CHALLENGES FACING HIGH POWER PROTON ACCELERATORS*

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Abstract

This presentation will provide an overview of the challenges of high power proton accelerators such as SNS, J-PARC, etc., and what we have learned from recent experiences. Beam loss mechanisms and methods to mitigate beam loss will also be discussed.

INTRODUCTION

There is an ever-growing world-wide demand for high power proton (and H^- ion) accelerators for neutron spallation sources, high energy physics experiments on the intensity frontier, and accelerator driven systems (ADS). Examples of new initiatives include the European Spallation Neutron Source (ESS), Project-X at Fermilab, the CERN SPL; and the ADS projects such as MYRHHA, the Chinese ADS, and the India ADS. All these new projects draw on experiences and lessons learned from the recently-completed high-power H^- ion accelerators at the Oak Ridge and J-PARC spallation neutron sources. The Oak Ridge neutron source (SNS) is particularly relevant since all the above-mentioned projects call for superconducting linacs (SCL), and the SNS accelerator complex includes the first and only high-power proton or H^- ion SCL.

The lessons learned are many, and include an important new beam loss mechanism (intra-beam stripping [1]), issues associated with high power RFQs, methods to quickly set SCL RF cavity phases, SCL trip rates, methods to minimize beam losses, the impact of errant beams on SCL cavities, and issues related to charge-exchange injection into synchrotrons or storage rings. In this paper we will highlight some of these lessons learned, and also discuss some of the challenges facing the next-generation high-power proton accelerators.

BEAM LOSS MECHANISMS

Beam loss is a key challenge for high power proton linacs. A widely accepted rule of thumb is to limit the beam loss to 1 W/m to keep the radioactivation levels low enough for hands-on maintenance. As beam powers grow ever higher, the corresponding fraction of the allowable beam loss necessarily becomes smaller and thus more challenging. For example, in a 1 MW accelerator facility, the allowable loss is just one part per million per meter of beam line.

One of the many advantages of superconducting linacs is the reduction in beam loss obtained by the large beam apertures that are made possible by the high quality factor Q of the RF cavities. For example, at SNS the aperture of the SCL cavities is 76 mm diameter, while in the warm linac section just upstream of the SCL the aperture is just 30 mm diameter. Also, due to cryogenic pumping, the SCL vacuum pressure is very low, which reduces beam loss caused by residual gas interactions.

Intra-beam Stripping

During the design phase of the Oak Ridge SNS, which accelerates H^- particles to 1 GeV with a design beam power of 1.4 MW, it was believed that the beam loss in the SCL would be negligible, due to the large apertures and low residual gas pressure. Yet, as we discovered during the commissioning phase, the beam loss was much higher than expected, with a measured fractional loss per meter of ~3×10^{-7}. The origin of this loss was recently traced to intra-beam stripping [1] (IBSt), where interactions of the H^- particles within the beam bunch cause loosely-bound electrons to be stripped off, leaving neutral H^0 particles, which are subsequently lost due to lack of focusing, steering, and acceleration. Experiments accelerating protons, rather than H^- particles, showed that IBSt is by far the dominant loss mechanism in the Oak Ridge SCL, as shown in Fig. 1. This loss mechanism has also been measured in the LANSCE linac [2].

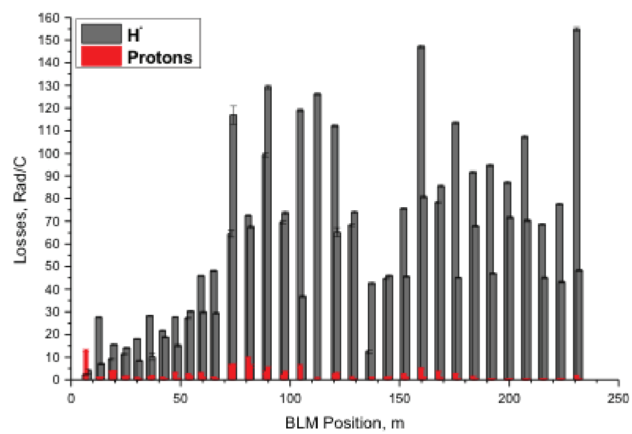

Figure 1: Beam loss monitors along the SCL, showing the proton (red) vs. H^- (grey) beam loss for the design optics case, for 30 mA beam current.

