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# MINIMIZING ERRANT BEAM AT THE SPALLATION NEUTRON SOURCE*

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*Abstract*

Since beginning neutron production operation in 2006 at the Spallation Neutron Source (SNS), one of the goals for the Accelerator Operations group has been to minimize beam trips. The beam trips which occur with the highest frequency are due to errant beam in the Super Conducting Linac (SCL). The process of minimizing the amount of errant beam and the frequency of faults will be described.

## DESCRIPTION OF THE SNS LINAC

The linear accelerator at the SNS consists of (in order of beam acceleration) an $H^-$ Ion Source ($H^-$IS), Low Energy Beam Transport (LEBT) which contains an electrostatic beam chopper (LEBT chopper), Radio Frequency Quadrupole (RFQ), Medium Energy Beam Transport (MEBT), Drift Tube Linac (DTL), Coupled Cavity Linac (CCL), Medium Beta Super Conducting Linac (MB SCL) (3 cavities per cryomodule), and High Beta Super Conducting Linac (HB SCL) (4 cavities per cryomodule). The fundamental RF frequency in the RFQ-DTL is 402.5 MHz, and 805 MHz for the CCL-SCL.

The SCL is physically the longest accelerating component of the linac, and also performs the majority of the beam acceleration. The nominal beam energy for the current SNS linac is 1 GeV, and the energy acceleration by the SCL is from 186 MeV to the design 1 GeV. Of the 96 RF structures used for accelerating, 81 are superconducting [1].

All systems ($H^-$IS and RF) are pulsed at a 60 Hz repetition rate for approximately 1 millisecond, for a duty factor of about 6%. Figure 1 shows the linac arrangement and relative lengths of the different structures.

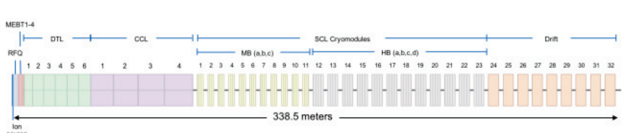


Figure 1: Ion source through SCL schematic.

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## ERRANT BEAM AND BEAM TRIPS

Errant beam is the resulting beam produced by malfunctioning accelerator equipment. When a glitch occurs, this errant beam does not transport through the accelerator properly (see Fig. 2). This beam typically triggers the Machine Protection System (MPS) to stop beam acceleration resulting in what is termed a beam trip. In general, errant beam trips typically take only a few seconds to reset. Occasionally errant beam events induce an SCL RF cavity trip which can take a few minutes to recover. If the frequency of errant beam trips is high enough, it can reduce the overall 60 Hz beam even with the relatively quick recovery.

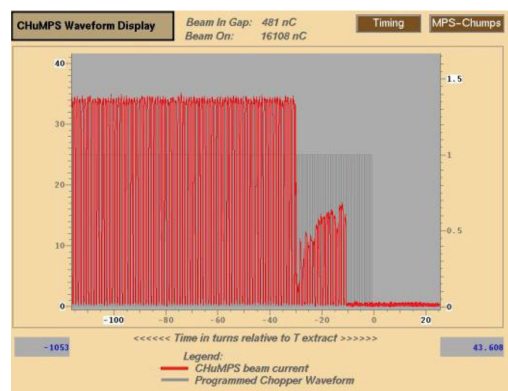


Figure 2: Example of LEBT high voltage malfunction.

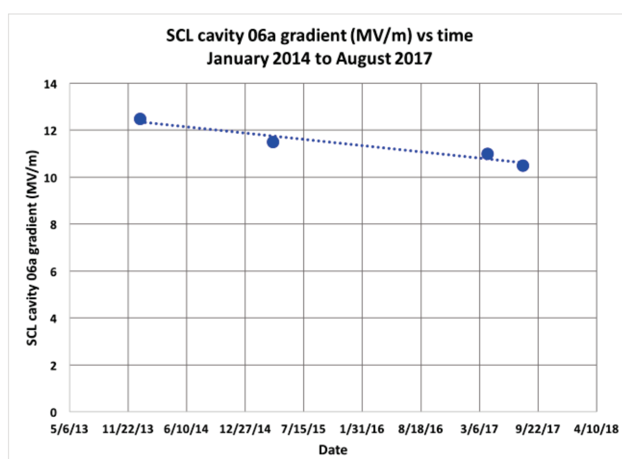


Figure 3: SCL cavity 06a gradient is declining at about 0.6 MV/m per year even with reduced errant beam frequency.

