BEAM DYNAMICS ISSUES IN THE SNS LINAC

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Abstract

A review of the Spallation Neutron Source (SNS) linac beam dynamics is presented. It describes transverse and longitudinal beam optics, losses, activation, and comparison between the initial design and the existing accelerator. The SNS linac consists of normal conducting and superconducting parts. The peculiarities in operations with the superconducting part of the SNS linac (SCL), estimations of total losses in SCL, the possible mechanisms of these losses, and the progress in the transverse matching are discussed.

INTRONUCTION

Today the SNS accelerator complex routinely delivers 1 MW of proton beam to the mercury target with an availability more than 87%.

The SNS linac consists of two parts. The fist part is a room temperature linac. It includes a front-end (FE), six 402.5 MHz drift tube tanks (DTL), and four 805 MHz coupled cavity linac (CCL) sections. The front end has a negative hydrogen-ion source, a low energy beam transport line (LEBT), a radio frequency quadrupole (RFQ), and a medium energy beam transport (MEBT) line. The second part is a superconducting linac (SCL) with two types of cavities designed for relativistic factors of 0.61 and 0.81 (so-called medium-β and high-β SCL sections). The SCL cavities operate at a temperature of 2°K. The structure and design output energies of the SNS linac are shown in Fig. 1. The ion source and RFQ are designed to deliver 38 mA peak current. Right now, the FE can provide up to 50 mA, but we are not using this much in production.

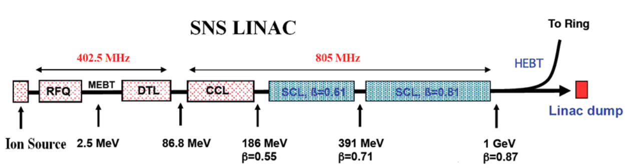

Figure 1: The structure of the SNS linac.

Beam Dynamics of SNS Linac

The SNS linac was designed to minimize the potential damage and activation of the accelerator resulting from beam halo generation and uncontrolled losses [1]. The estimated losses should not exceed 1 W/m. During the design, some conditions were imposed to minimize halo generation [1]:

- The transverse and longitudinal zero-current phase advances per period should never exceed 90^0.
- The transverse and longitudinal phase advances do not cross to avoid the second order parametric resonance. This condition is not maintained in DTL tank 1 nor in CCL module 4, where matching considerations prevail.
- The phase advances per meter are smooth functions along the linac. That minimizes possible mismatches and helps to create a peak current independent design.

The analysis of the emittance growth due to resonant modes showed that the SNS linac is too short for noticeable beam degradation [1].

Simulations of the beam dynamics in the superconducting part revealed a surprisingly tolerant design of the SCL [2]. The losses were not sensitive to even large errors in amplitudes and phases of the SCL RF cavities. This low sensitivity is, in part, a direct result of the nature of the SCL linac, where each cavity's phase can be adjusted individually and there are higher accelerating filed gradients than in normal conducting cavities. In contrast, the normal-conducting DTL and CCL are synchronous structures where each gap in any cavity is phase-locked to its neighbor, and its phase is not adjustable.

LOSSES IN SNS LINAC

During the design the fractional beam losses in the SNS linac were estimated to be about $5.0\text{x}10^{-5}$ in the CCL and $1.0\text{x}10^{-6}$ in the SCL [3]. The lower anticipated losses in the SCL are explained by a better vacuum (10^{-10} rather than 10^{-8} Torr), a different composition of residual gases (hydrogen instead of nitrogen), and an increased beam aperture radius (3.8 cm in the SCL compared to 1.5 cm in the CCL).

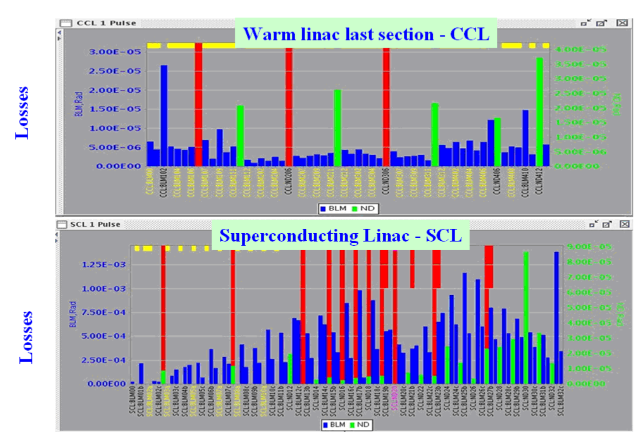

Figure 2: The production losses in the CCL and SCL.

