EXPERIENCE AND LESSONS WITH THE SNS SUPERCONDUCTING LINAC*

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Abstract

Experience and lessons with the SNS superconducting linac over the first 5 years of accelerator commissioning and operation are reviewed. As the beam power was ramped up to 1 MW, the linac beam loss has been maintained below 1 W/m and residual activation has been held to a safe level. This can be attributed mainly to a robust accelerator design as well as to dedicated beam dynamics studies during this period. In addition to a review of both transverse and longitudinal phase-space measurements, we will review several hardware lessons learned with this high-power proton SC linac − such as nonlinear multipole components of the linac quadrupoles, beam collimators, piezo tuners of the superconducting cavities, and high-order-mode couplers.

INTRODUCTION

With 1 MW proton beams striking a mercury target, Spallation Neutron Source (SNS) is the most powerful pulsed spallation source in the world. Its accelerator complex consists of a linac for high-intensity pulsed H^- beams, and an accumulator ring. The linac systems include a normal conducting section 100 m long and a superconducting linac (SCL) about 200 m in length, and most of the beam energies come from the SCL: from 186 MeV to 1 GeV. In the SCL, a total of 81 six-cell niobium elliptical cavities are installed in 23 cryomodules, and each cavity is driven independently by a 550 kW klystron; between each cryomodule, a quadrupole doublet provides beam transverse focusing. The SCL is the world's first superconducting linac for pulsed proton beams, and more details of the linac design see references [1, 2].

Beam commissioning of the superconducting linac started in July 2005, and neutron production began in October 2006 with an initial beam power of only 10 kW. Since September 2009, we have ramped up the SNS beam power to 1 MW [3]; it is critical to sustain less beam loss and maintain a low residual activation for this high-power accelerator complex in order to achieve an ultimate goal of > 90% availability. The situation is more severe with the SCL, because a loss level above 1 W/m may quench delicate superconducting cavities and interrupt operations. In the design, the estimated total fractional beam loss in the SCL is $< 1\times10^{-5}$. Because the beam aperture in the upstream normal conducting section is only 3 cm while the SCL is 8 cm, there is very little chance for those higher energy H^- beams to loss in the SCL [4].

In beam dynamics studies, however, we discover that both longitudinal beam halo and transverse issues may contribute to the SCL loss; therefore, the actual fractional loss is 10^{-4} – an order of magnitude larger than the design expected. Fortunately, we have been able to successfully hold the fractional beam loss no more than about 1×10^{-4}, and as a consequence, we are still under the safe limit of 1 W/m up to the SNS design power of 1.44 MW.

In this paper, Section II describes the longitudinal beam dynamics studies which have included beam emittance, longitudinal halo, and measurements of adiabatic phase damping; Section III discusses beam matching with laser wire (LW) profile measurements, and a weak transverse resonance at a phase advance close to 60°; Section IV includes a summary of achievements in the past as well as several lessons learned with this high-power SC linac – mostly hardware issues we have encountered; and at the end, a conclusion.

LONGITUDINAL BEAM DYNAMICS

Two types of superconducting cavities are installed in the SCL: 33 medium beta (0.61) cavities and 48 high beta (0.81) cavities; the design gradients are 10.2 MV/m for medium beta and 15.9 MV/m for high beta. In operations, however, acceleration gradients of most high beta cavities are below the design, and to have enough output energy, most medium beta cavities need to operate at a gradient 20% to 50% above the design. As shown in Fig.1, the acceleration gradient for 1 MW neutron production; and the cavity design gradient is also shown in the figure.

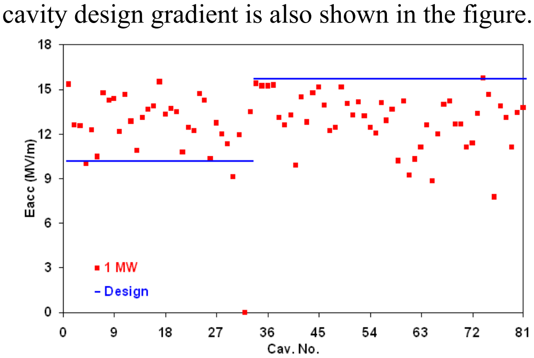

Figure 1: SNS cavity gradient for 1 MW neutron production and for the superconducting linac baseline design.

