ISBN: 978-3-95450-201-1 doi:10.18429/JACoW-IBIC2018-TUPA04

ANALYSIS OF INTERLOCKED EVENTS BASED ON BEAM INSTRUMENTATION DATA AT J-PARC LINAC AND RCS

N. Hayashi*, S. Hatakeyama, A. Miura, M. Yoshimoto, JAEA/J-PARC, Tokai, Ibaraki, Japan
K. Futatsukawa, T. Miyao, KEK/J-PARC, Tokai, Ibaraki, Japan

Abstract

J-PARC is a multi-purpose facility. Accelerator stability is the one of important issues for users of this facility. To realize stable operation, we must collect data on interlocked events and analyze these data to determine the reasons for the occurrence of such events. In J-PARC Linac, data of interlocked events have been recorded using several some beam loss monitors and current monitors, and these data have been are analyzed and classified. In J-PARC RCS, new instrumentation is being introduced to obtain beam position. We discuss the present status and future plans related to this subject.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a complex research facility consisting of three accelerators [1] and three experimental facilities. The first accelerator, Linac, was upgraded in 2014 by adding the Annular-ring Coupled Structure (ACS) after the separated drift-tube-linac (SDTL) and by replacing front-end system, a RF-driven ion source and a 50-mA Radio-frequency Quadrupole (RFQ). The injection system of the second accelerator, a 3-GeV Rapid-Cycling Synchrotron (RCS), was upgraded as well to accept 400 MeV H^- beams. Nominal RCS beam power of the Materials and Life Science Experimental Facility (MLF) was recovered to 500 kW in 2018. Because of the two neutron target failures in 2015, the beam power recovery program was executed with a very conservative schedule.

The design beam power for 1-MW operation was demonstrated for 1 h recently. Some fraction of the RCS beam is delivered to either the Neutrino Experimental Facility (NU) or the Hadron Experimental Facility (HD) through the Main Ring (MR) at intervals of 2.48 or 5.2 s, respectively. The beam power supplied to these two facilities was increased gradually to about 490 kW and 50 kW, respectively [2].

Availability of the facilities is as important as high beam power. To this end, the numbers of un-scheduled beam stoppage events, also called interlocked events, should be reduced. At least, it is necessary to understand the causes underlying accelerator interruption. Hence, we record and analyze interlocked events in detail. One of the J-PARC interlock subsystems is called Machine Protection System (MPS). There are several sources of MPS, for instance, mal-function of an apparatus, vacuum problem, or beam loss signal from the proportional-type Beam Loss Monitor (BLMP). Individual BLM MPS events lead to short down-times, but the number of Linac BLMP MPS events is large and comparable to the number of RFQ MPS events. The total down-time of such events is non-negligible [2]. BLMP MPS events are classified into three categories: events associated with other machine MPS, multiple BLMP MPS events without other MPS and finally single BLMP MPS events [3].

Especially, for the Linac, most of events are single BLMP triggered MPS. Neighboring BLMPs show no specific sign of being affected. In such an event,it may not be necessary to stop operation because the beam loss signal of single BLMP event continues only for one intermediate pulse length, which is less than 1 μs. However, in the case of RF-interlock-associated BLMP signal, the beam loss signal extends over multiple intermediate pulses. We believe that the single BLMP MPS does not represent significant beam loss. Hence, we are of the opinion that such events can be eliminated.

INSTRUMENTATION

Beam Loss Monitor

Most BLMs are proportional chambers [4]. The BLM detectors used in the Linac and the RCS are the same, but their operational conditions are different. In the Linac, the high voltage of the BLM detector is -2 kV, and its pre-amp input impedance is 50 Ω for better time response. Raw output signals from the signal amplifier are used for MPS in the Linac. By contrast, integral signals from BLMP are used to trigger MPS in the RCS. Different HV is applied to each BLMP because of individual optimization. High pre-amp input impedance is selected.

The present setting is excessively sensitive for the Linac, as discussed later. Therefore, we investigate a new parameter setting to reduce the number of single BLMP events. To this end, we decrease HV from -2 kV to -1.5 kV and select high impedance (10 kΩ). Pre-amp gain is maintained at ×100. The new settings are applied gradually because the pre-amp or the other filter module sets off an alarm if HV is lower than a certain value. Some pre-amps have a pre-set value is higher than -1.5 kV. Recent MPS statistics are presented in later.

