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ENHANCEMENTS TO THE SNS* DIFFERENTIAL CURRENT MONITOR TO MINIMIZE ERRANT BEAM

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Abstract

The existing Differential Beam Current Monitor (DBCM) has been modified to not only compare beam current waveforms between upstream and downstream locations, but also to compare the previous beam current waveform with the incoming beam current waveform. When there is an unintended change in the beam current, the DBCM now aborts the beam to prevent beam loss on the next pulse. This addition has proved to be crucial to allow beam during specific front-end problems. All data is saved when an abort is issued for post-mortem analysis. This paper describes the additions to the implementation, our operational experience, and future plans for the differential beam current monitor.

INTRODUCTION

The Differential Beam Current Monitor (DBCM) was implemented to abort beam in the Super-Conducting Linac (SCL) faster than the existing Beam Loss Monitors (BLM) [1,2]. The faster abort reduces the cavity degradation due to beam losses [3]. By comparing the incoming beam current (upstream) with the beam current leaving the SCL (downstream), beam loss anywhere in the SCL is detected. A dedicated optical fiber link sends an alarm directly to the Low Energy Beam Transport (LEBT) Chopper, see [4], to quickly abort the beam. The system can abort the beam in about 7 µs total, including signal and beam travel times and computation time.

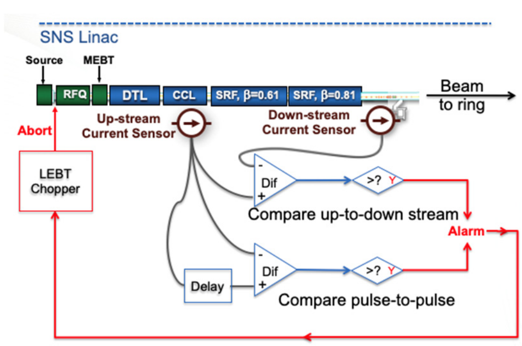

Figure 1: Differential Beam Current Monitor.

The layout of the DBCM is shown in Fig. 1. The upstream and the downstream beam current signals are compared, and an alarm is given if the difference exceeds a threshold. Note that with the single DBCM covering the whole SCL, there is no need to upgrade the abort response times for the many SCL BLMs.

Figure 1 also shows the new pulse-to-pulse comparison feature. The previously digitized current waveform is stored and compared sample-by-sample to the new pulse's current waveform.

The downstream sensor is a current toroid while the upstream sensor is a beam position pickup. The sum of the pickup plates signals is routed to a log amplifier to detect the Radio-Frequency (RF) signals envelope which is representative of the beam current. The DBCM converts the log signal to a linear signal to directly compare to the toroid's signal. Using the beam position pickup was necessary because suspected RF electrons burned a hole in the ceramic break of the upstream current toroid assembly and the assembly had to be removed, see Fig. 2.

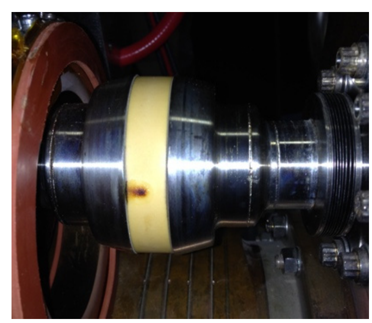

Figure 2: Damaged ceramic break.

ERRANT BEAM AND PULSE-TO-PULSE COMPARISON

There are two main sources of errant beam in the SNS linac: warm linac RF and the Ion Source.

The goal of the first iteration of the DBCM was to minimize the impact of beam loss from warm linac RF faults. Data analysis showed that the Drift Tube Linac (DTL) and Coupled Cavity Linac (CCL) cavities were the major cause for errant beam. As stated previously, the first iteration of the DBCM cut the beam turn off time in half. However, the need to lower SCL cavity gradients to maintain high reliability has continued.

The goal of the second iteration of the DBCM has been to minimize impact of beam loss from Ion Source malfunctions.

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Errant beam from the Ion Source is caused by high voltage arcing. During these high voltage arcs there is an abrupt drop in beam current output. The impact of abrupt changes in beam current is three-fold.

The first impact is from abrupt changes during the beam pulse. Due to varied linac RF cavity quality factors, the cavities react at different speeds. The Drift Tube Linac (DTL) cavities correct field variations in 10-15 µS while the Coupled Cavity Linac (CCL) and SCL cavities correct field variations in 2-7 µs and in 250 µs, respectively. This correction difference causes slightly incorrect beam energies along the linac, which results in small increases in beam loss. For comparison, the beam loss from an Ion Source arc is extremely small (1e-2 Rads) relative to a DTL or CCL cavity fault, which cause total loss of beam in the SCL.