Zero-current phase advance per cell of a lattice in both longitudinal and transverse planes are shown in Fig.2. To preserve beam emittance, efforts are needed to smooth both transverse and longitudinal focusing as acceleration gradient varies from cavity to cavity. In the simulation studies, both constant synchronous phase and constant longitudinal focusing algorithms could be applied for this purpose [5]. But in operations, the first several medium beta cavities are usually set differently to have a sufficient

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longitudinal acceptance and meanwhile, center injection beams to the acceptance space. Because it is believed that a significant portion of the beam loss has a longitudinal origin; therefore, a large longitudinal acceptance could be critical to control the SCL loss. Figure 3 shows IMPACT [6] simulated SCL beam loss when the beam is injected into the linac at a wrong phase, and out of the acceptance: about 50% of the injection beams are lost in the 5th medium beta cryomodule (MB5) [7].

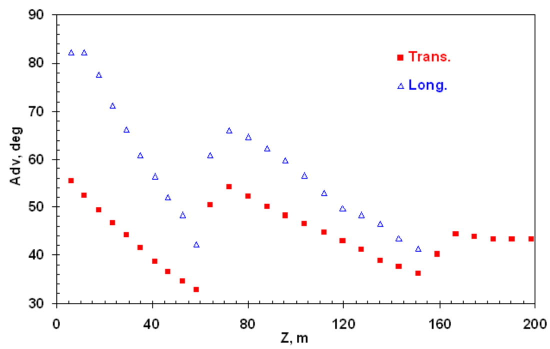

Figure 2: Zero-current transverse and longitudinal phase advance per cell for one of the SCL design lattices.

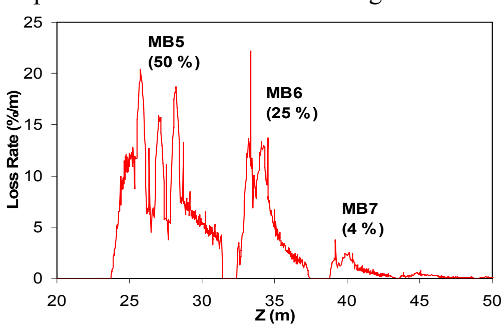

Figure 3: SCL loss distribution when a beam is injected at a wrong phase and out of the longitudinal acceptance.

There is no bunch shape monitor installed in the SCL, although the information is very important, because a beam interceptive device could contaminate the delicate cavity surfaces due to the beam power. We developed a new technique: first, measure longitudinal acceptance by recording beam current at the exit of the SCL while varying beam injection phase and energy – it agrees with model prediction; second, scan injection beam across the acceptance demarcations to measure bunch shape, energy spread, and longitudinal emittance. We may also measure beam halo with all the beam loss monitors, but in all these studies, only a very low power beam could be used [8].

In beam study, synchronous phase is reduced from -20° to -35°, the SCL acceptance is increased from about 200 MeV*deg by a factor of 3. However, no significant beam loss reduction is observed. As a comparison, longitudinal beam emittance in measurements usually varies from 0.4 to 0.8 MeV*deg. Figure 4 shows one of the measured beam isodensity contours at the entrance of the SCL for 1 MW production, and normalized beam rms emittance is 0.54 mm*mrad – about 80% larger than the design.

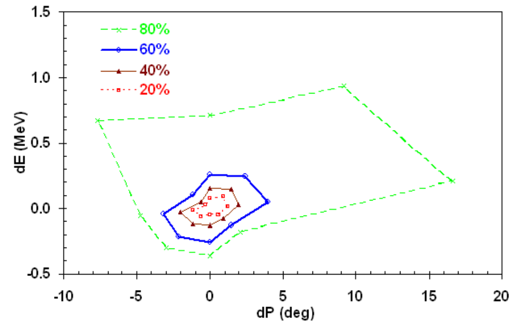

Figure 4: Longitudinal isodensity contours at the entrance of the superconducting linac for 1 MW production.

