First Observation of Intrabeam Stripping of Negative Hydrogen in a Superconducting Linear Accelerator

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The First Observation of Intra-Beam Stripping of Negative Hydrogen in a Superconducting Linear Accelerator

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Abstract. We report on an experiment in which a negative hydrogen ion beam in the Spallation Neutron Source (SNS) linear accelerator was replaced with a beam of protons with similar size and dynamics. Fractional beam loss in the superconducting part of the SNS accelerator was measured to be at least $2\text{x}10^{-5}$ for the H^- beam, and it was an order of magnitude lower for the protons. Also beam loss has a stronger dependence on intensity with H^- than with proton beams. These measurements verify a recent theoretical explanation of unexpected beam losses in the SNS superconducting linear accelerator based on an intra-beam stripping mechanism for negative hydrogen ions. This previously unidentified mechanism for beam loss is important for the design of new high current linear ion accelerators and the performance improvement of existing machines.

Keywords: intra-beam stripping, negative hydrogen ion, proton, beam losses, superconducting linear accelerator
PACS: 29.20.Ej (Linear accelerators), 29.27.Bd (Beam dynamics; collective effects and instabilities), 52.20.Hv (Atomic, molecular, ion, and heavy-particle collisions), 52.59.-f (Intense particle beams and radiation sources)

Injection into a circular accelerator by stripping an H^- beam was suggested by L. Alvarez [1]. Presently, such injection is a standard technique for accumulation of high intensity proton beam in a ring [2]. Typically, the initial H^- acceleration technology is based on a linac, such as the LANSCE 800 MeV linac [3] or the SNS 1 GeV superconducting linac [4]. With beam power at the megawatt level beam loss becomes a critical consideration in order to minimize the accelerator residual activation. Historically, the primary linac beam loss mechanisms have been considered to be halo formation by space charge effects [5] and gas stripping by the residual background gas [6]. Recently, a new H^- beam loss mechanism was identified, namely stripping of the outer electron of the H^- ion by intra-beam collisions within the linac beam bunch, or Intra-Beam Stripping (IBST) [7]. Understanding the difference between proton and H^- beam loss mechanisms in superconducting linacs is important for the design of future projects such as the European Spallation Source in Lund, Sweden and Project-X at Fermilab. In this letter we report experimental results performed at SNS that support the role of new IBST as an important beam loss mechanism.

From the beginning of the SNS power ramp up, unexpected and unexplained beam loss and beam line activation in the superconducting (SC) linac [8] were observed. The measured loss was in stark contradiction to the simulations supporting the view that the high energy part of the SNS linac is virtually "loss free," primarily due to the large aperture of the superconducting structures and the high vacuum. Eventually, the losses and activation there were lowered to a level that does not limit SNS operation by empirically reducing quadrupole gradients. This solution was counterintuitive because reduced quadrupoles gradients lead to larger transverse beam sizes, which in turn should increase loss on limiting apertures. The newly proposed IBST mechanism is specific for negative hydrogen ions. A replacement of the H^- beam with a proton beam having similar beam parameters in the same linac should eliminate the beam loss due to the IBST and lead to significant loss reduction if IBST is the primary loss mechanism.

Beam loss by IBST was first observed in LEAR [9] where inelastic scattering of ions inside an H^- bunch resulted in H^- stripping. The single-electron detachment $H^- + H^- \rightarrow H^- + H^0 + e$ is a dominating process. The created neutral hydrogen atoms are unaffected by electromagnetic fields and subsequently are lost from the bunch. The local loss rate inside the bunch is proportional to the square of the bunch density, so IBST explains the reduced loss trend for larger beam size observed at SNS. Also for the superconducting part of the SNS linac the losses from IBST were estimated to be at the level of $3\text{x}10^{-5}$ [7], while the indirect measurements based on H^- stripping by a short laser beam gave a comparable loss range between $2\text{x}10^{-5}$ - $7\text{x}10^{-5}$, in good agreement with the prediction.

The SNS linac includes a radio frequency quadrupole (RFQ) with an output energy of 2.5 MeV, followed by a 3.6 m long Medium Energy Beam Transport (MEBT) line section, then a ~100 m normal conducting section which accelerates the beam from 2.5 MeV to 186 MeV, and finally a ~200 m superconducting linac (SCL), where acceleration to 925 MeV occurs. To transform the H^- beam to protons, a retractable thin carbon foil was installed just

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downstream of the RFQ. For all data reported here a 5 μg/cm^2 carbon foil was used to strip the incoming H$^-$ beam, which is thick enough to strip 99.98% of the initial H$^-$ to protons (calculated value), and is thin enough to cause only 10 to 20% emittance growth from scattering (calculated and measured values). The emittances in the MEBT were measured with a device of the slit-harp type. The transverse phase-space distributions did not show any specific differences between the proton and H$^-$ beams. The calculated beam energy degradation after this foil was 0.6 keV. It is much less than the 12 keV of the bunch energy spread, and too small to be measured with existing SNS instrumentation. To avoid the possibility of foil thermal damage, we shortened the beam pulse length and reduced the repetition rate compared to normal high power operation. This reduced the charge per pulse from 18 to 0.5 μC, and the repetition rate from 60 to 1 Hz. Further changes of beam intensity were done by reduction of the ion source current, which reduced the peak current injected into the linac. This amount of charge was sufficient to provide reliable readings from the instrumentation. The vertical and horizontal rms sizes of the beam at the foil were 1.2 and 2.5 mm respectively, and a conservative estimation of the maximum foil temperature is 2200 K, which is far less than the carbon sublimation point of 3915 K. After the foil exposure to the H$^-$ beam for several hours, we did not see any degradation in the foil stripping ability.

