SNS EXPERIENCE WITH A HIGH ENERGY SUPERCONDUCTING PROTON LINAC*

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Abstract

The Spallation Neutron Source (SNS) requires a high power (> 1 MW) 1 GeV proton beam to produce an intense source of neutrons. The proton beam acceleration is primarily provided by a Superconducting Cavity Linac (SCL). This SCL is the first use of superconducting cavities to accelerate protons to energies this high and is also the first application of pulsed SRF with proton beams. The SCL has been in operation for over two years now. The experience in commissioning and operating the linac are discussed in this paper.

1 INTRODUCTION

Early in the course of the SNS construction project a decision was made to switch from an entirely copper structure linac to using Superconducting RF technology for the majority of the beam acceleration [1]. The SCL portion of the accelerator was provided by Thomas Jefferson National Lab (TJNL). The cavities were fabricated by industry, the cryomodules were assembled by TJNL, and shipped to SNS for installation in the tunnel. Cavity testing at SNS began in the spring of 2005, and proceeded along with cryomodules installation through July 2005. Beam commissioning of the linac occurred in August 2005, after which the machine was shutdown for three months to prepare for the downstream Ring and transport line commissioning. The SCL was quite stable for the initial Ring commissioning, and over the past 1.5 years the linac has been used for beam studies and neutron production, with an increasing fraction of the time being spent of neutron production as the facility matures. Table 1 shows the progression of pulse length and duty factor over the course of the startup of the SNS facility.

Section 2 briefly describes the design parameters of the SCL [2,3] and section 3 describes the cavity operational experience with a comparison to expectations and Section 4 describes the beam commissioning and operation.

2 SCL DESIGN

The SNS SCL is designed to accelerate the beam from 186 MeV to 1000 MeV. Two geometrical beta cavities are used, medium beta cavities (β_g=0.61) and high beta cavities (β_g=0.81). The medium beta cavities are packaged 3 per cryomodules and the high beta cavities are packaged 4 per cryomodule. Some of the design parameters are shown in Table 2-1. An important facet of the design is a single klystron powering each cavity. Also, the expected range in the SCL cavity performance was +15%, -5% range about the design value [2].

Table 1 Chronology of SNS SCL beam energy and pulse structure operational parameters

	Repetition Rate (Hz)	Flattop pulse length (μSec)	Energy (MeV)
Summer 2006	2	500	855
Fall 2006	5	500	890
Winter/Spring 2006	15	500	885
Summer 2007	30	600	885

Table 2. SNS SCL cavity and cryo-module parameters.

Cryomodule parameter	Medium Beta Section	High Beta Section
Output energy (MeV)	387	1000
No. of cryomodules	11	12
No. of cavities per cryomodule	3	4
Cryomodule length (m)	4.89	5.84
Warm section length (m)	1.6	1.6
Cavity Parameter	**Medium Beta Cavity**	**High Beta Cavity**
Geometric beta	0.61	0.81
EoT (MV/m)	10.1 at β=0.61	15.9 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
Qex	7.3×10^5 (±20%)	7.0×10^5(±20%)
Stored energy (J) at design EoT	33	85
Inter-cell coupling (%)	1.6	1.6
Available klystron power (kW)	550	550
Bore radius (mm)	43	48.8
Equivalent Cavity Length (cm)	68.2	90.6

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3. CAVITY PERFORMANCE

The initial experience in operating the SNS SCL has indicated several unexpected features. First cavity performance has proven to be much more varied from cavity to cavity than expected. In addition to higher than expected variations in the individual cavity superconducting characteristics sometimes peripheral equipment limits individual cavity performance. Also the linac has proved to be remarkably robust to running in conditions far from the design values. These issues are discussed below.

3a. Cavity Limits

The primary cavity limit is operating safely below any field emission quench limits. For most cavities radiation levels during the RF pulse are proportional to the field level in the cavity, as seen in Fig. 1a. However, some cavities exhibit behaviour with radiation spikes during the rise and fall of the field in the cavity, which is also mirrored in independent nearby electron probe measurements. While not completely understood, it is believed that this behaviour is related to electron generation near the ends of the cavities during the period with travelling wave conditions. The thermal cooling in the end group region is not designed to tolerate high electron heating loads, and some cavities are limited in gradient by this effect.

