SNS SUPERCONDUCTING LINAC OPERATIONAL EXPERIENCE AND UPGRADE PATH*

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Abstract

The Spallation Neutron Source (SNS) Superconducting Linac (SCL) has been providing a main acceleration in two different accelerating sections with 33 medium beta and 48 high beta superconducting radio-frequency (SRF) 6-cell cavities. The use of superconducting elliptical cavities for particles whose velocity are less than speed of light (beta<1), make this accelerator a very important milestone for learning operating conditions of this type of cavities. Since the SNS SCL is the first large-scale high energy pulsed-superconducting proton linac that provides high beam power utilizing H- beams, many aspects of its performance were unknown and unpredictable. A large amount of data has been collected on the pulsed behavior of cavities and cryomodules at various repetition rates and at various temperatures. This experience will be of great value in determining future optimizations of SNS as well in guiding in the design and operation of future pulsed superconducting linacs. This paper describes the details of the RF properties, performances, path-forward for the SNS power ramp-up goal, and upgrade path of the SNS superconducting linac.

INTRODUCTION

The SNS accelerator complex consists of a negative hydrogen (H-) RF volume source, a low-energy beam transport (LEBT) line with a first-stage beam chopper, a 4-vane radio-frequency quadrupole (RFQ) up to 2.5 MeV, a medium-energy beam transport (MEBT) line with a second-stage chopper, six drift-tube linac (DTL) tanks up to 87 MeV, four coupled-cavity linac (CCL) modules up to 186 MeV, a superconducting linac (SCL) with 11medium-beta cryomodules (up to 379 MeV) and 12 high-beta cryomodules (up to 1000 MeV), a high energy beam transport (HEBT) line, an accumulator ring with associated beam transport line, a ring-to-target beam transport (RTBT) line, and a mercury target. At a full duty, the linac will produce 38-mA peak, chopped H^- beam for 1-ms long at 60 Hz. In the ring, 700-ns long midi-pulse beam is accumulated over 1060 turns reaching an intensity of $1.5x10^{14}$ protons per pulse. After beam accumulation in the ring, the beam is extracted using the extraction kickers during 300-ns long midi-pulse gap in a single turn is transported to the mercury target through the RTBR line. Figure 1 shows the layout of the SNS.

A series of the beam commissioning, initiated in 2002 and completed in May 2006, was performed in seven commissioning runs for Front-End, DTL Tank 1, DTL Tanks 1-3, CCL, SCL, Accumulator Ring, and beam on target.

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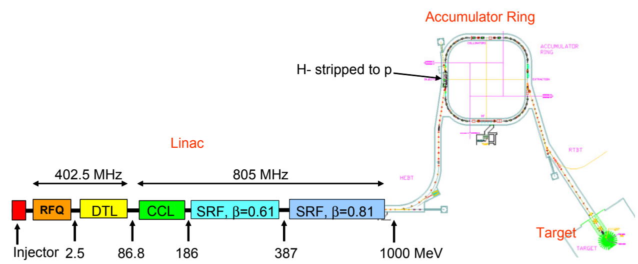

Figure 1: Layout of the SNS accelerator system.

Official SNS operations for scheduled neutron scattering experiments has been started since October 2006. The SNS is now nearly two years into the initial operations phase [1, 2].

The SRF cavities and the cryomodules were designed and developed at Jefferson Lab and installed at the SNS site in 2005. Major parameters are summarized in Table 1. As the first operational pulsed superconducting linac, many of the aspects of its performance were unknown and unpredictable. A lot of experiences and data have been gathered on the pulsed behavior of cavities and cryomodules at various repetition rates and at various temperatures during the commissioning of its components and beam operations. Careful balance between safe operational limits and the study of conditions, parameters and components that create physical limits has been achieved [3, 4]. The SCL is running at about 0.9-GeV output energy and is presently one of the most reliable systems in SNS. Figure 2 shows the accelerating gradients of SCL cavities at 60Hz in 2008 for the neutron production, which is set based on the 60 Hz collective limits achieved. Power ramp up plan to reach the design goal is set and various efforts are in progress.