BLMP detectors are located all over the accelerator bodies (93 in Linac and 90 in RCS). Particularly, one of the most important detectors is at the beam transport line from Linac to the 3-GeV RCS (L3BT). It is called L3BT:BLMP21, and it is located just before the first bending magnet BM01 of the 90-degree arc section. SCT12, a Slow Current Transformer for detecting beam current, is located between the last accelerating cavity ACS21 and BM01.

* naoki.hayashi@j-parc.jp

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Data Archive System for Linac

A waveform archive system consists of many oscilloscopes (Yokogawa DL1640). Its memory can be used in a segmented memory, and the last 20 triggered waveforms are stored in memory. If an MPS event is triggered, those waveforms are archived into the permanent storage disk. The sampling rate is 100 Msamples/s, and the record length is 100 ksamples, which translates into a recording duration of 1 ms [3]. The triggering condition is optimized for instantaneous trigger stop by abandoning the monitoring function. The system has almost no dead time. All BLMP integral signals are digitized using VME ADC boards. These boards can digitize all 25-Hz pulses encountered over the last 30 min. In addition, they record the maximum values within the last two seconds and store these data in long-term data archiver.

Data Archive System for RCS

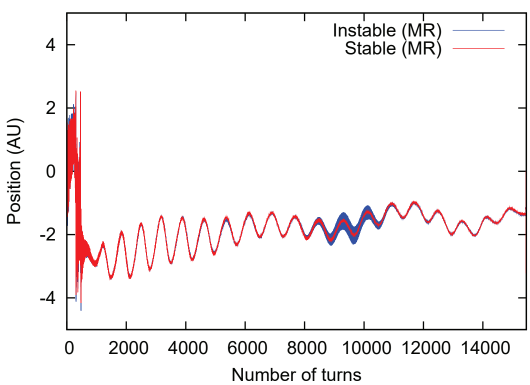

Figure 1: Bunch-by-bunch horizontal beam position data. Under the unstable condition (blue), the position data indicates slightly larger oscillation around 9000 turns.

The RCS archive system has been described in the literature [5,6]. Although its time resolution is limited, the system records all 25-Hz pulses, beam intensity, and BLMP integral signals. The RCS is required to provide a very different beam to the MLF and the MR. Hence, there is insufficient margin to satisfy the requirements of both MLF and MR at the same time. Occasionally, RCS may approach the beam instability condition. It is straight-forward to see turn-by-turn BPM (beam position monitor) data and useful to judge immediately whether instabilities occur. Libera Hadron [7] can provide bunch-by-bunch beam position online. Moreover, it can store event data whenever an interlocked event occurs. The stable beam and the slightly unstable beam are plotted in Fig. 1. The unstable part is shown in the middle of acceleration period. A BPM detector was used for tune measurement because its electrodes are configured as parallel four electrodes.

INTERLOCKED EVENTS

Linac Multiple BLMP Events

Such type of events are usually rare. However, last fall, the number of this type of events increased abruptly. Later, this increase was found to have been caused by a problem with the timing system. The timing system distributes three types of signals, namely, 12-MHz clock signal, 25-Hz trigger signal, and so-called "Type signal." The "type signal" specifies the delay parameter of each instrument for the next trigger in advance. It was noticed that some "type signal" were inconsistent. Each sub-system works properly without MPS because it only follows the sequences defined by its "type signal". Because the beam conditions are different between the MR and the MLF beams, the power supplies or other apparatuses must know the mode in which to operate for the next pulse. If a wrong "type signal" is received, the apparatuses work, but they are not synchronized properly.

It took some time to identify and solve the above-described problem because the problem is intermittent and does not reoccur for a few days at a stretch. These messy events occurred all over the Linac area, as opposed to a specific cavity or station. Hence, we suspected that the events originated in the uppermost part of the signal distributor. Probably, one of electric-optic converters degraded and the optic output signal weakened. Some receiver modules did not work properly owing to the weak signal. After replacing the electric-optic converter module, the problem disappeared, and multiple BLMP events were not detected.

