TITLE:

Overview of ten-year operation of the superconducting linear accelerator at the Spallation Neutron Source

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ABSTRACT

The Spallation Neutron Source (SNS) has acquired extensive operational experience of a pulsed proton superconducting linear accelerator (SCL) as a user facility. Numerous lessons have been learned in its first 10 years operation to achieve a stable and reliable operation of the SCL. In this paper, an overview of the SNS SCL design, qualification of superconducting radio frequency (SRF) cavities and ancillary subsystems, an overview of the SNS cryogenic system, the SCL operation including SCL output energy history and downtime statistics, performance stability of the SRF cavities, efforts for SRF cavity performance recovery and improvement at the SNS, and maintenance activities for cryomodules are introduced.

Keywords: superconducting linear accelerator; superconducting radio-frequency cavity; pulsed operation; spallation neutron source.

1. Introduction

The Spallation Neutron Source (SNS) provides the most intense pulsed neutron beams in the world for scientific research and industrial development. The neutrons are produced by the spallation process using an accelerator-based system that delivers short proton pulses to a target and neutron moderator systems [1]. Figure 1 shows the layout of the SNS accelerator system. The front end (FE) system produces the negative hydrogen ion beam required for the injection into the accumulator ring downstream. In the FE, the ion beam is also chopped for the clean extraction from the ring to the target. The beam from the FE is injected into the linear accelerator (Linac) that consists of conventional normal conducting (NC) radio frequency (RF) structures and superconducting RF (SRF) structures. For injection into the accumulator ring, the negatively charged ions are stripped of their two electrons using a diamond foil. The ring accumulates successive bunches from the Linac and compresses a 1-ms long beam pulse into a 700-ns pulse. Such intense pulses are sent into the target for neutron production at 60 pulses per second (pps), 5.2 million times a day. The time average beam power on the target is 1.4 MW. The SNS accelerator complex was commissioned in 2006 and tremendous efforts have been made for reliable operation at the design beam power. Since 2011, the SNS accelerator system has been providing neutron production with availability 90% – 92 %.

Insert Figure 1

Since the design beam power at the target was almost an order of magnitude higher than the then existing pulsed accelerator-based neutron facilities, all subsystems of the SNS were designed and developed for substantial improvements compared to existing accelerators and some subsystems are first of a kind. Many performance and reliability aspects were unknown and unpredictable, and it took time to understand the systems as a whole and to determine the need for additional performance improvements. From the series of tests and operational experience, more understanding of systems and their limiting conditions in the pulsed mode operation are being obtained at high duty factor operation. The main beam parameters for the accelerator, such as beam energy, beam pulse length at the target and beam repetition rate were determined from the needs of the neutron scattering science. To best achieve these parameters, accelerator design studies were conducted and the option of a full-energy Linac and accumulator ring was chosen [1-4]. The studies estimated that there was a minor difference in cost, however the full energy injection would be a simpler option for a single purpose machine and for a beam power upgrade to multi-megawatts in the future. For the Linac technology, a combination of a NC Linac and a Superconducting Linac (SCL) was adopted [5]. The FE system consists of a negative hydrogen ion source, a radio frequency quadrupole and a medium energy beam transport line for matching the beam into the Linac. The Linac consists of six drift tube Linac (DTL) structures, four coupled cavity Linac (CCL) modules and twenty three cryomodules in the SCL. The output energies at each structure are described in figure 1.

The SNS SCL is the first large-scale high energy superconducting proton Linac that provides high beam power using negative charged hydrogen beams. The use of superconducting elliptical shape cavities for the acceleration of non-relativistic particles makes this accelerator a very important milestone. Another important aspect of the superconducting Linac is the fact that it is operated under pulsed conditions. The SRF cavities in the SNS SCL have the characteristic of being powered in a pulse mode, 1-ms beam pulses at 60 pps, which is unique among superconducting accelerators for ions in routine operation. The SCL utilizes two SRF cavity geometries; medium beta cavity with a geometric beta of 0.61 and high beta cavity with that of 0.81 to cover the energy range in the SCL.

2. SNS Superconducting Linac design

After preliminary conceptual design studies for a SCL option were conducted in 1999 [5], the Linac baseline above 186 MeV was changed from NC CCL structures to SRF structures in 2000. Justifications for the SCL option for the SNS were; 1) higher real estate accelerating gradient leads to shorter Linac and klystron gallery lengths, thus cheaper construction cost, 2) Cheaper operating cost since SCL requires less electricity, 3) individually powered SRF cavity provides high operational flexibility which leads to high availability, and 4) the extremely low vacuum and larger beam acceptance in SCL results in lower beam loss.

Although the SNS SCL was the first application of SRF cavities for a pulsed high power ion accelerator, the science and technology for critical components such as SRF cavities and fundamental power couplers were well-developed and these served as the design basis for the SCL. Two constraints drove the high level design for the SNS SRF cavities: 1) limit the peak power of the fundamental power couplers to a maximum of 350 kW in the very early stage of the SNS SCL design, later increased to 550 kW and 2) limit the cavity peak surface electric field to 27.5 MV/m due to concerns related with field emission, later increased to 35 MV/m for the high beta cavities [6] by adopting electro-polishing as a surface processing technique. In reality, electro-polishing was only applied to several high beta cavities because the technology for production cavities was not sufficiently mature at the time of cavity production. The 550-kW RF power limit per SRF cavity corresponded to klystrons that were available commercially and did not require new development.

After investigating a variety of SCL configurations, a rough cost optimum was found using only two cavity geometries: medium beta cavity and high beta cavity. The cavity shapes were designed to optimize the transit-time factor, balance the peak surface magnetic and electric fields, increase the resonant mechanical frequencies, minimize the effects of Lorentz detuning, and take into account possible issues with higher-order cavity modes and available RF power [7-9]. The design accelerating gradients were chosen at 10.1 MV/m and 15.8 MV/m for the medium beta cavity and the high beta cavity respectively. The cavity unloaded quality factor was set to accommodate the possibility of operating under heavy field emission regime. A coaxial type fundamental power coupler (FPC) with a single window was chosen based on the 508 MHz FPC experiences at KEK [10]. The higher order mode (HOM) coupler geometry was scaled from the Tesla Test Facility (TTF) HOM coupler. The mechanical tuner was scaled from the TTF-Saclay tuner and later modified to incorporate a piezo actuator for dynamic detuning of the SRF cavities in case the effect of the Lorentz force detuning would be too large to be controlled with the low level RF system alone. The SNS cryomodule design was based on the CEBAF cryomodule with improvements from lessons learned at LHC, TTF and CEBAF 12-GeV upgrade programs. The cryomodules and all of the internal components were designed, processed, and assembled at Thomas Jefferson National Accelerator Facility (TJNAF) [11]. Between cryomodules there are 1.6-m long warm sections for magnets and diagnostics, and differential pumping stations were adopted at both ends of the SCL for vacuum transition [12]. Table 1 summarizes the parameters that describe the architecture of the SNS SCL and table 2 summarizes the design specification of the SNS SRF cavities and cryomodules.

