ISBN: 978-3-95450-202-8 doi:10.18429/JACoW-HB2018-MOP1WB02

UNDERSTANDING THE SOURCE AND IMPACT OF ERRANT BEAM LOSS IN THE SPALLATION NEUTRON SOURCE SUPERCONDUCTING LINAC*

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Abstract

The Spallation Neutron Source (SNS) Linear Accelerator (Linac) delivers a high power proton beam (>1 MW) for neutron production with high neutron availability (>90%). For beam acceleration, the linac has both normal and superconducting RF sections, with the Superconducting Linac (SCL) portion providing the majority of beam acceleration (81 of 96 RF cavities are superconducting). Operationally, the goal is to achieve the highest possible beam energy by maximizing SCL cavity RF gradients, but not at the expense of cavity reliability [1, 2]. One mechanism that has negatively impacted both SCL cavity peak RF gradients and reliability is beam lost into the SCL due to malfunctions of upstream components. Understanding the sources and impact of errant beam on SCL cavity performance will be discussed.

INTRODUCTION

The Spallation Neutron Source (SNS) is an accelerator driven pulsed neutron source used for scientific research and industrial development.

The facility utilizes a linear accelerator (linac), a storage ring, and a mercury target to produce short high intensity bursts of neutrons. The 6% duty factor linac produces a 1 millisecond long H- beam pulse at a 60 Hz beam repetition rate. Within each 1 millisecond beam pulse the beam is chopped into 750 nanosecond beam slices. Using charge-exchange injection the ring accumulates the beam by painting the slices in both horizontal and vertical phase space. After the 1 millisecond accumulation the protons are extracted using fast kicker magnets to a mercury target for neutron production [3].

SNS low power neutron production began in 2006, and since that time the beam power has been increased slowly up to 1.4 MW. The ramp up to the design power of 1.4 MW has been slowed mostly by mercury target reliability issues. Since 2016 a strict beam power ramp up plan has been followed, which has been productive for both the accelerator and target. Currently the neutron production beam power is at 1.3 MW, and in September 2018 the scheduled neutron production beam power will be 1.4 MW.

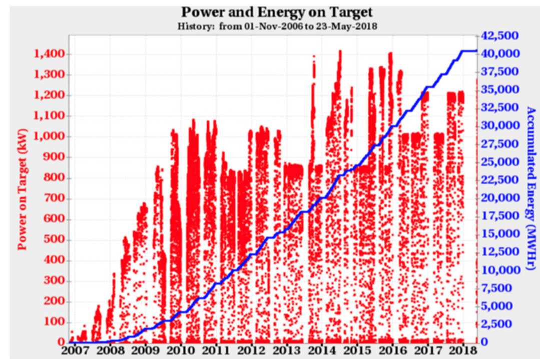

Figure 1: Beam power ramp up history.

The linac is currently the highest power pulsed proton linac in the world. The linac is capable of delivering >1.4 MW of beam power at beam availabilities >90%. Recently peak beam currents of >50 mA have been delivered to the target with nominal beam losses. This opens up the possibility of reaching average beam currents of >40 mA. The linac duty factor is 6% so this would make the linac capable of producing >2.8 MW of beam power with necessary High-Power RF (HPRF) upgrades.

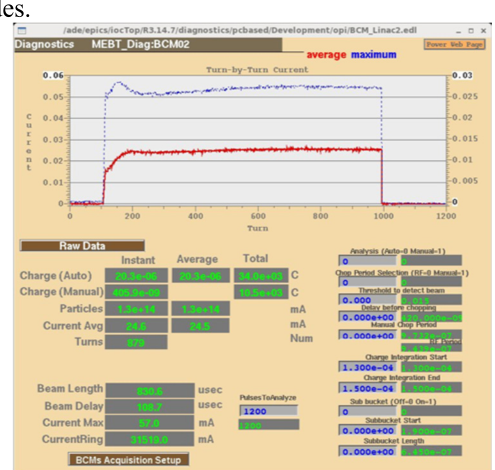

Figure 2: Linac peak beam currents are able to support beam powers exceeding 2.8 MW.

ERRANT BEAM HISTORY

In 2009 beam powers quickly reached 1 MW, and soon after the SCL began experiencing reliability issues.