Table 1: Major Design Parameters of the SNS SCL

Cryomodule Parameter	β=0.61 Section	β=0.81 Section
Output Energy (MeV)	379	1000
No. of Cryomodules	11	12
No. of cavities per cryomodule	3	4
Cavity Parameter	β=0.61 Cavity	β=0.81 Cavity
Geometric beta	0.61	0.81
EoT (MV/m)	10.1 at β=0.61	15.8 at β=0.81
Epeak (MV/m)	27.5	35.0
Hpeak (kA/m)	46.2 (580 Oe)	59.7 (750 Oe)
Q*Rs (Ω)	176	228
r/Q at design beta	279	483
Equivalent Cavity Length (cm)	68.2	90.6

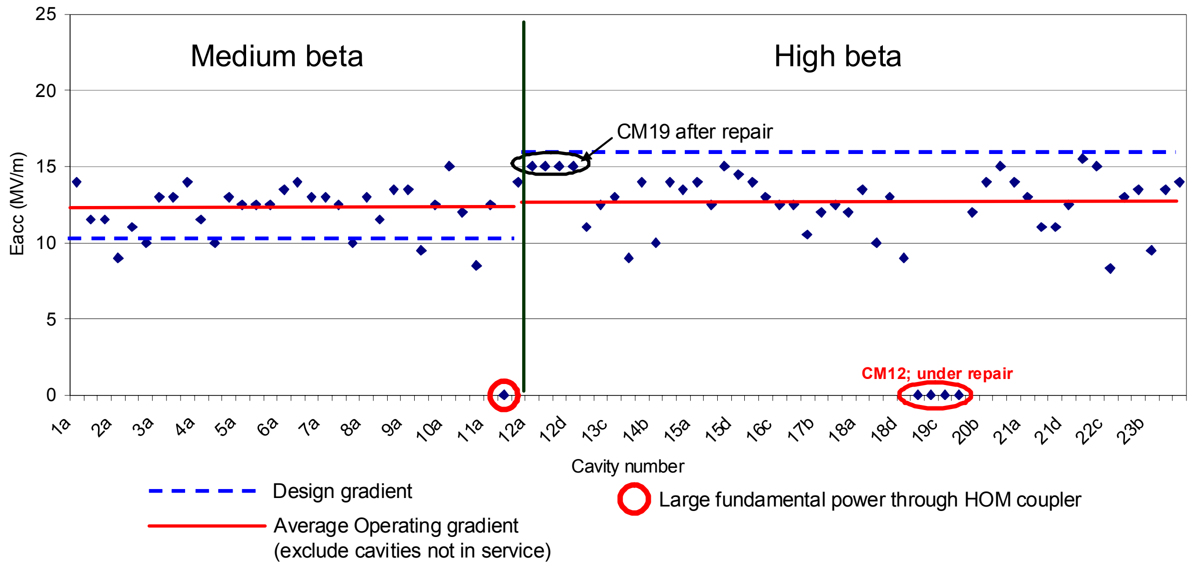

Figure 2: Operating setpoints of SCL SRF cavities at 60 Hz for the neutron production in 2008.

OPERATIONAL EXPERIENCES

Extensive testing on the SNS superconducting RF modules has been conducted starting in late 2004. Behavior peculiar to the SNS cavities and the overall design, as well as due to the pulse nature of the operation have been observed. These and other limitations have requires extensive studies and close attention in setting gradients which are both necessary for adequate energy gain and for reliable operation.

Operational Flexibility

One of the main characteristics of the superconducting linac is its flexibility and adaptability to adding or removing cavities. In many occasions, cavities' fields had to be temporarily or permanently changed, or in some cases cavities had to be removed from service. The linac flexibility has demonstrated itself in allowing complete retuning and rephrasing of the linac over times of the order of a few minutes. This characteristic is important as not just cavities, but other systems that may be removed temporarily from service and operations interrupted only for a modest amount of time [5].