Figure 5 shows peak and total beam loss measured with all the SCL beam loss monitors, and the signal of a beam current monitor at the exit of the linac during a beam phase scan. The measurements indicate that the injection beam has a longitudinal halo of approximately 30°, and a minimum SCL beam loss corresponds to a synchronous phase of -10° to -5° for the first cavity, which is quite different to the original design phase of -20°.

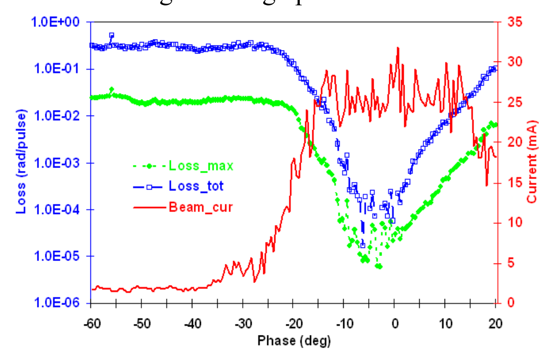

Figure 5: Maximum and sum of all SCL beam loss monitors versus beam current at the exit during a beam phase scan.

We studied phase adiabatic damping early in the SCL beam commissioning for a smooth longitudinal focusing, and proposed to use beam phase monitor measurement against model prediction to identify RF error in a low and medium energy proton or heavy ion linac that has many independently phased RF cavities [9]. In routine neutron productions, we tackled several RF issues using an RF shaker application to the normal conducting linac, and tuned all cavities more precisely [10]. But beam loss in the SCL is not equally affected: sometimes, a well tuned linac which closely agrees with the delta-t model has less loss; while most of the times, we have to adjust a few upstream cavities several degrees away from the design phase to achieve a minimum beam loss. Because a very tiny fraction – 10^{-5} to 10^{-4}, of the total beam is involved, nature of this halo has not been understood very well.

Figure 6 shows a measurement result with linac beam phase monitors when shaking all the SCL cavity phase by 8°, it agrees with the delta-t model of the design lattice. Because of ion source and RF drifts, cavity phase and RF amplitude errors, beam phase and energy jitters, as well as errors of the beam phase monitors, we would not expect that all those measured dots land exactly on the model predicted line. But beam loss in the linac is not so great. In order to minimize the SCL loss, a few upstream normal conducting cavities are adjusted, so that both beam energy and injection phase are different to the nominal design. Consequently, the measured beam phase damping for a production lattice could be quite different to the model.

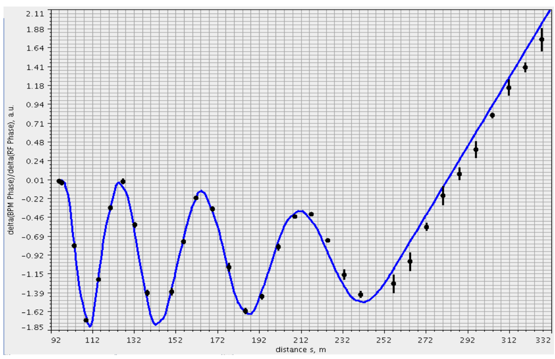

Figure 6: Linac beam phase monitors measured (dots) and the model predicted phase damping of beam centroid (line).

A cavity phase scaling technique to the SCL has been developed, which is also based on delta-t model of the linac, and it provides a very fast linac recovery remedy when a cavity fails. Within a few minutes, reset phases of all SC cavities and resume routine operation [11]. We had several SRF occasions in the past 5 years, including a failure of the first cavity of the 5th cryomodule in 1 MW production. Here, we fully take the advantages of a SCL over a normal conducting linac: bypass all cavities that have problems and restore production immediately.

In a period of time of the operation, we have totally 10 cavities not in service, including all the 4 in a same high beta cryomodule. But a smooth focusing is maintained by properly adjusting a couple of upstream and downstream cavities' phase around those unpowered ones – which are detuned by several ten kHz to reduce beam loading.

TRANSVERSE BEAM DYNAMICS

Transverse beam matching to the SCL is performed by fitting laser wire beam profile measurements [12] with a model. The online model is an envelope code with linear space-charge defocusing included [13], and it is based on TRACE3D [14]. In a linear system, one can actually solve linear equations directly, and no fitting is necessary for beam matching [15]. But if nonlinear forces are involved – such as the case of RF and space-charge effects in the SCL, unfortunately, the analytic method is not valid any more, and multiple solutions could be expected [16].

