HIGH POWER OPERATION OF SNS SC LINAC*

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Abstract

The SNS superconducting linac (SCL) provides 972 MeV, 1.5 MW H^- beam for the storage ring and neutron spallation target. It has now been in operation for 11 years, and we have gained experience in long-term operational aspects. Three inter-related aspects are gradient changes, errant beams, and trip rates. In this presentation we will provide an update on our progress to mitigate these aspects, and also report on the overall status of the SCL.

INTRODUCTION

The SNS SCL today accelerates an H^- ion beam from 186 to 972 MeV using a total of 81 superconducting 6-cell cavities [1]. The first 33 cavities are contained within 11 cryomodules and are optimized for $\beta = 0.61$ (245 MeV), and the remaining 48 are contained within 12 cryomodules and are optimized for $\beta = 0.81$ (662 MeV). SCL commissioning began in 2005, and by 2009 the beam power reached 1 MW. The design beam power of 1.4 MW was first reached in 2013. The design beam energy of 1 GeV has not yet been reached for high intensity production conditions, but we are making steady progress through plasma processing [2].

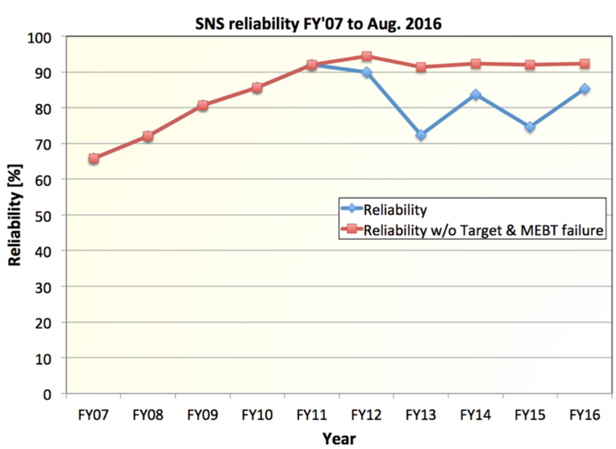

Figure 1: SNS reliability since 2007.

During the 11 years of operation we have learned a lot about operating a high intensity superconducting hadron linac. Highlights include: 1) a previously unrealized beam loss mechanism (intra-beam stripping) was found to be the source of surprisingly high beam loss [3]; 2) errant beam events were found to degrade the SCL cavities [4]; 3) warm linac RF cavity field collapse was found to be the cause of most of the errant beam events [4], and 4) a plasma processing technique was developed to improve cavity gradients [2]. In this paper we will review and update the status of errant beam events at SNS and discuss how to mitigate them, then broaden the discussion to include beam trips in general, and finally conclude with a discussion of beam energy, beam loss and activation.

Since 2011 the linac reliability has been very good, as shown in Fig. 1. It has exceeded 90% in every year except 2014 when it took several weeks to recover from a water leak in the medium energy beam transport a couple meters downstream of the RFQ.

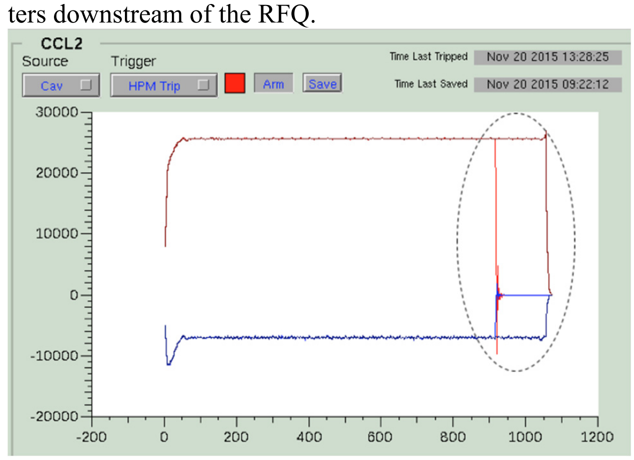

Figure 2: Example of RF field collapse in the warm linac – in this case in cavity CCL-2. The region circled by the dashed line shows the time of the field collapse. A normal pair of I/Q waveforms is superimposed on the field collapse waveforms. The x-axis is in units of microseconds.