The real production losses are shown in Fig. 2. The Beam Loss Monitor (BLM) signals in the SCL are two

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orders of magnitude higher than in the CCL. Part of this difference could be attributed to the higher energy and different BLM shielding, but the existing activation of the SCL indicates that the losses there are comparable to the CCL losses. The SCL losses and activation do not limit in any way the SNS power and maintainability, but the value and distribution of the losses are different from those in the simulations made during the design process.

SCL Beam Loss Measurements

J. Galambos performed the first experimental estimation of the SCL fractional beam loss using a Laser Wire Profile Monitor [4]. A laser beam was used to strip the negative hydrogen ions in the H^- linac beam of one electron, and the resulting hydrogen atoms were lost over several tens meters downstream. Knowing the differences in beam loss monitor readings with and without the laser beam, the time length of the laser beam pulse, transverse beam and laser density distributions, and the cross section of stripping, the fractional losses in SCL were found to be 10^{-4}. Later, the Laser Wire Profile Monitors were improved, and we measured the number of electrons stripped from the H^- beam directly with a Faraday cup. This eliminated uncertainties with the laser and ion beam distributions, and the losses were found to be in the range of (2 – 5) x10^{-5} depending on the position of the Laser Wire Profile Monitor station. This level of SCL losses is much higher than was anticipated.

A typical distribution of the additional losses created by the laser beam is shown in Fig. 3. The BLM signals created by the laser beam (Fig. 3) are comparable with the signals from the production beam (Fig. 2). The estimated fractional amount of stripped beam was 10^{-6}.

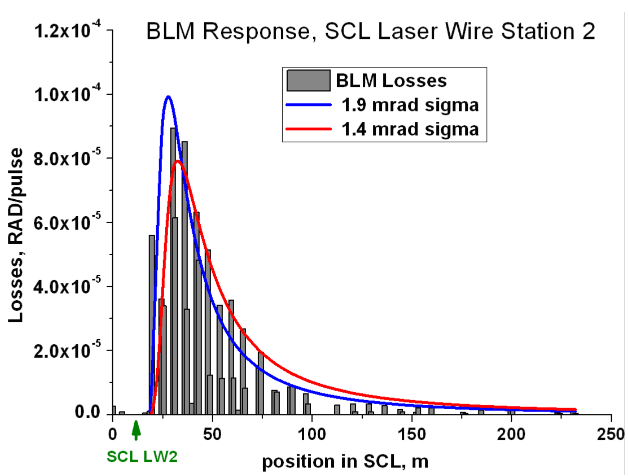

Figure 3: Loss distribution in the SCL after stripping of the H^- beam by the laser beam. The bars are BLM responses, blue and red curves are the simulated distributions for different Gaussian angular distributions of the ion beam.

There are differences between the SNS linac design and the existing machine that may contribute to the unexpected SCL losses:

- The MEBT chopper is mechanically different.
- The SCL RF cavities have amplitudes that are significantly lower than the design values. These amplitudes were lowered to avoid frequent discharge events.
- One possible loss mechanism was not taken into account during the design of the SNS linac.

Below we discuss these differences and their effects on the beam dynamics and the losses.

BEAM CHOPPING

The SNS linac has two stages of chopping. The first stage uses a relatively slow chopper in the low energy beam transfer line (LEBT) before the RFQ, and the second stage uses a very fast (according to the design) chopper in the MEBT. The MEBT chopper performs the final cleaning of the gap. The time structure of the SNS linac beam is shown in Fig. 4.

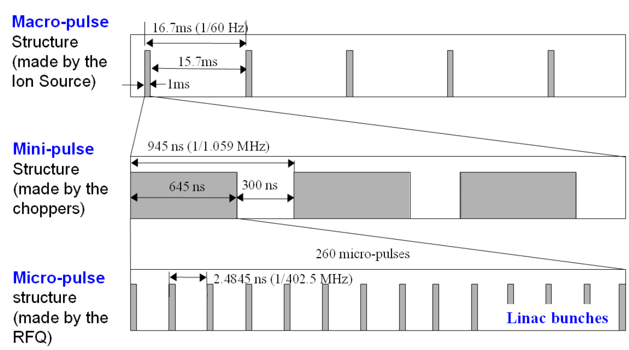

Figure 4: The time structure of the SNS linac beam.

The SNS linac beam is a set of 1 ms macro-pulses with a frequency 60 Hz (see the top diagram in Fig. 4). Each macro-pulse consists of 1060 mini-pulses with separated by 300 ns gaps (see the middle graph in Fig 4). The gaps are needed to accommodate injection and extraction in the SNS storage ring. Finally, the mini-pulses consist of micro-pulses or linac bunches (see the bottom picture in Fig. 4). Ideally, the bunches have the same charge (peak current is constant), but if the chopping is not fast enough, the mini-pulses have non-zero rise and fall times, and there will be some partially chopped beam in the linac.