Table 1 The SNS SCL architecture

Total real estate SCL length (m)	157
Space reserved for upgrade (m)	71
Frequency (MHz)	805
Input energy (MeV)	186
Output energy (MeV)	1000
Transverse magnetic focusing lattice	Warm quadrupole doublets
Warm section length between cryomodule valves (m)	1.6
Klystrons per cavity	1
Fundamental power couplers per cavity	1
HOM couplers per cavity	2
Length for differential pumping between CCL and SCL (m)	2.35

Table 2 Main design parameters for the SNS superconducting cavities and cryomodules

Cryomodule parameter	Medium beta section	High beta section
Output energy (MeV)	387	1000
Number of cryomodules	11	12
Number of cavities per cryomodule	3	4
Cryomodule length (m)	4.2	6.3
Mechanical tuner range (kHz)	+/- 200	+/- 200
Fast tuner	Piezo electric	Piezo electric
Cavity Parameter	Medium beta cavity	High beta cavity
Geometric beta	0.61	0.81
Number of cells per cavity	6	6
Unloaded quality factor Q_0	$> 5 \times 10^9$ at 2.1 K	$> 5 \times 10^9$ at 2.1 K
External quality factor Q_{ext}	7.3×10^5	7×10^5
* $E_{acc} = E_0 T_g$ (MV/m)	10.1 at $\beta=0.61$	15.8 at $\beta=0.81$

E_{peak} (MV/m) at design E_{acc}	27.5	35.0
H_{peak} (kA/m) at design E_{acc}	46.2 (58 mT)	59.7 (75 mT)
Geometric factor $Q \cdot R_s$ (Ω)	176	228
r/Q at geometric beta (Ω)	279	483
Equivalent cavity length (cm)	68.2	90.6

* E_{acc} : accelerating gradient at the geometric beta, T_g : transit time factor at the geometric beta

3. Cryomodule and SRF cavity qualification

Qualifying the components as a fully integrated system, and identifying and understanding the limiting conditions are critical to achieve a reliable operation of cryomodules. Figure 2 shows the cryomodules installed in the SNS Linac tunnel. Several extensive performance qualifications of cryomodules and SRF cavities at various operating temperatures and repetition rates were conducted with cryomodules installed in the tunnel in conjunction with all supporting systems [13]. Interlocks and machine protections have been improved based on results from the qualification studies and from the accumulated operational experience. Some important issues for reliable SCL operation such as end-group thermal instability, HOM coupler issues, cavity-coupler interactions, adsorbed gases on the cold surface of SRF cavities and collective effects between cavities were identified and studied. The term ‘collective effects’ in this paper refers to interactions of electrons between cavities in a cryomodule where electrons from one cavity can affect other cavities’ performances. In particular thermal instability in the end-groups of SRF cavities due to electron activity such as field emission and multipacting is the main limiting factor of the accelerating gradients in operation at the SNS. Also as the repetition rate was increased, more severe collective effect between cavities was observed. In the following, the limiting accelerating gradient refers to the maximum accelerating gradient that can be achieved in a cavity with RF loading only for a short period of time, typically less than 24 hours, while the stable accelerating gradient refers to the accelerating gradient that can be maintained stably during production run with beam acceleration. The stable operating gradient is found to be empirically about 85% of the limiting gradient at the SNS.

Insert Figure 2

3.1 Initial operation at 4.4K

Since most sub-systems were not commissioned for the operation at the full duty factor in the early stage of the SNS operation, the RF repetition rate was limited to 10 pps and stable accelerating gradients for all the SRF cavities were initially established at 10 pps. In addition, the cryogenic plant’s sub-atmospheric system was not available for the initial cavity and cryomodule tests in 2005 and the SCL system was initially operated at 4.4 K instead of the design operating temperature of 2.1 K. At 4.4 K and 10 pps, most SRF cavities in the SCL could be operated stably at their design accelerating gradients, and a good portion of the cavities could even be operated at higher gradients. The SCL operation for neutron production at 2.1 K started in 2007, once the sub-atmospheric part of the cryogenic plant became operational and the repetition rate was increased to 30 pps and then 60 pps. Additional studies of the maximum achievable gradients in the SRF cavities indicated that the limiting factors in the cavities were not related to the operating temperature. The operating temperature of the SNS SRF cavities were reviewed, and cavity parameters and their interplay were reevaluated, giving details on the possible range of operating parameters which can be achieved at SNS in pulsed conditions [14].

The transient nature of pulsed operation allows a larger variation of temperatures within the niobium surface, so that during the pulse the surface resistance of the material can change substantially. There are

no BCS limitations at the SNS duty and pulse length up to the critical field when the helium temperature is less than 4.5 K, which was also verified with individual cryomodule tests at 60 pps and both at 2.1 K and 4.4 K. It is mainly due to the pulsed nature of the SNS operation and relatively low operating frequency compared to frequencies for electron machines (e.g. 1.3 and 1.5 GHz). The SNS SCL operation at 4.4 K was conducted only at 20-pps or lower repetition rate because the cryogenic load from all cryomodules at a higher repetition rate exceeds the SNS cryogenic capacity designed for 2.1-K operation.

3.2 Stable operating gradients

The main limiting factor for the stable operating gradients of the SNS SRF cavities is related to the thermal load from electrons due to field emission and multipacting [15, 16]. In the SNS SCL, the cryogenic load from electron activities is equal or slightly higher than the thermal loads from BCS resistance at 2.1 K and residual resistance. Since the SNS cryogenic plant has an enough capacity for the 2.1-K operation as described in the section 4, there is no concern with the cavity quality factor as long as its operation is stable. However, this could be a critical issue for continuous wave machines, if there is a severe electron activity at an operating gradient. In the SNS SCL thermal instabilities caused by electron activities is more of an issue than quality factors of cavities. The thermal instability occurs in the end groups, leading to a partial quench or gas burst triggering a vacuum interlock. The thermal instability of the end groups of the SNS SRF cavities is not dominated by material defects because the magnetic field is low on those surfaces. In contrast, primary and secondary electrons emitted at various locations on surfaces of the SRF cavities can get accelerated by the electric field and end up depositing enough power on the end-group surfaces to generate a thermal instability especially because the end-groups are made of the reactor grade niobium whose residual resistivity ratio (RRR) is typically 30 and are not directly cooled by the helium bath. In order to increase the RRR of the SNS end groups during the cavity production, the end-groups were heat treated but the RRR increased only to around 50. When the end group reaches its instability threshold, an intermediate state or partially quenched state can develop, which is characteristic of low field region thermal instability. The main cavity body region has the opposite thermal stability characteristic, having a higher thermal stability against a thermal load from electron loadings than the end groups but having a faster thermal runaway with localized heating from material defect or from heavy multipacting. Most SRF cavities in the SCL show end-group instability evidenced by thermometry and slow quench developments over many pulses. Only a few cavities show evidence of main cavity body thermal instability. The radiation onsets were characterized in the SNS SCL after conditioning and were measured at an average gradient of 10 MV/m with 3-MV/m standard deviation.

At a repetition rate of 15 pps, the average limiting gradients of the medium- and the high-beta cavities are 16.7 MV/m and 17.5 MV/m respectively, which exceed the design gradients. At this repetition rates the individual limiting gradient that is measured by powering one cavity in a cryomodule at a time, are about the same as collective limits that are measured with operating all the cavities in a cryomodule simultaneously. Linac output energy of 1 GeV at 15 pps was first achieved in February 2007. The operating gradients were set to about 85 % of the individual limiting gradients and 78 cavities out of 81 cavities were in service for this run. In contrast, 1-GeV operation has yet to be achieved at the full duty factor and 60 pps.

Clear evidence of collective effects limiting the operating gradients of the SRF cavities can be observed at a repetition rate of 30 pps or higher. The severity of the collective effects are not only determined by the amplitude of the accelerating gradients in the cavities of a cryomodule, but also by their relative RF phases because both affect the trajectories of the electrons, energies of the electrons and the locations where the electrons impact on the cavity surfaces. Due to the collective effects, cavities become thermally unstable at lower gradients than the ones at lower repetition rate operation, thus limiting the final Linac output energy. When electrons hit any intermediate temperature region in the cavity string, bursts of

adsorbed hydrogen gas can be sometimes observed and trigger vacuum interlocks, which can also lead to redistribution of the adsorbed gas in the cavity string and to lower operating gradients.

Figure 3 compares the average accelerating gradients for both cavity geometries under several different operating conditions. At low repetition rate, individual limits are close to collective limits as mentioned above. All data in figure 3 except ‘individual limits in open loop at 10 pps’ were taken in closed loop operations with 1200- μ s long RF pulses including cavity fill time. For the open loop case a constant RF power was applied for 1200 μ s. Due to the gradient amplitude and phase regulation requirements and much longer duration at the highest field in closed loop, the limiting gradients in the closed loop is lower than in the open loop condition. The reduction of the average gradient between the 10 pps with cavities run individually and 60 pps with cavities run collectively is more pronounced for the high beta cavities than for the medium beta cavities because the electron acceleration is more efficient in the high beta cavities. Determining the stable operating gradients requires a careful evaluation of collective behaviors by powering all cavities simultaneously in a cryomodule. The stable operating gradient at 60 pps is set at about 88 % of the collective limit. There is a lack of correlation between limiting gradients from vertical tests during the cavity production and cryomodule tests. The main reason is believed to be related to the subsequent surface processing step applied to cavities after the vertical test. The data for high beta cavities shown in figure 3 was taken before the spare high beta cryomodule was installed in the SCL and before deploying in-situ plasma processing that will be mentioned later.