ERRANT BEAMS

We define an errant beam event to be an event that causes sudden beam loss due to an off-normal occurrence. For example, at SNS errant beam events often arise in the warm linac in the form of RF field collapse, most likely caused by an arc within the cavity or at the vacuum window. This field collapse causes beam loss to occur in the SCL. The onset of the beam loss is often just a few microseconds in duration, and the beam loss continues until the beam is terminated by the Machine Protection System – typically 7 or 8 µs today. An example is shown in Fig. 2, which shows field collapse in warm Coupled Cavity Linac module CCL-2. In this particular case the beam loss was spread over the first ~75% of the SCL, as shown in Fig. 3, and the event lasted for about 15 µs, as shown by the beam current monitors (BCMs) in Fig. 4. Most errant beam events cause complete loss of beam in the SCL – i.e. 100% of the beam enters the SCL, 0% exits the SCL

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(e.g. Fig. 4), and the loss is usually spread out over several to ten cryomodules in length.

When a large, sudden beam loss strikes an SCL cavity it can cause gas to be released. These can then travel to a new location within the RF cavity, perhaps to a location where the combination of high electric field plus the new contamination create a condition amenable to arc discharge. The discharge condition can be mitigated by lowering the cavity gradient, or in some cases the cavities must be turned off.

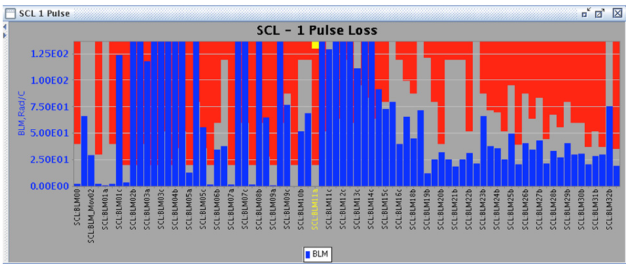

Figure 3: Beam loss monitors in the SCL due to the errant beam event shown in Fig. 2. The blue bars show the BLM signal level, and the red shows the trip limit thresholds.

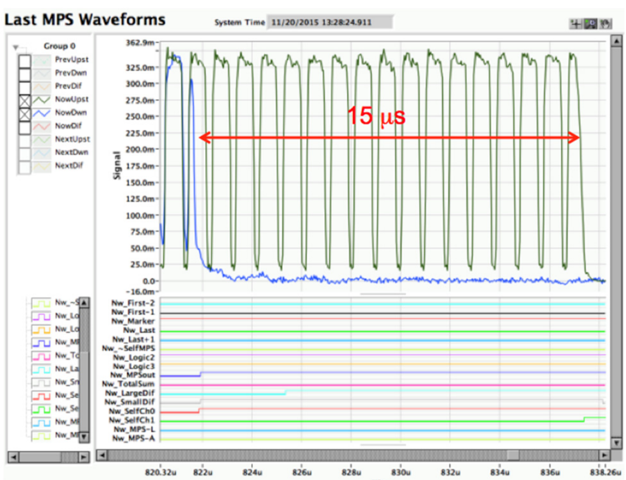

Figure 4: Beam current monitors upstream (green) and downstream (blue) of the SCL, for the errant beam event shown in Fig. 2.

Before installing the differential beam current monitor system (see discussion later) the beam loss event would typically last 10 – 20 µs, which met the original Machine Protection System design specification of <30 µs. Depending on the beam energy, this corresponds to as much as 467 J of total energy deposition. The normal continuous uncontrolled background beam loss does not typically deposit enough power to cause gradient reduction, and not all errant beam events will cause a cavity trip, but the probability of a trip increases with each successive errant beam event. Before addressing the errant beam problem we would typically see 20 – 30 events per day out of a total of 5 million beam pulses per day. This has been reduced to as few as ~5 per day, but as of this writing we see ~8 per day, possibly due to higher-than-normal RF fields in some of the warm linac cavities.