Unfortunately, the original fast MEBT chopper was damaged twice, and it was replaced by a slower, but more reliable, chopper [5]. As a result we can improve the rise and fall times of the LEBT chopper providing, but not up to the design value. The original fast chopper could provide the rise and fall times of 2.5 ns, which is approximately the time between two bunches. The more reliable replacement has the rise and fall times of about 15 and 10 ns, respectively. Fig. 5 shows an envelope of one mini-pulse and improvements at the beginning and the end of the pulse, after the MEBT chopper was switched on.

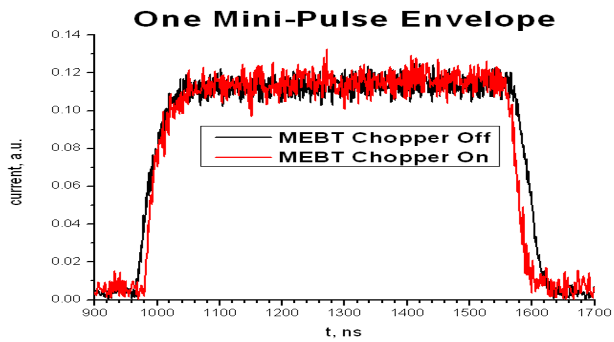

Figure 5: The envelope of one SNS linac mini-pulse and the effect of MEBT chopping.

Fig. 6 shows the measured integrated distribution of the bunch charges for MEBT chopper "on" and "off" cases. It demonstrates that we have from 4% to 6% of partially chopped beam with bunch charges from 0% to 50% of the maximum value. This is the beam at the front and back ends of the mini-pulses (see Fig 5). Fortunately, the SNS peak current independent design provides a good transmitting efficiency for this partially chopped beam. This type of beam does not create noticeable distributed losses along the linac. Therefore the main effect of the MEBT chopper is a fine cleaning of the gap between mini-pulses and a reduction in extraction losses in the SNS ring [5].

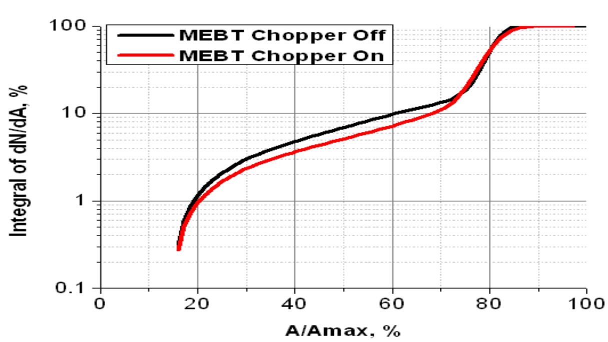

Figure 6: The integrated amplitude distribution of the SNS linac bunches.

Transverse Emittance and Beam Chopping

The slow LEBT chopping not only creates the partially chopped beam with reduced charges in the linac bunches, but it also gives non-zero injection angles to these bunches. Therefore, we observe a significant growth of an "effective" transverse emittance. We call this emittance "effective", because our MEBT emittance device does not have sufficient time resolution to distinguish between mini-pulses and gaps, and we measure a phase density of the sum of the ordinary and partially chopped bunches. Table 1 shows the transverse emittances with the LEBT chopper switched off and on.

Table 1: Normalized Beam Emittance in the MEBT

LEBT Chopper	Horizontal π*mm*mrad	Vertical π*mm*mrad
On	0.40	0.22
Off	0.29	0.19

It should be noted, again, that chopping does not create noticeable average losses along the linac. The beam loss is affected by the partially chopped beam only in particular places at the end of the CCL and the beginning of the SCL. The beam loss in these places is usually corrected with the MEBT scrapers. The typical amount of scraped beam is about 1-2%.

Therefore, the partially chopped beam can not be responsible for the unexpected high SCL beam loss.

SCL BEAM LOSS REDUCTION

In the beginning of the SNS accelerator power ramp-up, which started in the summer of 2007, the SCL activation and the beam loss were scaling with the average power on the target. It was clear that the SCL losses could limit the SNS power at some point in the future if not mitigated. At the end of 2008, it was suggested that these losses were created by off-energy particles, and by reducing the focusing strength in the SCL we could transport them further downstream [6]. This started a campaign for the SCL beam loss reduction by reducing field gradient in SCL quadrupoles. After several years of effort, a configuration that provides a local minimum of losses was found. Fig. 7 shows the comparison between the design quadrupole gradients and theoe that provide minimal SCL losses.

