H^- AND PROTON BEAM LOSS COMPARISON AT SNS SUPERCONDUCTING LINAC

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Abstract

A comparison of beam loss in the superconducting part (SCL) of the Spallation Neutron Source (SNS) linac for H^- and protons is presented. During the experiment the nominal beam of negative hydrogen ions in the SCL was replaced by a proton beam created by insertion of a thin stripping carbon foil placed in the low energy section of the linac. The observed significant reduction in the beam loss for protons is explained by a domination of the intra beam stripping mechanism of the beam loss for H^-. The details of the experiment are discussed, and a preliminary estimation of the cross section of the reaction $H^- + H^- \rightarrow H^- + H^0 + e$ is presented. Earlier, a short description of these studies was presented in [1].

INTRODUCTION

From the early days of the SNS, surprisingly high beam loss and beam line activation in the superconducting (SC) linac [2] were observed. Historically, the main beam loss mechanisms in linacs have been considered to be halo formation by space charge effects or mismatched beam or gas stripping by the residual background gas. In the SC part of the SNS linac the bore radius aperture is about 10 times larger than the rms beam size, and the vacuum pressure is almost one order of magnitude lower than in the warm linac (10^{-9} compared to 10^{-8} Torr). Simulations showed that the SC linac should be virtually free of beam loss and activation [3]. The measured loss was in stark contradiction to the simulations. Earlier, a similar big unexplained discrepancy between simulated and measured loss for the negative hydrogen ion beam was observed at the high energy part of the LANSCE Linac, but their proton beam loss were in a better agreement with simulations [4]. Eventually, the losses and activation at SNS SC linac were lowered to a level that does not limit present and future SNS operation by empirically reducing quadrupole gradients. This solution contradicts the existing linac beam loss paradigm, because reduced quadrupoles gradients lead to larger transverse beam sizes, which in turn should increase loss on limiting apertures.

In 2010, Valery Lebedev (FNAL) suggested that the unexpected beam loss at SNS is caused by the Intra Beam Stripping Mechanism (IBST) [5]. This mechanism is described by the following reaction occurring inside the H^- linac bunch

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

The neutral hydrogen atoms created in the reaction (1) are unaffected by electromagnetic fields and subsequently lost from the bunch. Inside the bunch, the local loss rate is proportional to the square of the bunch density, so IBST explains the reduced loss trend for reduced quadrupole strengths and larger bunch size observed at SNS. In [5] the losses from IBST at the SNS SC linac were estimated to be at the level of $3\text{x}10^{-5}$, while the indirect measurements, calibrated by H^- stripping with a short laser pulse, gave a comparable loss range between $2\text{x}10^{-5}$ - $7\text{x}10^{-5}$, in good agreement with the prediction.

This newly proposed IBST loss mechanism is specific for negative hydrogen ions. Therefore, the experimental check of this hypothesis is straightforward. A replacement of the H^- beam with a proton beam having similar beam parameters should eliminate the beam loss if the IBST is a leading mechanism of losses. This paper describes how this experiment was performed at SNS and its results.

PROTON BEAM IN THE SNS LINAC

The SNS linac includes an ion source (IS), a low energy transport line (LEBT), RFQ, a medium energy beam transfer (MEBT) line, six drift tube tanks (DTL), four coupled cavity linac (CCL) sections, and a superconducting linac (SCL). After the SCL, there is a high energy beam transfer line (HEBT) which sends the beam to the ring or to the linac dump (LD). The structure and output energies are shown in Fig. 1.

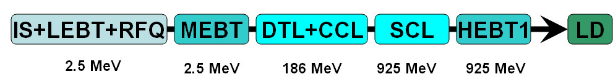

Figure 1: SNS linac structure.

To transform the existing H^- beam into protons, a thin carbon stripping foil was placed in the beginning of the Medium Energy Beam Transfer (MEBT) line, right after the RFQ. The H^- energy at this point is 2.5 MeV. After the foil, protons are accelerated in the Drift Tube and Coupled Cavities Linac (DTL and CCL), and then they are injected into the superconducting linac. The carbon foil thickness was chosen to be 5 $\mu g/cm^2$ to provide 99.98% stripping efficiency yet cause only 10 to 20% of emittance growth from scattering. To keep the same beam parameters for the proton beam we have to shift all phases of RF cavities in the linac by 180°, which can be easily done, and also change the polarities of the quadrupoles, which is impossible for permanent quadrupole magnets in the DTL. To solve this problem the 14 MEBT quadrupoles were used to provide the proton beam Twiss parameters at the entrance of the DTL for horizontal and vertical planes switched relative to the H^- beam, which is equivalent to a global quadrupole polarity change. The

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procedure of switching the SNS linac between the H^- and proton beam takes only several minutes. To avoid overheating the stripping carbon foil, the beam pulse time length and repetition rate were limited to 50 µs and 1 Hz correspondingly instead of the usual 850 µs and 60 Hz values for production runs. We compared beam loss for H^- and protons for peak currents from 5 to 30 mA, because the IBST mechanism predicts a strong dependency of the beam loss on the intensity.