Several matching attempts failed to improve the beam size beating. One of few successes was from dialling in IMPACT predicted target Twiss parameters. But it might be merely a coincidence, because the differences between the online model and IMPACT are usually 20% to 50%. However, we could not perform online beam matching with IMPACT, because the fitting may require several ten hours – it takes only a minute with the online model.

It is also noticed that the measured Twiss parameters of injection beams may vary over 50% during the matching with online model, but errors of beam size measurements from laser-wires are only about 5%. In off-line analysis with IMPACT, we found that alpha and beta functions of the injection beams are usually very stable. There are some nonlinear issues: phase of many cells are close to RF crest, gradient of SC cavities are high, and thin-lens approximation is not very appropriate because RF fields almost spread over the entire cavity as a larger aperture; emittance growth due to space-charge is also different to the envelop model. But because only 20 to 30 m of the linac is involved in matching, the differences within this short lattice should not be significant. In experiments, however, it does. So the behaviour of the online model is strange. Figure 7 shows one of the general cases: fit beam size for the first 4 laser wires with the online model, and then compare model prediction against measurement at the 5th wire – they do not agree at all. In contrast, a good agreement can usually be expected with IMPACT.

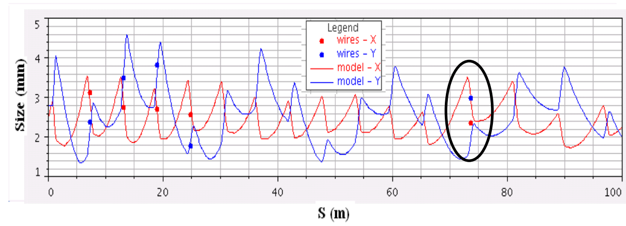

Figure 7: Online model and laser wire profile measurements for 1MW production: X and Y swap at the 5th laser wire.

In the design stage, multi-particle tracking simulations did not show any beam loss in the SCL design lattice with moderate errors and misalignments. Transverse beam halo either lost in the normal conducting linac – if big, as it has a smaller aperture, or fully transport through SCL – if not big enough. And in experiments, the SCL beam loss is not sensitive to beam transverse matching. Therefore, a major concern of the SCL beam loss is longitudinal halo.

However, there is no significant loss reduction with all the efforts over the longitudinal space. It was decided to manually reduce all linac quadrupoles' strength for better transport of halo particles, and about 50% loss reduction in the SCL was observed. But it caused other problems: beam emittance doubled and beam losses downstream of the linac were too high [17]. It might not be an adequate solution to transport beam halo downstream by reducing quadrupole strength in this high-power linac, because it may cause more activations if more energies acquired.

Another expectation with the reduced focusing is: the maximum beam size becomes less sensitive to the beam matching condition, and it might be smaller than that without the strength reduction for certain mismatched beams, therefore, beam loss may reduce [18]. But when the matching condition changes, the maximum beam size will also vary, it is not guarantied that the maximum beam size with the reduced strength is always the minimum. In the SCL, matching changes from run to run, or even in the same production routine, but loss is almost a constant.

To understand loss reduction with reduced quadrupole strength, multipole components of the linac quadrupoles are investigated. Simulation with ORBIT [19] for periodic doublet lattice without RF gap or space charge indicates that there is a very weak resonance when transverse phase advance closes to 60° [20]. This resonance occurs only when contributions of dodecapole forces are significant; and it causes a maximum emittance increases 5 times in the doublet lattice, although the rms emittance varies less than 1%. Because only large amplitude halo particles are significantly affected, and their total number are very few. Ratio of full emittance growth versus zero-current phase advance of the doublet lattice is shown in Fig.8, there are two peaks identified: at 60° and 90°, respectively.

