INCREASED UNDERSTANDING OF BEAM LOSSES FROM THE SNS LINAC PROTON EXPERIMENT *

J. Galambos#, A. Aleksandrov, M. Plum, A. Shishlo, ORNL, Oak Ridge, TN 37831, USA,
E. Laface, ESS, Lund Sweden, V. Lebedev, FNAL, Batavia, IL 60510, USA

Abstract

Beam loss is a major concern for high power hadron accelerators such as the Spallation Neutron Source (SNS). An unexpected beam loss in the SNS superconducting linac (SCL) was observed during the power ramp up and early operation. Intra-beam-stripping (IBSt) loss, in which interactions between H^- particles within the accelerated bunch strip the outermost electron, was recently identified as a possible cause of the beam loss. Results from a set of experiments using proton beam acceleration in the SNS linac support IBSt as the primary beam loss mechanism in the SNS SCL.

SNS BEAM LOSS EXPECTATIONS

The SNS accelerator consists of an RFQ (output energy of 2.5 MeV), a Drift Tube Linac (output energy of 85 MeV, a Coupled Cavity structure (output energy of 186 MeV) and an elliptical cell superconducting cavity structure with design output energy of 1 GeV. The SNS linac accelerates a 1 msec pulse H^- beam, which is subsequently captured in a storage ring to produce a sub μs intense pulsed neutron source.

A major advantage of superconducting RF linacs for H^- and proton acceleration is the inherently large beam aperture, which greatly alleviates the issue of beam loss relative to copper accelerating structures. During the design stage of SNS the multi-particle beam simulations indicated no beam loss in the superconducting linac (SCL) region [1,2]. Nonetheless, there was a reluctance to assume no superconducting linac beam loss and a minimal loss in this area was allocated in the beam loss budget [3], attributed to gas stripping in the warm sections between cryomodules.

OBSERVED SCL BEAM LOSS

Loss History

Early in the power ramp-up phase of the SNS operation, unexpected residual activation was measured along the SNS superconducting linac, in the warm sections between the cryomodules. The warm sections are the limiting aperture restrictions in the SCL, so it is not surprising that the observed beam loss is located in these regions. The build-up of measured residual activation over the period of the SNS power ramp-up and initial operation is shown in Fig. 1, where the the average warm section residual activation levels are superimposed on the operational beam power level. Initially, the loss detectors did not register the beam loss causing this activation, but they were moved closer to the beam pipe in the warm sections, and subsequently did detect the beam loss. Beam loss is rather uniformly distributed along the SCL.

Beam Loss Magnitude

Based on the measured residual activation levels, the beam loss can be expected to be < ~1 W/warm-section, which corresponds to < 10^{-4} fractional beam loss throughout the SCL at 1 MW. Quantifying beam loss fractions at this level is difficult. One method of producing very small fractional controllable beam spills in the SNS SCL is with a laser profile device [4]. The short pulse laser strips the outermost H^- electron from about 10^{-6} of a nominal beam pulse, creating H^0 that is subsequently lost downstream. By comparing the additional beam loss signal produced by the known amount of beam lost from the laser pulse to the measured beam loss during production, we estimate the fractional beam loss during neutron production in the SNS SCL to be a few $\times 10^{-5}$.

Possible Loss Causes

Initially, causes of the unexpected beam loss were suggested to be poor matching (transverse or longitudinal); beam halo from the ion source, or produced during acceleration; and residual gas stripping. Longitudinal tails were considered a likely loss contributor because of the sensitivity of SCL beam loss to the longitudinal setup of the upstream warm linac. Different longitudinal tunes were applied in the SCL, trading final energy for increased acceptance, but minimal impact was observed on the baseline SCL beam-loss level. The transverse match is a natural suspect, however adjustments of matching quadrupoles at the linac lattice transitions generally affect beam loss at local loss points, as opposed to the observed uniform beam loss through the SCL. Additionally, for the design transverse optics, beam mis-steering does not affect beam loss, indicating the presence of additional aperture available for the transverse tune. Finally, residual gas stripping in the upstream warm linac was addressed by measuring the change in beam loss with deteriorated warm linac vacuum to determine the impact from gas stripping and extrapolating back to ideal vacuum conditions. This indicated that gas stripping was not a major contributor to the SCL beam loss. The measured vacuum level in the warm sections between superconducting RF cryomodules is much lower than the design assumptions, and is too low to contribute to significant gas stripping beam loss.