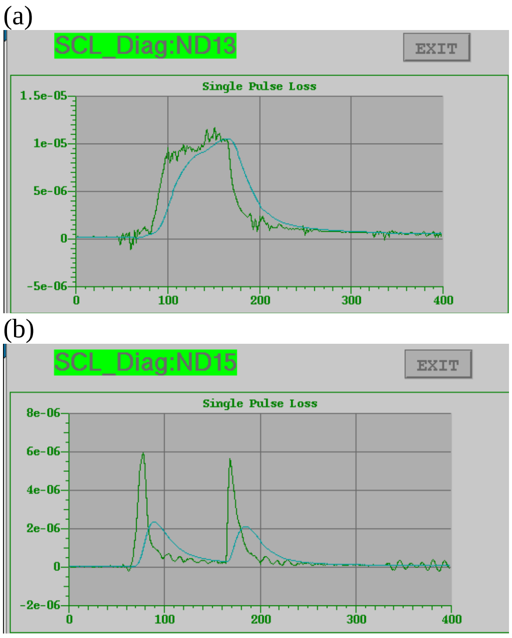

Fig. 1 a) Radiation vs. time signature adjacent to a normal cavity. This shape is similar to the RF forward power profile. B) Radiation signature of a cavity with end-group electron activity, exhibiting spikes during the rise and fall of the cavity field.

Another effect that limits some cavity gradients is the Higher Order Mode (HOM) coupler power. These couplers were added to remove HOM power and alleviate the remote possibility of cavity heating from HOM effects. They include a notch filter to inhibit fundamental power coupling, but some cavities show evidence of some fundamental power leaking into the HOM coupler. Since the HOM couplers have a limited power capability, this unexpected effect limits some cavities' performance.

Other peripheral cryomodule equipment has also affected the SCL operation in unanticipated ways. The Cold Cathode Gauges (CCG) used to measure vacuum in the SCL sometimes have long response times at the extreme vacuum levels of the cryogenic environment, and required intervention to evoke a response sufficient for the RF interlock to have confidence they are working. Cavity turn on procedures were developed to ensure safe operation while avoiding un-necessary protective measures. Another unexpected behaviour is the failure of piezo-tuners installed to correct the dynamic Lorentz force detuning. Several of these have failed requiring intervention to recover the use of the cavities. Because the present piezo-tuner implementation design is not optimal, and we have never used them in operation, we are removing these tuners from cryomodules that are worked on.

3b. Collective Cavity Limits

An unanticipated observation on the determination of reliable operating gradients is a dependency on neighbouring cavity conditions. Beam pipe temperature in one cavity can be affected by changes in a neighbouring cavity's phase or amplitude setting. Figure 2-1 shows an example for cryo-module number 13, indicating the various places where local heating is affected for each cavity, in addition to the cavity itself. This collective behaviour becomes more pronounced at higher pulse repetition rates. For reliable operations the cavities must be set at a gradient that not only is safe for the cavity itself, but also for neighbouring cavities.

3c. Overall SCL Cavity Performance

Figure 3 shows the operational gradients for all the SNS SCL cavities at the present time. The blue line indicated the design value, the green line is the average cavity gradient at 10 Hz and the red line is the average gradient for 60 Hz. The averages are indicated separately for the medium beta cavities (1a-11c) and high beta cavities (12a-23d). Some observations are: 1) there is a large spread in the cavity to cavity performance, 2) the medium beta cavities perform better than expected on average, 3) the high beta cavities perform worse than expected on average, 4) the 60 Hz limits are about 10% lower than the 10 Hz limits. The gradients shown in Figure 3 are for the present time. Over the past two years the operating gradients have changed as understanding of the limiting effects is better understood and the operational repetition rate has increased.

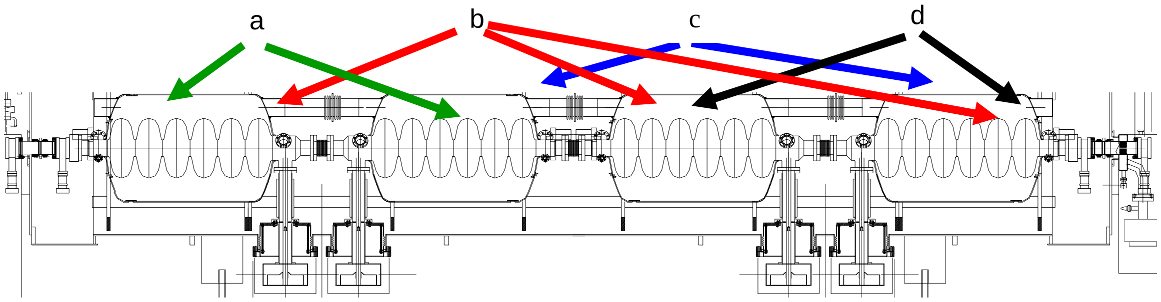

Figure 2. Local heating locations for the different cavities a, b, c and d in cryo-module 13. Each cavity affects multiple cavities within the same cryo-module.

