BEAM-LOSS MONITORING SIGNALS OF INTERLOCKED EVENTS AT THE J-PARC LINAC

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Abstract

It is important to understand why the beam loss occurs during user operation. It is understandable that the beam loss results from RF cavities failure. However, it would be still useful to study the beam loss detailed mechanism and to know which beam loss monitor (BLM) experiences the highest loss or is most sensitive. This may lead a reduction in the number of interlocked events and a more stable accelerator operation. The J-PARC Linac BLM has a simple data recorder that comprises multiple oscilloscopes. Although its functionality is limited, it can record events when an interlock is triggered. Of particular interest here are the events associated with only the BLM Machine Protection System (MPS). These may reveal hidden problems with the accelerator.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a high-intensity proton accelerator facility with three experimental hall, Materials and Life Science Experimental Facility (MLF), Hadron Experimental Facility (HD) and Neutrino Experimental Facility (NU). The accelerator parts are a 400-MeV linac, a 3-GeV Rapid-Cycling Synchrotron (RCS) and the Main Ring (MR), which is operated with 30 GeV. The designed beam power and intensity of the RCS at repetition rate of 25 Hz are 1 MW and 8.3×10^{13} protons per pulse (ppp), respectively. On a one-shot basis, this goal was achieved in early 2015 [1]. That same year, there were two MLF target failures at 500 kW. Since then, the nominal operational beam power and intensity of the RCS have been limited to 200 kW and 1.8×10^{13} ppp, respectively, for the MLF. The MR is operated with cycles of 2.48 and 5.52 s for the NU and HD, respectively. While most of the RCS beam is supplied to the MLF, four consecutive batches of two bunches each are injected from the RCS to the MR within either of these cycles. Operational MR beam powers of over 425 kW and 42 kW are achieved for the NU and HD.

The designed linac beam current and macro-pulse length are 50 mA and 500 μs, respectively. However, the peak current of the linac has been kept to 40 mA so far in 2016. The linac bunch structure has also been changed at the request of users. The typical bunch structure for the MLF is 300 μs macro-pulses in the linac and one bunch in the RCS. For the HD, the macro-pulse length is the same as that for the MLF, but the intensity is typically 1.2×10^{13} ppp. For the NU, the macro-pulse is the designed 500 μs length and a typical RCS intensity is 5×10^{13} ppp.

It is important to understand the over-all accelerator behavior, performance and characteristics, particularly in relation to the beam loss. The Machine Protection System (MPS) is usually triggered when a machine or instrument mal-functions or a beam loss monitor (BLM) hits its predefined threshold. The consequence in either case is that the beam is automatically stopped by the MPS.

It is certainly the case that failure of a RF cavity can cause a beam loss. Hence, it is useful to study the detailed correlation between RF cavity failures and the beam-loss pattern. This requires event data from many recorders with time identification. Sometime, a BLM will trigger the MPS without any sign of machine failure. This could be because of beam instability, accidental beam loss, or some other sources. Understanding beam losses and the entire machine characteristics further would help to reduce the number of MPS events and improve accelerator operation.

LINAC AND BEAM MONITORS

The linac comprises various sub-systems. Its front end is an RF-driven H^- ion source [2] and a 3-MeV RFQ [3]. Three drift-tube-linac (DTL) and 16 separated drift-tube-linac (SDTL) cavities then follow, and the H^- beam reaches 190 MeV at this point. After that, 21 annular-ring coupled structure (ACS) cavities that were added in 2013 accelerate the beam up to 400 MeV [4]. The linac-to-3 GeV RCS beam transport line (L3BT) has a length of 190.5 m[1] and includes a 90 degree arc section in between two straight sections. The final ACS cavity, is showing in Fig. 1, along with debunchers 1 and 2, and 0-degree and 30-degree beam dumps. There are two more beam dumps (100-degree and 90-degree) downstream of the second straight section. These four beam dumps are used during beam tuning. The arc section contains six bending magnets from the marked BM01 to BM06 in Fig. 1.