jdg@ornl.gov

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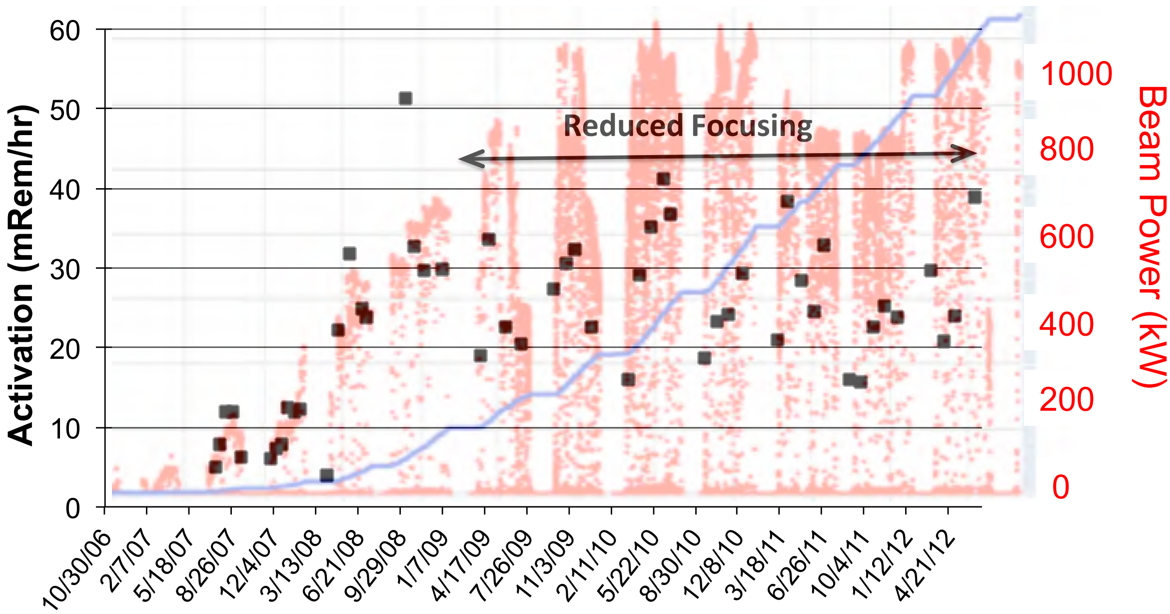

Figure 1: History of the SNS residual activation along the SCL (black marks) since initial operations, superimposed on the operational beam power level (red background). Activation levels are the average hot-spot measurement in the warm sections along the SCL, at 30 cm taken about 24 hours after the end of a run.

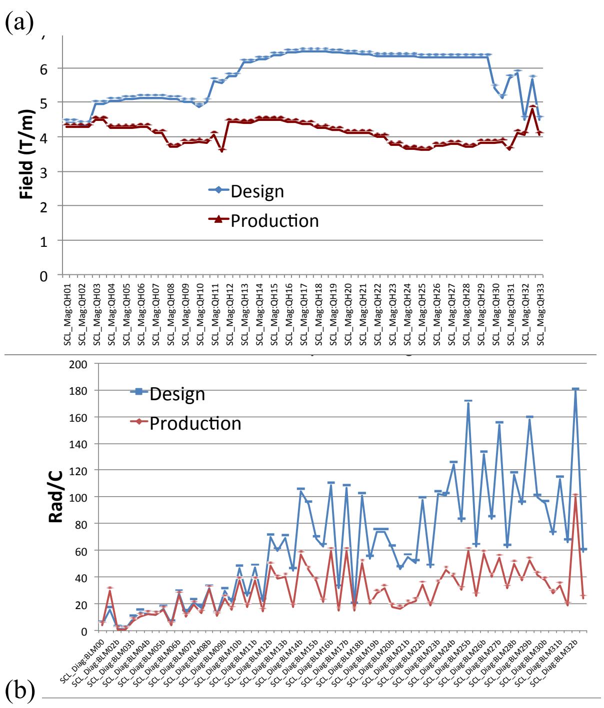

Figure 2: (a) Comparison of transverse field levels for design and production optics, (b) Measured beam loss distributions along the SCL for design and production optics. Beam loss is normalized to the transmitted charge.