Additionally, repeated errant beam events over weeks, months, and years degrade SCL cavity performance [2,3]. Degradation of cavity performance means that over time

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cavity gradients must be reduced in order to minimize SCL cavity trips and maintain high availability. Sensitive cavities can lose 5% in gradient per year (see Fig. 3).

Experience has shown that the need to reduce gradients does not occur for the entire SCL. There are particular sections of the SCL that get hit by errant beam. The sections hit are determined by a particular DTL or CCL RF cavity that faults. The problematic areas are SCL cryomodules 2, 3, 6, 7, 12, 16, 19, and 20 (there are currently 23 cryomodules installed). This amounts to about one-third of the total SCL cavities needing gradient reduction over time, which is significant.

The above information is degradation due to abrupt beam losses from DTL or CCL RF faults, but there are additional beam loss issues that contribute to the need to reduce SCL cavity gradients. Beam halo and protons introduced from the ion source can also impact SCL cavity availability, these issues are less typical, and will not be discussed within this paper.

What becomes important when discussing beam trips and errant beam are the fast field decay times for the normal conducting RF structures and the particular structure position along the linac.

The fast field decay times mean that almost immediately the beam energy is incorrect and beam will not transport to the target without massive beam loss in the SCL. However, in the SCL the field decay times are on the order of 250 microseconds so SCL cavity faults typically do not cause massive beam loss as the MPS can respond fast enough to prevent large beam loss even as the field decays. Only if there is an arc within the SCL RF system does the trip cause beam loss since the field decay is on the order of a few microseconds when an arc occurs.

When discussing position along the linac, earlier structures produce less beam loss in the SCL. For example, the DTL is broken up into six segments (DTL1-DTL6), and the CCL is broken up into four segments (CCL1-CCL4). The first cavity (DTL1) accelerates the beam from 2.5 to 7.5 MeV. If a fault occurs in DTL1, in only a few microseconds the field will be too low to provide the appropriate beam energy to properly accelerate the beam downstream. Because the structure is early in the linac (low beam energy) the beam does not transport very far. In fact, in this case the beam doesn't transport beyond DTL2.

For the case of a DTL1 fault the beam does not transport to the SCL, but beginning with cavities DTL2 and DTL3 beam loss occurs in the SCL during an RF fault. The amount of beam that actually transports to the SCL is too small to be detected with a beam current or position monitor. The effect on SCL cavity operation is minimal. However, beginning with DTL4 there is significant beam lost in the SCL during a fault.

## BEAM DELIVERY AT SNS AND THE MACHINE PROTECTION SYSTEM (MPS)

In order to properly describe the process of errant beam a description of beam delivery is necessary. As stated above, all of the systems in the linac are always being pulsed at 60 Hz (both $H^-$IS and RF). When the beam is "off" the beam is just not being accelerated beyond the RFQ. The timing system changes the $H^-$IS pulse to either align with the RF or be delayed to a time after the RF pulse has occurred. The system that determines whether beam is allowed to be accelerated is the MPS [4].

The MPS turns off the beam if an equipment malfunction occurs. It takes 15-20 microseconds to turn off the beam upon receipt of the malfunction by the MPS. The following is the process of how the beam is turned off. There are two types of MPS faults: Fast Protect Auto-Reset (FPAR) and Fast Protect Latch (FPL).

### *MPS FPAR*

When an FPAR fault is detected, the $H^-$IS timing gate is turned off (the $H^-$IS decay time is about 20 microseconds), the RFQ timing gate is turned off (it only takes about 1 microsecond for the RFQ field to decay enough to not transport beam), and the LEBT chopper chops all of the beam (no beam enters the RFQ) for 20 microseconds (the response time is about 1 microsecond). While the MPS is faulted the $H^-$IS timing gate remains delayed with respect to the RFQ and the RFQ is turned back on. When the fault condition clears the $H^-$IS trigger gate delay is removed and the beam pulse is synchronized with the RFQ (and all other RF systems). This is all automatic. This particular fault protection is typically used for fast response systems such as Beam Loss Monitors (BLMs) or Low-Level RF High-power Protection Modules (HPMs).

### *MPS FPAR Chatter Fault*

One additional feature within the FPAR is the ability to add a chatter fault feature. This means that if a certain rate of faults is reached the MPS will hold the beam off ($H^-$IS gate remains delayed) until an operator intervenes to reset the fault condition. This feature is important when discussing errant beam and beam trips.

