OPERATIONAL EXPERIENCE WITH HIGH POWER BEAMS AT THE SNS SUPERCONDUCTING LINAC*

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Abstract

The Spallation Neutron Source (SNS) accelerator is in a period of rapid beam power ramp-up, with operation of over 0.5 MW achieved to date. SNS is the first high power proton pulsed superconducting linac (SCL), and has unique challenges. Beam tuning methods have been developed for setting the many independently powered SCL cavities, and recover from faults. The challenges and experience of minimizing beam loss at the high operational powers are also presented.

INTRODUCTION

The Spallation Neutron Source provides a high power source of protons to drive a short pulsed spallation neutron source [1-5]. The beam acceleration is accomplished in a linac, with copper structures providing acceleration up to 186 MeV and superconducting RF structure providing acceleration to 1000 MeV. The linac design goal is a 1 msec long pulse of 26 mA average current provided at 60 Hz (~ 1.5 MW). This beam is injected into an accumulator ring and the pulse length compressed to ~ 1 µsec to provide a short pulse source of spallation neutrons. Many of the details of the power ramp-up over the last two years are provided in Ref [1-5]. Here we concentrate on the operational experience with beam of the Superconducting linac (SCL). Details of the operational experiences with the equipment are provided in Refs [6-7].

POWER RAMPUP PROGRESS

To date the beam SCL has provided over 550 kW of production beam. Typical beam operating conditions at this power level are 60 Hz repetition rate, 18 (32) mA average (peak) current, 600 μsec pulse length and 890 MeV. For neutron production conditions, the beam energy is reduced to 890 MeV because of the SCL equipment issues discussed in Ref. 6, pulse length is limited by availability concerns for the High Voltage RF support systems, and peak current is limited by Ion Source capability and availability concerns. Figure 1 shows the history of the beam on Target power ramp-up (We note that the SCL beam power is ~ 5% higher than that provided on the neutron producing Target, because ~5% of the beam is lost at the Ring Injection.

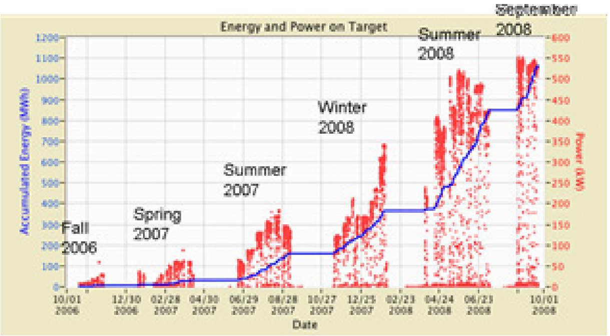

Figure 1. The beam on target power ramp-up progress since the start of neutron production at SNS.

SCL RF SET-UP

One of the most striking features we have come to realize regarding the SCL operation with beam is its flexibility. The copper structures tend to be large, high power cavities (> 1 MW klystron power level), with many (~ 100) individual RF-gaps. For these large structures there is a significant change in the beam β, as well as significant phase advance of the beam bunch in longitudinal phase space. The copper cavity geometries are manufactured to match the expected energy gain and provide appropriate longitudinal focusing. Only one klystron RF phase and amplitude setting is correct. If one varies the phase and amplitude setting about the nominal set-point in the warm linac cavities, the resulting effect on the beam is complicated and each warm cavity has a unique output beam "response signature" [7]. Figure 2 shows the measured response of the beam Time-of-flight (TOF) downstream of the first Drift Tube Linac (DTL) tank in SNS, to perturbations in its phase and amplitude.

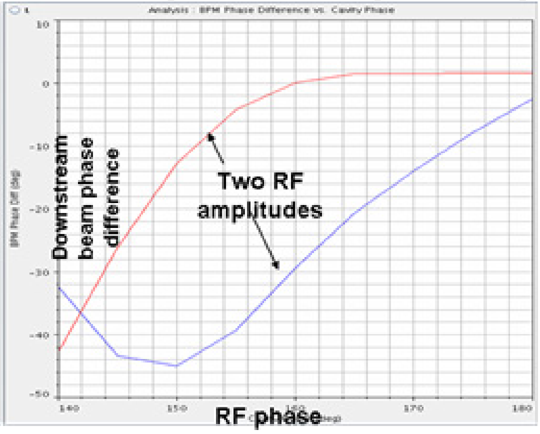

Figure 2. Measured change in the downstream beam velocity with changes to the RF phase and amplitude in the first DTL tank (Red is ~ 2 % below nominal amplitude; blue is ~ 2 % above).