Reduced Focusing Operation

A key feature of the SCL activation build-up, shown in Fig. 1, is a roll-over at the onset of reduced focusing operation. In early 2009, empirical observations revealed reduced beam loss with lower transverse focusing in the SCL. Initially modest quadrupole field level reductions were applied, but eventually the applied field level was reduced up to 40%, beyond which losses began to increase. Reducing the applied focusing strength was the primary contribution to the activation buildup "roll-over" in early 2009. Fig. 2 shows the transverse focusing field along the SCL for both the design level, and the empirically derived minimal loss condition (referred to as "production" optics here). Also shown in Fig. 2 is the measured beam loss distribution along the SCL for the design and production lattice optics. There is a systematic reduction of beam loss along most of the SCL with the reduction of the applied field. This was the single largest observed influence on loss reduction. While it initially seemed counter-intuitive that increasing the beam size would reduce beam loss, this observation proved to be a valuable insight into an unforeseen beam loss mechanism in H^- linacs.

INTRA-BEAM STRIPPING

Intra-Beam Stripping (IBSt) refers to the stripping of the outer electron from an H^- ion in an accelerated beam due Coulomb collisions with other H^- ions in the beam. This loss mechanism was examined at CERN over 20 years ago [5], but had not been considered in the SNS design. V. Lebedev first proposed this process as a loss mechanism for H^- linacs [6], and in particular for the SNS. The loss rate is proportional to the beam density squared and the cross-section for stripping. For the centre-of-mass relative velocities of the H^- particles in the bunch along the SNS SCL linac, the cross section is fairly constant [6].

PROTON BEAM AT SNS

A direct test of the IBSt loss mechanism hypothesis is to replace the H^- beam with a comparable proton beam. A set of experiments to this effect has been described in refs. [7, 8]. A simple way to produce a proton beam at SNS is to insert a thin foil into the beam to convert the H^- to H^+. The Medium Beam Energy Transport (MEBT) between the RFQ and Drift Tube Linac (DTL) is a convenient location for this purpose for the following reasons:

1. There is an available actuator for foil attachment near the start of the MEBT.
2. There are 10 independent quadrupole power supplies that can be adjusted to rematch the resultant proton beam into the downstream permanent magnet DTL.
3. Following the rematch, the beam transport through the linac is the same for H^- and protons.
4. Commercially available foils are suitable for this energy range (2.5 MeV).

Creating the Proton Beam

A 5 μg/cm^2 thick foil was chosen, which strips nearly all the beam (> 99.9%, and the un-stripped beam is lost soon afterwards in the MEBT). Foil scattering is estimated to produce minimal energy loss compared to the inherent beam energy spread, and a transverse emittance growth of only 10-20%. One limitation of the foil is beam heating. To avoid foil damage, we limit the beam pulse length to 50 μs, compared to production pulse lengths of 850 μs. The foil is 16 mm diameter, quite large compared to the RMS beam size of 1.5 - 2 mm.

Machine Setup for Protons

The foil is inserted just after the first quadrupole in the MEBT, leaving 9 additional adjustable quadrupole power supplies available to match the proton beam into the downstream DTL. The matching scheme swaps the H^- and proton horizontal and vertical Twiss parameters at the DTL entrance, while minimizing the beam size in the MEBT. The RF phases throughout the linac are adjusted by 180 degrees to provide the same longitudinal focusing and acceleration for protons as for H^-. The focusing elements in the coupled cavity linac (CCL) and SCL are left the same for the proton and H^- beams, with the exception of minor adjustments for loss tuning at the lattice transitions between the CCL and SCL.

Measured beam profiles at end of the SCL are compared for the proton and H^- beams in Fig. 3. The horizontal and vertical planes are swapped, as expected, and the general shape of the profiles is similar, indicating that the transport of the protons beam is comparable to that of the H^-. The Twiss parameters at the end of the SCL are also measured using a set of four profile measurement devices at the start of the transport section that directly follows the SCL. These parameters, shown in Table 1, indicate that the horizontal and vertical planes are effectively swapped between the two beams, as expected.

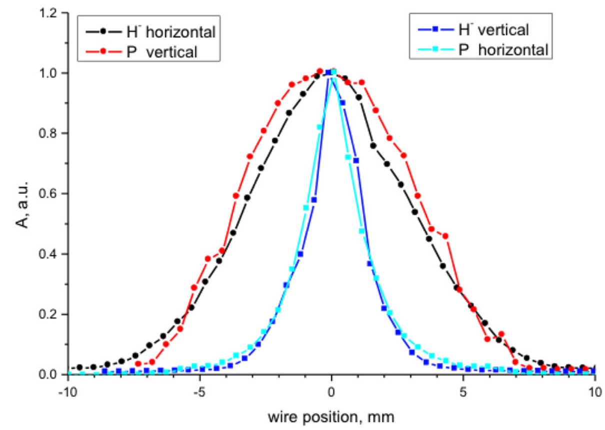

Figure 3: Measured beam profiles at the end of the SCL

Table 1: Twiss Parameters at the SCL Exit (from Ref. [7])