### *MPS FPL*

When an FPL fault is detected, the machine response is the same as the FPAR above except the $H^-$IS trigger gate delay remains delayed until an operator intervenes to restart the beam. When beam is re-enabled the $H^-$IS trigger gate delay is removed and the beam pulse is synchronized with the RFQ (and all other RF systems). The FPL fault is typically a pre-beam MPS check to verify the machine is ready for beam. This particular fault protection is typically used for slower response systems such as magnet power supplies or longer recovery time equipment such as High Power RF (HPRF) power supplies.

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## BEAM INSTRUMENTATION THAT DETECT ERRANT BEAM

The beam instrumentation equipment used to detect errant beam are the BLM system [5] (both BLMs and Neutron Detectors (NDs)), Beam Current Monitors [6] (BCMs), and Beam Position Monitors [7] (BPMs).

### *BLMs*

The BLM system (BLMs and NDs) is extremely sensitive for beam loss detection, and has been the most reliable for detection of errant beam.

The NDs are used in the DTL as they are more sensitive at lower energy (the BLMs are not sensitive at energies below 87 MeV). The NDs are a scintillator detector with a Photomultiplier Tube (PMT) surrounded by a thin layer of lead and a thicker layer of polyethylene. It is relatively rare to see an ND fault during an errant beam event, but they are useful for beam loss tuning for slower losses (over hours or days) that result in elevated activation levels over time. The NDs are connected to the MPS as an FPAR fault. They have a chatter fault setting (described above) of 2 faults in 60 beam cycles.

The BLMs are the main device used for beam loss detection in the CCL and all downstream segments. The BLMs are simple ionization chambers filled with Argon, and are very sensitive for localized beam loss detection at energies above 87 MeV. To gain further sensitivity in the SCL, the BLMs were moved directly onto the beam pipe in the warm sections between cryomodules. Other areas of the accelerator have BLM placement approximately 30 cm above the beamline. All BLMs are also connected to the MPS as an FPAR fault. In the CCL and downstream of the SCL the BLMs have a chatter fault setting of 2 faults in 60 beam cycles. In the SCL, however, the BLMs have a chatter fault setting of 1 fault in 60 beam cycles. This means that any time an SCL BLM trips it must be reset by operators before the MPS allows beam to be accelerated. This was done to eliminate the possibility of instances where errant beam faults occur in consecutive beam pulses. During early beam operations (2006 to 2012) this was highly probable due to the high fault rate for DTL and CCL cavities, but since that time RF faults have been reduced so the probability is quite low. Even with reduced RF fault rates the SCL BLM chatter fault setting remains at 1 in 60 beam cycles.

### *BCMs*

BCMs are calibrated current transformers used for measuring beam charge through the accelerator. There were ten BCMs initially installed in the linac. Of those ten only eight are still installed. Two of the BCMs installed near the CCL were damaged by field emitted electrons from the CCL cavities, and have been removed (see Fig. 4).

Currently, there are two MEBT BCMs, and six DTL BCMs installed. The 6 DTL BCMs are installed within the DTL RF cavities and have had significant noise issues. The signals need significant conditioning in order to provide accurate beam current measurements. These BCMs are not used (see Fig. 5). The most reliable are the two in the MEBT, but only one of those has been highly reliable, also due to noise issues (see Fig. 5). The two BCMs in the MEBT are used for a Differential Beam Current Monitor (DBCM) system to protect against beam loss in the MEBT.

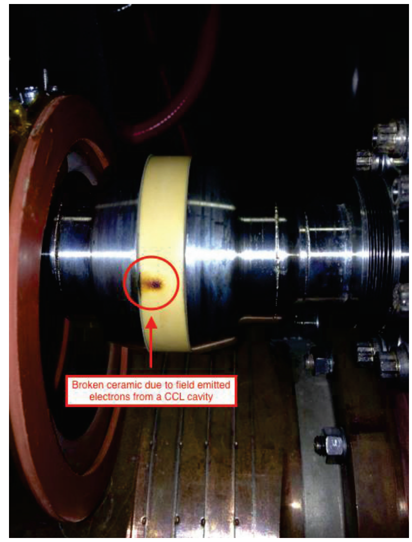


Figure 4: Picture of CCL BCM after being damaged by field emitted electrons.