A proportional chamber type BLM (BLMP) is adapted as the main BLM [5]. Its pre-amplifier is placed either in the sub-tunnel (B1F) or in the machine tunnel (B2F). The signal unit is in the klystron gallery (1F). Its high voltage (HV) is set to 2 kV. The maximum raw output is $<$ 5 V. There are many BLMs distributed all over the linac. In particularly, after 7^{th} SDTL, each SDTL and ACS cavity has its own BLMP. In total, 79 BLMPs are connected to the MPS. The number of BLMP is 31 and 5 in the L3BT and in the beam dump area, respectively. $BLMP14$, $BLPM18$, and $BLMP21$ are located between the debuncher cavity 1

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[1] It comprises four subsections. Straight section before arc is 33.0 m, Arc section is 44.9 m, Straight section after arc is 59.1 m, and Injection section (to the RCS) is 53.5 m.

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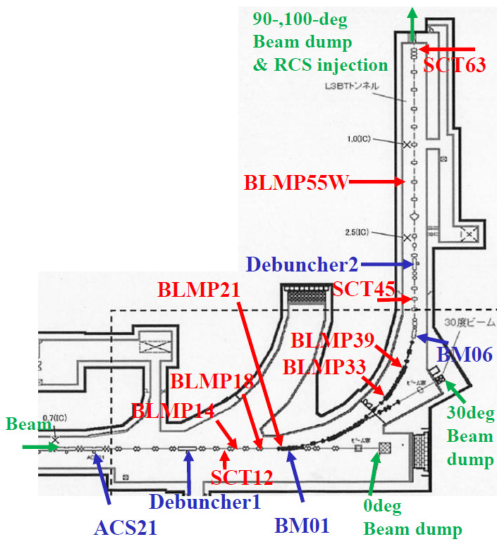

Figure 1: Downstream section of the linac after the final RF cavity ACS21. Locations of SCT and BLMP are indicated.

and the beginning of the arc-section. *SCT*12 (Slow Current Transformer, monitors the beam current) is also located at the right after the debuncher 1. *BLMP*33 is in front of BM04 and *BLMP*39 is in front of BM05. *SCT*45 and *BLMP55W* are in the second straight section. In contrast to the RCS or MR BLMP, the linac BLMP MPS is triggered by the raw waveform and not by a signal integral. Although the integrated value might be more stable, the response time would be longer. The MPS for the linac is designed to stop the beam within 5 μs. The MPS thresholds can be changed using EPICS, most are set to 1.3 or 1.6 V. Inside the MPS unit, a comparator and two PLCs judge whether the raw BLMP signal is too wide. Presently, the threshold width is set to 340 ns. Description about the MPS and a MPS unit can be found in references [6, 7].

WAVEFORM ARCHIVING SYSTEM

The raw BLM waveform archiving system comprises multiple oscilloscopes[2]. There are more than 50 oscilloscopes for the entire linac. At present, 12 of these actively archive the data when the MPS is triggered. The sampling rate is 100 Msample/s (10 ns/step), the record length is 100 ksample, and the sampling time is 1 ms. The scope parameters are monitored and can be modified through EPICS. During a communication between the EPICS IOC and the oscilloscopes, the system is locked, no trigger is accepted and the data are not archived for about a second. This interrupt occurs every several seconds and this dead time is a problem of this system.

The MPS stops the beam within several μs. However, the associated beam trigger from the timing system has an inherent delay. Several triggers are fired even after the MPS event, usually leading to some empty BLM data being recorded. That is why the archive system records 20 consecutive waveforms. The archive system records not only the BLM signals but also some SCT and fast current transformer (FCT, monitors the beam phase) waveforms.

[2] Yokogawa, DL1640.