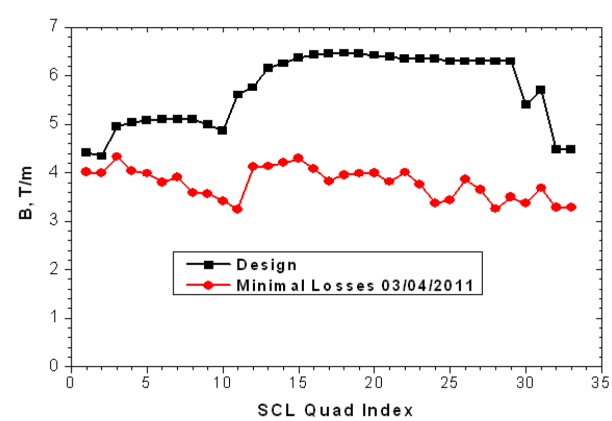

Figure 7: Quadrupole gradients for design and production.

After the SCL losses were reduced, they no longer limited SNS operations. It is not clear that these losses cannot be improved further. For the CCL the empirically found quadrupole settings are only a few percent different from the design values, and only in the beginning of the CCL (the matching region).

The explanation of the SCL beam loss reduction based on the off-energy particle transport was not the only one possible. In 2010 Valery Lebedev suggested a new mechanism for our SCL losses, namely Intra Beam Stripping [7].

INTRA BEAM STRIPPING

A mechanism of losses called Intra Beam Stripping takes into account the reaction

$$H^- + H^- \rightarrow H^- + H^0 + e \qquad (1)$$

that occurs inside a distribution of negative hydrogen ions. The hydrogen atom will not be affected by the linac lattice and will be lost somewhere downstream. The cross section of the reaction (1) has a plateau for hydrogen velocities between 1.0×10^{-4} and 1.0×10^{-2} the of speed of light, and the value on this plateau is about 3.6×10^{-15} cm^2. The rms relative velocities in the SNS linac bunches in the center-of-bunch frame are in this range [7].

According to the estimation in [7], the fractional total beam loss at the end of the SNS linac due to Intra Beam Stripping will be 1.5×10^{-4}, in the SCL it will be 4×10^{-5}, and the average power density of the loss in SCL is about 0.13 W/m for a 1MW production beam. These predictions are in good agreement with the measured SCL losses (2-7)$\times10^{-5}$ presented above. The suggested mechanism predicts that the use of weaker transverse focusing will produce a larger beam and less Intra Beam Stripping.

FLASHLIGHT EXPERIMENT

To figure out the nature of the losses in the SCL, an experiment called the "flashlight experiment" has been performed. From the early days of SCL loss studies, it was known that trajectory bumps in the SCL create the downstream losses. The initial explanation was that by introducing the bump we disturb the off energy particles, and later they will be thrown on the beam pipe.

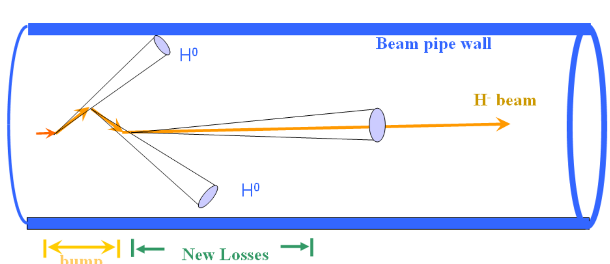

Figure 8: The "flashlight" experiment.

If we assume the new Intra Beam Stripping mechanism for losses, it can be explained differently. H-minus beam continuously creates neutral hydrogen through the stripping mechanism. The hydrogen atoms have the same angle distribution as the ions, and they are moving in the direction of the beam. If the closed trajectory bump is introduced, the cone of moving neutral hydrogen will be directed into another place on the beam pipe. As a result, there will be additional losses at this place. The new losses will be positioned downstream of the trajectory bump. A scheme of the process is shown in Fig. 8.

We can distinguish between these two possible explanations for the additional losses. If the particles are H-minus, the additional loss distribution can be changed by the downstream optics, and if they are neutral it cannot be done because neutrals are not affected by the electric and magnetic fields. This experiment, called a "flashlight" experiment, was performed at SNS in 2010. Two SCL optics set-ups were created. The difference between them started below the region of the proposed closed trajectory bump. The loss distributions for each set-up are shown in Fig. 9.