In addition to the ~90% of errant beam events caused by the warm linac there are the remaining ~10% caused by the ion source. Due to arcing the ion beam current sometimes drops precipitously by more than 50% in about one microsecond. An example of one such event is shown in Fig. 5. This causes beam loss because the sudden change in beam loading in the accelerating cavities cannot be immediately compensated by the low-level RF control system, so the beam will not be properly accelerated and focussed. In addition to a sudden drop in beam current the ion source beam pulse can sometimes have a delayed start due to unstable plasma ignition. This will similarly cause beam loss due to off-normal beam loading in the RF system.

There are other contributors to SCL gradient degradation besides errant beam. Two hardware-related examples are ion pumps and vacuum valves. An old or malfunctioning ion pump can sometimes emit contaminants that will enter the SCL cavity and caused gradient degradation. In 2014 we experienced a cavity degradation that was attributed to an aging ion pump [6]. Similarly the vacuum valves can also emit particulate contamination. To mitigate the valve problem we have chosen to minimize the number of times we operate them. Beam halo has also caused some cavity degradation in the upstream end of the SCL [6].

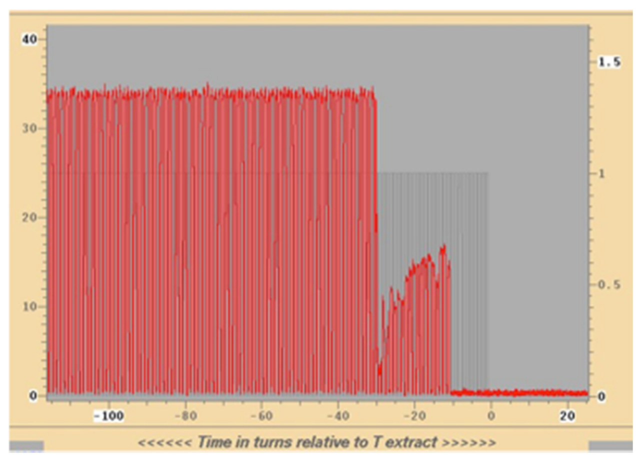

Figure 5: A beam current monitor near the exit of the RFQ. The beam intensity suddenly drops by ~90% in ~1 microsecond. Before it can climb back to full intensity the machine protection system terminates the beam ~20 µs after the beginning of the event. Figure reproduced from ref [5].

When a cavity gradient must be lowered (less than once per year now) it is often just by 1 – 2 MV/m (to be compared to a typical cavity gradient of 10 – 16 MV/m), and the SCL can usually tolerate this change without requiring a retune. Larger gradient changes do require a retune, but this is easily done, since we typically leave the last cavity in reserve at the beginning of each ~4.5 month run cycle to make up any beam energy deficits caused by gradient reductions. The entire SCL can be retuned in less than one hour. The gradient can almost always be recovered by

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warming up the cavity during a maintenance period, then reconditioning it at the beginning of the next run cycle.

Errant Beam Mitigation

The two main methods we use to mitigate errant beams are 1) shut off the beam faster, and 2) reduce the number of errant beam events. To employ the first method a differential beam current monitor system (DBCM) was installed and commissioned in 2016 to allow faster beam shut off [7]. The DBCM is based on two high-bandwidth beam current measurements – one upstream and one downstream of the SCL. Any significant difference between the two measurements is interpreted as beam loss in the SCL.