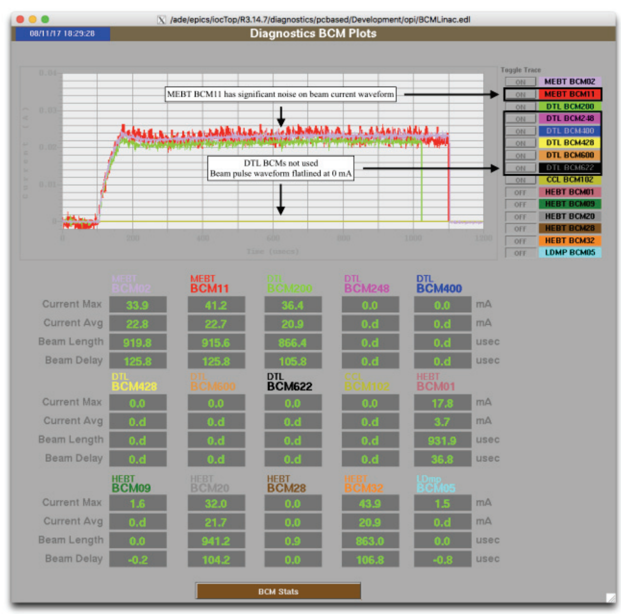


Figure 5: Example BCM waveforms showing a noisy signal in the MEBT, and that DTL BCMs are not used.

### *BPMs*

BPMs are used for measurement of beam position, phase, and also an uncalibrated measurement of beam current. The actual BPM beamline structure has been highly reliable, but the computers and software to relay this information to the control room has not. The BPM computers must be rebooted daily in order for reliable

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measurements. However, with different data processing now in the process of deployment the systems are highly reliable.

There are currently two BPMs used for errant beam detection. Both are used as a current measurement. One system is at the beginning of the MEBT, and it is connected to the MPS as an FPL. It looks for abnormal beam from the RFQ (see Fig. 2). The other BPM used is in the beginning of the CCL and is part of the SCL DBCM system.

The issue with using BPMs for current measurement is that they are not easy to calibrate by themselves and sensitivity to RF changes. Pairing a BCM with the BPM for detecting losses allows calibration of the BPM signal. The DBCM is such a system. The sum signal of the BPM pick-up plates is filtered and amplified with a log-amplifier to detect the RF power of the beam. The signal is then processed by the DBCM's FPGA to produce a current signal. Because the DBCM has access to the calibrated BCM signal, the two signals are compared, in situ, to calculate the calibration coefficients for the BPM signal.

## DETECTING ERRANT BEAM USING THE SCL DBCM

Initially, during early years of neutron production, the only indication of errant beam was faulting SCL BLMs. Much time was spent trying to understand what was causing errant beam. RF cavities were faulting, but the faulting was not linked directly to SCL BLM faults. Operations used RF fault rates to make adjustments to RF cavities to reduce cavity faults which in turn reduced errant beam [8]. However, there were not clear indicators that individual RF cavities were causing the SCL BLM trips. As the SCL cavity performance continued to degrade it was determined that more detailed investigation was needed.

The decision was made to measure the amount of beam lost in the SCL during an RF fault. The initial DBCM used existing hardware and software. A BCM in the beginning of the CCL, and one downstream of the linac in the High Energy Beam Transport (HEBT) line were used for determining beam loss. The system was first used only as a diagnostic. If the charges on the two BCMs differed by a settable level the system would trigger and save the two BCM waveforms to a file server. These data were easily viewable, and it was determined that the MPS was working properly turning the beam off in the predicted 15-20 microseconds.

Since it was understood that losing 15-20 microseconds causes degradation in the SCL the goal became to try to turn off the beam faster than the normal MPS if the DBCM system detected beam loss. The next-generation SCL DBCM system [9] was created for this purpose. The DBCM system is able to turn off the beam in about 8 microseconds (see Fig. 6). This DBCM system sends out two fault signals. One fault goes to the normal MPS, which turns off the beam in the normal 15-20 microseconds. The other fault signal goes directly to the LEBT chopper controller, which begins chopping all of the beam before it enters the RFQ. The system does this until the normal MPS can truncate the H⁻IS and RFQ pulses and prevent beam acceleration. The direct connection to the LEBT chopper reduces the beam turn off time.

