EXPERIENCE WITH THE SNS SC LINAC*

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Abstract

The SNS superconducting linac (SCL) is designed to deliver 1 GeV, up to 1.56-MW pulsed H^- beams for neutron production. Commissioning of the accelerator systems was completed in June 2006, and the maximum beam energy achieved was approximately 952 MeV. In 2007, the SCL was successfully tuned for 1.01 GeV beam during a test operation. In the linac tune-up, phase scan signature matching, drifting beam measurement, and linac radio frequency cavity phase scaling were applied. In this paper, we will introduce the experience with the SCL, including the tune-up, beam loss, and beam activation, and briefly discuss beam parameter measurements.

INTRODUCTION

The Spallation Neutron Source (SNS) is a short-pulse neutron scattering facility, and the accelerator complex consists of a linac for H^- beams, an accumulator ring, and associated beam transport lines. The superconducting linac is approximately 160 m in length; it comprises 81 independently phased 6-cell niobium SC cavities and provides acceleration for H^- beams from 186 MeV out of a normal conducting linac to 1 GeV. Through a carbon stripping foil at the ring injection, proton beams are accumulated in the ring, then extracted and transported to a liquid-mercury target for neutron production [1].

Tuning up the world's first pulsed-proton SC linac and ramping up the beam power to its design goal are challenging tasks. Efforts to mitigate beam activation and beam loss in the SCL are critical, and the 1-W/m quota gives an allowable fractional loss of approximately 1×10^{-4}. Precisely tuning all the components of the accelerator systems, including the upstream normal conducting linac, is very important, and accurately characterizing beam parameters in the linac is necessary. Traditional beam study techniques as well as newly developed methods are applied.

LINAC TUNE-UP

The design gradient of the SNS cavity is 10.2 MV/m for geometry beta 0.61 and 15.9 MV/m for geometry beta 0.81, but the operational gradient varies widely. Figure 1 shows the SCL gradient for one of the neutron production operations and also for the 1-GeV test run; compared with the design, the differences are from −100 % to +80 %. It is necessary to smooth the longitudinal focusing by adjusting the synchronous phase of several cavities, particularly around the unpowered ones, to preserve beam emittance in the linac. It is also important to model the linac phase oscillation and damping curves to provide helpful information about the longitudinal lattice [2]. It is equally important to optimize transverse focusing in the linac, which is done with an application code developed in the XAL infrastructure [3]. Before dialing them into the real machine, all the parameters are put into the IMPACT code [4] for verification.

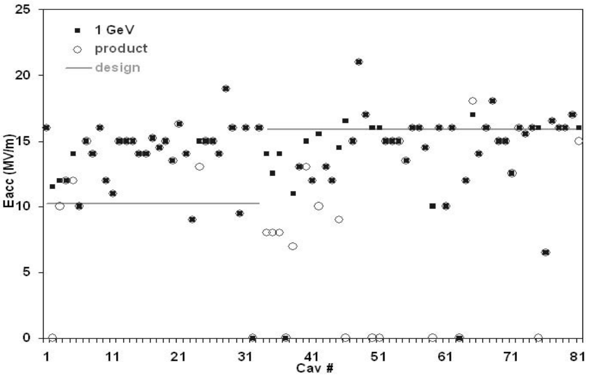

Figure 1. Cavity gradient for production and for 1 GeV.

Tune-up of the cavity phase is based on the phase scan signature matching method; in addition to the cavity phase, it provides the beam energy and the field amplitude [5]. During the linac tune-up and beam energy ramp-up, the focusing quads in the SCL and the downstream line are adjusted for several intermediate energies to reduce beam loss. It is time consuming to scan all cavities in the linac, so a fast cavity fault recovery method has been developed that is based on RF cavity phase scaling [6]. The drifting beam method based on measurement of beam-induced signals in a superconducting cavity also has been studied [7]. In the 1-GeV demonstration, all three techniques were used. Figure 2 shows the scaled SCL cavity phase from the production of approximately 900 MeV to the 1-GeV test operation.