A schematic description of the DBCM is shown in Fig. 6. The current monitor upstream of the SCL is actually a beam position monitor operated in sum mode, due to the lack of a more conventional current transformer close enough to the SCL. The downstream current monitor is a typical current transformer. Dedicated electronics compare the two signals and send an abort signal directly to the beam shut off device (LEBT chopper) if the difference exceeds the user-adjustable threshold. Before installing this system the beam shut off time was 10 – 20 µs. With this system it is now 7 – 8 µs.

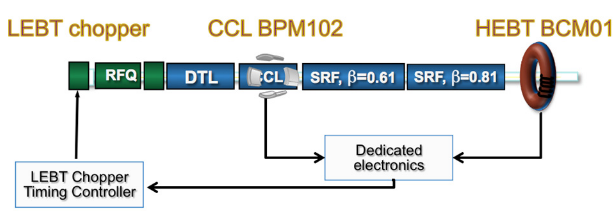

Figure 6: Schematic of the DBCM system.

We are also developing a next-generation fast beam current monitor system in the medium energy beam transport (MEBT) just downstream of the RFQ. This system is also based on a BPM in sum mode, and it is being designed to catch the errant beam events caused by sudden changes in the ion source and turn off the beam even faster than the DBCM system [8].

Beam Trips

The other way to mitigate the effects of errant beams is to reduce their frequency. As discussed earlier, the majority of these events originate in the warm linac and are due to RF field collapse. We have been able to significantly reduce the trip rate by 1) slight changes in resonant cavity frequency, 2) slight changes in the RF fill parameters, and 3) frequent NEG pump regenerations. Figure 7 shows the beam trip rate as a function of time since Oct. 2010, and specifically the errant beam trip rate since mid-2014. The trip rate reductions starting in 2012 are due to the changes discussed above. The errant beam trip rate varies depending on the overall health of the linac. Examples of equipment issues that have caused the errant beam trip rate to spike include problems with the ion source, and RF cavity vacuum windows that are beginning to fail.

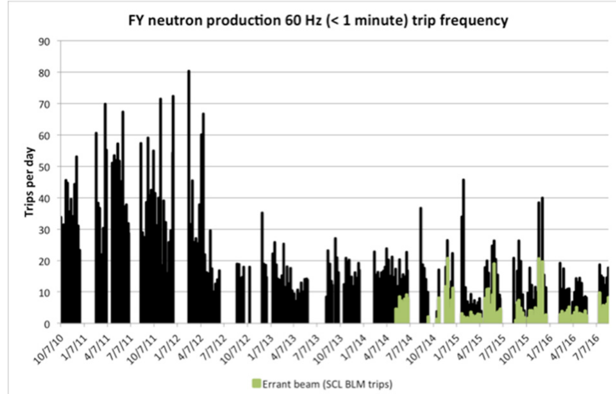

Figure 7: Beam trip rate since Oct. 2010. The green bars indicate errant beam trips.

The empirically-determined trip rate improvements made by slight changes in the resonant frequency are believed to be due to moving the location of the electron activity in the vicinity of the RF vacuum window to a more favourable location. The empirically-determined improvements made by changing the RF fill parameters are believed to be due to creating less-optimal conditions for an arc to occur. The improvements made by NEG pump regenerations are simply due to reducing the gas load in the cavities and nearby the RF windows. To eliminate the need for NEG pump regens, along with the substantial maintenance overhead required for frequent regens, we are now in the process of replacing all the warm linac ion and NEG pumps with turbo pumps.

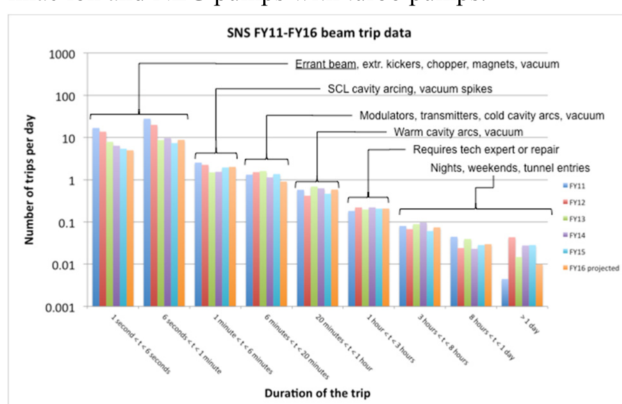

Figure 8: Beam trip durations for fiscal years 2011 through 2016.