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On the contrary, the SCL cavities are 6 cell elliptical cavities with independently controlled klystrons. The beam energy gain is ~ 10 MeV / cavity, for which the change in β is small and also there is only a small longitudinal phase advance through each cavity. In this case, the beam response to the cavity is similar to that of an ideal RF gap. Figure 3 shows the measured response of the downstream beam TOF to the variation of the RF phase over a full 360 degrees. It is very similar to a sine-wave response as expected from an ideal RF-gap.

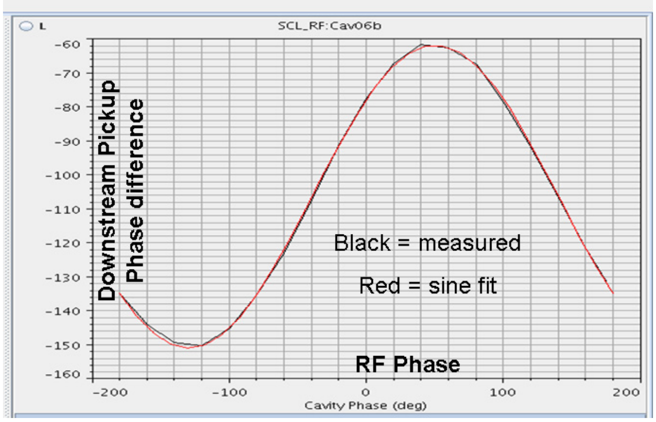

Figure 3. Response of the downstream beam TOF to a scan of the RF phase over 360 degrees.

This simple beam response to the RF set-up offers considerable flexibility. First, we tend to operate all our cavities at their maximum safe operating gradients, and only adjust the RF phase to the desired synchronous phase. Also it is simple to derive the input beam energy and calibrate the average cavity RF amplitude with this measurement [9].

Applying this scan technique to each cavity provides a measurement of the beam arrival time relative to the RF for each cavity (i.e. the synchronous phase setting for each cavity). This procedure takes 4-8 hours for the 75 SNS SCL cavities in use at present. If an upstream cavity phase and or amplitude is changed, the downstream cavity phases can change by 100's-1000's of degrees for the non fully relativistic SNS beam. However one can use a model to predict the change in downstream beam arrival time (or phase) to within a few degrees when an upstream cavity amplitude and/or phase is changed. Applying a model predicted perturbation to a beam based phase setpoint offers many possibilities. One can recover from a failed cavity without having to perform beam based measurements again. Also the technique can be used during beam studies to quickly test different longitudinal phase setupss. At SNS this scaling technique is is employed for multiple purposes. Figure 4 shows an example of the technique applied to resetting the RF phases of the SCL cavities when the operating temperature was changed from 4 to 2 K requiring change in almost ¼ of the cavity amplitude settings. The predicted RF phase settings changed by up to 2000 degrees (of 805 MHz RF cycles). Spot checks indicated the predicted phase changes to be accurate to within a few degrees. Beam loss – the primary indication of how well tuned RF systems are – is typically unchanged when applying this technique.

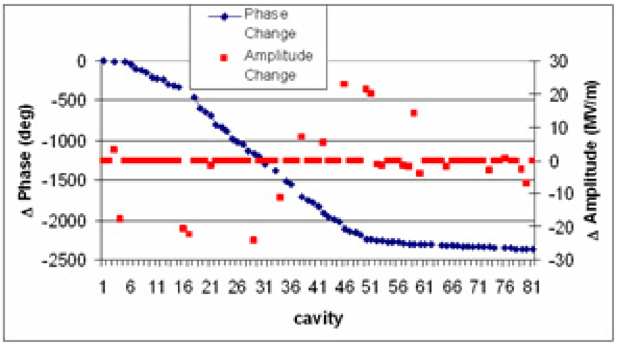

Figure 4. Change in the phase setpoints of the RF cavities (blue) resulting from changes in the cavity amplitudes (red).

