BEAM LOSS MECHANISMS IN HIGH INTENSITY LINACS

M.A. Plum, Oak Ridge National Laboratory, Oak Ridge, TN, USA

Abstract

Beam loss is a critical issue in high intensity linacs, and much work is done during both the design and operation phases to keep the loss down to manageable levels. Linacs for H^- ion beams have many more loss mechanisms compared to H^+ (proton) linacs. Interesting H^- beam loss mechanisms include residual gas stripping, H^+ capture and acceleration, field stripping, and intra-beam stripping (IBSt). Beam halo formation, and ion source or RF turn on/off transients, are examples of beam loss mechanisms that are common for both H^+ and H^- accelerators. The IBSt mechanism has recently been characterized at the Oak Ridge Spallation Neutron Source, and we have found that it accounts for most of the loss in the superconducting linac. In this paper we will detail the IBSt measurements, and also discuss the other beam loss mechanisms that are important for high intensity linacs.

INTRODUCTION

Beam loss is a critical issue in high intensity linacs, and much work is done during both the design and operation phases to keep the loss down to manageable levels. A generally accepted rule of thumb is to keep the loss to less than 1 W/m to allow for hands-on maintenance. For example, the SNS linac output beam power is ~1 MW today, and we plan to increase the power to its design value of 1.4 MW over the next few years, and then later to ~3 MW. The fractional loss per meter should then be less than 3×10^{-7}.

In general, beam loss in H^- linacs is more difficult to manage than H^+ linacs due to the greater number of loss mechanisms, including residual gas stripping, H^+ capture and acceleration, field stripping, and intra-beam stripping (IBSt). Mechanisms such as beam halo formation, and ion source or RF turn on/off transients, can cause loss in both H^+ and H^- linacs.

At SNS, we have recently discovered [1] that IBSt is the cause of most of the beam loss in the superconducting linac. In this paper we will first detail the IBSt measurements at SNS, then discuss other loss mechanisms important to SNS and other high-intensity linacs.

INTRA-BEAM STRIPPING

In the SNS linac [2], the H^- ion beam is first accelerated to 2.5 MeV by an RFQ, then to 87 MeV by a Drift Tube Linac (DTL), to 186 MeV by a Coupled Cavity Linac (CCL), and finally to 1000 MeV by a Superconducting Cavity Linac (SCL). The SCL has a beam aperture of 76 mm diameter, which is quite large compared to the warm linac (DTL + CCL) aperture of 25 and 32 mm diameter respectively. Due to this large aperture, particle tracking simulation codes predicted zero beam loss in the SCL. Additionally, the vacuum levels in the SCL are very low due to the cryogenic pumping. Therefore, prior to commissioning the beam loss was anticipated to be negligible.

However, as we started to increase the beam power it became clear that the beam loss in the SCL was not negligible. The measured fractional loss per meter was ~3×10^{-7}, which, although it meets the value required for hands-on maintenance, was nevertheless a puzzle. The beam loss was eventually lowered by a factor of about two by empirically lowering the SCL quadrupole gradients by up to 40%. This is counterintuitive, since lowering the gradients increases the beam size, which makes it more likely for beam halo to strike the beam pipe walls.

In 2010 a possible explanation of intra-beam stripping (IBSt) was proposed by V. Lebedev [3]. In this beam loss mechanism, interactions of the H^- particles within a beam bunch cause electrons to be stripped off, converting a portion of the particles to H^0, which are then lost due to lack of focusing and acceleration. The reaction rate is proportional to the particle density squared, so this explains why the loss is reduced as the beam size is increased. Further measurements showed that the fractional loss is also reduced by lowering the ion source current, in a parametric manner consistent with IBSt. Yet these data could not unambiguously prove that IBSt was the dominant loss mechanism. In 2011 an experiment was conducted that showed that IBSt is in fact the dominant mechanism.

The IBSt Experiment

A thin 5 μg/cm² carbon stripper foil was inserted just downstream of the RFQ to create a proton beam that has nearly identical beam dynamics properties to the H^- beam. This foil gives a stripping efficiency of ~99.98%, and a kinetic energy loss of just 0.6 keV (to be compared to the beam energy spread from the RFQ of ~12 keV). Beam scattering increases the emittance by ~12%, and the beam duty factor limit to avoid damaging the foil is about 45 μs per second, which is sufficient to accurately characterize the beam loss.