Operating Temperature

The transient nature of pulsed operation allows larger variation of temperatures within the niobium surface, so that during the pulse the surface resistance of the material can change substantially (see Fig. 3). The operating conditions 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 [6]. Due mainly to the pulsed nature of the SNS operation and the relatively low operating frequency the cavities can still be operated at 4.2 K up to the critical field. Both calculations and experiments tell us that there's no difference in performances of the SNS SRF cavities as long as the operating temperature is lower than 4.5 K.

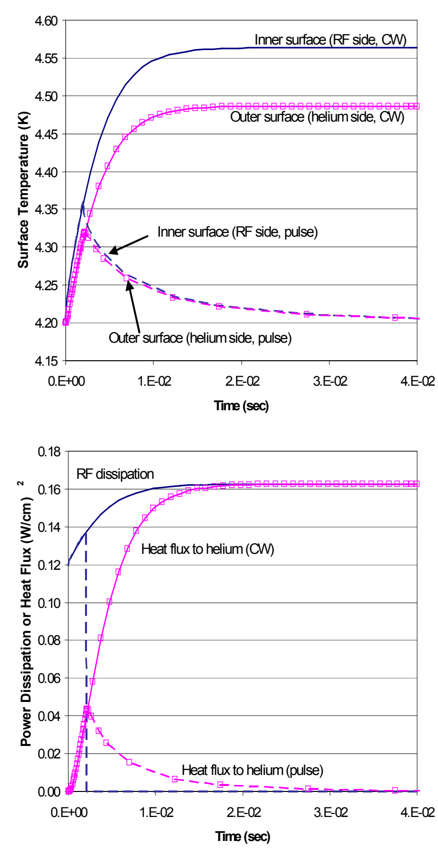

Figure 3: Comparisons of thermal parameters between CW and pulsed operations. Both cases are stable. (solid line; CW operation, dashed line; pulsed operation, lines with symbols; for surface at helium side, lines without symbols; for surface at RF side).

Electron Activities and Collective Behaviors at High Repetition Rate

Most of the cavities exhibit heavy field emission and/or multipacting which directly or indirectly (through heating of end groups) limits the gradients achievable in normal operation with beam. The overall phenomena are complex and the final operational cavity gradients need to be determined individually for each cavity based on the equilibrium between electromagnetic, electron emission and thermal phenomena, each affecting the overall stability of the system on a pulse by pulse basis. In addition to individual cavity field emission limitations, collective effects have been observed which affects neighboring and second neighbor cavities. Bigger heating by these collective effects is clearly observed when the repetition rate is 30 Hz or higher. Heating of cavity elements are driven not only by the amplitude, but also by the relative phase of neighboring cavities. Since in the SCL neighboring cavities' amplitudes and phases are correlated, operation into heavy field emission is prevented by stability concerns, thus limiting the final available energy. Figure 4 compares the average limiting gradients at three different conditions. At low repetition rate (20 Hz or less), individual (powering one cavity at a time) limits are about same as collective limits (powering all cavities in a cryomodule at the same time) at the same low repetition rate, which enabled 1-GeV demonstration at 15 Hz. The difference between limits in open and closed loops results from llrf regulation and much longer duration at the highest field in closed loop.

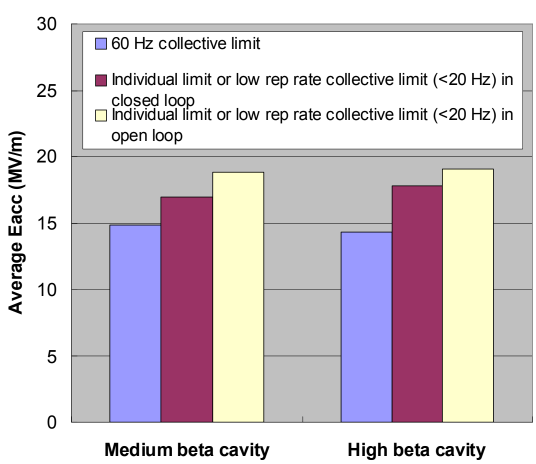

Figure 4: Comparisons of average limiting gradients at 60 Hz collective, individual (or low rep rate collective) in closed loop and that in open loop.