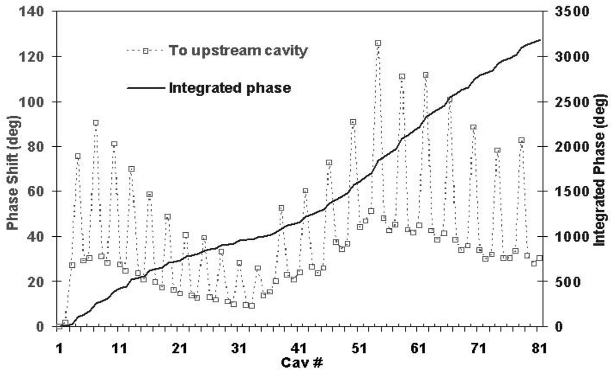

Figure 2. Predicted phase from 900 MeV to 1 GeV.

In the phase scaling, each cavity phase is set according

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to the integration of the time (phase) shift of all the upstream cavities due to beam energy variations predicted with the linac model. For example, in Figure 2, from the production 900 MeV to the 1-GeV demo, the absolute phase of the last cavity is shifted by approximately 3200°. Phase scaling can adjust the entire linac in a few seconds, as it does not need any beam phase measurement; it could have errors of several degrees but be acceptable to the SCL [8]. In 2007, we operated the SCL at 1.01 GeV (models predicted 1.02 GeV) for approximately 4 hours.

BEAM LOSS AND ACTIVATION

In the early design stage of the SNS, very low beam loss was anticipated in the SCL because of the large beam pipe compared with the normal conducting linac (8 cm versus 2 to 3 cm) and the huge beam acceptances—transverse as well as longitudinal are several ten times larger than the nominal beam. The ultra-high cryogenic vacuum of 10^{-10} mbar also reduces the effects of residual gas scattering. To mitigate beam losses after the linac, beam halo scrappers are installed at the high-energy beam transport (HEBT). But they do not provide any protection to the linac itself, and beam losses in the SCL due to longitudinal halo have not been studied thoroughly.

In neutron production, unexpected large beam loss and activation are observed in the SCL, and the loss persists – we tested transverse matching and trajectory flattening without significant improvement. It appears that the SCL beam loss is mainly a longitudinal issue, as shifting phase of upstream cavities may significantly affect the beam loss pattern. Both simulation and measurement show that the hottest activation spot located between cryomodule 2 and cryomodule 3 (CM 2 and 3) is caused by beam phase halo at the DTL-CCL transition. Figure 3 shows the beam loss measurement of the nominal linac and when the CCL1 phase was intentionally offset to simulate halo, beam loss is peaked at CM 2 and 3.

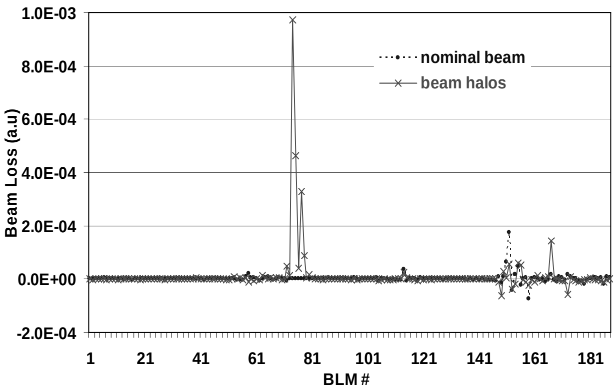


Figure 3. Beam loss measurement in the entire linac.

The origin of the beam longitudinal halo is not fully understood yet; however, the total amount of beam in the halo is larger than 1×10^{-4}, and mitigating beam loss and activation in the SCL will be critical for the SNS power ramp-up. In simulations, increasing the SCL longitudinal acceptance by a different synchronous phase other than the design phase –20.5° is a possible solution to the acceptance problem, although the actual effect is limited. In linac beam studies, we increased the SCL longitudinal acceptance from 200 deg*MeV to 400 deg*MeV but did not observe any beam loss benefit. In computer models, a perfectly tuned normal conducting linac provides a much better solution, as growth of halos is controlled and most halo particles are cleaned up in the upstream linac; but this may not be the case in a real machine.

Figures 4 and 5 show the measured SCL beam loss for a 340-kW neutron production early this year and the beam activation measured after the 340-kW production. From this measurement, we could linearly scale the SNS beam power up to approximately 1 MW and have tolerable residual activation. Beyond this power, more study is necessary to understand the origin of the beam halo and to further reduce the SCL beam loss.