The phase scaling techniques is also used in beam studies. One example is the beam acceptance measurement technique [12]. Figure 5 shows the longitudinal acceptance for the SNS linac, for two perturbations on the production setup. The linac beam emittance is much smaller than the area shown in Fig. 5. The phase scaling technique has been used to enable a raster scheme of the input beam across the longitudinal phase space. By measuring the beam transmission with downstream current toroids (or measuring beam loss with loss monitors) throughout this raster it is possible to experimentally measure the acceptance. An example of this is shown in figure 6 (taken from Ref. 12). Also use of the phase scaling techniques permits rapid testing of different RF setups, without having to perform beam based measurements for each cavity. Foe instance we have tried many different variants of constant focusing (adjusting the synchronous phase ϕ_s, so that the product $E_0 \sin\phi_s$ is constant) and constant ϕ_s RF setups.

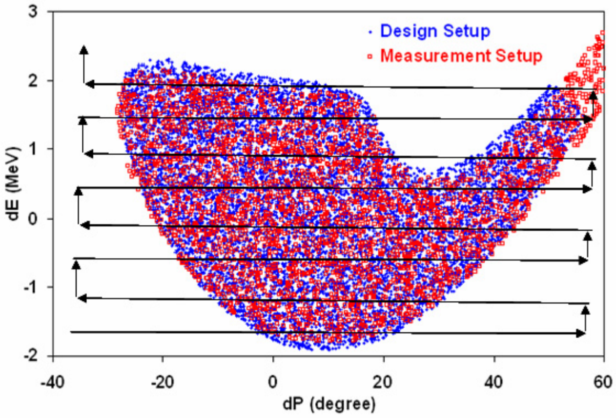

Figure 5. Model predicted longitudinal acceptance for the SNS SCL (taken from Ref. 12) with a superimposed path for rastering the input linac beam for experimental measurement.

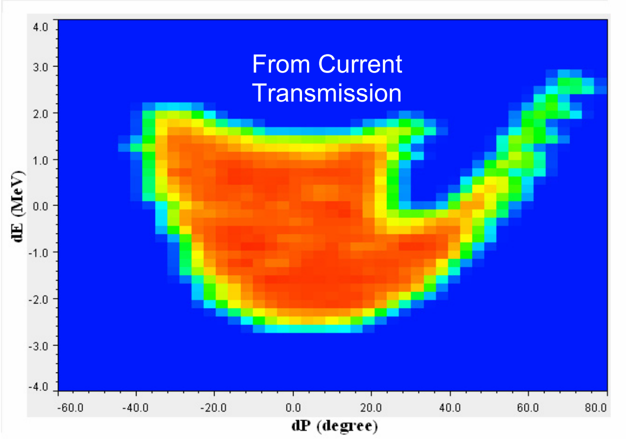

Figure 6. Measurement of the SNS SCL longitudinal acceptance using current transmission, taken from Ref. 12.

BEAM LOSS

The SNS is expected to be a beam loss limited machine. The design basis is 1 W/m for uncontrolled beam loss, which is predicted to result in about 100 mrem/hr at 30 cm 4 hours after shutdown, and years of operation. This criteria was taken as a rough rule-of-thumb for hands-on-maintenance without significant dose to the workers. However, in the SCL region, losses were expected to be lower, due in large part to the large aperture associated with the SCL technology [13]. As the beam power exceeded about 50 kW, un-expected residual activation in the warm sections between the SCL cryomodules began to be measured after beam production. Subsequent movement of the loss monitors to within ~ 10 cm of the beam pipe in the warm sections verified measureable beam loss.