	Proton vertical	H^- horizontal
ε_{norm} (π-mm-mrad)	0.47	0.55
α	-2.0	-2.2
β	10.3	12.9
	Proton horizontal	**H^- vertical**
ε_{norm} (π-mm-mrad)	0.71	0.80
α	1.8	2.4
β	10.0	11.9

Proton Beam Transmission

For H^- beams, the transmission from the MEBT through the SCL is better than the accuracy of the current measurement (> 99%). However, for the proton beam, the transmission varies from 98% at nominal current to 86% at reduced beam intensity, with losses occurring primarily in the MEBT. This is due to the fact that the MEBT optics are intensity dependent (due to space charge), but are not adjusted with current here. Because the proton beam size is larger than the H^- (in the upstream MEBT near the foil), it is more sensitive to transmission loss.

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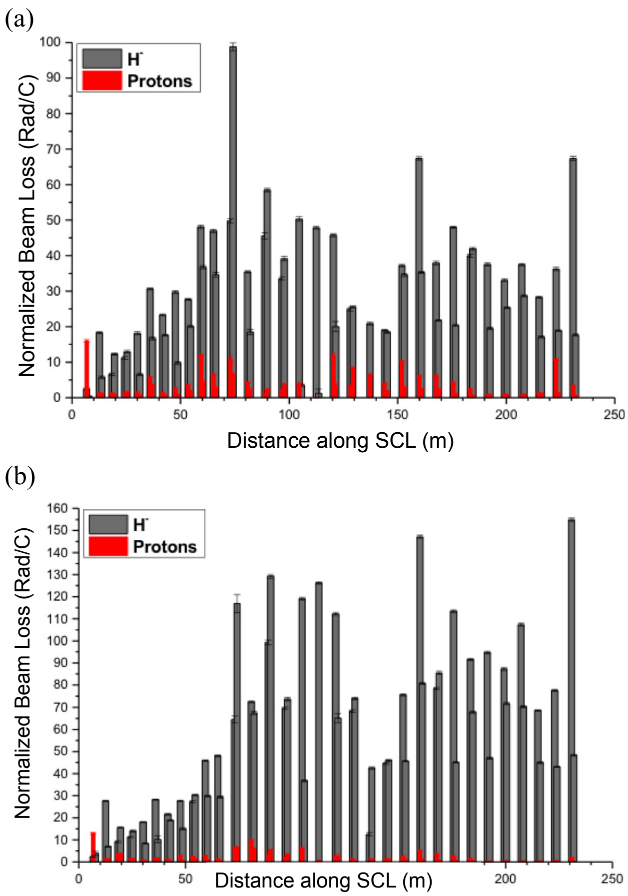

Figure 4: Beam loss along the SCL for the case of 30 mA, for proton and H-; (a) for production optics, and (b) for design optics. Reproduced from References 7 and 8.

PROTON-H- BEAM LOSS COMPARISON

Beam loss is primarily detected in the SNS SCL by ion chamber beam loss monitors (BLMs) [9], distributed 2 per warm section between cryomodules. Figure 4 shows a comparison of the measured beam loss along the SCL for the case of an H- and a proton beam, with a 30 mA current. Beam loss shown here is normalized to the transmitted charge, and the values represent an average over 20 pulses, although the pulse-to-pulse variation is small. Both the H- and proton beam cases are for 45 μs pulse lengths. Minor adjustments of the proton beam setup were performed to minimize loss (adjustments of linac RF phases by 1-2 degrees and lattice matching quadrupoles up to a few percent), as was also done for the H- beam.

There is a dramatic reduction in beam loss throughout the SCL for the proton beam case. Many BLM readings are near the limit of detectable beam loss for the proton beam case. The BLM response for equivalent proton and H- beam loss was verified to be the same by inserting intercepting devices into the beam directly upstream and downstream of the SCL. The much reduced beam loss throughout the SCL for protons, for a beam with similar properties as the H- beam, signifies a beam loss mechanism unique to the H- beam.

Loss Dependence on Intensity

It is interesting to examine the dependence of the beam loss on the beam intensity. The IBSt loss rate scales with the square of the beam density or, for constant bunch length and transverse beam size, with the square of beam current. The measured beam loss normalized to the transmitted charge (shown in Fig. 5) should vary linearly with the beam current for IBSt. Fig. 5 shows the beam loss for protons and for H- vs. beam current. In this case each loss measurement shown in Figure 5 is the average of all BLMs along the SCL. Measurements are shown for both the design optics (strong focusing) and for the production optics (weak focusing).