Insert Figure 3

3.3 Electron loading and associated radiation

The electron loading in the SNS SRF cavities is from both field emission and multipacting, and some cavities show radiation waveforms indicative of both multipacting and field emission.

Both high and medium beta cavities show the same indication of intense multipacting between 9 MV/m and 14 MV/m. During an initial RF conditioning, for example after a cryomodule is thermally cycled, multipacting usually starts from about 3 MV/m and such multipacting at low gradients is easily conditioned out. The multipacting at higher gradients in contrast cannot be always completely conditioned out and even is the main limiting factor for some cavities in the SCL. The resonant portion of the electrons generated by multipacting are not always the ones inducing thermal instabilities because the non-resonant secondary electrons can be strongly accelerated, especially in the high beta cavities, and be responsible for the main thermal load and generation of radiation in the SNS cavities limited by multipacting. Figure 4 shows the radiation waveforms from multipacting in open loop RF operation after RF conditioning was completed. The radiation onset is around 10 MV/m in this example. Up to 12.3 MV/m, the radiation waveform kept the same overall shape but its intensity increased exponentially very similar to a field emission process. As the gradient is increased further, the amplitude of radiation starts to saturate and the waveform splits into two spikes, one during the fill time and the other during cavity field decay time as shown in figure 4. In this example, the multipacting cannot be completely conditioned out but it is not the main limiting factor for the accelerating gradient. For some cavities, the multipacting is too severe and quenches occur in the end-group at 60 pps operation, which limits an achievable accelerating gradient. Very careful attention is needed especially during the initial conditioning period since a weak component could be damaged by the initial violent electron activity.

Insert Figure 4

Field emission is the main limiting factor for SRF cavities in operation at the SNS. The average field emission onset in the SNS SRF cavities is about 12-13 MV/m. Figure 5 shows the typical radiation waveforms from field emission in open loop operation. It is found empirically that for SNS SRF cavities, the end group becomes thermally unstable at 3-MV/m above the field emission onset at 60 pps operation.

Insert Figure 5

After enough RF conditioning, the radiation level becomes stable over time for both multipacting and field emission. It is not surprising that the field emitters after RF processing became stable, however very stable multipacting has been also observed in some cavities after 10 years of operation and is indicative of stable secondary emission yield and not only multipacting originating from adsorbed gases.

In order to monitor the background radiation level in the SNS tunnel, the beam pulse repetition rate is actually 59.9 Hz while RF repetition rate is 60 Hz. Every 10 seconds, one pulse with RF only is dedicated for background radiation measurement without beam. Several cavities show slightly elevated x-ray levels during operation. When a cavity shows elevation of its x-ray level during operation and begins to trip more frequently, the cavity surface condition, because of gas redistribution for example, is believed to have changed and the cavity operating gradient is lowered preemptively by 1 MV/m or less. The cavity is usually successfully reconditioned using RF and the drop in accelerating gradient is recovered.

3.4 Ancillary subsystems

The Higher Order Mode (HOM) Filters are ideally designed to damp longitudinal modes excited by the beam while avoiding damping the accelerating mode at 805 MHz. The probability that a cavity HOM frequency will coincide with a beam driving spectral line was estimated to be very small during the Linac design phase. However, many factors can cause HOM frequencies to move around with time, and to permanently satisfy the damping requirement the SNS cavity installed a HOM coupler on each end group as a simple precautionary measure [17, 18]. Unfortunately operational experience showed that the accelerating mode can sometime be coupled out and lead to failure of the HOM RF feedthroughs. About 15% of installed cavities in the SNS SCL are showing abnormal signals through their HOM feedthroughs. All attenuators for the HOM signals were damaged in 1 year of operation during the early days of commissioning and operation. Observations and physical conditions near the HOM couplers imply that HOM coupler failures or degradation seem to be a result of electron activity originating from multipacting, field emission, and even gas discharge at the fundamental mode. A few cavities were inoperable due to large coupling with the fundamental accelerating mode. In 2007, the SNS reevaluated the HOM characteristics including dangerous HOM modes measurement for all installed cavities. It was concluded that HOM couplers are not needed for the SNS and it was decided to remove HOM couplers whenever cryomodules are taken out of the tunnel for repairs. Four cryomodules have been taken out of the tunnel so far and leaks were detected in half of their HOM feedthroughs.

The SNS FPC is designed and scaled from the one KEK developed for 508.8 MHz. Simple window geometry was chosen to facilitate manufacturing and assembly. The design of the SNS FPC is based on a simple 50 Ω coaxial line. The planar alumina window includes impedance-matching elements as well as a TiN anti-multipacting coating. The chokes at both sides of the ceramic window have the important role of improving the window matching [19]. The outer conductor of the FPC has a direct conduction path to room temperature. To minimize heat transfer to the end group, the FPC outer conductor is designed to be cooled by supercritical helium at 3 atm and 5 K with 0.04 g/s of mass flow rate, which removes about 30 W of static and dynamic heat load. The static heat load comes from the heat transfer between cryogenic

temperature and ambient temperature, and the dynamic heat load refers to an additional heat load from RF operation of the system. The inner surface of the outer conductor is designed to be copper-plated with 15 μm (RRR=10) on stainless steel to reduce wall dissipation. The inner conductor of the FPC is made of copper and does not have active cooling in the vacuum side. The FPCs were tested up to 2-MW peak for the full travelling wave condition in the test stand and over 550 kW peak power in real cavity operation at various standing wave ratios limited by the operational envelope. Multipacting in the FPCs are also observed, and mostly happens at the near full travelling wave condition during filling time, during cavity field decay after RF is turned off or during cavity field flattop at high beam loading. The FPC is equipped with an electron probe at the FPC ceramic window and the probe's pulse waveforms are very useful to monitor multipacting in the coupler region [20]. Aggressive multipacting is observed in some FPCs at 300 kW or above. Positive DC biasing of the inner conductor at around 800 V efficiently suppresses the multipacting in those FPCs.

Lorentz force detuning in SNS SRF cavities can be significant because the pulsed operation can potentially drive mechanical resonance modes. The observed amount of dynamic detuning agrees quite well with expectations in most of the cavities. The detuning coefficients are about $3\text{-}4\text{ Hz}/(\text{MV}/\text{m})^2$ and $1\text{-}2\text{ Hz}/(\text{MV}/\text{m})^2$ in the medium- and high-beta cavities respectively. A few cavities show larger detuning coefficients at the higher repetition rates, implying that mechanical resonances are excited in these cavities. The amount of dynamic detuning of the high beta cavities during the RF flattop is less than $0.5\text{ Hz}/(\text{MV}/\text{m})^2$. Since the cavity bandwidth is relatively large ($\sim 500\text{ Hz}$) or the external Q is relatively low ($<10^6$) due to the high beam loading, the additional RF power needed to compensate the dynamic detuning is minor [21]. This amount of detuning is well managed by the adaptive feed forward implemented in the SNS low level RF (LLRF) system. Fast piezo tuners were installed to mitigate any unexpected mechanical resonance conditions. Up to now there is no strong need to utilize them and they have never been operated.

4. Cryogenic system

The SNS central helium liquefier (CHL) system consists of gas storage, helium purifier, warm compressors, 4-K refrigerator, liquid helium storage, distribution system, and 2K cold box. Table 3 summarizes the capacity of the SNS CHL system [22].