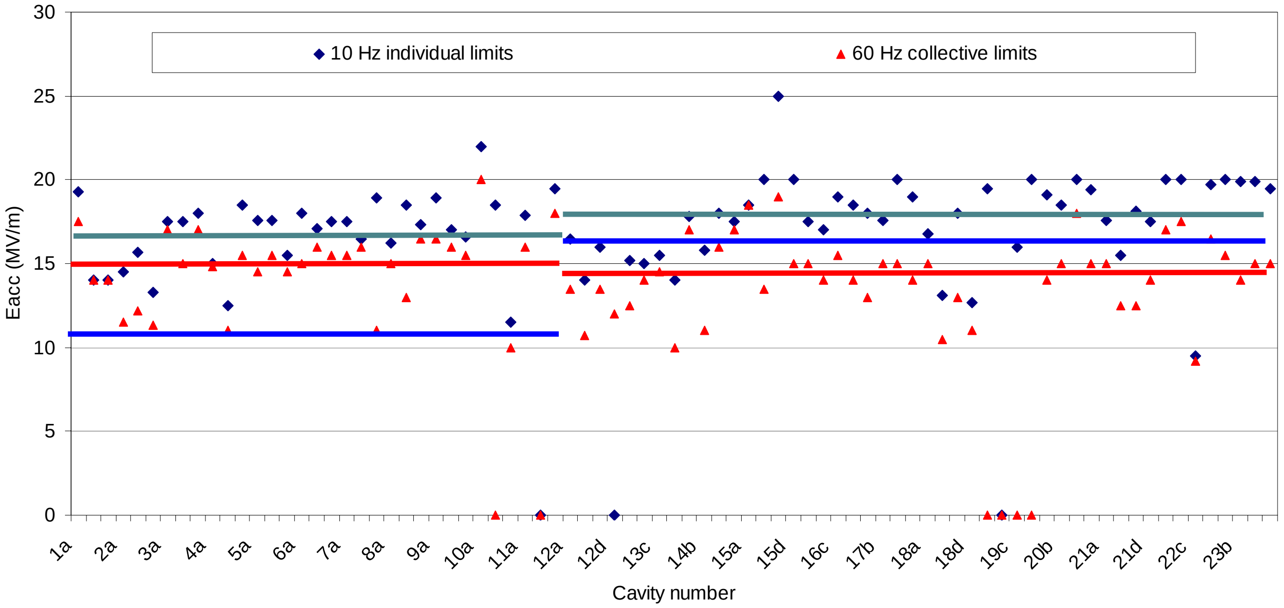

Figure 3. Operational gradients for the SNS cavities. The blue line indicated the design value, the green line is the average cavity gradient at 10 Hz and the red line is the average gradient for 60 Hz. The averages are indicated separately for the medium beta cavities (1a-11c) and high beta cavities (12a-23d). The medium beta cavities perform better than expected, and the high beta cavities have lower operational gradients than expected. The net effect is lower operational output beam energy than expected.

4. BEAM COMMISSIONING AND OPERATION

4a. Tools

The method of SCL cavity use at SNS is to operate each cavity at its maximum safe gradient and set its phase relative to the beam. We have used constant phase and constant focusing schemes. A key issue in this area is the tool used to set the cavity phase relative to the beam. We use a phase scan technique to determine the phase setpoint (shown schematically in Figure 4. A cavity phase is varied, and its arrival time measured at two downstream positions (using beam position monitors). All intervening cavities are set to not affect the beam during the pulses when the measurements occur. Each cavity has only 6 cells and the net effect of cavity acceleration on the beam is much like an ideal RF gap (β changes only slightly in each cavity). As a result, this phase scan can be employed throughout a 360 degree range and the measurement data is easily matched to model predictions to determine the input beam energy, cavity amplitude and klystron phase offset from the synchronous phase [4,5]. Figure 5 shows a typical scan for an SCL cavity. The resulting phase scan is much like the sinusoidal result expected from an ideal RF-gap, and all cavities show a similar behaviour. The line represents measured data and the dots are model predictions after solving for the input beam energy, cavity gradient and klystron phase offset. A standard drift-kick-drift longitudinal acceleration model is used [5]. As it is important to ensure there is no RF affecting the beam in between the cavity being varied and the two BPMs used to measure the Time-of-Flight. For the SNS arraignment of cavities and diagnostics there can be up to 7 intervening cavities, and in order to proceed through the 81 cavities quickly we have implemented a LLRF feature to allow "blanking" of the RF whenever beam pulses are triggered for these measurements. This allows the entire SCL RF system to be turned on and left on at a typical 30-60 Hz rate, with beam pulses periodically applied at 1 Hz for the phase setting studies. It still requires at least 5-10 hours to measure and set all cavities, from a cold start.