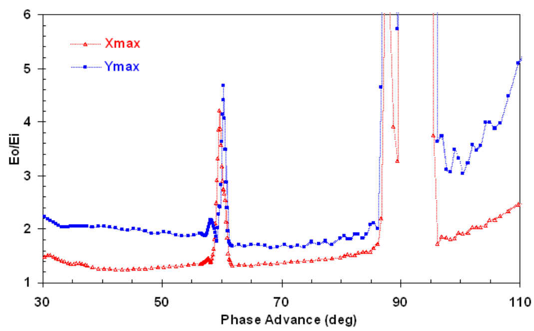

Figure 8: 60 and 90 degree resonance due to dodecapoles.

PARMILA code [21] is used for estimation of the SCL loss due to this weak resonance. We compared 3 lattices: zero-current transverse phase advances 50°, 60°, and 70°; for a 38 mA beam, space-charge depressed advances are: 30°, 40°, and 50°, respectively. When dodecapole strength is no more than 10 units (1 unit equals to 1×10^{-4} of the quadrupole field), there is no beam loss for all the three lattices. But with the average bench-tested strengths: 30-unit dodecapoles, the 60° baseline lattice is the worst in beam loss: about 3×10^{-4} fractional loss in the SCL. And in simulations, the 70° lattice may slightly reduce beam loss, but the 50° lattice is more significant. In measurements, the 50° lattice reduces the beam loss by 50%; and the 70° lattice by 10%, which is very marginal. We compute beam loss versus dodecapole strength for the baseline lattice, as shown in Fig.9. When dodecapole strength reduced to 10 units or less, beam loss disappears completely.

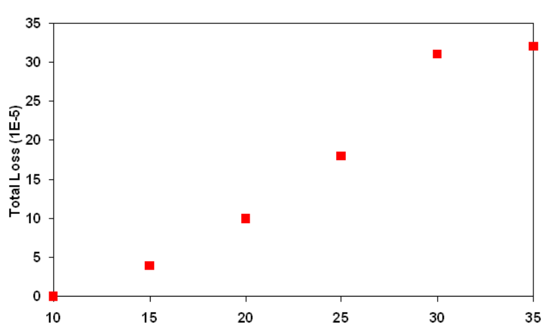

Figure 9: Total SCL beam loss versus dodecapole strength for the baseline design lattice, in simulation with PARMILA.

We turned off all the SCL cavities and transport 186 MeV H^- beams through a pure doublet lattice at different phase advances. And measurements of the total loss with all the SCL beam loss monitors are shown in Fig.10. The weak transverse resonance at 60° phase advance appears, even no RF force, nor significant space-charge effect.

Loss reduction with the reduced quadrupole strength could also be explained as low energy tails, which was an initial guess; or intrabeam stripping, which we began to learn recently [22]. But we do not know how many low energy tails are involved in the measured beam loss. And in intrabeam stripping, longitudinal focusing should also play a very important role. In beam loss measurements, however, we did not observe a strong longitudinal effect.

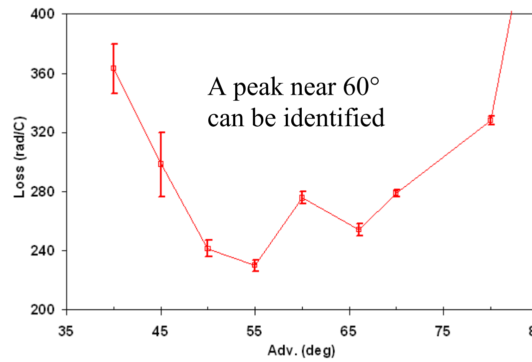

Figure 10: Sum of the SCL beam loss versus transverse phase advance per cell, with all SC cavities turned off.

LESSIONS LEARNED

Table 1: SCL Design Paramaters and Achievements.

Parameters	Design	Achieved
Beam Energy (GeV)	1.0	1.01
Peak Current (mA)	38	42
Power on Target (MW)	1.44	1.08
Repetition Rate (Hz)	60	60
Pulse Length (ms)	1.0	1.0
Number of Cavities	81	80
Proton per Pulse	1.5×10^{14}	1.55×10^{14}
Availability (%)	90	85

There are several lessons learned with the world's first superconducting linac for proton beam. But before going through all the lessons, we need to review the important achievements first. Table 1 lists most of the major design parameters of the SCL, and those best achieved in the first 5-year with beam. Most of the SCL design goals have been satisfied, thanks to a very robust linac design.