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Machine Protection System (MPS) Issues

In 2009 SCL cavity reliability began to abruptly decrease. In order to maintain as high reliability as possible SCL cavity gradients were decreased. This in turn reduced the linac output beam energy. SCL experts investigated the issue and were able to correlate beam loss events with SCL cavity downtime events.

Investigation into the beam loss events narrowed down the issue to the Machine Protection System (MPS) [4]. The goal turn-off time for the MPS is 20 microseconds [5], and testing showed that in some cases the MPS turn off time was >1 millisecond. In Figure 3 below is an example of a turn time of 200 microseconds, which is an order of magnitude longer than design.

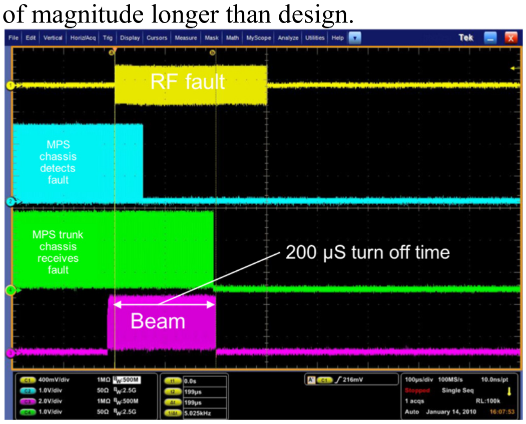

Figure 3: Scope snapshot showing delays of 200 microseconds during the MPS issues found in 2009.

The issue was found to be delays from poorly chosen MPS chassis input capacitors, and MPS sublink output drive circuits [6]. The capacitors were removed and the drive circuits were upgraded. This reduced the beam turn off time to the design requirement of 20 microseconds.

Though the MPS issues were resolved SCL degradation has continued, though at a reduced rate compared with the abrupt degradation from the MPS issues.

SLOW DEGRADATION OF SCL CAVITY RF GRADIENTS

Operationally at SNS the highest priority is neutron availability. If an SCL cavity begins to trip off repeatedly then the RF gradient will be reduced until reliability improves [7].

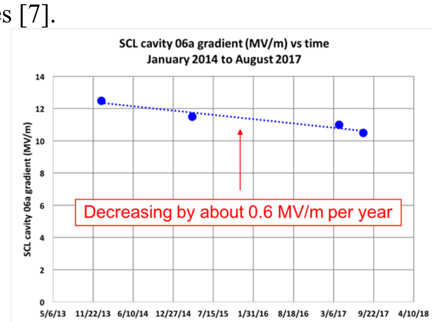

Figure 4: The plot above shows the need to decrease SCL cavity 06a gradient over time. The reduction is about 0.6 MV/m per year.

To compensate for the reduced energy the remaining SCL cavity phases will be adjusted to maintain the same linac output beam energy. The last SCL cavity is always left non-accelerating to leave energy reserve to be used in case issues listed above develop. Figure 4 shows an example of the decreasing SCL cavity 06a gradient over time due to slow degradation from errant beam.

ERRANT BEAM TASK FORCE ESTABLISHED

In 2012 it was realized that SCL cavities were still being damaged by errant beam, and additional analysis needed to be done to limit SCL cavity degradation.

The task force came up with the following plan to try to limit the impact from errant beam.

- Verify proper MPS operation.
- Gather errant beam statistics.
- Reduce errant beam frequency and the amount lost per event.

MPS Operation Verified

The first check done was to measure the amount of beam being lost during an errant beam event. This would verify the MPS was working properly by showing the beam turn off time, and also gather statistics on the frequency of errant beam events. The system used Beam Current Monitors (BCMs) upstream and downstream of the SCL. The system ran at 60 Hz (the maximum beam repetition rate), and saved the BCM waveforms to a webserver for viewing after each event. The system was just a diagnostic with no connection to the MPS.

First and foremost the BCMs in the MEBT, CCL, and HEBT showed that the beam turn off times ranged from 15-20 microseconds. This verified that the MPS was working properly. Figure 5 shows a typical snapshot of BCM waveforms during an errant beam event. The BCM in the High Energy Beam Transport (HEBT) downstream of the SCL shows about 16 microseconds less beam compared with the BCMs in the MEBT and CCL.