Linac Vacuum MPS Event

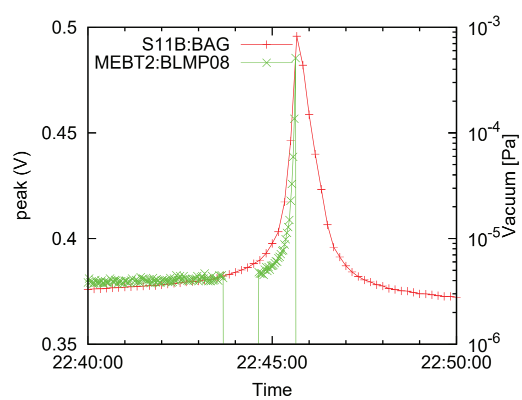

Figure 2: Occurrence of vacuum MPS events close to SDTL11 cavity. One BLMP shows increased signal owing to bad vacuum.

Occasionally, the vacuum pressure worsens and a BA gauge triggers MPS. The BA gauge threshold is 1×10^{-4} Pa. Particularly, worsen vacuum event often happens at SDTL section. One BLMP at MEBT2 (medium-energy beam-transport line between SDTL and ACS section) shows a very clear correlation, as in Fig. 2, although the signal is not sufficiently large to hit the MPS threshold. The BA gauge data are archived at intervals of 10 s. Hence, the pressure

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data are not very precise, but the vacuum worsened and recovered by itself within a few minutes. During that period, the amplitude of the integrated BLMP signal of MEBT2 BLMP08 increased by about 20% within a short period.

Linac BLMP Integral Signal

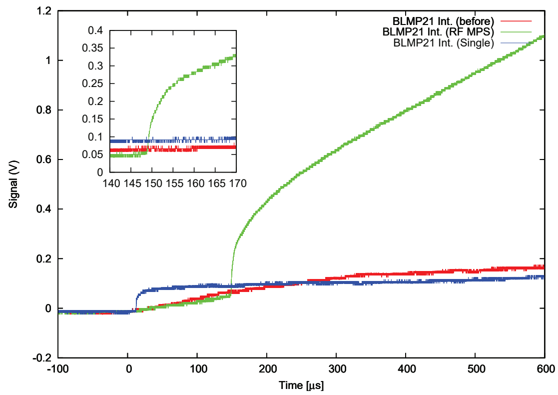

Figure 3: L3BT:BLMP21 integral signal comparison for various categories. Normal (red), RF MPS (green), and single BLMP events (blue).

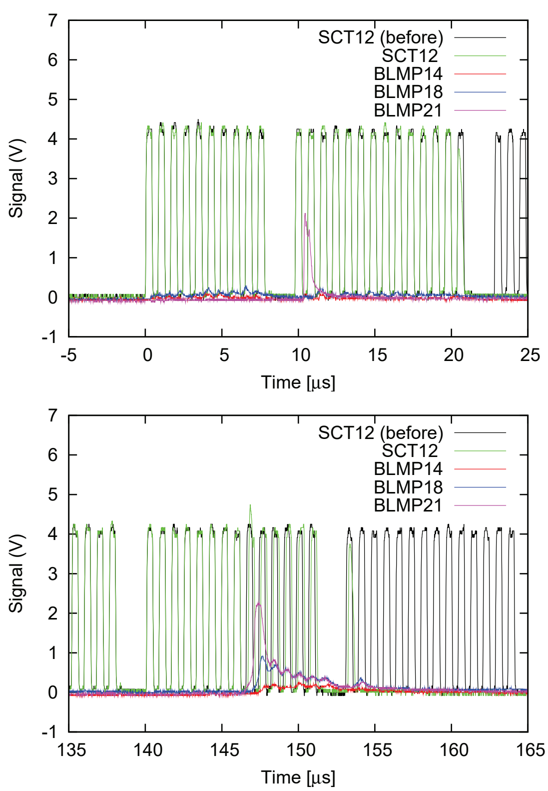

Figure 4: L3BT:BLMP raw signals and SCT for single BLMP (upper) and RF failure associated events (lower).