Beam trip durations are shown in Fig. 8 for nine ranges varying from as little as 1 second up to more than 24 hours. The shortest duration trips happen more often but of course do not impact the reliability much. The typical errant beam trips are captured in the first two ranges of 1 to 6 seconds and 6 seconds to 1 minute. This is because recovery from an errant beam trip is typically quite fast since it usually just requires that the beam be manually turned back on. The first two categories also illustrate the year-to-year improvements in the overall trip rate and the errant beam trip rate discussed earlier.

SCL BEAM ENERGY

The SCL output energy today is 972 MeV with the last cavity in reserve. This is the highest beam energy we have used for production beam intensities. Higher beam energies, up to 1.07 GeV have been achieved for physics experiments, but these energies can only be reached at lower duty factors. Figure 9 shows a plot of production beam energy vs. time since 2007.

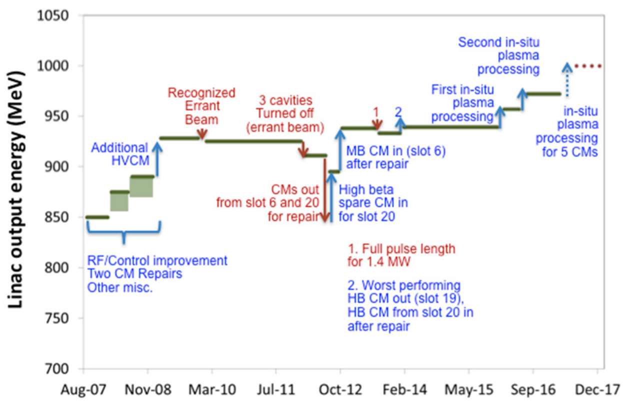

Figure 9: SCL output beam energy vs. time. Figure reproduced from [6].

Today two medium beta SCL cavities are turned off. One cavity has been off since the SCL commissioning due to excessive fundamental power coupling to the higher order mode filter. The other cavity has been off since April 2015, most likely due to damage from errant beams. The recovery of these two cavities await the construction of a spare medium beta cryomodule because repairing these particular cavities will require each entire cryomodule to be removed from the linac tunnel for several months. A spare high beta cryomodule was completed in 2012 and it has been put to good use in repairing several high-beta cavities.

The path to achieving the design output beam energy lies in plasma processing. This technique, which can be performed in-situ without removing any cryomodules, was developed at SNS over the last several years. It has been used for the last two beam outage periods to increase the beam energy from 940 to 972 MeV. It is described in more detail in a separate paper at this conference [2].

In spite of the less-than-design beam energy we have been able to reach our beam power goal of 1.4 MW on target by increasing the average beam current beyond the design value. The two most effective parameters were 1) a reduction in the LEBT chopper rise and fall times, and 2) a reduction in the chopped gap duration. The chopper rise and fall time improvements [9] were made by modifications to the chopper electronics, reducing some resistors, and reducing stray cable capacitance. The reduction in the chopped gap duration (required for clean beam extraction from the storage ring) were made by adjustments to the firmware that, in retrospect, overly constrained the allowable gap times to the design values but in practice we can accept even shorter times and still achieve clean beam extraction.