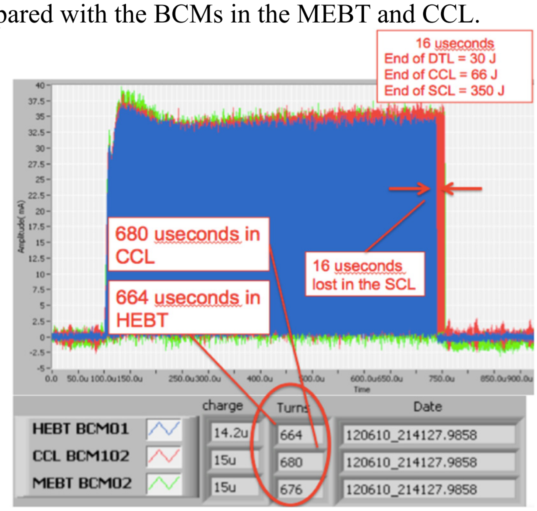

Figure 5: The above figure shows the BCM system used to verify that the MPS was turning off the beam at the design time of 20 microseconds.

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Not all of the errant beam pulses looked similar to Figure 5, but most did. Some of the errant beam pulses showed that it was introduced in the MEBT from malfunctions in the ion source. Most of the errant beam events came downstream of the MEBT and upstream of the SCL from malfunctions in the warm linac.

Low-Level Radio Frequency (LLRF) Adaptive Feed Forward (AFF) Background

High beam currents at the SNS make it necessary to use a LLRF feed-forward based approach in order to maintain the appropriate cavity field and phase under heavily beam-loaded conditions [8]. At the SNS a system of Adaptive Feed Forward (AFF) was developed for this compensation.

The system works by the following method. A beam pulse is triggered. The system creates error waveforms as it measures the field and phase errors during the beam pulse. The LLRF "learns" from those errors and adjusts LLRF gains for the next beam pulse (the system is currently only capable of running at a 20 Hz repetition rate). The system works extremely well as long as pulse to pulse beam current shapes are reproducible.

The AFF system does not "learn" if an MPS fault is detected during the beam pulse.

Ion Source Ignition Instability and LEBT Arcing

The ion source can trigger errant beam in multiple ways. One way is an abrupt change in beam current output.

An abrupt change in beam current can have a two-fold effect on SCL cavity reliability. As stated above the AFF system expects a certain beam current shape from pulse to pulse. If the beam current shape changes unexpectedly the AFF will be unaware and the LLRF gain settings will be incorrect for the odd beam pulse. Figure 6 shows an example of an ion source pulse during a high voltage arc. The reduced beam current means the LLRF system will overdrive causing an elevated cavity field creating a higher probability for an arc. The elevated field and likely incorrect phase will also cause incorrect beam acceleration and result in beam losses. So, the effect is two-fold: overdriving to high fields, and beam loss due to incorrect field and phase.

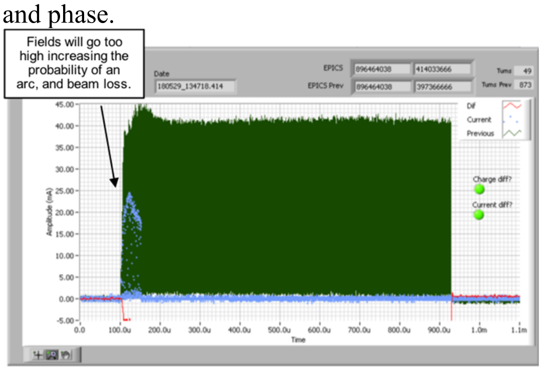

Figure 6: Example of an ion source high voltage arc. The green pulse is a nominal pulse and the blue is the beam current during an ion source malfunction.

Ion Source Beam Halo

Another source of errant beam from the ion source is beam halo.

Ion source equipment is not monitored by the MPS. If equipment malfunctions within the ion source or LEBT the indications of a problem come from secondary equipment.