The magnitude of the beam loss appears to be small. We have performed controlled beam spills of small amounts of beam throughout the SCL to calibrate the loss monitors. Localizing the beam loss is difficult, resulting in large variability along the SCL for the calibrations (factors of $\pm$ 3 in our medium beta cavities (below 450 MeV) and factors of $\pm$ 2 in the high beta cavities). We estimate an upper bound of about $2x10^{-6}$ fractional beam loss per warm section. The present warm section residual activation one day following a neutron production run is 10-60 mrem/hr at 30 cm. These values are consistent with < 1 W/m (or $< 2x10^{-6}$ for the 500 kW power level). Measuring and modeling beam effects at this level are challenging. Presently, the beam loss monitor system is the only instrument sensitive enough to measure fractional beam at this level. To date the SCL residual activation has not significantly contributed to worked dose, nor is it expected to cause pre-mature end of component life [7].

Figure 7a shows the history of the buildup of the measured SCL warm-section activation following production runs of 1-2 weeks over the past year. There is some variability in the time between end of production and radiation surveys, with this time delay varying between one and two days. Also indicated are the beam power levels during these periods. The power is generally increased with time during each production run. There tends to be a saturation of the activation levels each run, despite the increase in operational beam power. Figure 7b shows the residual activation levels taken just downstream from the Ring injection foil (hottest region in the SNS which was expected and designed to have high beam loss). The Ring Injection area activation levels do not show the saturation. Beam pipe for both the SCL warm section and Ring Injection use 304 stain-less steel. Also we note that the SCL activation is much less than the Ring Injection (which is expected to be a high loss area).

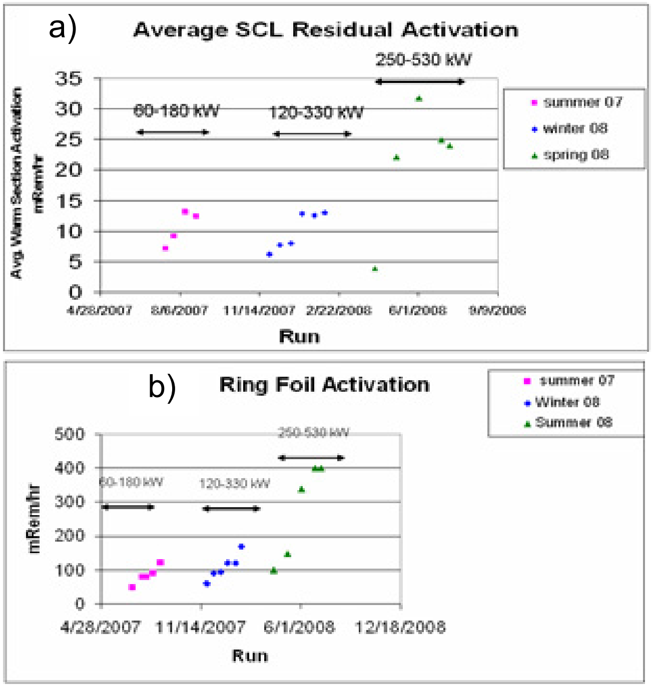

Figure 7. Buildup of the residual activation levels after production runs during the past year of power ramp-up for a) the average of all SCL warm sections, and b) the region downstream of the Ring injection foil.

At present the cause of the beam loss in the SCL is not well understood. Some of the sensitivities that have been experimentally addressed indicate that the loss is:

- Sensitive to upstream warm linac RF set-up
- Insensitive to the SCL matching quadrupole settings
- Insensitive to the SCL longitudinal tune scheme (constant phase or constant focusing)
- Sensitive to 5 mm upstream local trajectory bumps
- Insensitive to increase in the CCL background gas pressure.

SUMMARY

The SNS SCL operational beam power has increased from a few kW to over 500 kW during the first two years of operation. The many independently powered cavities that comprise the SCL offer a flexible operational setup. A model based phase scaling method has been developed that facilitates quick adjustments of the RF phase settings for upstream cavity changes. This scheme is useful to quickly adapt to failed cavities as well as performing beam studies. There is also a low level (< 1 W/m) of beam loss in the SCL warm sections between cryo-modules, which is unexpected but not limiting beam power. The source of the loss is not understood.

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