To accelerate the proton beam, all the RF cavity phases were shifted 180 deg. To focus the beam it is not practical to reverse the polarities of all the quadrupole magnets, so instead the magnets in the beam transport line between the RFQ and DTL where adjusted to swap the Twiss parameters of the horizontal and vertical planes at the entrance of the DTL. Therefore, starting from the beginning of the DTL, the beam dynamics of the proton beam are nearly identical to those of the H^- beam.

Consistency checks were performed using the four-wire-scanner emittance station at the exit of the SCL. As expected, the Twiss parameters of the horizontal and

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vertical planes of the proton and H⁻ beams were swapped, as shown in Table 1, and also the beam sizes at a wire scanner where the horizontal and vertical beam sizes were markedly different were also swapped, as shown in Fig. 1.

Table 1: Twiss Parameter Comparison Showing the Horizontal and Vertical Twiss Parameters are Swapped for the H^- and Proton Beams

Twiss parameter	**H^- horiz**	**H^+ vert**
$\varepsilon_{rms,\ norm}$ [pi-mm-mrad]	0.71	0.80
α	1.8	2.4
β [m]	10.0	11.9
Twiss parameter	**H^- vert**	**H^+ horiz**
$\varepsilon_{rms,\ norm}$ [pi-mm-mrad]	0.55	0.47
α	-2.2	-2.0
β [m]	12.9	10.3

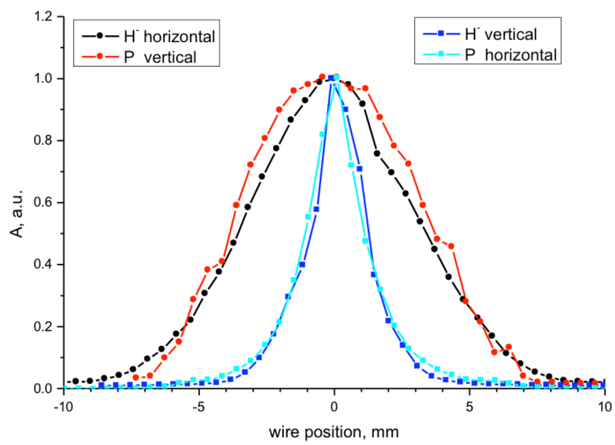

Figure 1: Wire scanner at exit of linac, showing the horizontal and vertical profiles are swapped for the H^- and proton beams.

Results

Measurements were conducted for two sets of optics, labeled design and production. The design optics are the quadrupole magnet set points from the original machine design studies, and the production optics are the result of empirical adjustments to the magnet fields to minimize the beam loss. As discussed earlier, the production optics lowers the beam loss by about half.

In Fig. 2 we show the results for the design optics case at 30 mA beam current. For this case the beam loss for protons is about 20 times less than for H^-. Beam losses were also measured for a range of ion source currents, or charge per pulse. These results are shown in Fig. 3. The black points show the loss for the H^- design optics, the red points show the loss for the H^- production optics, and the blue and green points show the corresponding losses for the proton beams. The loss for the proton cases are significantly less, and the difference grows with ion source current, which is expected since the IBSt reaction rate is proportional to the particle density squared (or the normalized beam loss is linearly proportional to the ion source current).

SNS is not the only linac where IBSt has been observed. Careful measurements conducted at LANSCE [4] show that about 75% of the H^- beam loss in the coupled cavity warm linac is due to IBSt. Other linacs where IBSt may play a role include J-PARC and ISIS, but these facilities have not identified any IBSt-related losses.

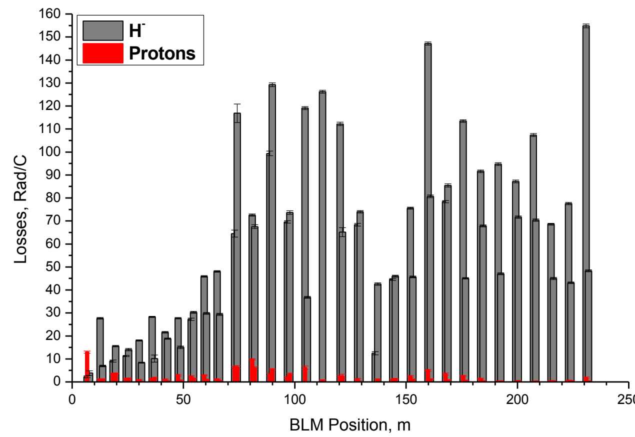

Figure 2: Beam loss monitors along the SCL, showing the proton vs. H^- beam loss for the design optics case, for 30 mA beam current.