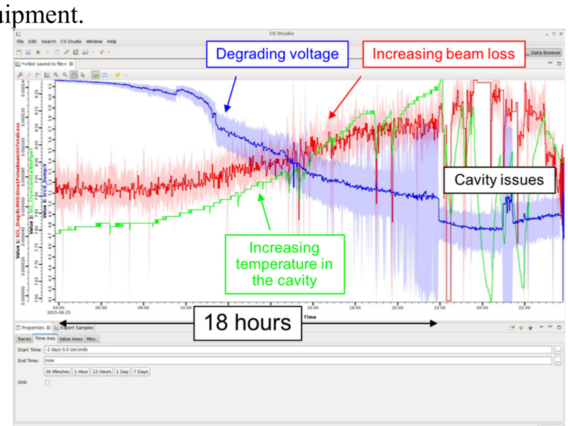

Figure 7: The plot above shows the degrading ion source voltage (blue), increasing beam loss (red), and the increasing beam pipe temperature (green) in an SCL cavity. After ~18 hours of increasing beam loss SCL cavity issues developed requiring reduced gradient.

Figure 7 above shows an example of a decaying high voltage in the ion source. As the voltage decays beam losses begin to increase in the SCL. Beam pipe temperature within a cavity correlates with the beam loss, and after about 18 hours of the increasing beam loss the SCL cavity begins to fault off. The cavity gradient must be reduced in order to maintain high reliability. After a few hours operators retune the ion source to reduce the beam halo, but even after the tuning the cavity gradient must remain reduced. The cryomodule must be warmed up to restore the previous gradient setting.

Errant beam from the ion source has been significantly reduced due to significant analysis and development work performed by ion source experts at the SNS [9].

Warm Linac Arcing/Multipacting

The dominant source of errant beam was found to be the warm linac. When a warm linac cavity faults from arcing or multipacting the field decay is on the order of a few microseconds so the beam loss is fast and significant.

Most of the arcing and multipacting seen in the warm linac cavities occurred during the fill time of the RF cavities. The point where the RF wave is transitioning from a traveling wave to a standing wave. In order to affect the fault rates two methods were employed.

The first method was to use a linear fill of the forward power to minimize the reflected RF power during the fill time of the cavity. The normal filling method used is to start with nominal forward power and maintain the forward power fixed during the fill, but early in the pulse the reflected power is elevated. Though these faults would normally occur before the beam pulse the reduction in the

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fault rates translated to fewer faults later in the RF pulse when beam is present. Figure 8 shows an example of the difference in RF waveform shape with the natural RF cavity fill versus the linear forward power fill.

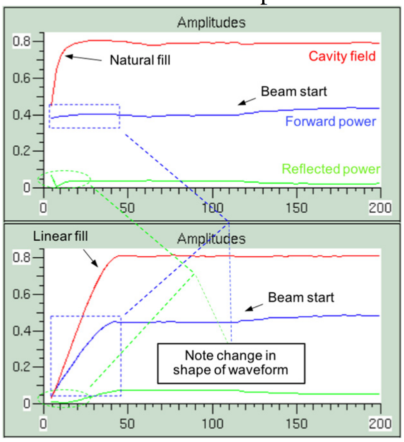

Figure 8: Top shows the natural cavity fill. The bottom shows the adjustment to the linear forward power fill.

The second method used was to slowly change the resonant frequency of the cavities while monitoring the vacuum and reflected power RF waveforms. Minimum fault rates for the Drift Tube Linac (DTL) cavities occurred with minimal reflected power during the fill time of the cavity. When running the cavities at frequencies slightly below 402.5 MHz the vacuum near the ceramic RF window decreased though the reflected power near the end of the beam pulse actually increased. Figure 9 shows the significant decrease in fault rate for DTL5 when lowering the resonant frequency by 2.5 kHz.

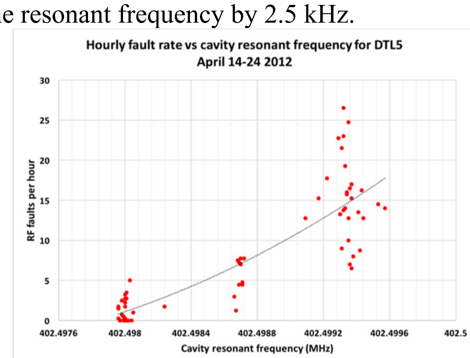

Figure 9: Reduction in fault rate by lowering the DTL5 cavity resonant frequency.