However, the 1.01 GeV energy has not been achieved in neutron production, instead, it is in a low repetition rate beam test. In the production, the beam energy is usually only about 930 MeV. Because most SNS cavities suffer from field emission, and end group heating – as where no direct helium cooling is applied. The situations become much worse at a high repetition rate of 60 Hz due to some collective effects [23]. Therefore, we have to reduce the acceleration gradients of many cavities in a routine neutron production.

We could only operate 80 cavities out of the totally installed 81. The missing one is caused by electron activities in the high-order-mode (HOM) couplers. Each SNS cavity is equipped with two HOM couplers to extract beam-induced HOM RF powers that otherwise, would be trapped in the cavity. Early in the design, it is known that there is no beam instability issue to the SNS cavity, and only thermal loading is a concern [24].

We adopted HOM couplers of the DESY cavity type, which is essentially a notch filter to the fundamental RF [25]. But once there are electron activities in the coupler, it could easily runoff. Besides one cavity not functional from day one, acceleration gradients of several cavities are limited by these HOM couplers [26].

In short-pulse mode, dynamic Lorenz force detuning posses a challenge to the SC cavity which has a thin wall, and a high gradient; it requires much more RF powers and could significantly deteriorate stability of cavity phase and RF amplitude. A thicker niobium wall would not only increase the cost, but also deteriorate thermal stability, which is out of the question. To actively compensate for the dynamic detuning, a piezo tuner is equipped to each SNS cavity [27]. But unfortunately, the piezo actuator is designed as part of the cavity mechanical tuning system.

Because the piezo ceramic becomes the weakest link of the mechanical system, there are several failures in the operation. We would not increase the risks of activating the piezo tuner, as the efforts may easily break it; and in such a case, the cavity is completely lost. The piezo tuner has never been activated in the production, but we still need to replace several broken piezo parts with stainless steel dummy rod. Without active compensation, dynamic Lorenz force induces mechanical oscillations and may detune the cavity by several hundred Hz. But fortunately, because of a high gain low-level RF control system, cavity phase and RF amplitude are well within ±0.5° and ±0.5% in routine operation [28] with a penalty of about 15% more RF power.

It is one of the reasons that RF duty factor of the high voltage converter modulator system is below the design, so that beam pulse length only reaches 0.8 ms in a 60 Hz production. Because safety margin of the system reserved in the design is not sufficient, and it caused the most down times during the beam power ramp up.

Beam collimators are installed downstream of the SCL, but they do not offer any protection to the linac itself. Because limited by physical space, an online energy separator for the purpose of halo mitigation in the SNS linac is not practical: even if longitudinal matching is not a problem, magnet stripping loss may not be tolerable as H^- beams are transported. We are not currently beam loss limited, but linac beam collimator could be helpful.

Transverse matching has no obvious effect to the beam loss. Either our matching is not correct, or the halo itself – in which the loss is involved, is completely different to the beam core. However, it is necessary to have a reliable beam matching technique. We need either to develop an envelope model more accurate, or a parallel solver much faster for multi-particle tracking code – such as IMPACT, with a powerful cluster dedicated to beam matching; or alternatively, do not rely on any model.

It is not sufficient to study beam loss with simulations only focused on beam rms features, or in a short piece of the linac lattice. Multipole components of the quadrupoles show very little effect to the core, but they may form halo and cause beam loss. A total fractional loss to 10^{-4} is well beyond the design anticipated. And in the simulations, it is eliminated after dodecapole components reduced to less than 10 units. This should be the right solution to a MW superconducting linac. And other beam loss factors, such as intrabeam stripping, also need more investigations.

CONCLUSIONS

Most of the design features of the superconducting linac have been achieved in the first 5-year of accelerator commissioning and operation, and we may demonstrate a great success of the project. But several issues, such as nonlinear multipole components of the linac quadropole, beam collimator, cavity high-order-mode coupler, piezo tuner, and duty factor of high-power RF system, need to be addressed. Performance of future high power SC linac will improve, if early in the design stage, all those trivial problems are considered carefully and solved properly.

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