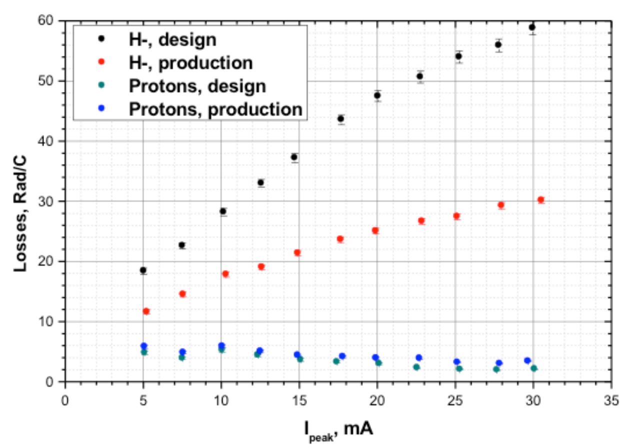

Figure 3: Beam loss for two different optics cases, as a function of ion source current, for both protons and H^-. Reproduced from ref. [1].

OTHER BEAM LOSS MECHANISMS

Of course IBSt is not the only beam loss mechanism. Some of the more interesting mechanisms specific to H^- beams include H^+ capture and acceleration, residual gas stripping, magnetic field stripping, and black body radiation stripping. These mechanisms are tabulated for some of the high-intensity H^- linacs in Table 2. Not contained in this table is blackbody radiation stripping, which would be an issue for high H^- beam energies, like the 8 GeV linac considered for Project X at FNAL.

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Table 2: Beam Loss Mechanisms Observed at Various H^- Linacs

Beam loss mechanism	**SNS**	**J-PARC**	**ISIS**	**LANSCE**
Intra-beam stripping	Yes, dominant loss in SCL linac	Not noted as significant	Not noted as significant	Yes, significant, 75% of loss in CCL
Residual gas stripping	Yes, moderate stripping in CCL and HEBT	Yes, significant, improved by adding pumping to S-DTL and future ACS section	Yes, not significant when vacuum is good, but can be significant if there are vacuum problems	Yes, significant, 25% of loss in CCL
H+ capture and acceleration	Possibly, but not significant concern	Yes, was significant, cured by chicane in MEBT	Not noted as significant	Yes, significant if there is a vacuum leak in the LEBT
Field stripping	Insignificant	Insignificant	Yes, <1% in 70 MeV transport line, some hot spots	Insignificant

Residual Gas Stripping

In this beam loss mechanism, the loosely-bound electrons on the H^- particles are stripped off by interactions with the residual gas, leaving H^0 particles which are quickly lost since they can no longer be focused or controlled. The stripping cross sections are highest at low beam energies [5].

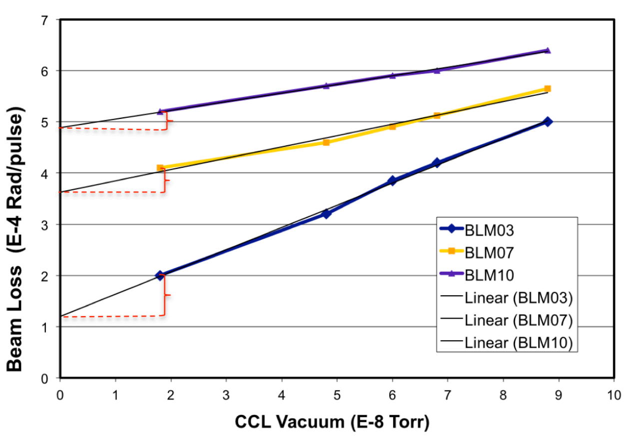

Figure 4: Beam loss in the SCL as a function of gas pressure in the last CCL tank. The nominal gas pressure is ~2×10^{-8} Torr, and the red brackets indicate the beam loss due to residual gas stripping during nominal operations.

At the SNS, we have measured beam loss due to residual gas stripping in the CCL. It is present to a small degree during normal operations, and it can become significant if there are vacuum problems. Figure 4 shows beam loss monitor signals as a function of the gas pressure in the last CCL tank, for three different BLMs in the SCL. The difference between the loss at the operating pressure and the loss extrapolated to zero pressure gives the loss due to residual gas stripping. The effect is greatest at the upstream end of the SCL, as expected. Residual gas stripping is also probably the cause of a hot spot in the HEBT, at a dipole magnet downstream of a straight section.