Warm Linac Vacuum

Throughout the warm linac vacuum capture pumps were used as the dominant pumping system. Ion pumps were used on the cavities and Non-Evaporable Getter (NEG) pumps on the ceramic RF windows.

The NEG pumps had to be routinely regenerated, and if not regenerated routinely the systems would burst and cause the protection system to interlock the LLRF, and cause errant beam.

The entire vacuum system was upgraded for both the DTL and Coupled Cavity Linac (CCL) to replace all capture pumps with turbopumps. The upgrade has not only reduced errant beam faults, but it's also decreased overall downtime by 2%.

Warm Linac Operating Practices

One specific area of additional concern in the CCL has been damage to secondary equipment from field emitted electrons. Two BCMs in the CCL have failed due to cracked ceramics. A vacuum valve downstream of CCL cavity 4 has repeatedly been damaged.

One correlation is increases in vacuum pressures when the CCL RF is on without quadrupole magnet power supplies energized. Figure 10 shows multiple points in time where a specific magnet power supply was off and on with RF on for CCL cavity 1.

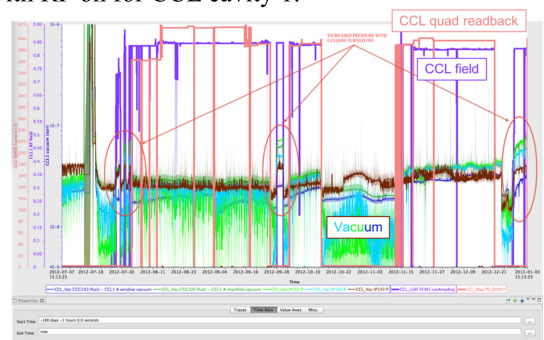

Figure 10: The plot above shows elevated vacuum pressures when quads powered off with RF on.

The likely issue is heating up of an upstream vacuum valve from the field emitted electrons. It appears with quads on the electrons are disbursed instead of striking a localized spot somewhere on secondary equipment. Administrative rules were established to always have quadrupole magnet power supplies on when RF is on in the CCL. This is not an issue with the DTL because the quadrupole magnets are permanent magnet installations.

The previous method to condition the RF window was to increase the RF power to the beam loaded level (about a 10% increase over the nominal cavity field level). Increasing the field in the structure to that level significantly increased field emission levels. The field emitted electrons were striking a vacuum valve downstream of the cavity, and causing contamination.

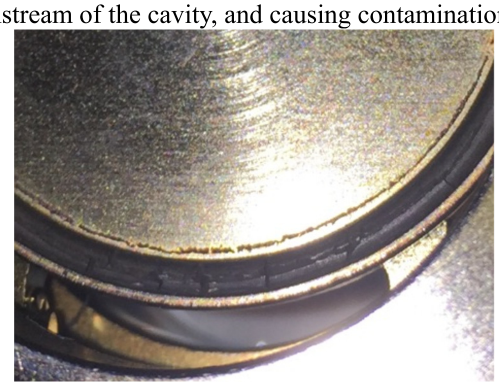

Figure 11: The picture above shows a damaged o-ring seal on a vacuum valve after being damaged by stray field emitted electrons.

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Errant Beam Frequency Reduced

The largest reduction in errant beam frequency came in 2012, and has been slowly decreasing since. The fault frequency cannot be reduced to zero, and at any point the fault rate can increase abruptly. Figure 12 shows the reduction in fault frequency.

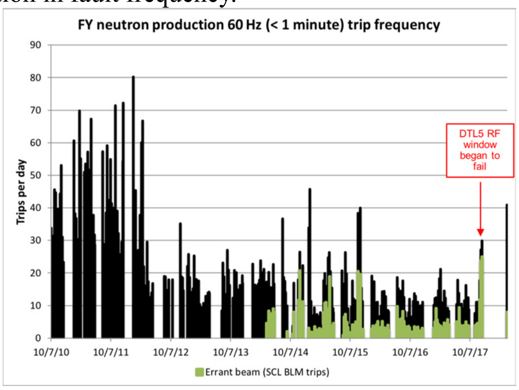

Figure 12: The plot above shows the reduction in short fault frequency dominated by errant beam faults.