For both the strong and weak focusing cases the H- normalized beam loss varies close to linear with beam current, consistent with IBSt expectations. Also the strong focusing case (design optics) shows a higher loss rate than the weak focusing case (production optics) at all intensities, consistent with IBSt expectations. For the proton beam cases, there is no meaningful variation of the normalized beam loss with beam intensity, as expected without the possibility of IBSt mechanism (the slight decrease in normalized beam loss with intensity may be an artifact of the background subtraction method used in the BLM signal processing). There is also no meaningful difference in the normalized beam loss between the weak and strong focusing cases for the proton beam, also consistent with the lack of an IBSt loss mechanism. The slight fall-off from a linear dependence of the H- loss vs. beam current at high values is not understood. It may be due to a dilution of the beam density due to increasing space charge forces.

SUMMARY

A series of beam measurements using a proton beam at the SNS accelerator shows much-reduced beam loss compared to an equivalent H- beam. The H- beam loss scaling with both intensity and focusing strength and the lack of an observable effect of the proton beam loss rate on intensity or focusing strength are all consistent with expectations of the IBSt beam loss mechanism. This loss mechanism should be considered for all future H- linac designs. Evidence for IBSt has also been found at LANSCE [10].

For SNS, we expect to be able to tolerate the present beam loss rate with beam powers of up to 2-3 MW, without incurring the penalty of high radiation areas throughout the linac. However, efforts are aimed to reduce existing halo and operate with even larger beam sizes in an effort to further minimize IBSt effects.

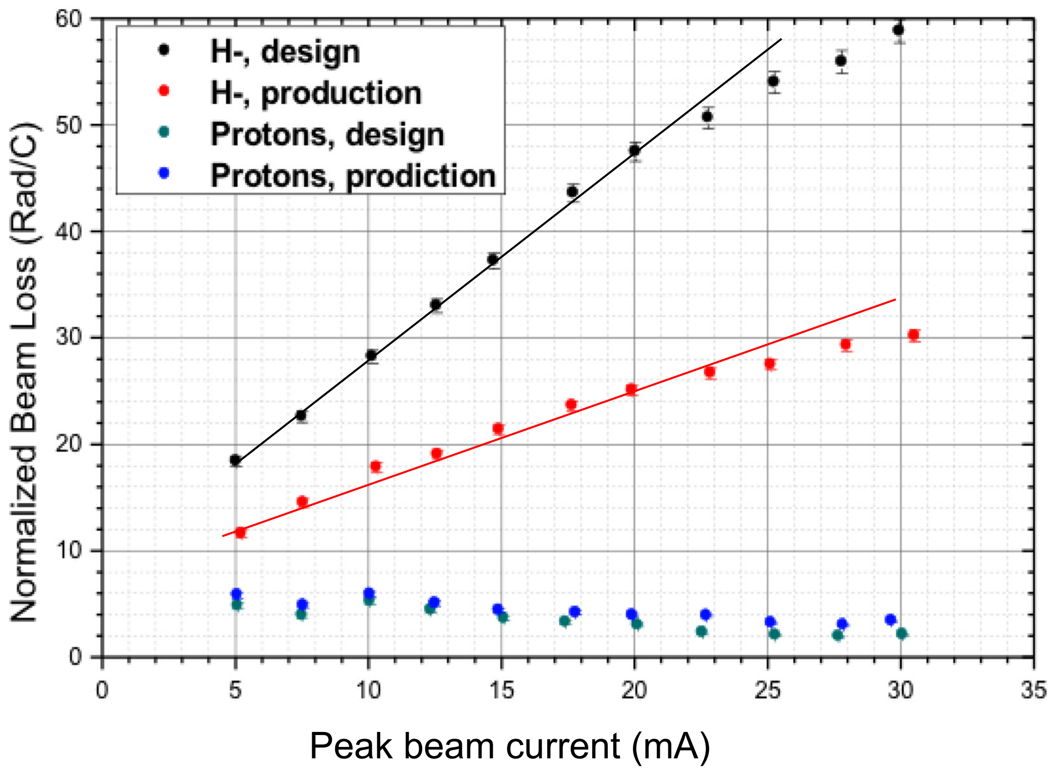

Figure 5: Beam loss vs. beam current for protons and H beams, for the cases of strong focusing (design optics) and weak focusing (production optics). The straight curves along the H- loss measurements indicate the expected dependence from IBSt. Reproduced from Reference 8.

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