Gas stripping was found to cause significant loss during the commissioning phase of the J-PARC linac [6]. It was subsequently reduced to acceptable levels by adding vacuum pumps to the to S-DTL and the upstream portion of the linac reserved for future expansion. Also, in the LANSCE linac, residual gas stripping has been estimated [4] to cause about 25% of the H^- beam loss along the linac. In the ISIS linac, gas stripping is present under nominal conditions, but not at a significant level [7]. However, if the gas pressure increases due to vacuum issues, the ISIS loss can become significant.

H^+ Capture and Acceleration

In this beam loss mechanism, the H^- beam is doubly-stripped to H^+ by residual gas, and the newly-created protons are then captured in the RF buckets, whereupon they are accelerated 180 degrees out of phase with the H^- beam, only to be lost mostly after the exit of the linac, often at the first bend in the high energy beam transport line. The double stripping is most likely to occur at low beam energies, where the stripping cross sections are greatest. The cross section for double stripping is about 4% of the cross section for single stripping.

The double-stripped H^+ beam cannot be accelerated across certain RF frequency jumps in the linac, as illustrated by Fig. 5. For example, at the SNS, the DTL RF frequency is 402.5 MHz, and the CCL RF frequency is 805 MHz (factor of two higher). After the frequency jump the timing is such that any H^+ beam is now being decelerated, so it will fall outside the RF bucket and be quickly lost. Even frequency jumps prevent acceleration

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across the jump, while odd jumps (e.g. 402.5 to 1027.5 MHz) allow acceleration across the jump.

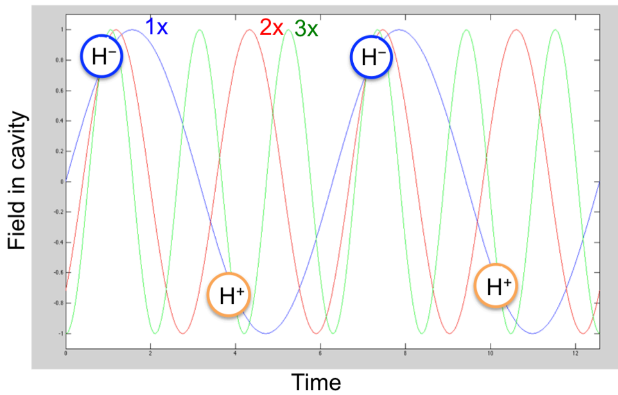

Figure 5: Electric fields in a linac for three different frequencies.

This loss mechanism does not play a significant role at SNS. Although there is a slight hot spot near the beginning of the CCL (location of the frequency jump), it could equally well be explained by, e.g., the lattice transition. During the J-PARC linac commissioning significant beam loss due to H^+ capture was found [8], and it was mitigated by installing a chicane in the medium energy beam transport line. The LANSCE linac also sees significant H^+ capture loss [9] when the vacuum is poor in the low energy beam transport.

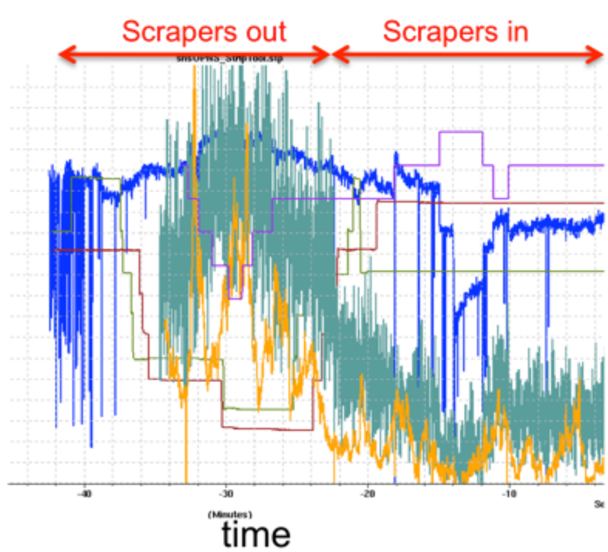

Figure 6: Beam loss reduction due to low energy scraping. Magenta, light green, and violet show the scraper positions. Blue shows the beam charge, and orange and dark green show BLM signals. The beam loss is reduced 50 to 60% by scraping 3% of the beam.