Table 3 SNS cryogenic system design specifications

	Primary	Secondary	Shield
Supply temperature [K]	4.5	4.5	38
Return temperature [K]	2.1	300	55
Supply pressure [bar]	3	3	4
Return pressure [bar]	0.041	1.05	3
Capacity	125 g/s	15 g/s	8300 W

Each cryomodule is functionally equipped with five valves; shield supply valve, primary Joule Thomson (JT) valve, secondary JT valve, cool down valve, and primary return (RT) valve. The shield supply valve regulates the exiting temperature of the cryomodule shield. However in mature operation, many of the valves are placed in manual control to avoid unnecessary cycling of the shield valves. With the valves in manual position, the outlet temperature of the shield varies by less than 1 K. The primary JT valve regulates the liquid level within the cryomodules ensuring that the cavities are completely submerged during RF operation. The secondary JT valve provides cooling to the FPC flanges and the FPC outer

conductor in the vacuum side. This flow returns to the cryogenic system through an ambient heat exchanger thus making it a liquefaction load on the plant. The cool down valve is used during cool down or warm up of the cryomodule so that any contaminants that may be in the cryomodule can be routed to the purifier rather than the main cryogenic system. The RT valves remain 100 percent open during operation so that helium gas can return to the cryogenic system. These valves are only closed during warm up and cool down operations.

The cryogenic system and cryomodule design closely resembles that of CEBAF at TJNAF. One key change made to the cryomodule design was to incorporate a heat exchanger in every cryomodule as opposed to one large heat exchanger in the 2K cold box. This change resulted in greater efficiency by reducing the 2K envelope and absorbing the transfer line heat at the 4K level rather than the 2K level. The system is primarily operated by the automated sequences which were developed in the initial cryogenic system commissioning time frame of 2004-2005. The control system is equipped with an alarm auto-dialer that calls a cryogenic engineer in the event of an alarm. Currently, the cryogenic system is only manned one shift per day for minor adjustment of processing parameters.

After developing much of the control of the system manually, automated sequences were developed to assist the operator in operating the plant. The main sequences are backfill, 4-K pump down, 2-K pump down, and the heater control sequence. Figure 6 describes the function of each of these sequences. In addition to these sequences, a 2-K cold box trip sequence is important to the operation of the SCL. In the event of a trip of the 2-K cold box, a trip sequence was developed to protect the cryomodules during this event.

Insert Figure 6

When transitioning from 4-K to 2-K operation, the first sequence is the 'Backfill' sequence. The term 'backfill' refers to flowing helium gas into the return transfer line and raising the pressure of the cryomodules to a defined value. In the SNS 'Backfill' sequence, cold helium gas flows from the liquid helium Dewar to the return transfer line. This sequence prepares the 2-K cold box for pump down by backfilling the Linac to around 1.1 bar, cooling the 2-K cold box down, establishing the correct flow path, and starting all four cold compressors at a minimum speed. Upon successful completion of backfill, the '4-K Pump Down' sequence is activated. This sequence controls the 4.5-K cold box and cryomodules during the pump down. After this sequence is activated, the '2-K Pump Down' sequence is initiated. This sequence controls the 2-K flow by adjusting the speed of cold compressor (CC) 4 which is the last stage of the cold compressors. All three of the other cold compressors are controlled by preset gear ratios within the sequence. The gear ratio of a cold compressor is the command speed of the other cold compressors divided by the command speed of cold compressor 4. For example if a CC has a gear ratio of 0.175, it is controlled at a speed that is 0.175 times the command speed of CC4. The gear ratios for pump down are developed to keep each CC in its operating envelope between the surge and the stall curves and within the maximum motor current limit to attain the desired pressure in the SCL with minimal dependence on process instrumentation (i.e: one speed, one pressure and one flow) during the pump down process.

The '4-K Pump Down' and '2-K Pump Down' sequences are active until a stable pressure of 0.04 bar is achieved in the SCL. At that point, these two sequences stop. A 'Heater control' sequence is then activated to control the Linac pressure. Typically, a pump down takes about two hours to reach the final 0.04 bar from the starting 1.1 bar in the SCL. [23] The helium pressure in the SCL is quite stable and only requires very rare adjustment of the cavity mechanical tuners. The dead band of the mechanical tuner adjustment is typically set to 200 Hz, where a tuner adjustment is disabled. The dead band is designed to avoid unnecessary tuner movements. A typical pressure stability maintained in the SCL by the cryogenic

system control sequences is shown in figure 7. Except RF turn-on and turn-off for all SRF cavities, which corresponds to the square shape of the cavity heater power in figure 7, the long-term helium pressure maintains with the pressure stability less than 0.3 mbar. The frequency sensitivities are 100 Hz/mbar and 30 Hz/mbar for medium and high beta cavities respectively.

Insert Figure 7

When transitioning from 2-K to 4-K operation, the 2K cold box is shut off which initiates the 2K cold box trip sequence. Since helium has approximately 20% density change when it crosses the lambda point, care must be taken to avoid overflowing the cryomodule helium vessels into the return transfer line. If this takes place, the liquid must be removed from the transfer line prior to transitioning back to 2K. If the helium level within a cryomodule gets over 94%, the trip sequence automatically backfills the cryomodules to 1 atmosphere and allows the cryomodule cool down valves to open. Because there is less pressure drop through the cooldown header than the primary return, the liquid preferentially enters the cool down system as opposed to the transfer line. The liquid vaporizes in the cool down header and is directed to the first stage warm compressor suction through an ambient heat exchanger.

The static load of the SCL is 540 W and the dynamic load at the present operating condition is 400 W. Currently the CHL is running at the low flow mode [24]. The helium flow at 2-K operation in this mode is 105 g/s.

Cryogenic interlocks for the 'RF permit' to allow the RF operation of the SRF cavities consist of various parameters. RF power can be applied to a cavity if the following conditions are met; helium level in a cryomodule is not too low, helium pressure within the cryomodule is not too high, FPC and beam pipe temperatures are not too high, and FPC ceramic window temperature is not too high or low. Originally, the beam pipe and couplers were equipped with low temperature interlocks as well. However, these produced nuisance trips due to temperature sensors being damaged by radiation resulting in erroneous readings. In practice, the low temperature interlock for beam pipes and couplers does not provide any protection, and were removed. Additional protective interlocks are provided for the cryomodules in the cryogenic system. If the helium level or helium pressure in a cryomodule gets too high, the primary JT valve closes automatically. If the helium level in a cryomodule gets too low, the heater automatically shuts off to avoid damage to the heaters within the cryomodule.

During the pump down, the 2-K cold box is protected by multiple interlocks. One of the most important interlocks is for cold compressor surge. Since the actual surge curve for each cold compressor would be complex to program into the control system, a more simplified interlock is utilized. If the differential pressure across the 2-K flow meter, located downstream of the last stage of cold compressor and upstream of the 4.5-K cold box injection point, drops by 375 Pa in ten seconds, the 2-K cold box trips on surge. This logic is simple and reliable. While it is true that every actual surge in the cold compressor train will result in a loss of flow, the SNS protection system is conservative because it trips the cold box based on a substantial reduction in flow, even if the flow reduction is caused by the system and no surge is actually occurring.

5. SCL operation

Each cavity is run at its stable operating gradient, but the setting of the phase requires a measurement relative to the beam. The most recent set of operating gradients is shown in figure 8, which is initially based on the collective limiting gradients at 60 pps and following additional adjustment from operational

experience. The average operating gradient of medium beta cavities is higher than the design gradient while the opposite is true for the high beta cavities. As mentioned in the sections 3.2 and 3.3, the acceleration of electrons from multipacting and field emission is more efficient in the high beta cavities. Thus, the electron activities are more problematic for thermal stability of high beta cavities. Optimizing the operating parameters for stable operation requires continuous updates of operating gradients and settings of other supporting systems, since operational stability of the SCL depends on not only the operating gradients, but also on conditions of other supporting systems and machine conditions. The current set of cavity accelerating gradients along with all other supporting system parameters is providing a very stable and reliable operation of the SCL system. The Linac output energy is presently 972 MeV with the last cavity mostly running at zero beam-loading to provide an energy reserve. All Linac structures are running at the design duty factor.