The IBSt reaction rate is proportional to the beam particle density squared, which explains why, at the SNS, we were able to empirically reduce the beam loss by lowering the SCL quadrupole focusing strengths by up to ~40%. The lower focusing strengths increased the transverse beam size, which lowered the beam particle density, and in turn lowered the IBSt reaction rate. Next-generation H^- accelerators, such as the Fermilab Project X, should include IBSt considerations in the design process. Next-generation proton accelerators, such as the one being built at ESS, will not have to be concerned with this beam loss mechanism.

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H^+ Capture and Acceleration

Inadvertent proton acceleration is another interesting source of beam loss in H^- accelerators. Double stripping, where both electrons on the H^- particle are stripped off, can occur due to residual gas interactions. If these newly-created protons are captured into RF buckets, they are accelerated 180 deg. out of phase along with the H^- particles, and then eventually lost at high beam energies.

The most likely place for H^+ capture to occur is at low beam energies, where the double-stripping cross sections are maximized. The cross section for double stripping is about 4% of the single-stripping cross section.

For example, recent measurements at LANSCE [3] showed that fully accelerated 800-MeV protons can be easily detected downstream of the linac while only the H^- ion source is in use. The protons are from double-stripping of the H^- beam in both the 0.75-MeV Low Energy Beam Transport (LEBT) and in the 100– 800 MeV Coupled Cavity Linac (CCL).

This beam loss mechanism is also observed at J-PARC, where unexpectedly high activation levels were discovered in the beam transport line from the linac to the rapid cycling synchrotron [4]. Adding a chicane bump in the 3 MeV medium energy beam transport solved the problem by allowing the protons to be intercepted before they could be accelerated to higher beam energies.

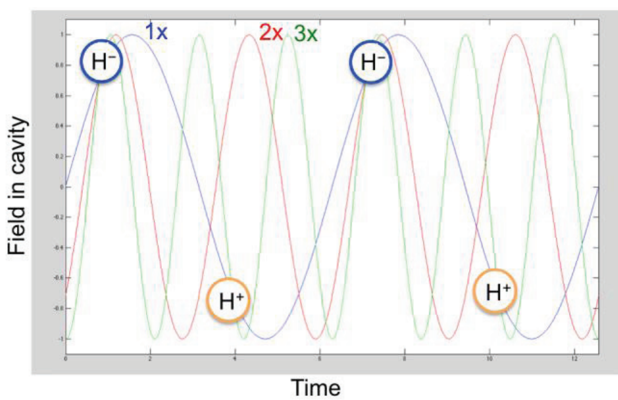

Figure 2: Electric fields in a linac for three different frequencies.

One interesting aspect of H^+ capture and acceleration is that the protons are unlikely to survive even RF frequency jumps in the linac, as illustrated in Fig. 2. For example, at the Oak Ridge SNS, where the RF frequency jumps from 402.5 MHz to 805 MHz in the transition from the Drift Tube Linac (DTL) to the CCL, the protons are unlikely to survive because they are suddenly within decelerating RF buckets after the frequency jump. Alternatively, in the J-PARC linac, where the frequency jumps from 324 to 972 MHz in the transition from the S-DTL to the ACS Linac at 191 MeV, the protons are accelerated all the way to the end of the linac, only to be lost in the arc leading to the rapid cycling synchrotron.