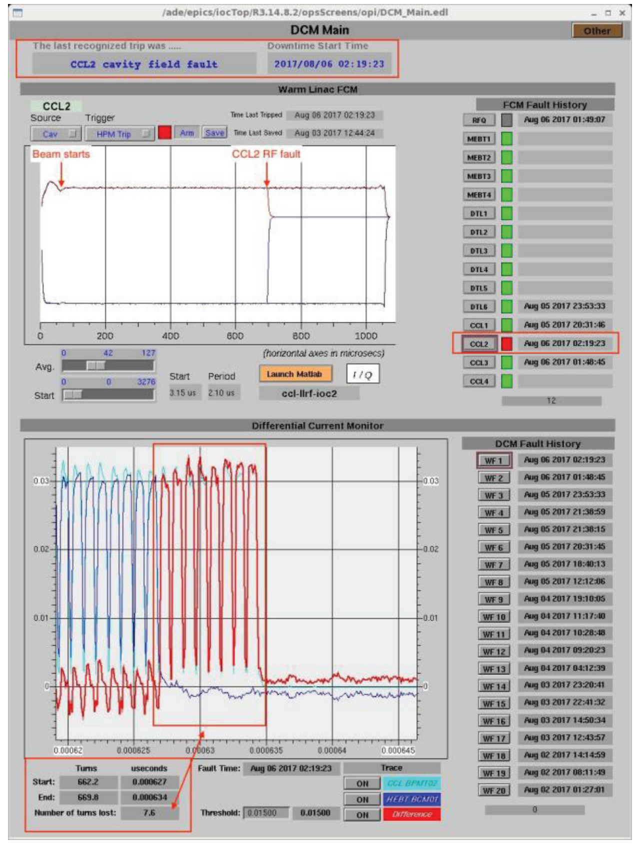


Figure 6: Example errant beam EPICS screen. It shows the particular cavity that faulted with a timestamp (gets counted and archived), the beam profile upstream and downstream of the SCL, and the time during the beam pulse when beam started being lost along with the time it took to turn off the beam. Operators know what happened immediately after a beam trip.

The goal of the DBCM was to reduce the amount of beam lost during an errant beam event and the system does this reliably. However, the 8 microsecond turn off time does not eliminate SCL cavity degradation. Even with the reduced amount of beam being lost in the SCL the cavity gradients still need to be lowered over time. For example, during extended maintenance periods (1 month or more) the Central Helium Liquefier (CHL) raises the SCL cavity temperature from 2 to 4 K, to reduce electricity cost. When the cavities are again cooled from 4 to 2 K after maintenance periods the first errant beam pulse (even with reduced beam turn off time) will cause SCL cavities to fault off. After a few errant beam pulses the cavities begin to “condition”, and will no longer fault during an errant beam event. Even with this conditioning effect the probability of an SCL cavity trip during errant beam event is never zero.

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## RECORDING ERRANT BEAM FREQUENCY

From the beginning of neutron production operation in 2006, the beam downtimes have been recorded manually by operators. The first step in reducing machine downtime is to record any significant downtimes to look for trends, and fix any equipment that cause downtime. The downtime recording system is completely manual. The system is web-based with a nearly complete selectable list of equipment with entries available for fault description and fault length. The time structure for recording is broken down into tenths of hours. If a downtime is greater than 3 minutes then it is considered a 0.1 hour downtime and recorded by operators. Conversely, downtimes shorter than 3 minutes are not recorded in the downtime recording system. In this way, the short downtimes taking only a few seconds to recover are not recorded into the system for statistics information. In the case of errant beam this is problematic, because the longer downtimes due to errant beam take weeks or longer to develop.

In order to better understand the different beam trips (focusing on short trips) and study fault trends an automated downtime recording system was developed. The system detects when the beam is not at the nominal 60 Hz repetition rate and starts counting the time when the beam is not at 60 Hz as downtime. When the beam returns to 60 Hz repetition rate the system bins and counts the downtime analyzing beam trips in real-time. The system also detects and counts errant beam faults to specific RF cavities (see Fig. 6). These data are archived, plotted (see Fig. 7), and discussed weekly with the Machine Health Report (MHR). The MHR is a list of equipment issues for the latest run period. It is used to examine all beam trips to try to find the causes. Analysis is done by the machine specialist to determine the cause and fix for the issue. At weekly meetings, these issues are discussed and solutions are found to be implemented during the next maintenance opportunity.