Insert Figure 8

A sophisticated machine protection system is required for reliable operation and should be designed to ensure a good balance between beam availability and machine safety. To turn on the SRF cavities, the LLRF system first requires 'RF permit' from various sub-systems such as high power protection module (HPM), vacuum system, cryogenic system, inner conductor water cooling at air side status, and control system. The HPM plays a major role as an interlock for the protection of SRF cavities [25] along with cryomodule interlocks from the cryogenic side mentioned in the previous section. HPM monitors seven RF waveforms, one electron probe signal and five arc detectors for each SRF cavity and related RF system. When a fault condition is detected, the HPM truncates the RF pulse or disables 'RF permit' depending on the fault condition. The pulse truncation or disabling of the RF operation occurs in less than 100 ns after a faulty condition is detected and lasts longer than a predefined persistent time. The persistent time is implemented to minimize nuisance trips and is typically set to 3 μ s. The faulty condition for the accelerating gradient waveform has both low and high limits. In particular, the low limit of accelerating gradient is very useful to detect and quickly disable the RF operation of an SRF cavity when it quenches. All other RF waveforms such as forward and reflected power waveforms only have high limits.

RF waveforms during operation are shown in figure 9. The cavity fill time is 250 μ s and feed forward RF control only in open loop is active during this period. Typically forward power required for cavity fill is about three times higher than the RF forward power required during the flattop without beam loading. After the cavity fill is completed, LLRF feedback control starts for regulating the RF field amplitude and phase. There is a settling time of 30 μ s after feedback control starts. The adaptive feed forward control starts after the settling time for beam operations.

Insert Figure 9

5.1 Linac output energy

Figure 10 plots the SNS Linac output energy for 60-pps operation since 2007. The Linac output has gradually increased except during the 2012 operation. No global performance degradation of SRF cavities has been observed so far and the main changes of the Linac output energy have been related to specific activities or events. The main activities and events shown with a number index in figure 10 are:

- 1) early stage learning curve, improvement of LLRF and control system for operation at 60 pps, repair of two cryomodules and other miscellaneous fixes to avoid nuisance cavity trips;
- 2) addition of one high voltage converter modulator (HVCM) for high beta SRF cavities, which increased available RF power for each SRF cavity to the full design RF power of 550 kW and shortened the cavity fill time to 250 μ s;
- 3) first recognition of potential damages from errant beam discussed in the section 6;
- 4) one cavity in each beta region disabled due to vacuum leak through the FPC ceramic windows;
- 5) one high beta and one medium beta cryomodules out from the tunnel for FPC replacements;
- 6) the spare high beta cryomodule [26] is installed in the SCL in replacement of the high beta cryomodule removed during the same outage as item 5);
- 7) one medium beta cryomodule back to service after FPC replacement;
- 8) several SRF cavities at slightly lower gradients for the operation at the full duty factor;
- 9) replacement of the worst performing high beta cryomodule with the offline high beta cryomodule after FPC replacement;
- 10) application of the in-situ plasma processing to a high beta cryomodule as discussed in the section 6;
- 11) application of the in-situ plasma processing to another high beta cryomodule;
- 12) application of the in-situ plasma processing to five additional cryomodules (plan);

The spare high beta cryomodule was developed by in-house SNS resources and has been in service for neutron production since summer 2012. All four cavities in this cryomodule are running at 16 MV/m limited by available RF power and do not show measurable x-rays while running at 16 MV/m. The high beta spare cryomodule allows removal of an operating high beta cryomodule for complex repairs while maintaining the same beam energy. Rework is the only option for the unrecoverable damages of cavity surface and parts. In 2007, the US Department of Energy enacted 10CFR851, the Worker Safety and Health Program. To comply with this requirement, the SNS made a decision to use the vacuum vessel and the end can envelopes as the pressure boundary due to the difficulty in applying the pressure code to the helium circuit material such as niobium, titanium and niobium titanium alloy [26]. There are some design changes for this pressure vessel compliant issue and the spare high beta cryomodule developed in 2012 is the world's first code stamped cryomodule. The design changes will be incorporated in the cryomodules produced for the SNS Proton Power Upgrade Project.

Insert Figure 10

5.2 SCL downtime statistics

The SNS SCL operation has improved over time and the SCL system is running reliably. The availability of the SCL, which includes all sub-systems such as HVCM, RF, vacuum and control, has been 98% as shown in figure 11. The availability is the accumulated up time divided by the planned neutron production time. The availability of the SRF cavities, cryomodules and CHL system has been 99.5% which corresponds to 25 hours of down time per year [27].

Each neutron production run has issues with various equipment that affect the machine availability. Statistically most of downtime comes from the high power RF system, HVCM, faulty electronic boards and sensors, SRF cavity trips, and CHL 2-K cold box trips. The frequency of SRF cavity trips from all SRF cavities is less than one per day which account to less than five minutes per day. The 2-K cold box averages less than one trip per year during beam operation, however the resulting downtime per event is typically 10 hours. Quick changes in heat load of the cavities caused by simultaneous quenches of multiple cavities, incorrect heater settings and operator error, have resulted in surges and tripped the 2-K

cold box. Electric power dips due to lightning have also caused 2-K cold box trips, which could be improved with a power stabilizer. However this is a very expensive solution with minor impact on the machine availability since the CHL down time caused by electric power dips is less than a few hours per year on average.

Insert Figure 11

One of the main benefits of the SNS SCL, with each SRF cavity individually powered by one klystron, is operational flexibility [28]. The last SRF cavity in the SCL is set for zero acceleration and used as an energy reserve. As explained in section 3.3, when the frequency of an SRF cavity trips increases, its accelerating gradient is preemptively lowered to minimize the downtime until further investigation and RF conditioning can be performed. The last cavity is then used to keep the Linac output energy constant. Almost every run, a few cavities have problems in sustaining the nominal operating gradients for various reasons such as redistribution of the adsorbed gases on the cavity and FPC surface or issues with the high power RF system. The operating accelerating gradients of the affected cavities are typically lowered by less than 1 MV/m but can occasionally be turned off completely in case of a significant issue is identified such as arcing and FPC window leak. At every start of a 4.5-month long operation, the SCL is tuned and the last SRF cavity is kept as an energy reserve for this purpose. At the SNS, an unstable cavity is defined as a cavity having more than 1 trip per day for several consecutive days.

6. Operational stability and performance improvement of SRF cavities

Slight performance degradations have been observed in ten cavities during operation. When a cavity shows a symptom of performance degradation, i.e. cavity quenches more than once a day, the gradient is lowered by 1 MV/m or less to avoid further degradation and to minimize downtime.

As mentioned above, the Linac output energy is lower than the design output energy 1 GeV, mainly due to electron activity and thermal instability of the end-groups in the high beta cavities. In order to reach 1-GeV operation, the electron activity in high beta cavities needs to be mitigated and the operating gradients of the high beta cavities need to be increased by 15 % on average from the present operating gradients.

6.1 Potential sources for SRF cavity performance degradation

Operational statistics indicate that the performance degradation of the SNS SRF cavities is mostly related to vacuum activity that can be triggered by errant beam, beam halo, electron activity and gas bursts from ion pumps. Sometimes, arcing or discharge following the vacuum activity can damage the cavity surface or ancillary equipment such as the FPCs and RF feedthroughs.

The term ‘errant beam’ hereafter refers to an off-energy beam generated anywhere in the accelerator, and transported downstream in a fault condition; this is different from the continuous uncontrolled beam loss in a normal operating condition. Since the errant beam is an off-energy beam, it is mostly lost during transport through the Linac. This results in significantly higher beam loss in the Linac, which triggers multiple BLM trips and consequently beam trips. During an errant beam condition in the SNS Linac, the beam loss region typically ranges from several to ten cryomodules in length. Two mechanisms have been identified as sources of errant beams at the SNS: (1) RF truncations in upstream RF structures and (2) abnormal beam generation in the front end, which includes the ion source, the low energy beam transport system, and the RF quadrupole [29].

Each RF structure has its own fast interlocks, which truncate an RF pulse when a fault condition is detected, such as a vacuum burst, discharge, arc, or any abnormal RF signal. These interlocks trigger the machine protection system, which aborts the beam. There is a delay time for the machine protection system to abort the beam, as illustrated in figure 12. When an interlock of any RF structure truncates its RF pulse, the beam from the start of the RF truncation until the beam abortion by the machine protection system will be an off-energy beam. The second type of errant beam arises from unusual conditions in the front-end system, such as a lower-than-nominal current beam pulse, a partial beam pulse or another abnormal beam condition arising from high-voltage arcing, unstable ion source plasma, or mis-triggered RF for plasma generation. The beam under these conditions becomes an off-energy beam while it is accelerated, since the RF adaptive feed forward is only for the nominal beam pulse. In this case, beam loss monitors are the first indicators of the event. The machine protection system delay is the same as for the RF truncation case. The original requirement of the machine protection system delay at the SNS is 30 μ s.