INTERLOCKED EVENT

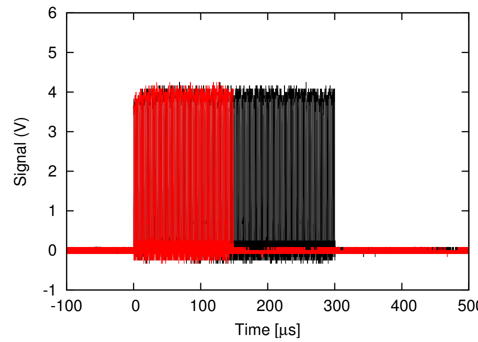

Figure 2: The linac beam current pattern recorded by SCT12. The vertical axis is the beam current; 1 V corresponds to 10 mA. Black is the normal case, and red is a pattern of an MPS event that interrupts beam.

In this section, we present SCT and BLMP waveform examples associated with an MPS trigger. In several cases, an accompanying MPS of the RCS BLMP is observed. As the RCS injection, a painting scheme is adopted for an injection period, which is now 300 μs macro-pulse (see the black line in Fig. 2). If the linac MPS stops the beam sooner than expected (e.g., the red line in Fig. 2), the beam already injected in the RCS becomes unstable, leading to further beam loss and a BLMP MPS signal.

BLMP MPS Associated with RF Failure

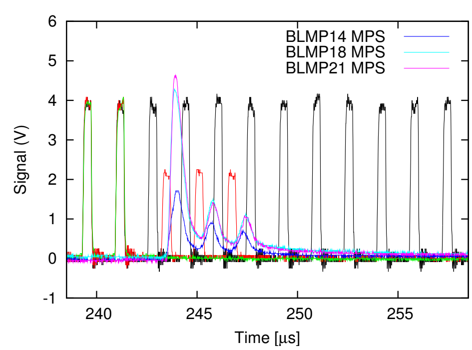

Figure 3: Snapshot of an interlocked event. MPS was triggered by SDTL04. Black and red are same as Fig. 2. Green is *SCT*45, blue, sky-blue and cyan are BLMP signals. The beam was stopped after 247 μs, but the the interlock occurred around 243 μs.

These events are relatively simple, and hence, it is reasonable to observe beam loss. The beam cannot be properly accelerated because of RF failure. Since we know which RF cavity is causing the problem, we can use these events as references. An obvious feature is the delay of the intermediate

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pulse. To match it to the RCS RF bucket, the linac beam is immediately chopped after the RFQ exit. This pulse is referred as the intermediate pulse. If one RF cavity fails, the acceleration chain breaks down at that point. Since no acceleration afterwards, the intermediate pulse is observed as delayed pulse at the SCT.

Figures 3 is a typical example of delayed pulse. By comparing black and red lines, the delay is about 700 ns. Beam loss is associated with the three peaks that correspond to the following intermediate pulse. The amount of beam loss should be constant, but $BLMP21$ signal peak decreases from one pulse to the next, probably because of BLMP signal saturation. The same BLMP pattern is also detected on $BLMP14$ and $BLMP18$. It takes 5 μs before the beam is stopped. Similar examples for SDTL11 and ACS01 are

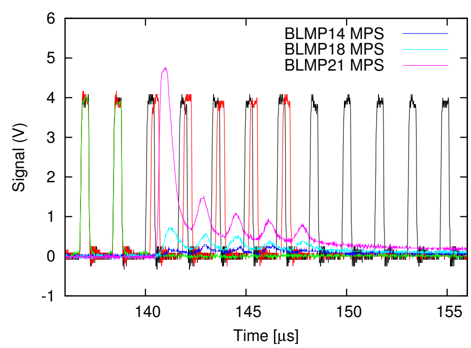

Figure 4: Same as Fig. 3 but for SDTL11 MPS.