Proton Beam Transmission to SCL

At the SNS linac, there are two types of diagnostics that can be used to measure the peak current along the linac. First, the Beam Current Monitors (BCM) are capable of measuring the peak current with accuracy of about 5%. The BCM signals are noisy, and they were used only for a charge sign indication and a rough estimation of the peak current value. Second, Beam Position Monitors (BPM) measure not only transverse and longitudinal center of the bunch positions, but they also provide the amplitude of the second Fourier harmonic of the longitudinal bunch density. This amplitude is proportional to the peak current if the longitudinal bunch size is small relative to a RF period, which is exactly what we have in the SCL section. The measured transmission from the entrance of the MEBT to the SCL as a function of the peak current for the proton beam is shown in Fig. 2.

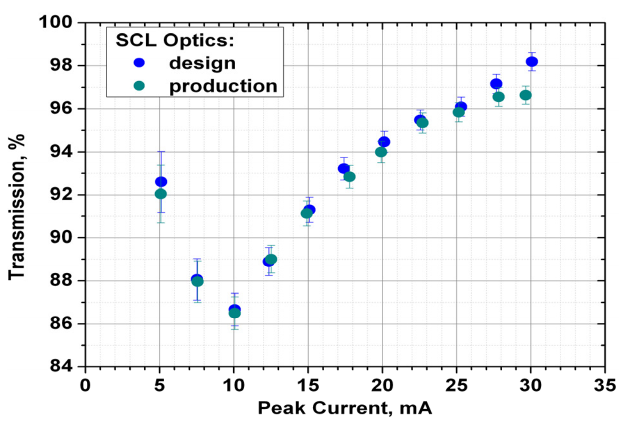

Figure 2: The proton beam transmission in the linac.

For the highest peak current of 30 mA, the transmission of the proton beam was 97%–98% for both cases of the SCL quadrupole settings called "design" and "production" which will be discussed later. The measurements took several hours, so the difference between curves should be attributed to the uncontrollable changes in the lattice and the ion source. For the lower currents we lost up to 10% of the beam in the MEBT, because we could not create a MEBT lattice independent of the peak current without changing the polarity of quadrupoles. The measurements with the MEBT emittance device showed that we scraped the proton beam in the vertical direction. The reason why we could not reach 100% transmission is not clear. Still, the amount of the proton beam transported to the SCL was sufficient to provide stable beam loss monitor (BLM) signals.

Two SCL Optic Settings

As was said before, the reduced beam loss in the SCL was achieved by empirically reducing the design quadrupole strengths step by step over a period of two years. This setting is providing the lowest H^- beam loss, which we call "production". The comparison between the design and production quadrupole gradients is shown in Fig. 3. The values for the H^- and proton beams are slightly different, because, after the switching to the proton beam, we spent about half an hour to empirically improve the SCL matching and to provide a realistic comparison.

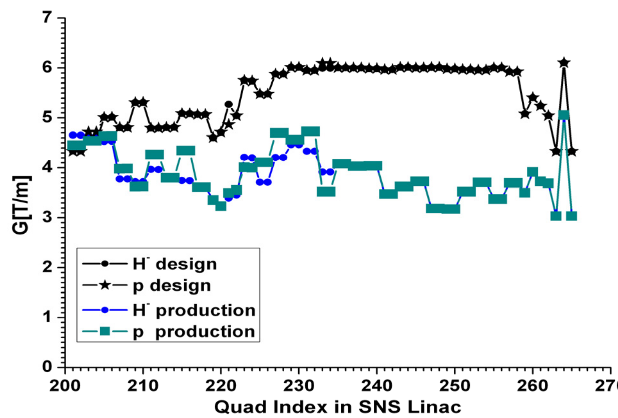

Figure 3: The SCL quadrupole gradients for different SCL optics.

H^- vs. Proton Beam Parameters

To compare the transverse parameters of the H^- and proton beams we used four wire scanners in the HEBT section right after the SCL. By using the measured four transverse rms sizes we calculated the Twiss parameters of the beams shown at Table 1.