Insert Figure 12

Figure 14 shows an example of signals from the two beam current monitors shown in figure 13 due to an errant beam condition caused by RF truncation in one of the DTL structures. In this example, 25 μ s of beam was lost in the SCL. An example of errant beam events from the FE is shown in figure 15. The beam current waveforms after the front end and before the superconducting Linac are shown. The other waveform is the cavity field in one NC RF structure. In this example, the beam current dropped during a pulse from the front end. As a result of this change of beam current, the cavity fields of all Linac RF structures do not remain constant, because of the nature of the adaptive feed forward. The corresponding portion of the beam became an off-energy beam and was lost in the Linac. As mentioned earlier, beam loss monitors trigger the machine protection system and the machine protection system shuts off the beam.

Insert Figure 13

Insert Figure 14

Insert Figure 15

The severity of the events depends on the location where the errant beam is lost, duration of the errant beam, and the frequency of events that are associated with the conditioning status of errant beam sources (NC RF structures and FE). Usually, in the first few weeks after a long maintenance shut-down period, errant beam events are more frequent. The average number of errant beam events in the past at SNS was about 30–40 times a day out of five million daily pulses. Most errant beam events result in beam loss monitor trips and sometimes small vacuum excursions. However, when similar events occur multiple times, there is a chance that an errant beam might lead to larger vacuum excursions and a following RF interaction could create an environment for severe discharge or arcing. The energy of one mini pulse (about 1 μ s beam) at the SNS is up to 24 J. Since the beam loading in the SNS superconducting RF

cavities is high, the available RF power is large enough to create a dangerous discharge. Unwanted consequences from errant beam events could be additional gas or particulate contamination, surface damage that leads to RF performance degradation, and component damage, such as failures of FPC ceramic windows and ceramic feed-through. The FPC window failures described in section 5.1 was caused by arcing from errant beam events. Various improvements have been implemented to minimize the number of errant beam events, such as careful conditioning for the FE and the NC RF structures, routine maintenance of vacuum systems, and continuous adjustment of operating parameters for NC RF structures. Presently, the frequency of errant beam events is less than 10 times per day. In addition, a new dedicated protection system to abort the beam within 8 μ s has been developed [30] and integrated into beam operation.

Degradation of SRF cavity performances can also originate from gas bursts from ion pumps. For example, an SRF cavity was found to trip in correlation with an ion-pump pressure spikes and lead to slight performance degradation by about 1 MV/m. The cavity trip and pressure spikes became more frequent over time. The ion pump on this cryomodule was eventually turned off in conjunction with a change of the corresponding vacuum interlock logic. Since then, the cavity has not ever tripped.

Gate valve operation has been identified as a potential source for particulate contamination and cavity performance degradation. For a few gate valves in the Linac tunnel, gate valve actuations have been correlated to spikes in pressure. Minimizing the number of valve operations during work associated with maintenance periods is being implemented as risk mitigation for possible cavity performance degradation. In addition, a few gate valves from different manufacturers have been tested using particle counters on the test bench in the SNS clean room. The test results indicated that valve conditioning or verification is required before installation.

Performance degradation from beam halo has been observed in a few SRF cavities of the first few cryomodules of the SCL. This issue is difficult to diagnose since the amount of beam loss is small and thus the related process is slow, however it was found that there are some correlations with the ion source condition and beam tuning. Temperature diodes around the SRF cavities sometimes indicate slight temperature increase before quench.

6.2 Symptoms and recovery from cavity performance degradation

The most frequent symptom after performance degradation is a hot spot creation in the end group. There are no changes of x-ray levels, but the dynamic heat load increases by about a factor of ten. Some cavities can run stably in this condition while some others require lowering their accelerating gradient by less than 1 MV/m typically. Once a hot spot is developed, there is no correlation with beam operation. Figure 16 shows an example of the temperature profile in the end group. For this simulation, a hot spot is assumed at the joint between the FPC port and the beam pipe. Some areas in the end group are normal conducting and sustain the meta-stable condition during the SNS pulsed operating condition. The thermal stability is quite sensitive to the location of the hot spot.

Insert Figure 16

Figure 17 and 18 show examples of thermal load changes after performance degradation. When a hot spot appears, the primary JT valve opens more by 10% to keep the helium level constant. This corresponds to additional 50-60 W thermal load to the primary helium circuit. The sensor for the coupler flange temperature is located at the side of the FPC port in figure 16 and is the only temperature sensor installed in the end-group at the FPC side. The location of this sensor is not necessarily the hottest spot.

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736 Cavity performance has been successfully recovered through RF conditioning at various repetition rates
737 or through thermal cycling. Typical thermal cycling at SNS has been done by warming up a cryomodule
738 to ambient temperature and cool back down to cryogenic temperature. During a long maintenance period,
739 the 2-K cold box is shut off and the CHL transitions from 2-K operation to 4-K operation. The SNS
740 cryomodules can be thermally cycled individually during 4-K operation of the CHL. Thermal cycling has
741 been done for cavities that cannot be recovered by RF conditioning. This indicates that the most probable
742 cause for the performance degradation during operation is gaseous contamination. Nonetheless, two
743 cavities did not show performance recovery even after thermal cycling and are running at lower
744 accelerating gradient by 1 MV/m than before. These cavities presumably have particulate contamination
745 or surface damage.

746 747 *6.3 SRF cavity performance improvement* 748

749 In-situ processing of SRF cavities in the tunnel has been identified as an important area of research to
750 improve the performances of SNS SRF cavities while minimizing the impact on machine operation and
751 reducing cost for the improvements. R&D for in-situ processing using plasma has successfully
752 demonstrated that the accelerating gradients in operating cavities can be increased by 2 MV/m or higher
753 on average [31, 32]. The plasma processing developed at the SNS mainly focuses on removal of residual
754 hydro-carbons using low density reactive oxygen plasma at room temperature. The technique has so far
755 been successfully applied to cavities in the horizontal test apparatus, cavities in one off-line cryomodule
756 and cavities in one of the cryomodules in the tunnel. After applying in-situ plasma processing, reductions
757 of field emission, multipacting, vacuum activities and thermal loads in the end group have been observed.
758 Figure 19 shows the hardware setup for in-situ plasma processing in the tunnel. Figure 20 shows an
759 example of radiation measurements before and after the plasma processing. Several more high-beta
760 cryomodules will be processed in the near future to achieve the Linac output energy at 1 GeV.

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771 **7. Cryomodule maintenance** 772

773 Statistics for cryomodule repair at SNS have been recorded since 2007. A variety of repairs on
774 cryomodules have been performed. These repairs can be broken into two categories; repairs that require

thermal cycling of the cryomodule and repairs that do not require thermal cycling. When a cryomodule must be thermal cycled for the repair, the cryogenic system has to transition to 4-K operation. The u-tubes that connect the cryomodule to the cryogenic transfer line are removed and the cryomodule is warmed up. Issues that require thermal cycling include helium leaks, cavity performance degradation, inoperable or unstable tuner, issues with cables, excessive power coupling to the HOM couplers, and FPC coupler window leaks. Issues that do not require thermal cycling include instrumentation damage that is mostly helium pressure transducers in the tunnel, faulty valve actuator, power supply failures, and coupler cooling system adjustments. Figure 21 depicts the repairs performed on cryomodules at SNS since 2007.

Insert Figure 21

With all of the repairs that have been completed, it was necessary to perform thermal cycles of the cryomodules. Since 2007, there have been 40 instances of cryomodules being thermally cycled.

The number of repairs does not necessarily indicate the severity associated with the repair. The most significant repairs conducted that required removal of cryomodule from the tunnel are related to HOM feedthrough removal, FPC replacement, and the repair of helium leaks due to failures in the cold feedthroughs in the helium line. These specific repairs are detailed in [33]. Thermal cycling for tuner repair was the most frequent occurrence in the early days of operation but there have been no tuner repairs in the last three years.