Equipment and Sub-components

Some sub-components have shown peculiar behaviors. The cold cathode gauges, which provide interlock protection to the fundamental power coupler window, have behaved erratically, with a response which is often not correlated at all with other independent measurements of gas pressure at the window.

The Higher Order Mode (HOM) notch RF filters, which are designed to extract RF power at frequencies potentially harmful to the stability of the beam, have shown signs of multipacting, discharges and transient detuning, which can lead to critical components damage.

One high beta cryomodule (CM19) had been removed from the tunnel and been repaired at the SNS SRF test facility by removing HOM coupler feedthroughs from one cavity. Two thermal diodes (TD) were installed where the possible multipacting places according to the analysis as shown in Fig. 5. During the test at the SNS SRF test cave, very aggressive electron activities were observed from the signals of TD ranges from 5 MV/m to 15 MV/m, which led drops of gradients by several percents and detuned cavity bandwidth that corresponds to a few kW deposition of RF power to electrons. All were processed very carefully, which was possible by removing HOM coupler feedthroughs. The first explorer such as the first turn-on, pushing limits, increasing repetition rate must be closely watched and controlled since aggressive multipacting and burst of field emitter could damage weak components. Also we experienced similar situations during subsequent turn-ons after long shutdown and thermal cycle.

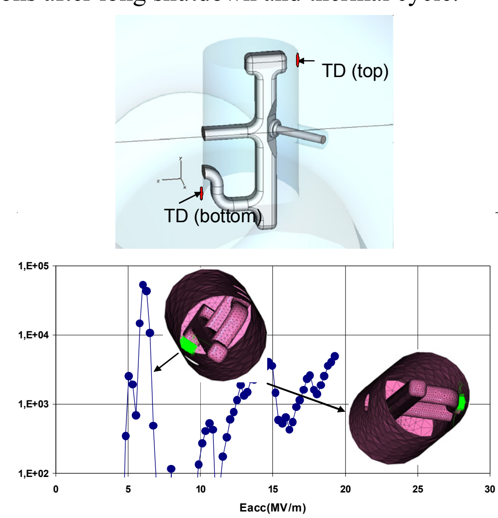

Figure 5: Thermal diodes locations of the 19b after removing the feedthrough (top). Multipacting simulation of the SNS high beta cavity HOM coupler [7] (bottom).

Limiting Factors of SRF Cavities

Statistics of limiting factors achieved during 60-Hz collective tests are summarized in Fig. 6. Two cavities are showing larger mechanical resonances at higher repetition rate while dynamic detuning of all others can be managed by RF feedback and feed-forward only. So far piezo-tuner compensation has not been used in operation. Three cavities are limited by hard quench at a relatively low gradient (around 10 MV/m). One cavity is not in service due to the large power coupling with RF only. The limit tests are stopped for five cavities at about 15 W of fundamental power coupling through HOM coupler. About fourteen cavities are limited by coupler heating, but they are close to the limits by radiation heating. All others are limited by electron loading that leads end group heating, gas burst and quench. Actual operating gradients are set around 85-95 % of limiting gradients achieved at 60-Hz collective tests.

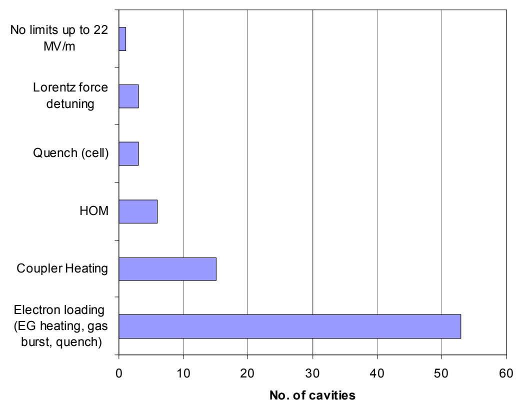

Figure 6: Statistics of limiting factors at 60 Hz collective condition.

SRF Cavity Operating Regime

As seen in Fig. 2 cavities in the medium beta section of the SCL are operating above the design gradient of 10.1 MV/m whereas those in the high beta sections of the SCL are operating below the design one of 15.8 MV/m mainly due to radiations and related heating effects.