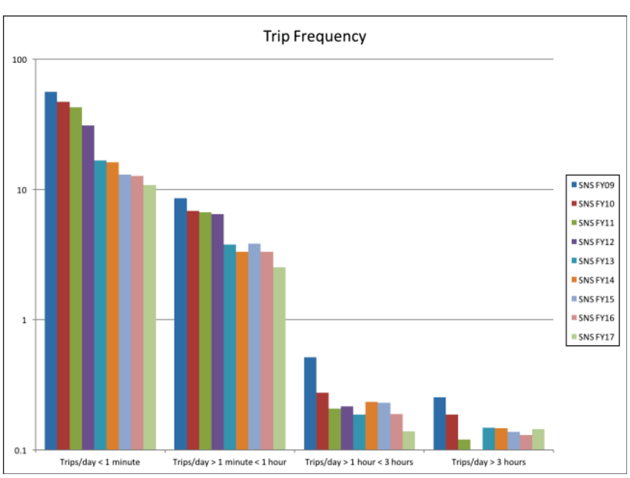


Figure 7: Trips per day for varying beam downtime bins. In most cases the trend is fewer trips per day.

## REDUCING NORMAL CONDUCTING RF FAULTS

Warm linac RF faults during the beam pulse are the main cause for errant beam in the SCL. As stated earlier the RF cavities that cause significant beam loss in the SCL are cavities DTL4, 5, 6, and CCL1, 2, 3, and 4. That means 7 cavities pulsing at 60 Hz 24 hours per day or 36,288,000 pulses per day with a goal of 0 faults. It is not an easily achievable goal.

The method to reduce RF faults was the same used to reduce the longer recorded downtimes. The systems faulting the most were investigated first. As those issues were resolved the next system faulting was investigated. Luckily many of the cavities have had similar issues so once a particular issue is understood there are significant drops in fault rates in a short time.

Each RF system was broken down into cavity tank and RF coupler issues, LLRF issues, and HPRF issues.

### *Eliminating Cavity Fill Faults*

The LLRF Field Control Module (FCM) is able to save RF waveforms during a cavity fault that can be viewed quickly and easily in the central control room. The waveforms are the cavity field, forward power to the cavity (downstream of the RF circulator), reflected power from the cavity, and LLRF output to the klystron. The important piece of information that the waveforms provide is the time during the RF pulse when the fault occurred. Based on the time of the fault during the RF pulse there are different methods used to correct the issue. If the RF faulted during the cavity fill then the way the cavity is filled can be adjusted (see Fig. 8).

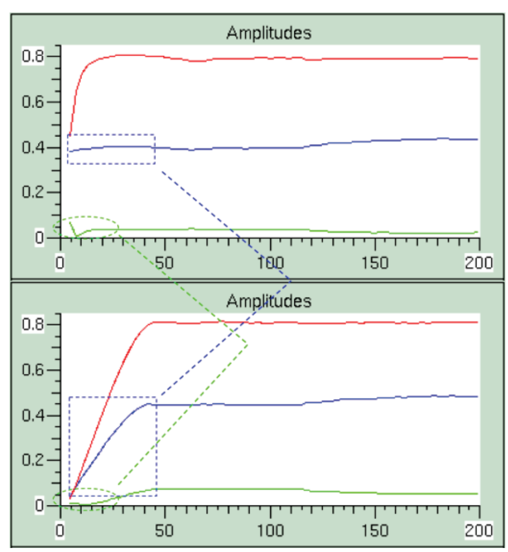


Figure 8: Y-axis is arbitrary FCM field units and x-axis is time in microseconds. Red is cavity field waveform, blue is cavity forward power waveform, green is cavity reflected power waveform. Changing the forward power fill from constant (top image) to a slower linear ramp (bottom image) changed the reflected power structure during the fill and reduced RF faults.

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Instead of a constant forward power to fill a cavity the forward power can be linearly ramped. Doing this during the transition from a traveling wave to a standing wave reduced RF fault frequency. However, these faults are occurring before beam is entering the cavity and do not produce errant beam. For some of the cavities these changes appear to have helped to reduce some portion of RF faults occurring during the beam pulse as well. Perhaps the vacuum environment caused by faults during the fill contributed to an increase faults later in the RF pulse.

In addition to the adjustment with different forward power filling schemes, changing the resonant frequency of cavities also reduced fill time faults [8] (see Fig. 9).