8. Summary

The SNS SCL with all related supporting systems is currently providing stable operation for the neutron production up to 1.4-MW beam power on target with a high availability. During the commissioning and initial operation periods, better understanding was gained about the operation of the pulsed superconducting Linac and the impacts from various aspects such as operating temperature, heating by electron loading, SRF cavity turn-on difficulties associated with multipacting, HOM coupler issues, RF control issues, mechanical tuner issues, uncontrolled and errant beam loss, interlocks, and machine protection system. Cryomodules consist of numerous components and subsystems that need to be successfully integrated for reliable operation. As the understanding about the physics and engineering of SCL operation including all sub-systems increased over the years of operation, the SNS SCL has been providing more stable and reliable operations.

One of the most severe events for the SRF cavity performance degradation is arcing or discharges. Once an irreversible damage occurs after arcing or discharge, performance of a SRF cavity would get worse over time. In this context, first turn-on must be closely watched and controlled since there is an associated risk to create irreversible damage of RF surfaces, HOM couplers, and FPCs. First turn on includes initial powering of cavities in a cryomodule, exploring limiting gradients, and increasing repetition rate. During first turn-on, most cavities show aggressive multipacting and sometimes bursts of field emitters that can potentially lead to arcing and a discharge condition. Similar situations may occur when cavities are turned on after long maintenance periods or after thermal cycling. Careful RF conditioning is then required since the behavior of a cavity can be significantly altered due to redistribution of gas on the RF surfaces.

Root causes for performance degradation of the SRF cavities at SNS during operation have been identified. Early diagnostics and prompt involvement from system experts are critical to minimize additional degradation. No systematic performance degradation of SRF cavity performances has been observed at the SNS. Continuous efforts to develop dedicated diagnostics and more performant

protection systems have contributed to further reduce the occurrence of performance degradation during operation. Recovery actions including RF conditioning, thermal cycling and offline repair are actively ongoing to sustain the SCL performance.

Performance improvements of SRF cavities using an in-situ plasma processing technique have been demonstrated at the SNS and recent deployment to a cryomodule in operation led to the highest Linac output energy at the SNS at 60 pps operation to date. In-situ plasma processing will be applied to several additional cryomodules in the near future, aiming at reaching 1-GeV Linac output energy at the full duty factor.

ACKNOWLEDGMENT

We would like to thank Percy Harrell and Dale Heidenreich for their help during the tests with the HTA. This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy.

REFERENCES

- [1] S. Henderson, W. Abraham, A. Aleksandrov, C. Allen, J. Alonso, D. Anderson, et al., Nuclear Instruments and Methods A 763 (2014) 610-673, <http://dx.doi.org/10.1016/j.nima.2014.03.067>.
- [2] J. Galambos, D. Olsen, Parameter and cost model for spallation neutron source studies, in: Proceedings of the 1997 Particle Accelerator Conference, Vancouver, Canada, May 12-16, 1997, (<http://accelconf.web.cern.ch/AccelConf/pac97/papers/pdf/7P119.PDF>).
- [3] L. Blumberg, A. Luccio, A. Ruggiero, A. Steenbergen, Comparison of synchrotron and accumulator scenarios for a 5-MW pulsed spallation neutron source, Proceedings of the 1996 European Particle Accelerator Conference, Barcelona, Spain, June 10–14, 1996, pp. 533-535, (<http://accelconf.web.cern.ch/AccelConf/e96/PAPERS/TUPG/TUP012G.PDF>).
- [4] J. Tang, Review of Accelerator Science and Technology, 6 (2013) 143-169, <http://dx.doi.org/10.1142/S1793626813300077>.
- [5] Y. Cho (Ed.), Preliminary Design Report – Superconducting radio frequency linac for the Spallation Neutron Source, SNS–SRF–99–101, December 1999.
- [6] J. Stovall, J.H. Billen, S. Nath, H. Takeda, L.M. Young, D. Jeon, K.R. Crandall, R. Shafer, Expected beam performance of the SNS linac, in: Proceedings of the 2001 Particle Accelerator Conference, Chicago, IL, June 18–21, 2001, pp. 446–450, (<http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/WOPB007.PDF>).
- [7] S-H. Kim, M. Doleans, Y. Kang, Efficient design scheme of superconducting cavity, in: Proceedings of the 20th International Linear Accelerator Conference, Monterey, CA, August 21–25, 2000, pp. 923–925, (<http://accelconf.web.cern.ch/AccelConf/100/papers/THD09.PDF>).
- [8] D. Barni, A. Bosotti, G. Ciovati, C. Pagani and P. Pierini, SC cavity design for the 700 MHz Trasco linac, in: Proceedings of the 2000 European Particle Accelerator Conference, Vienna, Austria, June 26–30, 2000, pp. 2019–2021, (<http://accelconf.web.cern.ch/AccelConf/e00/PAPERS/THP7B05.PDF>).
- [9] S-H. Kim, Challenges and the future of reduced beta superconducting radio-frequency (SRF) cavity design, in: Proceedings of the 21st International Linear Accelerator Conference, Gyeongju, South Korea, August 19–23, 2002, pp. 549–553, (<http://accelconf.web.cern.ch/AccelConf/102/PAPERS/WE203.PDF>).
- [10] S. Mitsunobu, T. Furuya, T. Tajima, T. Kijima, T. Tanaka, High power input coupler for KEKB SC cavity, in: Proceedings of the 9th Workshop on RF Superconductivity, Santa Fe, NM, November 1–5, 1999, pp. 505–507, (<http://accelconf.web.cern.ch/AccelConf/SRF99/papers/wep032.PDF>).

874 [11] W.J. Schneider, I.E. Campisi, E.F. Daly, T. Hiatt, J. Hogan, P. Kneisel, et al., Design of the SNS
875 cryomodule, in: Proceedings of the 2001 Particle Accelerator Conference, Chicago, IL, June 18–21, 2001,
876 pp. 1160–62, (<http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/MPPH162.PDF>).

877 [12] D.S. Stout, I.E. Campisi, F. Casagrande, R. Cutler, D. Hatfield, M. Howell, et al., Installation of the
878 spallation neutron source (SNS) superconducting linac, in: Proceedings of the 2005 Particle Accelerator
879 Conference, Knoxville, TN, May 16–20, 2005, pp. 3838–3840,
880 (<http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/RPPT071.PDF>).

881 [13] S-H. Kim, I.E. Campisi, IEEE Transactions on Applied Superconductivity 17 (2) (2007) 1299–1304,
882 <http://dx.doi.org/10.1109/TASC.2007.897857>.

883 [14] S-H. Kim, I.E. Campisi, Physical Review Special Topics–Accelerators and Beams 10 (2007)
884 032001, <http://dx.doi.org/10.1103/PhysRevSTAB.10.032001>.

885 [15] I.E. Campisi, S. Assadi, F. Casagrande, M. Crofford, G. Dodson, J. Galambos, et al., Status and
886 performance of the Spallation Neutron Source superconducting linac, in: the 2007 Proceedings of Particle
887 Accelerator Conference, Albuquerque, NM, June 25–29, 2007, pp. 2502–2504,
888 (<http://accelconf.web.cern.ch/AccelConf/p07/PAPERS/WEPM072.PDF>).

889 [16] S-H. Kim, I.E. Campisi, F. Casagrande, M. Crofford, Y.W. Kang, Z. Kursun, et al., Status of the
890 SNS cryomodule test, in: the 2007 Proceedings of Particle Accelerator Conference, Albuquerque, NM,
891 June 25–29, 2007, pp. 2511–2513,
892 (<http://accelconf.web.cern.ch/AccelConf/p07/PAPERS/WEPM076.PDF>).

893 [17] R. Sundelin, D. Jeon, S-H. Kim, M. Doleans, SNS HOM damping requirements via bunch tracking,
894 in: Proceedings of the 2001 Particle Accelerator Conference, Chicago, IL, June 18–22, 2001, pp.
895 1984–1986, (<http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/TPPH135.PDF>).

896 [18] S-H. Kim, M. Doleans, D. Jeon, R. Sundelin, Nuclear Instruments and Methods A 492 (2002) 1–10,
897 [http://dx.doi.org/10.1016/S0168-9002\(02\)01286-X](http://dx.doi.org/10.1016/S0168-9002(02)01286-X).