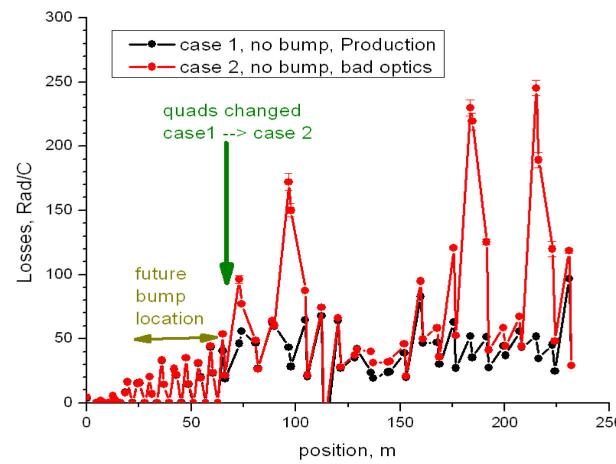

Figure 9: The SCL beam loss monitor signals for two optics set-ups without the closed trajectory bump.

Then the same closed trajectory bump was applied for each case and the change in the loss measured. The results of measurements are shown in Fig. 10.

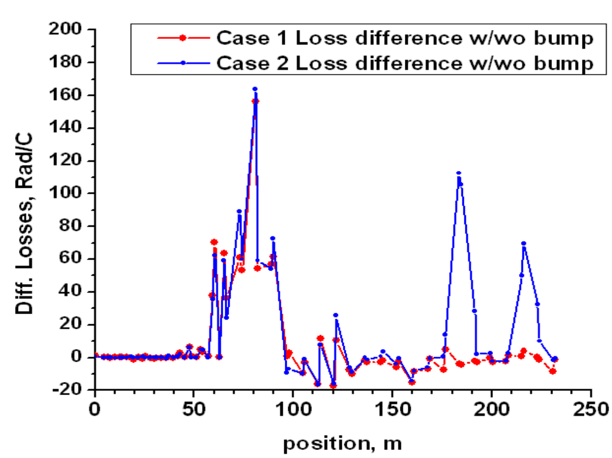

Figure 10: The SCL beam loss change after the closed trajectory bump was created.

Fig. 10 shows two regions in the SCL. The first is the region between 50 and 150 meters from the beginning, where losses change identically. The second region lies around 200 meters, where the loss difference is sensitive to the optics. The first region is created by H^0 generated by Intra Beam Stripping and directed by the closed bump, and the second is created by H-minus disturbed in the bump. The change in loss is comparable with the production losses in Fig. 9. The results of this experiment show that a significant part of the losses can be attributed to Intra Beam Stripping.

We should not be very alarmed by the two last peaks in Fig. 10 that related to H^- ions, because a very bad optics set-up caused these losses. In production we do not use such lattices. Nevertheless, off-energy ions and beam halo should not be dismissed as possible contributors to the SCL losses until we fully understand and control these losses.

Assuming that a significant part of the SCL losses is produced by Intra Beam Stripping, the losses can be reduced by matching the incoming beam into the SCL lattice with reduced quadrupoles' strength. To do so the initial Twiss parameters should be known. The next section discusses the progress that has been made in this subject.

INITIAL SCL TWISS PARAMETERS MEASUREMENTS

Previously, we reported that we have problems with matching the beam from the warm part of the linac into the superconducting part [8]. We could not find unique initial Twiss parameters at the SCL entrance that will reproduce the profile measurements for different SCL optics settings. The spread of the estimated initial Twiss parameters was more than 50 % [8]. This also means that transverse matching could not be performed. After a detailed review of our procedure for finding the initial Twiss parameters by using downstream profile measurements, we included into the procedure additional error analysis and the measurements planning. The error analysis is based on the fact that even in the presence of strong space charge effects we can calculate the linear transport matrix for the rms parameters of the beam. After applying this modified procedure, we are obtaining consistent measurements of the initial Twiss parameters, which we are planning to use in the matching.

CONCLUSIONS

Most of the design criteria of the SNS linac have been achieved in the first 6-years of accelerator commissioning and operation, and we are demonstrating great success of the project.

The SNS linac delivers routinely 1 MW beam power with acceptable losses and activation.

The beam in the linac includes some partially chopped beam. This component accounts for 4 to 6% of the beam. Due to the peak current independent design and the MEBT scraping the partially chopped beam is delivered to the ring without noticeable losses in the linac.

There is strong evidence that the Intra Beam Stripping mechanism is responsible for significant part of the SCL losses.

Progress has been made in our knowledge about the matching process into the SCL and we will continue to work in that direction.

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