The BLMP signal unit provides two outputs: one is a raw waveform signal and the other is a signal integrated over 2 ms. As mentioned above, RCS uses integrated BLMP signals for MPS because they are more stable, whereas the raw signal is used in Linac. As examples, the integrated BLMP signals of two different types of events are shown in Fig. 3. For these events, the length of the beam pulse was 320 μs. The red part in Fig. 3 indicates a normal event. The blue part is a single BLMP (this L3BT:BLMP21 only) MPS, and it corresponds to Fig. 4 (upper). There is a small jump at the beginning, but the integral signal is lower than the normal signal after 250 μs. The RF MPS associated BLMP event (green in Fig. 3), the signal is considerably larger at the end. However, its rise time is not adequately fast to distinguish it within 10 μs, if MPS threshold is set to 0.3 V or higher.

New BLMP Setting for Linac

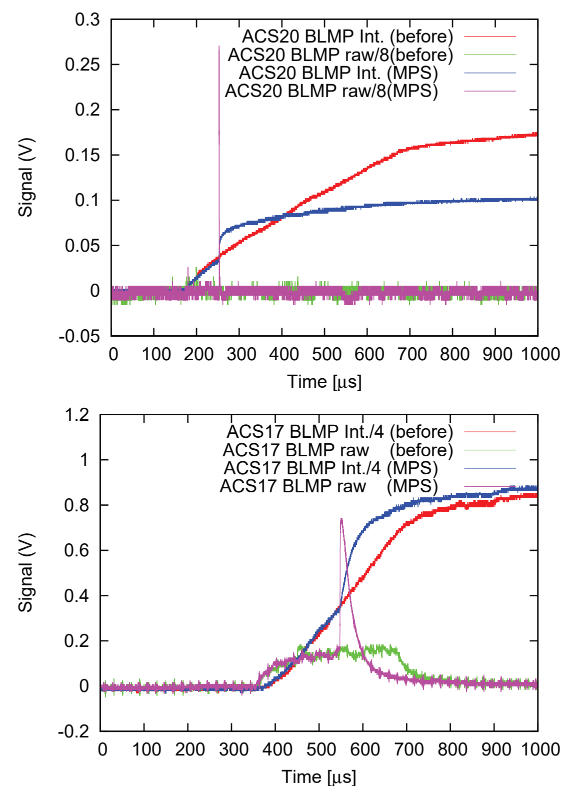

Figure 5: BLMP signals of old (upper) and new (lower) settings for various events.

A similar study was performed for the ACS section BLMP, and the new BLMP setting was applied to it. Signals of ACS20 and ACS17 BLMP are shown in Fig. 5. These BLMPs did not show any MPS event related to RF MPS. There are only single BLMP MPS events. Raw BLM signals of MPS events contain very sharp peaks, but the integrated signals of MPS event are smaller than those of normal events.

Application of the new parameters was started in user runs over the last month. As a result, the number of single BLMP events decrease significantly. Although these statistics are inadequate, the number of events seems to have decreased by one order of magnitude. Various L3BT BLMP signals are shown in Fig. 6. New (BLMP23, 27, 30) and old (BLMP21) setting data are plotted together. The expanded time window

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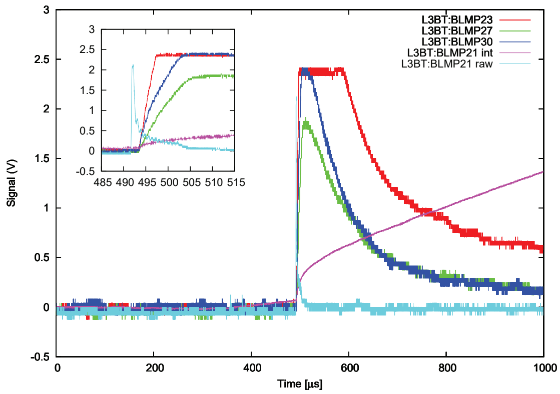

Figure 6: BLMP integral signal comparison with RF MPS events. Signals are saturated over 2 V.

is shown for visualizing the rising edges of these signals. The raw signals are fast enough to be compared with the integral of the old setting. MPS response may depend on its threshold, but even with 1 V, the response time would be within 5 μs, which is acceptable.