898 [19] Y.W. Kang, S-H. Kim, M. Doleans, I.E. Campisi, M. Stirbet, P. Kneisel, et al., Electromagnetic
899 simulations and properties of the fundamental power couplers for the SNS superconducting cavities, in:
900 Proceedings of the 2001 Particle Accelerator Conference, Chicago, IL, June 18–22, 2001, p. 1122–1124,
901 (<http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/MPPH147.PDF>).

902 [20] S-H. Kim, SNS superconducting linac operational experience and upgrade path, in: Proceedings of
903 the 24th International Linear Accelerator Conference, Victoria, Canada, September 29–October 03, 2008,
904 pp. 11–15, (<http://accelconf.web.cern.ch/AccelConf/LINAC08/papers/mo103.PDF>).

905 [21] M. Doleans, S-H. Kim, Nuclear Instruments and Methods 496 (2003) 51–63,
906 [http://dx.doi.org/10.1016/S0168-9002\(02\)01660-1](http://dx.doi.org/10.1016/S0168-9002(02)01660-1).

907 [22] M. Howell, B. DeGraff, S-H. Kim, B. Morris, T. Neustadt, W.H. Strong, IOP Conference Series:
908 Material Science and Engineering 101 (2015) 012127, [http://dx.doi.org/10.1088/1757-](http://dx.doi.org/10.1088/1757-899X/101/1/012127)
909 899X/101/1/012127.

910 [23] M. Howell, F. Casagrande, B. DeGraff, V. Ganni, S-H. Kim, P. Knudsen, et al., IOP Conference
911 Series: Material Science and Engineering 101 (2015) 012128, [http://dx.doi.org/10.1088/1757-](http://dx.doi.org/10.1088/1757-899X/101/1/012128)
912 899X/101/1/012128.

913 [24] F. Casagrande, P. Gurd, D. Hatfield, M. Howell, W.H. Strong, D. Arenius, et al., SNS 2.1K cold box
914 turn-down studies, in: Proceedings of the 2006 European Particle Accelerator Conference, Edinburgh,
915 UK, June 26–30, 2006, pp. 514–516,
916 (<http://accelconf.web.cern.ch/AccelConf/e06/PAPERS/MOPCH193.PDF>).

917 [25] M. Crofford, M. Champion, K. Kasemir, H. Ma, M. Piller, Operational experience with the spallation
918 neutron source high power protection module, in: Proceedings of the 2005 Particle Accelerator
919 Conference, Knoxville, TN, May 16–20, 2005, pp. 3311–3313,
920 (<http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/WPAT058.PDF>).

921 [26] M. Howell, R. Afanador, D. Bruce, M. Crofford, D. Douglas, B. Hannah, et al., The first ASME
922 code stamped cryomodule at SNS, in: Proceedings of the 2012 International Particle Accelerator

Conference, New Orleans, LA, May 20–25, 2012, pp. 2465–2467,
(<http://accelconf.web.cern.ch/AccelConf/IPAC2012/papers/weppc106.PDF>).
[27] S-H. Kim, R. Afanador, W. Blokland, M. Champion, A. Coleman, M. Crofford, et al., The status of
the superconducting linac and SRF activities at the SNS, in: Proceedings of the 16th International
Conference on RF superconductivity, Paris, France, September 23–27, 2013, pp. 83–88,
(<http://accelconf.web.cern.ch/AccelConf/SRF2013/papers/mop007.PDF>).
[28] J. Galambos, S. Henderson, Y. Zhang, A fault recovery system for the SNS superconducting cavity
linac, in: Proceedings of the 23rd International Linear Accelerator Conference, Knoxville, TN, August
21–25, 2006, pp. 174–176, (<http://accelconf.web.cern.ch/AccelConf/106/PAPERS/MOP057.PDF>).
[29] C. Peters, A. Aleksandrov, W. Blokland, M. Crofford, D. Curry, C. Deibele, et al., Superconducting
radio frequency cavity degradation due to errant beam, in: Proceedings of the 2015 International Particle
Accelerator Conference, Richmond, VA, May 3–8, 2015, pp. 805–807,
(<http://accelconf.web.cern.ch/AccelConf/IPAC2015/papers/mopha013.PDF>).
[30] W. Blokland, C. Peters, A new differential and errant beam current monitor for the SNS accelerator,
in: Proceedings of the 2nd International Beam Instrumentation Conference, Oxford, UK, September 16–
19, 2013, pp. 921–924, (<http://accelconf.web.cern.ch/AccelConf/IBIC2013/papers/thal2.PDF>).
[31] M. Doleans, P.V. Tyagi, R. Afanador, C.J. McMahan, J.A. Ball, D.L. Barnhart, et al., Nuclear
Instruments and Methods A 812 (2016) 50–59, <http://dx.doi.org/10.1016/j.nima.2015.12.043>.
[32] P.V. Tyagi, M. Doleans, B. Hannah, R. Afanador, C. McMahan, S. Stewart, et al., Applied Surface
Science 369 (2016) 29–35, <http://dx.doi.org/10.1016/j.apsusc.2016.02.030>.
[33] M. Howell, R. Afanador, B. DeGraff, M. Doleans, D. Douglas, B. Hannah, et al., History of
cryomodule repairs at SNS, in: Proceedings of the 27th International Linear Accelerator Conference,
Geneva, Switzerland, August 31–September 5, 2014, pp. 1108–1110,
(<http://accelconf.web.cern.ch/AccelConf/LINAC2014/papers/thpp109.PDF>).

948 Figure 1: Layout of the SNS accelerator complex.

949 Figure 2: The SNS cryomodules in the tunnel.

950 Figure 3: Average gradients of the SNS SRF cavity at various conditions.

951 Figure 4: Example of radiation waveform patterns from multipacting in open loop RF operation.

952 Figure 5: Example of radiation waveform patterns from field emission in open loop RF operation.

953 Figure 6: Control sequences for 2-K operation at SNS.

954 Figure 7: Helium pressure in the SCL, total power of heaters in helium vessels and 2-K helium flow
955 during the 2-K operation.

956 Figure 8: Operating gradients of the SNS SRF cavities as of July 2016.

957 Figure 9: Waveforms of accelerating gradient and RF powers; (a) RF only without beam and (b) with
958 beam loading. In this example, accelerating gradient is 16 MV/m and average beam current is 26 mA.

959 Figure 10: Linac output energy history at 60-pps operation.

960 Figure 11: Availability statistics of the SNS SCL for the fiscal year (FY) 2011 to 2015.

961 Figure 12: Machine protection system delay time until abortion of beam. BLM, beam loss monitors;
962 MPS, machine protection system.

963 Figure 13: Layout of SNS LINAC and positions of beam current monitors for errant beam monitoring.
964 BCM, beam current monitor; CCL, Coupled Cavity Linac; DTL, Drift Tube Linac; FE, Front End;
965 HEBT, high-energy beam transport; SCL, superconducting Linac.

966 Figure 14: Examples of beam current monitor (BCM) signals in the event of RF truncation in a NC RF
967 structure. In this example, an RF truncation in a NC RF structure happened at around 300 μ s after beam
968 started in a pulse and the beam was aborted by the MPS system 25 μ s after RF truncation.

969 Figure 15: Example of errant beam generated in the front-end system. Beam current monitor signals after
970 the FE and in the CCL region, and cavity field amplitude of a NC RF structure.

971 Figure 16: Example of temperature profile when the end group is in a meta-stable condition (numbers in
972 the legend are temperature in K).

973 Figure 17: An example of performance degradation resulting from a hot spot. In this example, the cavity
974 accelerating gradient can be kept stable with much higher dynamic load. 10-% increase of the JT valve
975 position in this example indicates that dynamic heat load increased by 50-60 W. The JT valve position
976 refers to an amount of the JT valve opening in percentage.

977 Figure 18: An example of performance degradation resulting from a hot spot. In this example the cavity
978 accelerating gradient needs to be lowered by 0.5 MV/m to avoid a quench.

979 Figure 19: Hardware set up for the plasma processing in the tunnel.

980 Figure 20: An example of radiation level comparison before and after the plasma processing.

981 Figure 21: SNS cryomodule repairs since 2007.

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