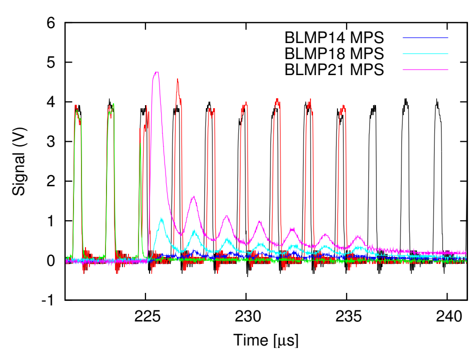

Figure 5: Same as Fig. 3 but for ACS01 MPS.

shown in Figs. 4 and 5. There are five BLMP signal peaks for the SDTL and seven for the ACS section. It takes 5 to 7 μs to stop the beam at the SDTL and 10 μs at the ACS.

Two more examples are shown in Fig. 6 and 7, this time for ACS15 and ACS21 MPS, respectively. In the case of ACS15, $BLMP21$ shows a similar pattern to that seen in the upstream cavity. However, in the case of ACS21, there is no significant loss at $BLMP21$, and intermediate pulse after the 90-degree arc section is observed on $SCT45$. The estimated energy up to ACS20 is about 390 MeV. However, sending lower energy beam through the arc section with some loss on $PBLM55W$ is possible.

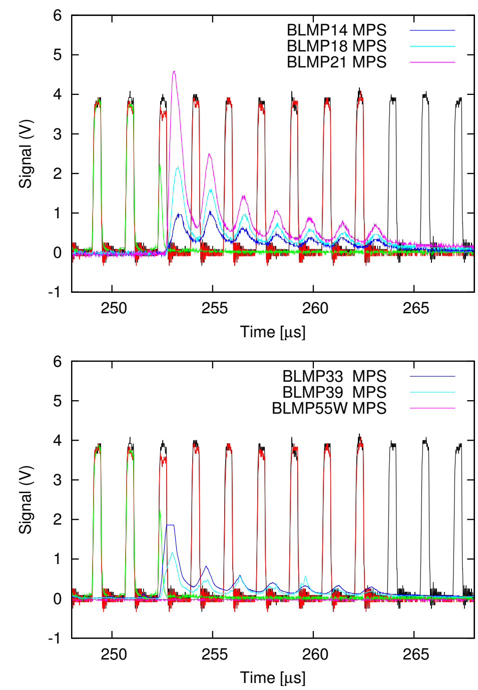

Figure 6: Same as Fig. 3 but for ACS15 MPS. Because $SCT45$ is located after the 90-degree arc, the beam did not reach at $SCT45$ after the interlock occurred. The BLMP groups before the arc and in the middle of it show a large beam loss. A part of $BLMP33$ signal peak was overshot.

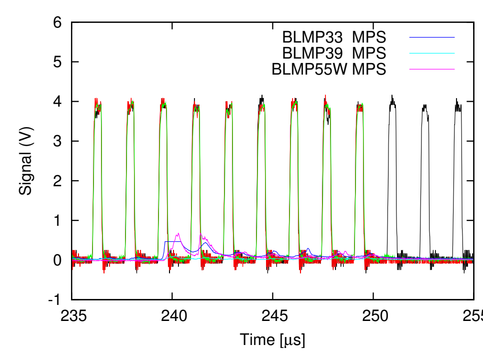

Figure 7: Same as Fig. 3 but for ACS21 MPS. The beam was stopped at 250 μs, but the moment of interlocked is estimated to have occurred just before 245 μs. A part of $BLMP33$ signal peak was overshot.

BLMP MPS only (part 1)

Although rare, multiple BLMP MPS signals can be triggered without any other machine failure. An example of such an event is shown in Fig. 8. This pattern can be compared with the previous cases in relation to the delay of the intermediate pulse and the number of BLMP signal peaks. We believe that some ACS cavity causes problems without generating an MPS signal.

There were noticeable number of multiple BLMP MPS events at the end of last February and at the beginning of last March. This type of event has not been recently detected.