We used MEBT quadrupoles to match the beam into the rest of the linac. To transport the proton beam through the accelerator lattice and to keep the same dynamic beam parameters for proton and H$^-$ beams, we shifted the phases of all accelerating cavities by 180 degrees and prepared the proton beam with the transverse Twiss parameters switched between the horizontal and the vertical planes with respect to the H$^-$ beam. The switching of these parameters was performed in the MEBT by changing the strengths of the last four quadrupole magnets. After these changes, the equation of motion for protons in the rest of the linac is the same as for H$^-$ ions, because the only optics elements in the SNS linac are the standing wave accelerating cavities and quadrupoles. The space charge internal forces should also be the same for both types of the beam, because we kept the same beam sizes with only the horizontal and vertical planes being switched. The data in **TABLE I** show the measured Twiss parameters for the H$^-$ and proton beams in the linac section directly following the superconducting linac. The Twiss parameters were found by analyzing measured transverse beam profiles. The data in **TABLE I** clearly show that the parameters for the horizontal and vertical planes are switched for H$^-$ and protons. The differences can be explained by our inability to match the proton beam into the warm linac 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 used the design parameters. **FIGURE 1** shows the examples of switched transverse profiles measured for H$^-$ and protons at the exit of the linac, at the wire scanner where the difference between vertical and horizontal sizes of beams is greatest. The profiles demonstrate that the proton and H$^-$ beams have the same quality of the distributions for cores and tails.

TABLE I The Twiss parameters of the H$^-$ and proton beams right after the superconducting linac. Parameters were obtained for the case of the production optics in the SNS linac for the peak current of 30 mA. The beam energy was 925 MeV. H and V are used to mark horizontal and vertical plane parameters respectively. The design normalized emittance for both planes is 0.46 [π*mm*mrad].

Twiss Parameter	**H$^-$ Beam**	**Proton Beam**
H norm. rms emittance, [π*mm*mrad]	0.71	0.47
H alpha	1.8	-2.0
H beta, [m]	10.0	10.3
V norm. rms emittance, [π*mm*mrad]	0.55	0.80
V alpha	-2.2	2.4
V beta, [m]	12.9	11.9

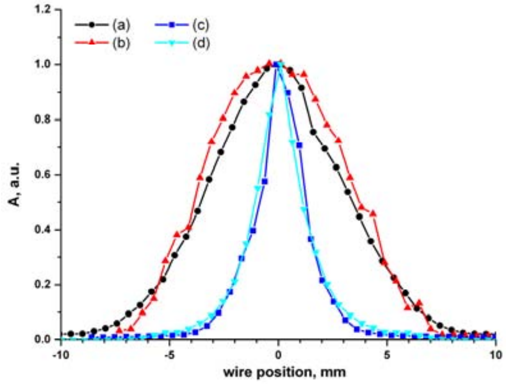

FIG. 1. The transverse profiles of the H$^-$ and proton beams after the superconducting part of the SNS linac for 30 mA peak current. All profiles are normalized to the same maximal value of 1 for convenience of comparison. (a) H$^-$ horizontal, (b) protons vertical, (c) H$^-$ vertical, and (d) protons horizontal.

The measured beam loss was normalized to the total charge transmitted in a pulse to the superconducting part of the linac. The charge is measured using Beam Position Monitors (BPMs) in the MEBT and SCL. The BPMs in the SNS linac are capable of measuring both the transverse beam positions and the relative beam peak current. The total charge at the entrance of the MEBT was calculated as an integral of the peak current signal of the first MEBT BPM. The electronics of this first BPM was calibrated to give the correct value for the integrated charge. The position of this BPM is upstream of the foil, so this signal was used for both H$^-$ and proton beams to measure the total injected charge. The SCL BPMs were not precisely calibrated before this experiment, and their signal is just linearly proportional to the peak current. We calibrated these BPMs by using the H$^-$ production beam. For this case and for the calibration purpose we can safely assume nearly 100% transmission from MEBT to SCL. **FIGURE 2** shows the proton beam transmission from the MEBT to the SCL as a function of the peak current at the entrance of the MEBT. For the highest peak current of 30 mA, the transmission of the proton beam was 97-98%. 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. Still, the amount of the proton beam transported to the SCL was sufficient to provide stable Beam Loss Monitor (BLM) signals. All cases shown here use the design optics for the SNS SCL.