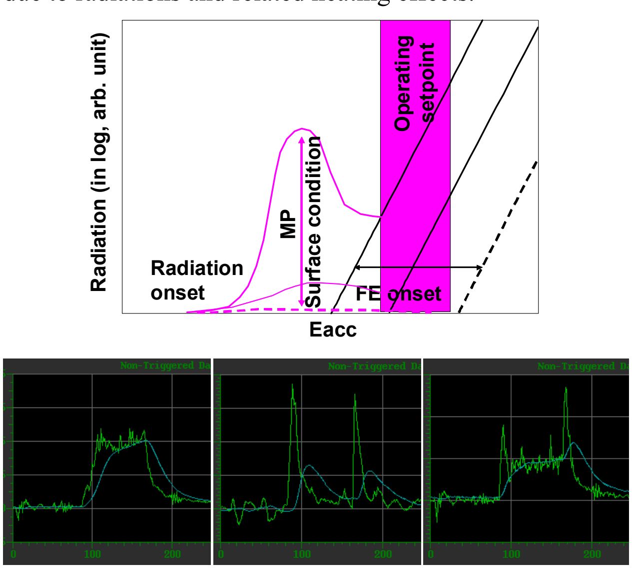

Figure 7: SNS SRF cavity operating regime at 60 Hz and radiation waveforms from RF operations depends on contents of electron activities in a cavity.

Figure 7 is schematically explaining operating regime of most of the SNS SRF cavities, which is higher than big multipacting region and/or lower than the considerable field emission region. During commissioning, testing, and 3-yrs long operation so far, mild contaminations must have been gone, which causes multipacting or mild field emission. In an operational cryomodule, removing a bad contamination is quite difficult. The field emitters on the processed surfaces are known to be very stable. Majority of the SNS SRF cavities are showing radiation waveforms of field emission like the radiation waveform in the bottom left in Fig. 7, while some are showing multi-pacting dominant radiation waveform (bottom center in Fig. 7) and some others are showing both field emission and multipacting (bottom right in Fig. 7).

Since the lack of the final linac output energy, the gradient of each cavity is set to maximize the gradient based on the collective limiting gradients that was achieved through a series of SRF cavity/cryomodule performance test at SNS, rather than having uniform gradients as designed.

POWER RAMP-UP

Most of equipment in SNS requires substantially higher operational ratings compared to existing accelerators, since the design beam power is almost an order of magnitude higher compared to existing neutron facilities. As beam power increases at higher duty factor during previous runs, down-times of some equipment such as LEBT and high-voltage convertor modulator led lower machine availability than expected. Some systems like the SNS SCL are the first attempt for pulsed operation. Many of the aspects of its performance were unknown and unpredictable, for which it takes time to understand the systems as a whole and/or needs additional performance improvements. A power ramp-up plan has been revised based on the operation experiences and understandings of limits and limiting conditions through extensive studies, which emphasizes more on machine availability (Fig. 8). The plan covers main driving factors for beam power such as chopping efficiency, ion source improvement, high voltage convertor modulator (HVCM) improvement, and SCL output energy. The followings are short descriptions of issues and plans for the power ramp-up at the SCL side.

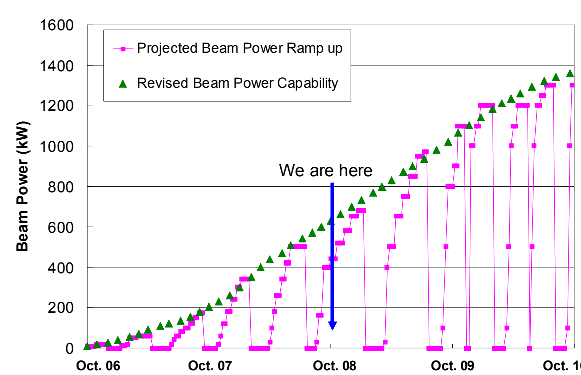

Figure 8: SNS beam power ramp-up history and plan.