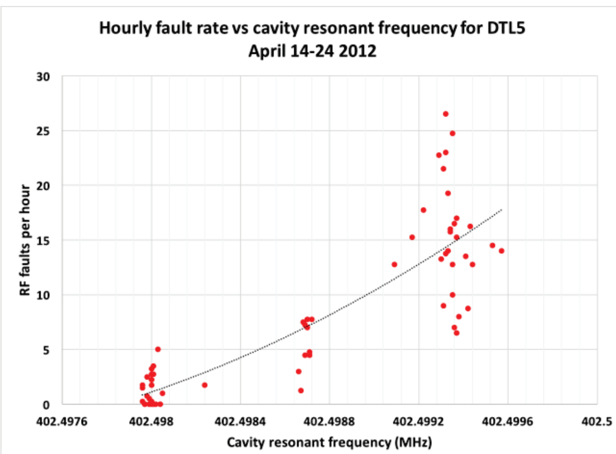


Figure 9: The plot shows the DTL5 hourly fault rate versus cavity resonant frequency during a 10 day period in April 2012. Decreasing the cavity frequency from 402.500 MHz to 402.498 MHz significantly reduced the fault rate.

Changing the temperature of the RF structure changed the resonant frequency of the structure. This was done to try to mimic the effect seen by changing the RF fill method. The reflected power waveform during the fill is affected by the change in resonant frequency. The variable monitored to determine whether a change was good was the vacuum reading near the RF window. As the resonant frequency was changed the window vacuum reading decreased. For DTL cavities running with a negative resonance error (higher reflected power over the majority of the RF pulse) reduced window vacuum levels correlated with a reduced RF fault frequency. For one normal conducting cavity at a time the resonant frequency was changed while monitoring RF fault rates (not necessarily errant beam fault rates). The resonant frequency adjustments made were the main decrease in errant beam faults during early 2012.

## *Vacuum System Improvement*

The vacuum system for the DTL and CCL initially consisted of only capture pumping. Each DTL tank was pumped with 3 ion pumps, and each RF coupler with a Non-Evaporable Getter (NEG) pump. Each CCL tank was pumped with 10 ion pumps, and each RF coupler with a NEG pump. For the DTL there were a total of 18 ion pumps and 6 NEG pumps, and in the CCL there were a total of 40 ion pumps and 8 NEG pumps. Over time the pumping speed of the pumps was not sufficient to maintain proper vacuum levels, and the pumps were bursting inducing errant beam faults and causing significant downtime.

When the DTL RF cavities are energized the structures heat up. When the RF is turned off the different parts of the structure cool at different rates. This differential cooling causes large bursts of air into the structure, and previously the ion pumps were unable to maintain vacuum below interlock levels (1x$10^{-6}$ Torr). The pump down after turning RF off required the structure to reach thermal equilibrium (30-45 minutes) before the vacuum system could maintain levels below the interlock. Eventually Turbo-Molecular Pump (TMP) carts were added to DTL tanks 2-6 for additional pumping speed to eliminate the need to wait for thermal equilibrium.

In addition to the large vacuum bursts requiring additional pumping the NEG pumps on all windows would burst periodically causing the LLRF HPM to interlock the LLRF causing errant beam. Preventative maintenance was done to regenerate the NEG pumps regularly which eliminated the periodic bursts.

The vacuum systems for the DTL and CCL have now both been upgraded to replace all of the ion pumps and NEG pumps with TMPs. There are now 24 TMPs for the DTL, and 32 TMPs for the CCL. Since the upgrade downtimes from the DTL and CCL structures have been eliminated. The overall accelerator availability has increased by a few percent.

## *Change in RF Conditioning Procedure Reduced Field Emission*

The initial version of the RF conditioning procedure for the normal conducting RF was a two-step process to first condition the cavity and then to condition the RF window. The theory was that to condition the window the RF power needed to be increased to beam loading levels. In order to achieve these levels the RF field in the structure was increased to significantly higher levels than required to properly accelerate the beam. Field emission is an exponential process with voltage so increasing the field to reach beam loaded forward power levels created a large increase in the amount of field-emitted electrons. These electrons would hit equipment in or near the cavity heating them to the point where material was released into the vacuum system. This part of the RF procedure actually caused a constant contamination issue each run as the conditioning process was always done after extended maintenance periods.

After an RF window was damaged in 2015 while performing RF conditioning the decision was made to no longer do RF conditioning at beam loaded levels. Since that time x-ray readings from field emitted electrons have dropped significantly, and they continue to decay at a

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slow pace. It takes months to years for the decay to occur (see Fig. 10).