The second impact relates to the fact that the beam loading during the beam pulse requires a 25% increase in RF power. With abrupt drops in beam current from Ion Source arcs, the additional RF power no longer goes to beam acceleration and is converted to higher RF fields within cavities. The field increases by 5% during these events. If cavity gradients are set within 5% of maximum gradient, then each event will place the field in an unstable region, though only for a very brief time. The higher the abrupt drop out frequency, the more times fields reach unstable regions, and the higher the probability of RF cavity arcing.

The third impact relates to the fact that the Ion Source high voltages are not monitored by the Machine Protection System (MPS). The MPS turns off beam if a system connected to the MPS detects a problem. Therefore, if an MPS fault occurs, this is an indication of a bad beam pulse. The Low-Level RF (LLRF) system, which controls RF cavity field and phase, monitors whether an MPS fault has occurred. If an MPS fault occurs, the LLRF system will not adapt RF field and phase according to the load of the bad beam pulse for upcoming beam pulses. If the Ion Source produces a non-normal beam pulse that does not cause an MPS fault, the LLRF will adapt RF cavity field and phase to the non-normal beam pulse for upcoming beam pulses. If the next beam pulse is normal, then RF field and phase setting will be incorrect. This will result in increased beam loss. It is also true that if the LLRF is expecting a normal beam pulse, and a non-normal beam pulse is present, the RF field and phase settings will be incorrect, which will result in increased beam loss. With the pulse-to-pulse interlock enabled, an MPS fault occurs during every non-normal beam pulse so LLRF will never learn from these bad beam pulses.

IMPLEMENTATION

The DBCM is implemented using a PXI crate with a digitizer card, 14-bits at 100 MS/s mounted on a FPGA board, see Fig 3. All samples are processed point-by-point and a running window sum of differences is compared against an alarm threshold. The Event Link (EL) and Accelerator Real-Time Data Link (RTDL) provide the trigger for beam arrival and information about the beam, such as the intended beam pulse length. The Optical Fiber and MPS board sends an abort signal to the MPS system and directly to the LEBT Chopper. The optical fiber connection to the LEBT Chopper, see [4], allows for a faster abort than through the MPS system, reducing the abort time by half from around 15 µs to about 7 µs.

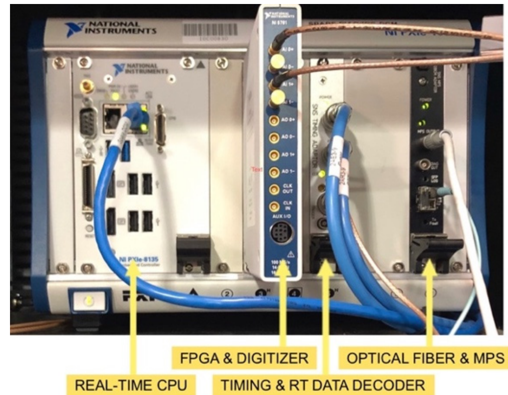

Figure 3: DBCM Hardware in PXI crate.

The DBCM has always had the capability to detect pulse-to-pulse differences but did not discriminate between intended changes and non-intended changes. To be able to practically use this mode, the timing decoder algorithm implemented on the FPGA was programmed to also decode RTDL information about the beam length, aka the chopper and beam gate settings, see Fig. 4. If these settings are changed, the next pulse-to-pulse comparison is disabled.

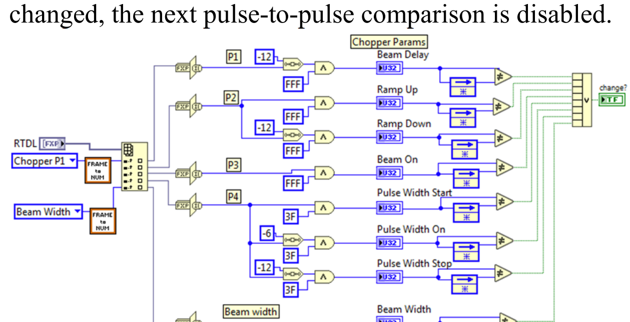

Figure 4: LabVIEW FPGA code to detect beam length change.

Besides the hardwired connections to the abort system, the DBCM uses the EPICS (Experimental Physics and Industrial Control System) Channel Access protocol to display data in the control room. The main control room screen is shown in Fig 5.