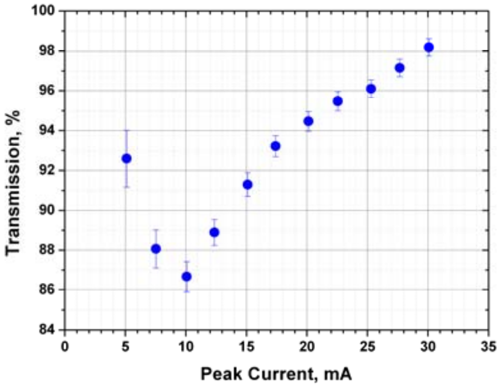

FIG. 2. The transmission of the proton beam from MEBT to SCL vs. peak beam current.

Beam loss in the SCL was measured by 64 ionization chamber BLMs evenly distributed along the linac. Equal BLM response to the same amount of H$^-$ and proton beam loss was verified at low energy (by inserting a Faraday cup) and at full energy (by inserting a tungsten wire into the beam). The BLM signals for ion and proton beams for the design SCL optics used here are shown in **FIGURE 3.** The peak current was 30 mA, and the signals were normalized to the total charge per pulse transmitted through the SCL. The existing beam loss in the SNS SCL is estimated to be ~ 0.05 – 0.17 W/m, and does not limit the SNS operation at 1 MW or 1.4 MW average power. All SNS SCL maintenance is performed "hands-on." The reduced beam loss for protons shown in **FIGURE 3** implies that a proton superconducting linac should be able to provide several times higher power than SNS with reduced beam loss. The distribution of the losses for H$^-$ beam is a typical distribution observed for many different SCL optics and beam intensities. Presently we do not have sufficient model capability to predict the loss distribution, because loss generation for IBST is not a localized process. The hydrogen atoms created by IBST can travel several tens of meters down the linac before hitting an aperture limitation.

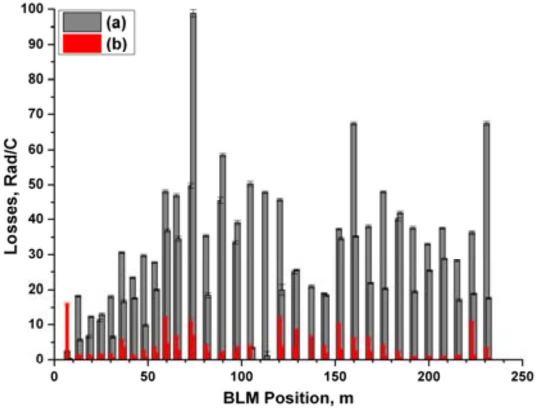

FIG. 3. The normalized (loss per charge of transmitted beam) BLM signals for (a) ion and (b) proton beams along the superconducting part of SNS linac.

To present the data of our experiment more clearly, we averaged losses over all SCL BLMs varying the beam current from 5 to 30 mA. The results are shown in **FIGURE 4**. The normalized ion beam loss demonstrates an almost linear dependency on the peak current. This is consistent with the IBST loss mechanism. For IBST the normalized loss/pulse shown here should be proportional to the numbers of particles in the bunch (therefore to the peak current) if the geometrical sizes and velocities distributions are constant. The saturation effect for the normalized ion beam loss at higher peak currents can be explained by space charge effects increasing the bunch sizes with beam current.

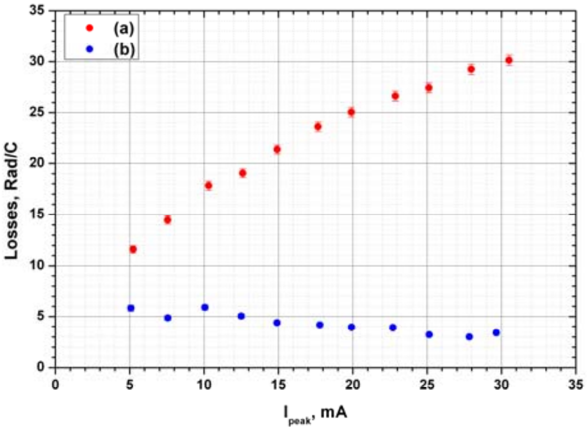

FIG. 4. The normalized BLM signals vs. peak current for H$^-$ (a) and protons (b).

The proton loss values shown in **FIGURE 4** are quite low and are near the background level, which has heretofore not been an issue with H$^-$ beams. The detailed analysis of the BLM signals showed that we probably have very low non-zero background noise caused by x-rays from the superconducting cavities. This background is not created by the beam, and it is responsible for the apparent growth of the normalized proton beam losses with the smaller peak current values in **FIGURE 4**. The correct measurements of the very low losses are a task for future studies. The non-zero background for losses means that our results for such low-level proton beam loss measurements should be considered as a conservative estimate.

In conclusion, we experimentally showed that proton beam loss in the SNS superconducting linac for the 30 mA peak current is about one order of magnitude lower than the loss relative to a comparable H^- beam with similar current, size and dynamic characteristics. The IBST mechanism has been shown to dominate beam losses in the SNS superconducting accelerator, and it will be the major focus of attention for loss reduction efforts at the SNS linac. This mechanism should be considered in the design of future high power H^- linear accelerators where beam loss needs to be controlled.

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