Table 1: The Twiss parameters of the H^- and proton beams right after the superconducting linac. The normalized emittances are in [pi*mm*mrad]. The data from [1]

Twiss Parameter	H^- beam	Proton beam
Hor. norm. rms emittance	0.71	0.47
Hor. alpha	1.8	-2.0
Hor. beta [m]	10.0	10.3
Vert. norm. rms emittance	0.55	0.80
Vert. alpha	-2.2	2.4
Vert. beta [m]	12.9	11.9

The data in Table 1 clearly show that the parameters for the horizontal and vertical planes are switched for protons and H^-. The differences can be caused by our inability to match the proton beam into the DTL section with exactly the same parameters as for the H^- beam. For example, we do not have any diagnostics in the MEBT to control the longitudinal parameters of the beam, so in our models we

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used the design parameters. This also could be a reason for less than 100% transmission of the protons that was discussed before.

BEAM LOSS COMPARISON

Beam loss in the SCL was measured by 64 ionization chamber BLMs evenly distributed along the linac. Equal BLM signals for equal amounts of H^- and proton beam loss was verified at both low and full energies, using a Faraday cup at the end of DTL, and a tungsten wire from a wire scanner inserted into the beam in the HEBT. The BLM signals for H^- and proton beams for the production SCL optics are shown in Fig. 4. The peak current was 30 mA, and the signals were normalized to the total charge per pulse transmitted through the SCL.

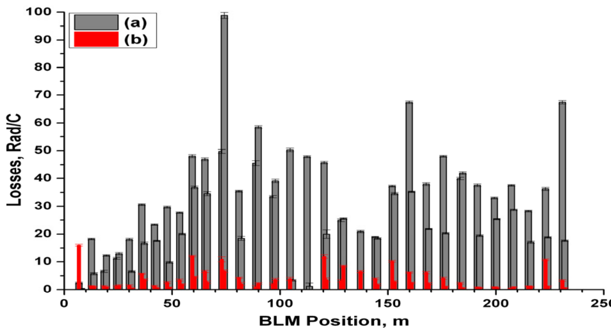

Figure 4: The BLM signals along the SCL normalized by charge of the beam transmitted to the SCL for (a) H^- ion and (b) proton beams. The Fig. is from [1].

The reduced beam loss for protons implies that a proton superconducting linac should be able to provide several times higher power with the same low activation and "hands on" maintainability as the existing SNS linac.

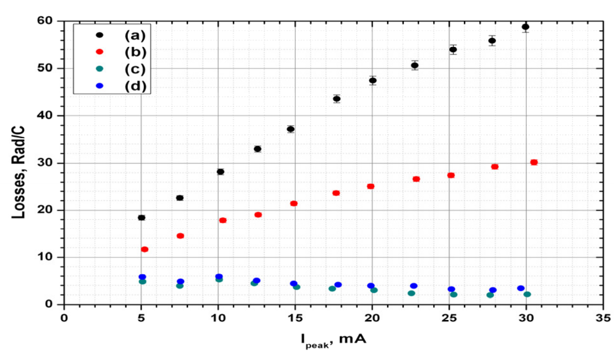

Figure 5: The normalized BLM signals vs. peak current for different beams and optics: (a) and (b) H^- beam for the design and production SCL optics respectively; (c) and (d) proton beam for the design and production SCL optics respectively.

To present the comparison more clearly, we averaged losses over all SCL BLMs for various beam currents. The results are shown in Fig. 5. The normalized ion beam loss demonstrates an almost linear dependency on the peak current. This is consistent with the IBST loss mechanism. The analysis of the BLM signals showed that we probably have very low nonzero background noise caused by x-rays from the superconducting cavities. It is responsible for the apparent growth of the normalized proton beam losses with the smaller peak current values in Fig. 5. The nonzero background for losses means that low level proton beam loss measurements should be considered as a conservative estimate.

By using the latest beam Twiss parameters measurements for the production beam in the SCL and our estimation of the losses discussed before, the estimation for the cross section of the reaction (1) is between 3.2×10^{-15} and 11.2×10^{-15} cm^2. This estimation was calculated by formulas from [5], and it is in a good agreement with an expected value of 4×10^{-15} cm^2 [6].

CONCLUSIONS

It was experimentally showed that proton beam loss in the SCL is about one order of magnitude lower than the loss relative to a comparable H^- beam with similar current, size and dynamic characteristics. This observed loss reduction is consistent with the prediction of a strong presence of the intra beam stripping loss mechanism for negative hydrogen ion beams. The IBST should be taken into account during the design of future H^- linear accelerators.

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