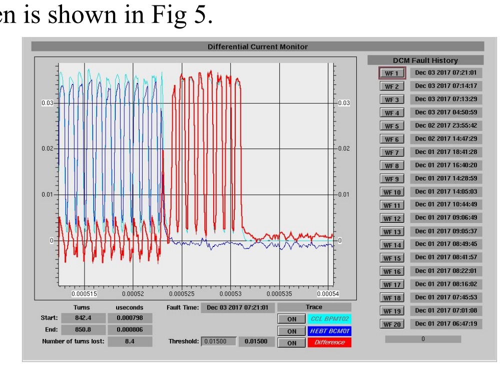

Figure 5: DBCM Control Room Screen.

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Every time a DBCM fault occurs, the EPICS softIOC (software Input/Output Controller) saves the upstream data from CCL BPM102 and downstream data from High Energy Beam Transport (HEBT) BCM01 to files for offline analysis. The softIOC also does real-time calculations of the number of turns lost during the fault and identifies the component that caused the fault to occur. The displayed difference waveform can either be the upstream downstream difference, as is shown in the figure, or the pulse-to-pulse difference. A rolling buffer of the last 20 faults is available for display.

RESULTS

With the SCL DBCM pulse-to-pulse interlock enabled, Beam Loss Monitors (BLM) trips caused by high voltage arcing from the Ion Source have been eliminated. The arcing is still occurring, but the non-normal beam pulses are detected in 1-2 µs and beam is turned off in approximately by 6-15 µs after detection, depending on the threshold setting and the difference in beam intensity. Figure 6 shows a case of the source producing a below normal intensity beam and resulting in the cavity fields becoming too high. Because the beam losses are moderate, it takes the BLMs well over 100 µs to integrate enough signal for an abort given normal operational thresholds.

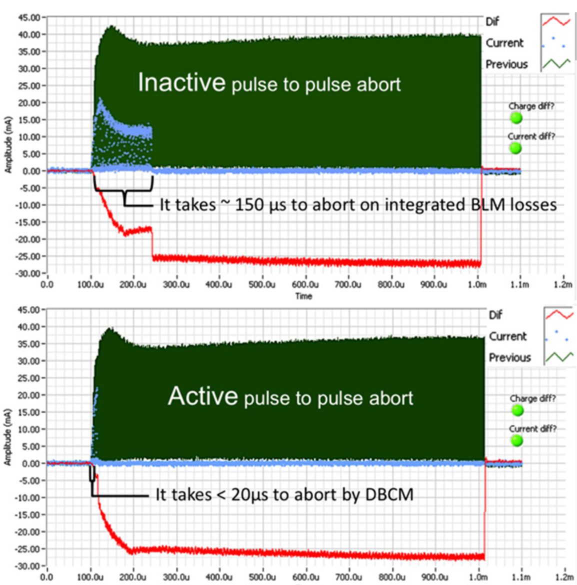

Figure 6: The top graph shows how long it takes to abort without the pulse-to-pulse feature enabled, while the bottom graph shows a much shorter abort by the pulse-to-pulse feature.

In the beginning of 2019, the Ion Soure increasingly arced, causing beam loss in the SCL. Figure 7 shows a huge increase SCL BLM hourly trip rate (red). Shortly thereafter operators respond by reducing Ion Source voltage (blue) to minimize arcing, but the trip rate remained elevated. During a maintenance day, the pulse-to-pulse interlock (green) was enabled and, after beam was restored, the SCL BLM hourly trip rate returns to zero. The light blue trace shows the beam power. Notice that the DBCM trip rate increases above the previous SCL BLM trip rate. This is because the DBCM is finding more non-normal beam pulses, such as RFQ truncations, than just the non-normal beam pulses caused by Ion Source high voltage arcing.

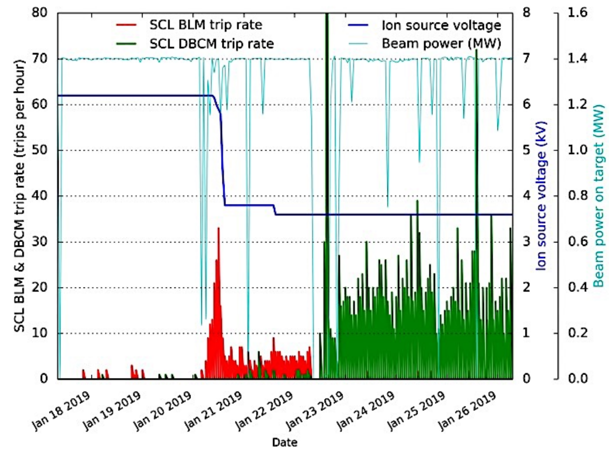

Figure 7: The effect of the pulse-to-pulse interlock.