To avoid having to redo beam base measurements to set the SCL cavity phases whenever an upstream cavity phase or voltage changes a model based technique has been developed to calculate the changes in beam arrival time in downstream cavities when a cavity fails and to automatically adjust the downstream cavity phase setpoints [5]. Turning off an upstream cavity can result in changes in the arrival time at the downstream end of the linac equivalent to over 1000 degrees. Checks show that the recovery technique is accurate to within a few degrees. This technique has been used often to compensate for changes in SCL operating levels and for beam studies.

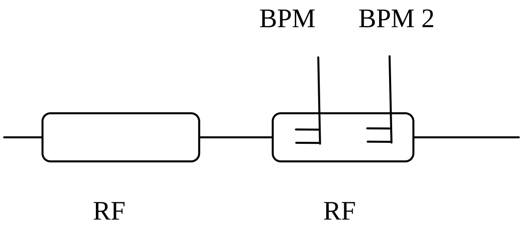

Fig.4. Schematic of the device layout used in the measurement to determine the SCL RF phase setting.

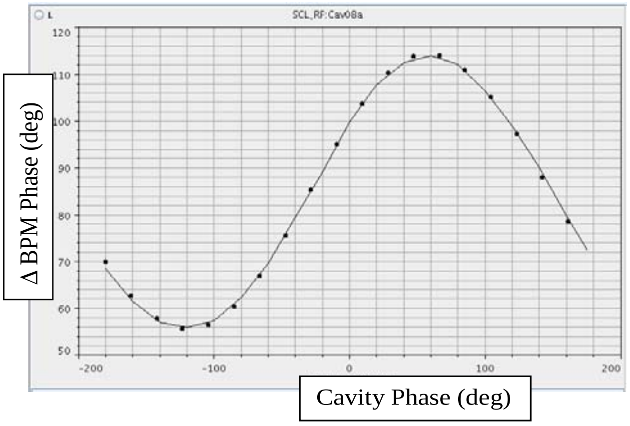

Fig.5 Example BPM phase difference vs. RF phase scan for a SCL cavity. The solid lie is a measurement and the dots are model predictions after matching the input beam energy, cavity voltage and RF phase offset.

Another technique that can be used to measure the cavity phase setpoint relative to the beam and also the cavity amplitude is the drifting beam technique [6]. This technique involves drifting the beam through an unpowered cavity. The beam readily excites the cavity and by comparing the measured cavity excitation with model based predictions it is possible to determine the proper cavity phase setpoint and the cavity amplitude. This technique requires knowledge of the beam energy and a good measurement of the beam current.

4b Beam Performance

Table 3 shows the SNS SCL high level beam performance parameters. All the design parameters have been met individually except beam power. The maximum beam power used during a neutron production run to date has been 200 kW. While this is a significant beam power, there is still a factor of 7 increase required for the beam power. This increase will be achieved by increasing the beam current, pulse length and beam energy. Some of this increase is possible with existing hardware capabilities. Hardware improvements are also envisioned for the RF, High Power Converter Modulators, ion source and cavities to reach the final beam power. At present we observe some residual radio-activation in the warm sections separating the cryomodules (and containing the focusing quadrupoles) of about 10 mRem/hr measured 30 cm from the beam pipe 12 hrs after shutdown. This level of activation represents a small beam loss fraction (< 1 part in 1000) and is believed to be longitudinal in nature. There do not appear to be any fundamental beam dynamic issues to prevent attaining the expected final beam power.

Table 3. Summary of SNS SCL beam parameters achieved.

	Design	Highest Ever (Individual)	Highest Beam Power (Simultaneous)
Energy (GeV)	1.0	1.01	0.85
Rep Rate (Hz)	60	60	60
Pulse Length (mSec)	1	1	0.27
Avg. Beam Current (mA)	26	20	15
Beam Power (MW)	1.5	0.20	0.20

5 SUMMARY

The SNS SCL is the first high energy (~ 1 GeV) superconducting RF pulsed proton linac. Operation of the SNS SCL over the first two years has turned out quite different than expected during the design period. Cavity operational gradients are more varied than expected, often limited by the performance of auxiliary equipment such as HOM couplers. The behaviour of the SCL as an overall system, governed by many components, has become better understood during the initial operational period. As the understanding of the cavity performance improves, operational limits change. Operation of the linac under these unexpected and dynamic conditions has proven to be remarkably robust. An advantage of the SNS accelerator complex is that it can tolerate different output energies of the linac. So for example, energy reduction due to removal of a cryo-module for repair is tolerable. Tools have been developed to rapidly tune up the SCL, with its many cavities. Also tools have been created to rapidly adapt to failed cavities or changes in the cavity operational limits.

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