Field Stripping

In this beam loss mechanism, the H^- beam is stripped to H^0 by the magnetic fields, which are Lorentz-transformed to electric fields in the rest frame of the beam. This is rarely a problem since the maximum allowable fields are readily calculable and usually avoidable. However, it is easy to overlook the possible scenario where, after adjusting quadrupole gradients to minimize the beam loss, the beam size is larger than expected inside quadrupole magnets whose gradients are larger than expected, which could lead to field stripping. The ISIS facility sees a small amount of field stripping in the 70 MeV transport line between the linac and the ring, at the level of <1%, just enough to create some minor hot spots [7].

Dark Current and Turn On/Off Transients

Another beam loss mechanism, possibly unique at SNS, is due to dark current from the ion source. The dark current, or very low current H^- beam, is created by the 13 MHz CW RF used to facilitate the ion source plasma ignition. While this is not a problem when the linac RF is off, it does cause beam loss during RF turn-on and turn-off. This type of beam loss was not expected during the design phase of the SNS, and it was discovered during commissioning. It is now mitigated by reversing the phase of the first DTL tank when beam is turned off, and by using the LEBT chopper to blank the head and tail of the beam when the beam is turned on.

Both H^+ and H^- type linacs, without some sort of beam chopper or beam blanking system, can expect similar losses due to either the source turn on/off transients, or the RF turn on/off transients.

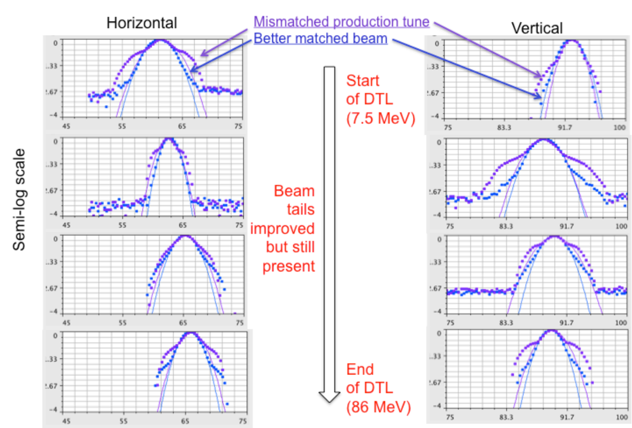

Figure 7: Normalized horizontal and vertical beam profiles in the DTL showing beam tail formation in the DTL. Purple is the production tune, and blue shows the result of matching the beam at the entrance to the DTL. The solid lines show Gaussian fits to the data.

BEAM LOSS MITIGATION

At the SNS we mitigate as much as possible the beam loss due to all the mechanisms discussed above that are particular to H^- beams, but of course there will always be the conventional loss mechanisms that are present even for H^+ beams. Examples include beam tails and beam halo formation and control.

Scraping at low beam energy in the MEBT has proven to be very effective for SNS. Left and right horizontal

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scrapers were installed during the low power operations phase of the SNS power ramp with good results. In addition some scraping of the top of the beam is possible using the MEBT chopper target. Figure 6 shows a typical beam loss improvement.

An open question at SNS is how to best match the beam from one lattice to the next in order to minimize the beam loss (e.g. MEBT to DTL to CCL to SCL to HEBT). In theory matched beams should minimize beam tail formation, and thereby the beam loss. However, in practice, the low-loss tune that has been empirically derived is clearly mis-matched, as shown in in Fig. 7. The low-loss tune has much larger beam tails present at levels as high as 20% of the peak. The matched beam case shows non-Gaussian tails at the beginning of the DTL, but they still develop by the end of the DTL. We are working to better understand this phenomenon and to better minimize beam tails formation and control.

SUMMARY

There are many interesting beam loss mechanisms that occur for H^- beams but not H^+ beams. The intra-beam stripping mechanism has been recently characterized at the SNS linac, and we have found that it causes about 90% of the loss in the SCL linac. There are other loss mechanisms also at play at SNS and other H^- linacs, including residual gas stripping and H^+ capture and acceleration. These latter two mechanisms result in negligible beam loss at SNS, but have caused problems at other high-intensity H^- linacs. In addition to H^- loss mechanisms, SNS also has beam loss due beam halo/tails. This loss type is best mitigated using scraping at low beam energy.

The IBSt experiment also showed that the future is bright for H^+ superconducting linacs. They expect very low beam losses, and take full advantage of the large beam apertures and flexible RF set up.

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