RCS BLM MPS Data

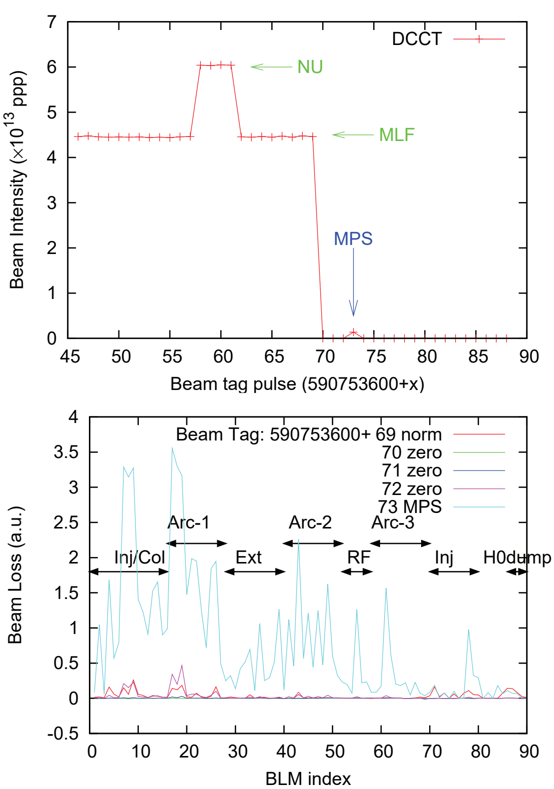

Figure 7: RCS beam intensity (up) and BLM pattern data (low) of the MPS and just before events. The intensity is almost zero for just a few pulses before. The MPS event causes massive beam loss, but its intensity is considerably lower than that of normal pulses.

The number of RCS BLM MPS events is considerably smaller than the number of Linac events. However, once an event occurs, it trends to be followed by the other events. The reason for this tendency is not known at present. The total number of RCS MPS events was about 150 over three months of user operation, whereas the number of Linac BLMP MPS events is around one thousand. Similar to Linac, these events classified into a few categories. The most major category is BLMP-only events. They can be divided into two types: only single or a few BLMP events, and multiple BLMP events. In the single BLMP case, usually, a few specific BLMPs, are located in the dispersion peak area. Most likely, the injected beam momentum is shifted slightly from the target value. This was proved by the beam position variation in the L3BT dispersion section. There were some evidences that the Linac momentum fluctuated within 0.1%. In the multiple BLMP event case, the amplitude of the BLMP signal increased, and large losses were encountered all around the ring. One example is shown in Fig. 7. It was suspected to have occurred owing to beam instability. However, it was a very low intensity event because RCS setting are very sensitive, and it is difficult to accelerate a low-intensity beam under the stable condition.

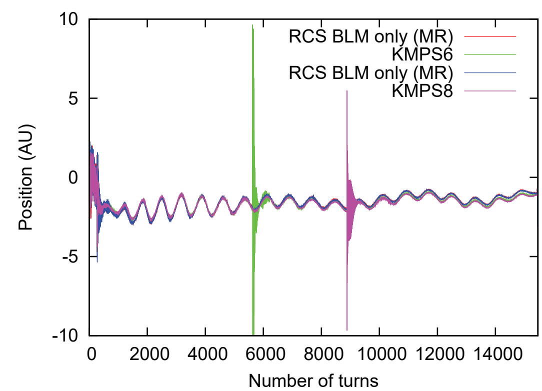

Figure 8: Same as Fig. 1, but they are kicker magnet mis-fire events (green and magenta) and large beam loss events (red and blue).

But it is not all the case. Another example is shown in Fig. 8 (red and blue), although there is no clear evidence of instability. Other than BLMP MPS, a few kicker magnet misfire events are shown (Fig. 8, green and cyan). The figure can be used to determine when one of the kicker magnets mis0fire and show how the beam is forced to oscillate by an accidental kicker mis-fire.

SUMMARY

Data on MPS events caused by subsystem failure can be used to determine what should be improved. However, events caused by BLMP alone must be analyzed to determine the underlying essential reasons. The Linac BLMP encounters excessive single BLMP events, which seems to be not related to substantial beam loss. A new BLMP operational condition is investigated and applied. The number of

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single BLMP events has decreased since the application of this condition. In addition, RCS MPS events were analyzed partly. However, we should continue to analyze more events and improve accelerator stability.

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