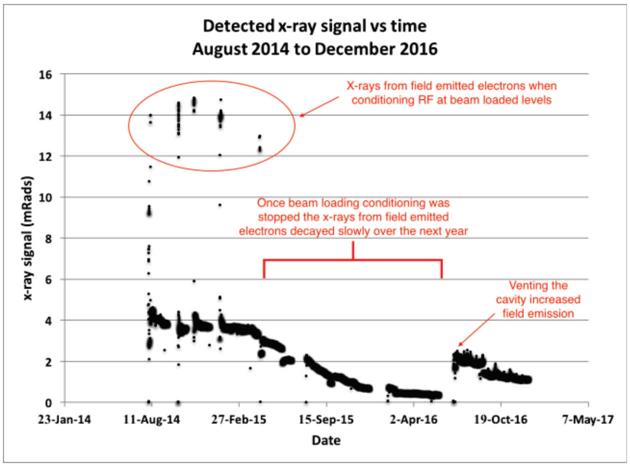


Figure 10: Detected x-rays from field emitted electrons versus time. After removing beam loading conditioning levels from the RF conditioning procedure the amount of field emitted electrons decreased significantly.

### *Reduction in Normal Conducting RF Fields*

In late 2016 the errant beam frequency increased at the beginning of a run. Investigation found that the RF power calibration for the normal conducting RF changed. Fields were incorrect and were higher than they needed to be to accelerate the beam with minimal beam loss. The fields were accidentally increased due to a change in calibration.

The fields in the normal conducting RF were decreased to nominal levels and the beam losses tuned by hand. The thought was then to further reduce RF fields and attempt to properly accelerate the beam and also maintain beam losses at minimal levels. Cavity fields in the normal conducting linac were reduced by up to 5%, and beam losses have not increased. RF cavity faults and consequently errant beam faults have been further reduced.

### *HPRF Klystron Instabilities*

In addition to all of the cavity issues the HPRF system is another cause for errant beam in the SCL. In 2016, after further reducing RF faults, there was a significant increase in errant beam faults for a specific RF cavity in the CCL. By the process of elimination the cause was narrowed down to the HPRF system. An oscilloscope was added to the system that triggered with a LLRF HPM fault. The issue was found to be instability with the klystron. This issue remains, and studies continue to try to further understand how to alleviate the issue without making significant changes to the klystron.

### *LLRF False Fault Detection*

The only issue of note was the installation of arc detector circuits in the DTL and CCL that were too sensitive. The circuits detected arcs even with no RF on in the system. The DTL cards were replaced many years ago, but the sensitive CCL cards remained. From 2015-2017 ~65% (681 out of 1044) of the errant beam faults from the normal conducting linac came from the CCL. These false arc detections are a significant portion of these faults (about 25%). The arcs are detected at all times (during or outside of the RF pulse) so there was a 6% (duty factor) chance of the false arc detection to turn off RF during the beam pulse and cause errant beam (BLM trips).

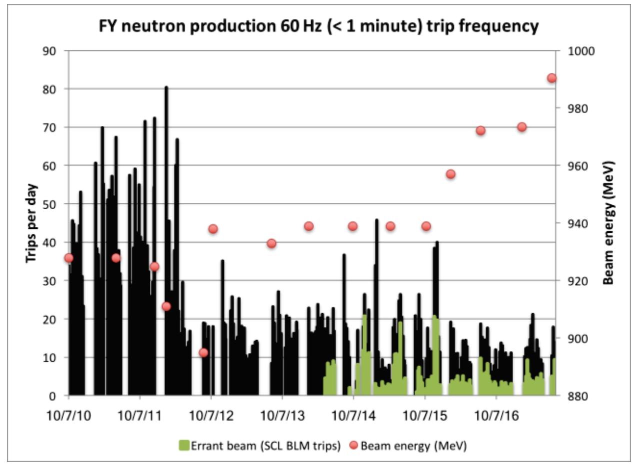


Figure 11: Week by week trip statistics for faults taking less than 1 minute to recover from 2010 until now. Errant beam trip frequency is shown in green.

## CONCLUSION

Errant beam events may seem to not be a significant issue because recovery from these events typically only takes a few seconds. However, repeated errant beam events do cause degradation of SCL cavities with the need to reduce gradients to maintain high availability.

In order to reduce the impact of errant beam the amount of beam lost during an event and the frequency of events have been significantly reduced (see Fig. 11). This has slowed the need to continually reduce cavity gradients and allowed SRF personnel to implement techniques to restore previously degraded cavities and actually improve cavity performance by increasing maximum gradients.

## ACKNOWLEDGMENT

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