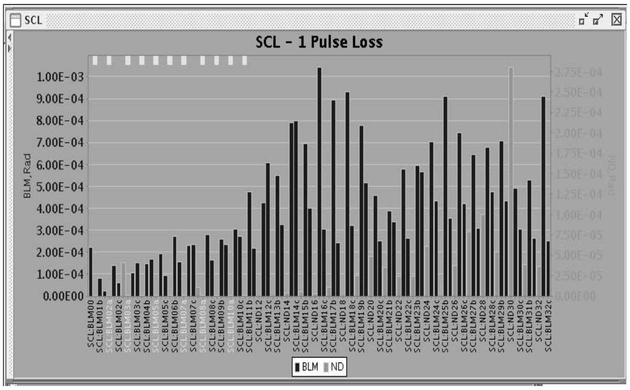


Figure 4. SCL beam loss in 340 kW neutron production.

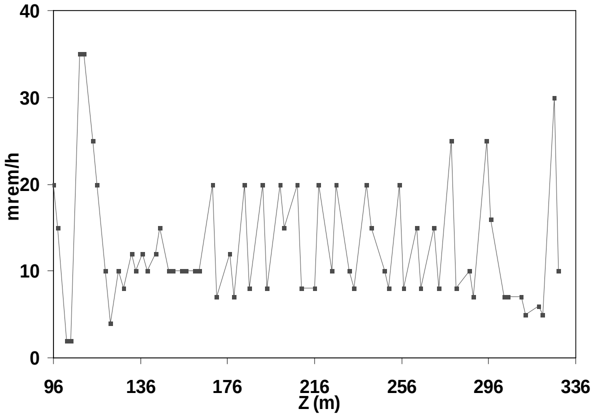


Figure 5. SCL activation after the 340 kW production.

BEAM MEASURMENTS

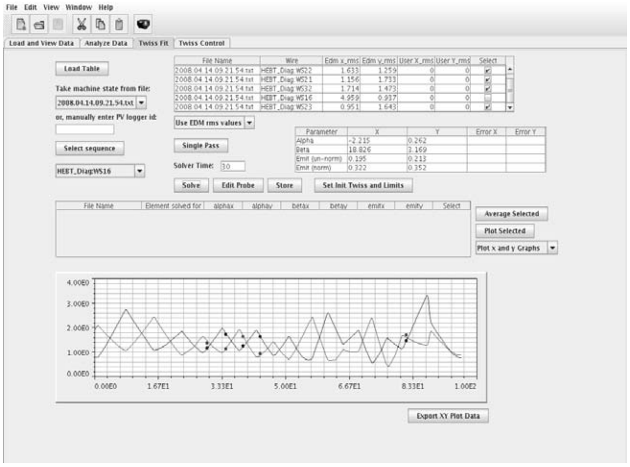
SCL injection and exit beam twiss parameters and beam emittance measurements are performed with multi-wire scans in the upstream normal conducting linac and in the downstream HEBT, where conventional wire scanners are available. By fitting the measured beam RMS sizes in a linac model, transverse emittance and twiss parameters are derived, and the same model can be used to set a few matching quads to recover the design twiss parameters. Laser wire scanners (LWs) are installed at several selected locations in the SCL, and beam profiles measured with

LWs could also be used for transverse matching purposes. However, currently, operating the LWs is very complex, requiring an additional laser expert plus a control software engineer, so beam matching with LW measurements has not been studied routinely.

The measured SCL beam RMS size and transverse emittance are usually close to the design specifications. The design SCL normalized emittance is 0.4 mm*mrad, and in measurements it is generally 0.3 to 0.4 mm*mrad. Beam parameters measured in 2006 for two high beta CMs (CM 13 and 16) on and off are compared in Table 1. After scaling of the SCL cavity phase, as well as minor longitudinal and transverse re-matching, beam emittance is preserved in the linac with two high beta CMs missing. We are currently running the SCL with CM19 offline, and we may continue this status for years. Figure 6 shows a recent beam measurement for 400-kW production.