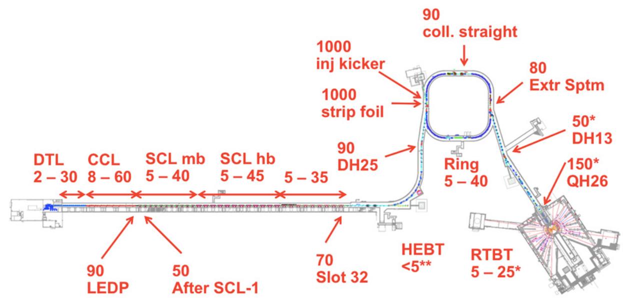

Figure 10: Typical activation levels in the SNS accelerator after 1.3 MW operations and 3 – 5 hour cool down. The numbers are in units of mrem/h at 30 cm.

BEAM LOSS IN THE SCL

Although the beam loss in the SCL is higher than anticipated, it is acceptable and well below the rule-of-thumb limit of 1 mSv/h (100 mrem/h) for hands-on maintenance. Typical values are shown in Fig. 10 for a recent case of 1.3 MW operation followed by a 3 – 5 hour cool down period.

The main contributor to beam loss in the SCL is intra-beam stripping (IBSt) [3]. The IBSt rate is proportional to the square of the beam density, and to minimize it we have lowered the quadrupole gradients in the SCL by about 40% to increase the transverse beam size until the onset of beam halo scraping. To date the beam loss reduction has been almost entirely done by empirical tuning. However we believe that further improvements can be achieved by more precisely matching the transverse beam size to the available aperture, by minimizing the beam halo, and by matching the longitudinal size to the longitudinal dynamic aperture. Efforts to do this have been underway for several years now [10] and are making good progress.

SCL FUTURE

The Proton Power Upgrade (PPU) project [11] intends to increase the beam power capability to 2.8 MW by increasing the beam energy to 1.3 GeV and the average SCL beam current to 2.3 mA. The beam energy increase will be accomplished by adding seven new cryomodules to the SCL. Space for nine new cryomodules was reserved during SNS construction with such an upgrade in mind, but due to advances in SRF technology the energy increase can now be accomplished with two fewer cryomodules. The new cryomodule design will be the same as the spare high beta cryomodule recently constructed at SNS (except for the end group design), with an accelerating gradient specification of 16 MV/m. Some of the existing cavity gradients will actually have to be reduced slightly to accommodate the higher beam current while maintaining the LLRF control margin, as shown in Fig.

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11. We anticipate that the 1.3 GeV beam energy can be reached with 1 – 3 cavities in reserve. The 1.3 GeV specification is a relatively hard upper limit due to the design of the high energy beam transport (HEBT) beam line from the linac to the ring. As the energy is increased above 1.3 GeV the beam loss in the HEBT quickly becomes excessive due to magnetic field stripping of the H^- ion beam.

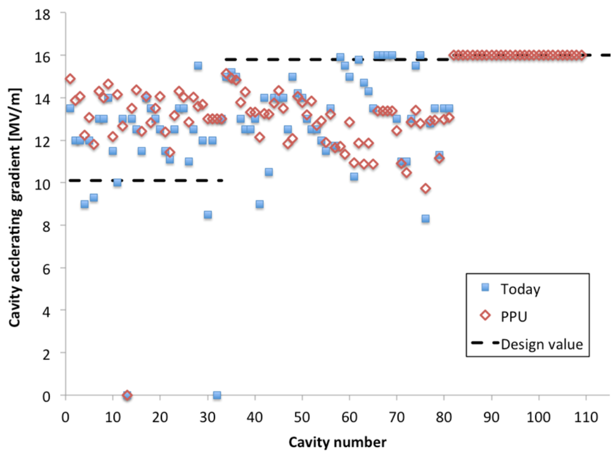

Figure 11: SCL gradients today (blue) vs. PPU (red).

SUMMARY

The SNS SCL has performed very well over the years and the lessons learned now guide designs of several next-generation high intensity hadron linacs. New knowledge and advances are still made every day. The Proton Power Upgrade project will provide even better performance from the SCL.

ACKNOWLEDGMENT

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