The final output beam energy mainly depends on SCL gradients. Presently the SCL is providing output energy of 900 MeV without reserve, which is lower than the design energy due to the facts mentioned in the previous section. The goal of the SCL performances is 1-GeV output energy with 30- to 40-MeV energy reserve for fast recovery of operation from unexpected long-lead down time of not only cavities but also the related systems. Cryomodule repair works are in progress to get all 81 cavities in service [8]. One cavity in the cryomodule 11 is not operable due to the large power coupling through the HOM port from the RF operation. One high beta cryomodule (CM12) was removed from the linac tunnel for repair in the SNS SRF test facility, which had beam line vacuum leaks and showed biggest radiation from RF operation. It is revealed that the beam line leak was resulted from the HOM feedthroughs. Three leaky feedthroughs (plus one feedthrough at the cavity with a leaky feedthrough) were removed out of eight HOM coupler feedthroughs. This cryomodule will be brought in service after RF performance tests in the SNS SRF test facility in the next year. As mentioned above CM19 had been repaired and has been back in service in the slot of CM12 since March, 2008 and is the best performing cryomodule in the SNS SCL. Very recently one cavity, SCL-10b was repaired in the tunnel, which showed noisy field probe signals and had been turned off for about a year at 30- and 60-Hz operations. The final output energy is expected to be about 950 MeV after having all cavities available. For the design energy with some energy reserve like 40 MeV, an active effort for improvement of cavity performance is needed especially for high beta cavities. An R&D program is just started to develop an in-situ surface processing such as helium processing and plasma processing to get about 100-MeV additional output energy.

Each SCL cavity is fed by an individual klystron rated 550-kW RF output at saturation and has independent RF control systems. Eighty one klystrons for the SCL are powered by seven HVCMs; four HVCMs running at 69 kV for twelve klystrons each and three HVCMs running at 71 kV for eleven klystrons each. The voltage of HVCMs needs to be increased up to 75 kV to utilize the rated RF power of the klystrons. To ensure a high intensity beam loading with a good machine availability, a decision was made to have one additional HVCM for the SCL, which is planned to be installed in early next year, so that most of SCL HVCMs will power 10 klystrons at 75 kV with fair reliability.

The beam pulse width is presently major driving factor for the SNS power ramp-up mainly depends on HVCM pulse width and stability of chopper. There will be another beam pulse extension by reducing SCL cavity filling time form 300 μs to 250 μs with the additional HVCM for the SCL mentioned above.

POWER UPGRADE

Many of the accelerator subsystems are designed to be able to support higher beam intensities and higher beam energy. Upgrades to the SNS accelerator and target systems to increase the beam power to at least 2 MW, with a design goal of 3 MW, are in the planning stages. A beam power upgrade to 3 MW can be achieved by increase the linac beam energy from 1.0 GeV to 1.3 GeV by adding 9 additional high-beta cryomodules in the already prepared empty slots in the linac tunnel and by increasing beam current from 38 mA to 59 mA. The duty factor will be kept at 6 % and most of beam transport lines and ring have capability for 2 MW, 1.3 GeV operations. The newly defined Power Upgrade Project (PUP) includes only the beam energy upgrade portion and the beam current increase and target improvement will be accomplished through R&D activities and so-called Accelerator Improvement Project (AIP). The SNS power upgrade project is waiting for CD-1 approval and the planned project period is from 2011 for about 4 years.

SUMMARY

The SNS has begun the official operations since October 2006 after completion of the construction project in June 2006. The SNS is in the middle of three-year power ramp-up period to reach the design specifications and high availability for the user services. The presently achieved beam power for the neutron production is about 0.62 MW. From the series of tests and operational experiences more understandings of systems and their limiting conditions in pulsed mode are being obtained at high duty operation. The machine availability is steeply increasing concern as a user facility. The trip rate from the cavity/cryomodule side is now approaching zero and the SCL is providing beam acceleration for the neutron production as one of the most reliable systems. Beam power is keeping on track with the power ramp-up plan that is generated based on the previous operational experiences and studies. The Power upgrade project for energy upgrade from 1 GeV to 1.3 GeV is in planning stage and is waiting for CD-1 approval, which will double the beam power up to 3 MW, incorporated with so-called Accelerator Improvement Project (AIP).

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