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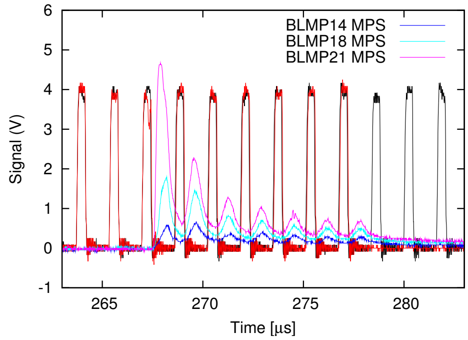

Figure 8: Same as Fig. 3 but due to multiple BLMP MPS.

All archived events show a delay in the intermediate pulse from the head of the macro-pulse. This might be related to a problem with the timing-module (e.g., a missing trigger).

BLMP MPS only (part 2)

This is an important issue that needs to be solved to ensure stable accelerator operation. For most of the linac BLMP MPS, only single BLMP triggers the MPS. Although we searched for a coincidence signal, no such event was found. The $BLMP21$ signal peak was similar to that in the RF MPS case, but it was only a single peak and not a continuous loss. The BLMP signal width might be slightly thinner than that in the RF MPS case. These examples are shown in Figs. 9 and 10. It takes approximately 10 μs because of $BLMP21$ and 20 μs because of $BLMP55W$. In either case, the intermediate pulse pattern from $SCT45$ does not show any beam loss. At worst, there are over 20 events per day, whereas on others there can be fewer than five per day.

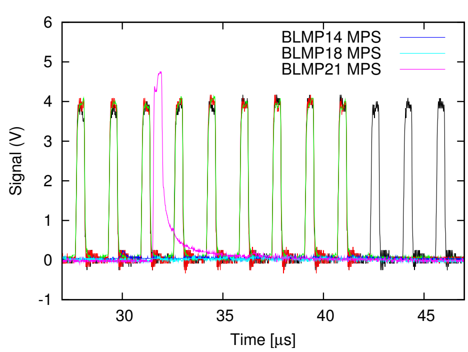

Figure 9: Same as Fig. 3 but for a single BLMP21 MPS. The difference here from RF MPS event, is that there is no continuous loss and no coincidence with $BLMP14$ or $BLMP18$.

DISCUSSION

The majority of single BLMP MPS events do not necessarily interrupt the beam. Rather, they cause relatively small beam losses that are not continuous. However, the justification for this is not straightforward. The overall frequency of this kind of MPS event seems to fluctuate, which is presumably related to a particular beam condition. It

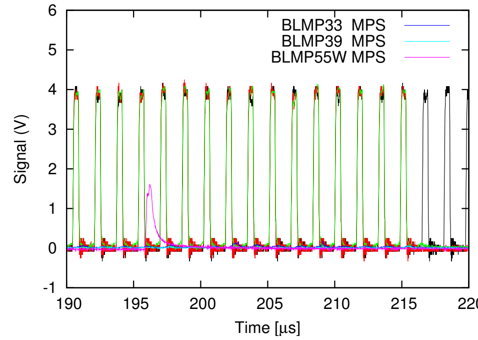

Figure 10: Same as Fig. 3 but for a single BLMP55W MPS. It takes longer than that of $BLMP21$ to stop the beam.

would be better to identify the true source, but this has not proved possible so far. High sensitivity is good for detecting small beam-loss signals. However, the signal of a large loss is relatively small because of saturation. The BLMP MPS threshold cannot be an integrated signal. As an ad-hoc solution, it might be an idea to reduce the HV setting and/or change the MPS threshold or signal-width criteria.

Because of timing-module problems, once the chopper that creates the intermediate pulse structure did not properly work. It did not cause the beam loss in the linac, but a heavy beam loss occurred in the RCS. A bad bunch structure can be confirmed by using this archive system.

CONCLUSION

We have presented BLMP waveform data with interlocked events. The failure of an RF-cavity MPS is associated with BLMP MPS events. The delay of chopped pulses depends on the location of the failed RF cavity. Although rare, events occur that suggest that some RF cavities must be failing without leaving an identifying signature. This can be estimated by comparing reference RF MPS events. There are many single BLMP MPS events, and action should be taken to reduce them. The archive system itself should be made more intelligent to reduce the dead time.

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