. The DC power supply board by the maker of the EQ P.S. has two types, low power and high power ones. Though the high power type must be used from the power consumption, the lower power type had been misused. The low power type does not have any heat sink on a voltage regulator and any power transistor supporting the voltage regulator. The voltage regulator was overheated by an excessive power consumption. The surface temperature achieved to $130°C$. As a result, The voltage generated by the regulator dropped and fluctuated

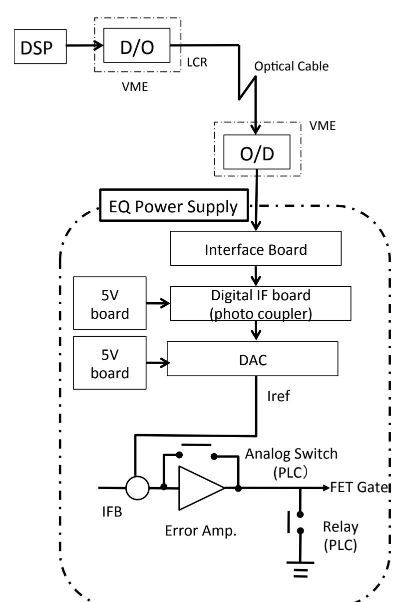

Figure 4: Block diagram of the EQ current control.

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near 3 V. In this situation, the photo-couplers can not work well. A voltage generator was prepared instead of the DC power supply board for the test. A sawtooth current pattern was sent from the DSP. When the voltage from the voltage generator is set to 3.45 V, the digital signal is normally transmitted to the DA, on the other hand, for 3.18 V, abnormal digital signals makes a step response for the DAC output. This is similar as the behavior at the malfunction shot. The DC power supply board has been replaced to the high power type after this investigation.

PREVENTIVE MEASURES FOR EQ POWER SUPPLY

The cause of the malfunction has been identified and the direct source of the malfunction has been replaced to an appropriate one as described in last section. Preventive measures supposing possible other risks are taken for the coming slow extraction operation. The main improvements are as followed.

Adding Interlock Items

The output current of the EQ P.S. had been stopped by the over-voltage and over-current detections before the accident. The following items are added as interlocks stopping the output current; (1) strobe and parity errors in the digital signal, (2) deviation between set and actual output current (3) two external interlock channels.

Fast Interlock Board

A fast interlock board are newly introduced. The logic ICs in this board detect trip signals and control analog switches connected to the FET gates. The fast action for stopping the FET output is possible by the board. The measured propagation time in the board is just 100 nsec.. In the 159 A step command test, the output current stopped at just 0.37 A from 0 A and rapidly decreased by the deviation trip. This test result shows the new interlock system considerably reduces the target damage risk.

Current Deviation Detection System

The current deviation in the EQ P.S. can be detected as described in the previous section. Adding this detection, we introduce a new current deviation detection system. An analog signal of the output current monitor in the EQ P.S. are AD-converted in the KEK-VME board. The synchronized digital signal with the DSP strobe is converted to the optical signal. The optical signal is again converted to the digital signal and sent to the DSP. The DSP checks the deviation between the spill feedback command value and the actual output current value at 100 KHz. If the deviation is large, the DSP sends an interlock signal to the external interlock port on the fast interlock board and the output current was rapidly stopped. This deviation system can detect an anomaly in the digital/optical transmission lines from the DSP to the EQ P.S. as well as an internal anomaly in the power supply. The basic performance of the system has been already checked.

PROBABLE OTHER RISKS AND COUNTER MEASURES

- When the defocusing quadrupole power supply is tripped, the horizontal tune increases and approaches to the third integer resonance. This trip could extract the short pulsed beam. This has been once observed in a user operation before the accident. Though the beam pulse width was 2 msec., the target was safe since the extracted proton number was low, 1.3×10^{12}. Avoiding a similar risk, a pairing focusing quadrople family is stopped not so as to approach the horizontal tune to the resonance, when the defocusing quadrupole trip happens.
- At the end of slow extraction, the remained beam is kicked to the beam dump by kickers in the fast extraction section. The thyratrons for the kickers are accidentally fired to a certain rare rate. If the accidental fire happens during the slow extraction, some part of the circulating beam could reach to the target in very short time. The beam can hit on the electric and magnetic septa and could give a damage for them. To avoid this risk, the charging start timing will be set as near as possible the scheduled fire timing (the end of slow extraction).
- In the accelerator study for a higher beam performance, something inexperienced could happen. To avoid the target damage risk in the study run, the beam will bypass the target by shifting the beam orbit for the study run.

SUMMARY

The radiation leakage accident by a target damage occurred at the J-PARC hadron experimental hall was triggered by the malfunction of the spill feedback EQ P.S. in the main ring. The 30GeV proton beam of 2×10^{13} was hit to the gold target in a short time of 5 msec.. The cause of the malfunction has been identified and the source was replaced. Various preventive measures are taken to reduce the risks with the target damages for resuming of the slow extraction operation.

REFERENCES

[1] M. Tomizawa *et al.*, "Design of Slow Extraction from 50 GeV Synchrotron", Proc. of EPAC'02, p. 1058.

[2] M. Tomizawa *et al.*, "Performance of Resonant Slow Extraction from J-PARC Main Ring", Proc. of IPAC'2012, p. 481.

[3] A. Kiyomichi *et al.*, "Beam Spill Control for the J-PARC Slow Extraction ", Proc. of IPAC'10, p. 3933.

[4] A. Schnase *et al.*, "Application of Digital Narrow Band Noise to J-PARC Main Ring ", Proc. of IPAC'10, p. 1446.