Part of what the DBCM is minimizing is the degradation of the SCL cavities. This degradation shows itself by operators having to lower the gradient fields of cavities to maintain stable operations, see Fig. 8. In 2017, the cavity field had to be reduced presumably due to the Ion Source problems. The same happened again in the begin of 2019, but now the pulse-to-pulse interlock minimized losses at the cavity and the field gradient was maintained.

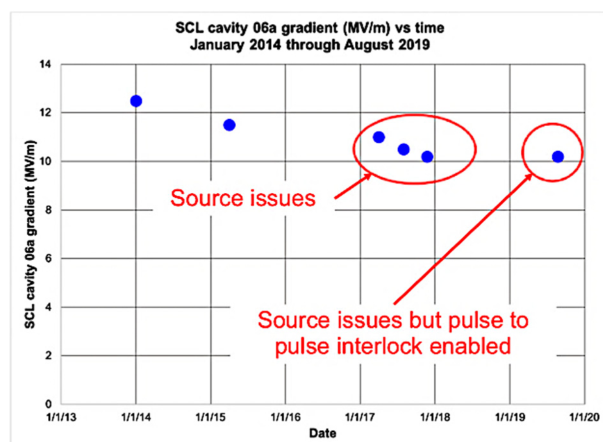

Figure 8: The graph shows the continued need to decrease cavity gradient to maintain high reliability. The most recent reductions came during a time with increased Ion Source arcing issues.

Adding an interlock to the Ion Source High Voltage can also minimize beam losses on the SCL. However, this would require new hardware, while the DBCM only required a firmware modification and can catch other issues as well. The arcing is often due to a bad insulator in the source. Replacing this would require significant downtime, thus we prefer to be able to delay maintenance to a scheduled downtime period.

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FUTURE

One of the unique features of the DBCM has been that the beam current waveforms from before, during, and after each errant beam event have been saved. This makes it possible to investigate using Machine Learning (ML) tools to see if there are precursors of errant beam in a previous pulse. Indeed, statistically relevant information was found with a true-positive rate of up to 90%, see [5,6]. The plan is to bring the most successful ML algorithms to the Errant Beam softIOC for online (but not real-time) analysis. For real-time analysis and to prevent the errant beam, such an algorithm will most likely be implemented in the DBCM itself. We hope that the ML tools will find anomalies that, once discovered, can be detected with simple and fast methods to enable a real-time response.

We also plan to start saving and analyzing signals from other data-acquisition systems such as Beam Position Monitors (BPM), BLMs, and cavity RF signals. Figure 9 shows an example of the BPM phase changing well before the beam loss occurs, indicating that for some errant beam, losses can be avoided with simple trend detection. The top plot shows that the beam current stays within the maximum and minimums over the last 3 seconds (at 60 Hz for a total of 180 waveforms), while the phase, shown in the bottom plot, starts deviating at over 200 µs before beam is aborted.

Besides minimizing downtime or damage to the accelerator, we also plan to derive from the data which equipment is responsible for the errant beam and needs to be repaired.

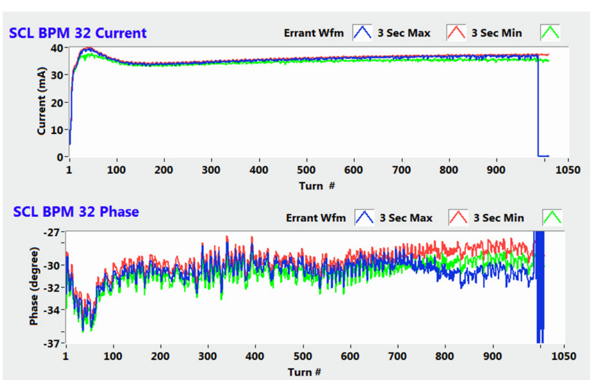

Figure 9: Data from the SCL BPM shows errant beam well before beam is aborted. Courtesy of Cary Long.

CONCLUSION

The direct fiber optic abort line and the new pulse-to-pulse feature have made the DBCM an important tool to improve the uptime of the accelerator. It has already helped us continue production during Ion Source problems. We plan to keep looking for errant beam precursors and indicators in the data to further optimize operations.

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