In 2017, for example, the DTL cavity 5 RF window began to slowly fail. Since the failure was slow the decision was made to continue running until the end of the scheduled run period before changing the failing window.

Reducing Beam Loss During Each Errant Beam Event

The last step to try to minimize the effect of errant beam on the SCL was to reduce the turn off time of the MPS. Instead of trying to figure out a way to modify the MPS beam turn off mechanism the decision was made to have a separate system connect directly to the LEBT chopper without going through the MPS.

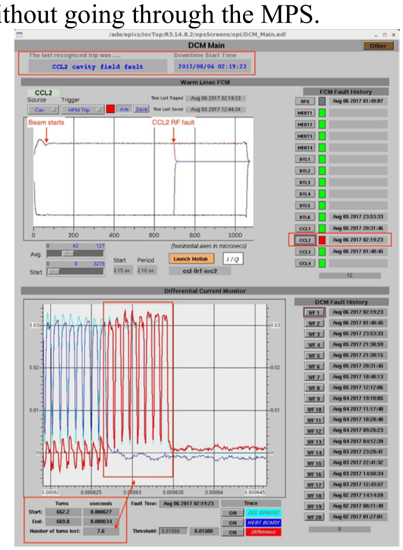

Figure 13: The snapshot above is an example fault detection by the SCL DCM system.

The system implemented was based on the system used during the MPS checkout to use a differential charge measurement between BCMs upstream and downstream of the SCL. The system uses a Beam Position Monitor (BPM) in the CCL and a BCM in the HEBT and compares the charge difference based on a settable level. The system runs at 60 Hz and is able to detect a charge difference within 1 microsecond. The fault signal then goes directly to the LEBT chopper and is able to turn off the beam within about 8 microseconds [10]. Figure 13 shows an example of the system interlocking due to a CCL cavity 2 fault.

The system also sends the fault information to the MPS. The LEBT chopper chops the beam for approximately 30 microseconds, which gives the MPS time to turn off the ion source and RFQ timing gates.

FUTURE UPGRADES

Even with the factor of two reduction in turn off time SCL cavity downtime can still happen with an errant beam event. There are plans to install a pulse to pulse system to monitor beam pulses in the MEBT to reduce damage from ion source malfunctions. It is not logical to expect to reduce the turn off time much more than is currently being done. One possibility is to use a machine learning algorithm to predict errant beam. Recent analysis suggests that using the SCL DCM waveforms it is possible to predict errant beam pulses with up to a 94% success rate [11]. Far from the likely >99% certainty needed to be used as a production system.

CONCLUSION

The frequency of errant beam events as well as the amount of beam lost per errant beam event have been significantly reduced. Even with the reductions SCL cavity degradation continues at a slow rate. Figure 14 shows that plasma processing is increasing the output energy of the linac, and with continued diligence with errant beam reduction there will be no loss of the gains from plasma processing.

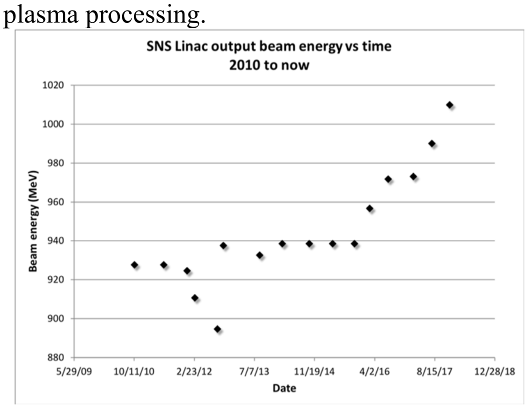

Figure 14: The plot above shows the linac beam output energy versus time. Since 2016 plasma processing has significantly increased the beam energy.

ACKNOWLEDGMENTS

Authors would like to thank Control Room Shift Supervisors and Accelerator Specialists for taking data that were used for errant beam analysis.

ISBN: 978-3-95450-202-8 doi:10.18429/JACoW-HB2018-MOP1WB02

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