Table 1. Normalized emittance w/o CM13 and CM16

(mm*mrad)	CM13 & 16	Horizontal	Vertical
HEBT1	With	0.35	0.29
	Without	0.35	0.31
HEBT2	With	0.35	0.32
	Without	0.43	0.27



Take machine state from file: 2008.04.14.09.21.54.txt

or, manually enter PV logger id:

HEBT_Diag:WS16

File Name	Wire	Edm x_rms	Edm y_rms	User X_rms	User Y_rms	Select
2008.04.14.09.21.54.txt	HEBT_Diag:WS22	1.633	1.259	0	0	☑
2008.04.14.09.21.54.txt	HEBT_Diag:WS21	1.156	1.733	0	0	☑
2008.04.14.09.21.54.txt	HEBT_Diag:WS32	1.714	1.473	0	0	☑
2008.04.14.09.21.54.txt	HEBT_Diag:WS16	4.959	0.937	0	0	☐
2008.04.14.09.21.54.txt	HEBT_Diag:WS23	0.951	1.643	0	0	☑

Use EDM rms values

Solver Time: 30

Parameter	X	Y	Error X	Error Y
Alpha	-2.215	0.262		
Beta	18.826	3.169		
Emit (un-norm)	0.195	0.213		
Emit (norm)	0.322	0.352		

File Name	Element solved for	alphax	alphay	betax	betay	emitx	emity	Select

Figure 6. Emittance measurement in 400 kW production.

Longitudinal beam space information of the SCL used to be unknown to us, as no beam intercepting device such as a bunch shape monitor was installed in the SC linac because of the high-power beams and the SRF techniques. We developed a new longitudinal measurement method for the SCL based on cavity phase scan, beam loss, and beam current measurements. Longitudinal beam halo, beam emittance and the SCL longitudinal acceptance, are measured with this novel method [9]. Figure 7 shows a recent energy profile measurement at the second SCL cavity; the beam energy spread (sigma) is approximately 0.29 MeV, in agreement with the model prediction for the first SC cavity at a synchronous phase of -90°.

Figure 8 shows a recent beam longitudinal emittance measurement result for 400-kW production. Beam RMS emittance is approximately 1.8 deg*MeV and comparable to the nominal design beam of 1.3 deg*MeV. However, in the previous neutron production operations, the measured longitudinal emittance was usually between 2.7 and 3.0 deg*MeV, approximately twice that of the design. Very large beam halos are shown in all those measurements, phase tails more than 40°, energy tails more than 3 MeV, and longitudinal beam halos are comparable with the SCL acceptance. The longitudinal beam halo inherited from the upstream linac is considered as one of the major causes of the SCL beam loss and beam activation.

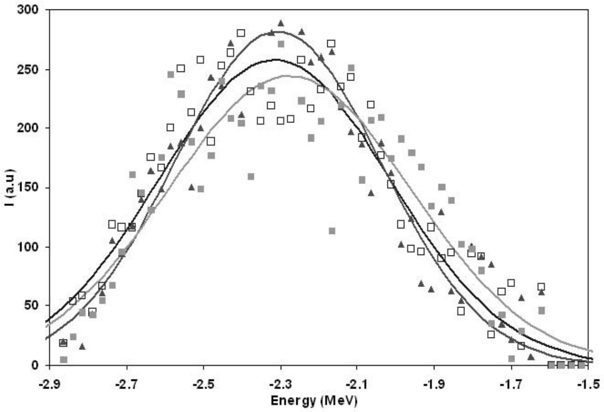


Figure 7. Recently measured SCL beam energy profile.

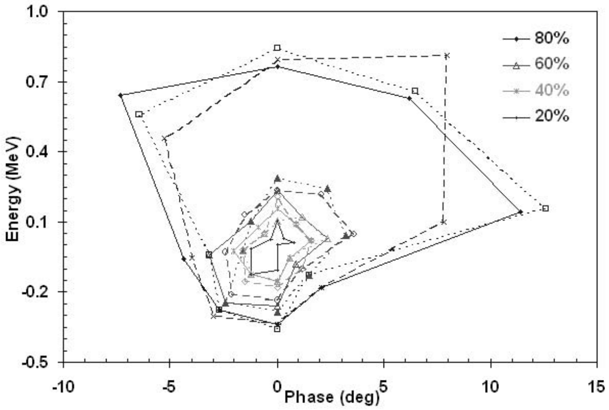


Figure 8. Recently measured longitudinal beam contour.

SUMMARY

Study of the SNS superconducting linac tune-up, beam measurement, and characterization has proved fruitful, but more investigation of longitudinal and transverse beam halo and understanding of the origin of the beam halo are needed to mitigate beam loss and beam activation in the superconducting linac.

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