Residual Gas Stripping

Residual gas stripping is another beam loss mechanism of concern to high power H^- ion accelerators but not for proton accelerators. In this mechanism electrons are stripped off the H^- particles, most likely leaving neutral H^0 particles. The phenomenon is well known and understood, yet it still sometimes requires installation of additional vacuum pumps beyond those specified in the design phase. The vacuum levels can easily be worse than anticipated due to small vacuum leaks, higher-than-expected outgassing rates, etc.

In the SNS linac we have measured beam loss due to residual gas stripping in the 87 to 185 MeV CCL. As shown in Fig. 3, it is present to a small degree during normal operations, and it can become significant if there are vacuum problems. There is also unexpected beam loss in a section of the high-energy beam transport line between the linac and the ring, where additional ion pumps were installed to mitigate the loss.

Gas stripping was found to cause significant beam loss during the commissioning phase of the J-PARC linac [5]. It was subsequently reduced to acceptable levels by installing additional vacuum pumps in the S-DTL and the upstream portion of the linac reserved for future expansion. Also, in the LANSCE linac, residual gas stripping has been estimated [2] 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 [6]. However, if the gas pressure increases due to vacuum issues, the ISIS loss can become significant.

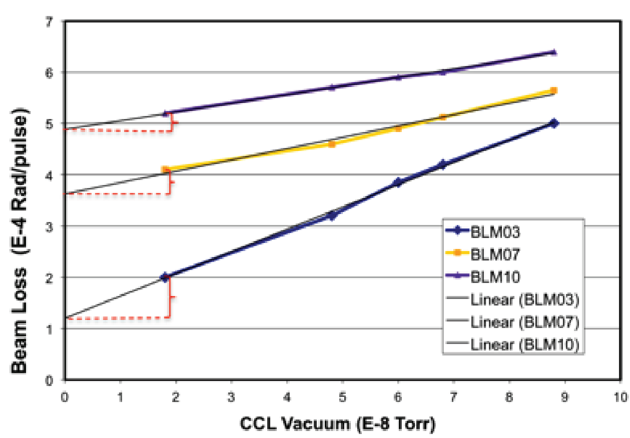

Figure 3: Beam loss in the Oak Ridge SCL as a function of gas pressure in the last CCL tank. The nominal gas pressure is ~2×10^{-8} Torr, and the red brackets indicate the beam loss due to residual gas stripping during nominal operations.

Field Stripping

Yet another beam loss mechanism that is important for H^- ions but not for proton accelerators is magnetic field stripping. This is rarely a problem since the maximum allowable fields are readily calculable and usually avoidable. Magnetic fields are Lorentz-transformed to electric fields in the rest frame of the H^- particles, and if

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Table 1: 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

the field is high enough it will strip off some electrons. 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 [6]. SNS, J-PARC, and LANSCE have not reported any significant beam loss due to this mechanism. Table 1 shows a summary of the various beam loss mechanisms relevant for H$^-$ accelerators.

Dark Current and Turn on/off Transients

An unanticipated beam loss mechanism at SNS, discovered during the commissioning phase, is due to dark current from the ion source. The ion source is pulsed at 60 Hz to create the required 38 mA peak H$^-$ ion beam, but it also emits a continuous low level beam of about 3 μA ("dark current") due to the 13-MHz CW RF transmitter used to help ignite the pulsed plasma. As the pulsed RF accelerator systems turn on and off at 60 Hz, the dark current is only partially accelerated during the on and off transients, which creates beam loss. Even when the dark current is properly accelerated it is undesirable. To mitigate this beam loss mechanism during normal operation, the LEBT chopper was modified to fully blank the head and tail of the beam pulse throughout the entire RFQ pulse length. Also, when the beam is turned off or the machine rep rate is less than 60 Hz, the low level RF system for the first DTL tank was modified to automatically shift the RF phase 180 degrees to prevent acceleration of the dark current beyond this point.

Both H$^+$ and H$^-$ linacs, without some kind of beam chopper system, may experience similar beam loss issues due to the ion source turn on/off transients and/or the RF turn on/off transients, and/or dark current from the ion source.

Beam Halo / Tails

A well-known source of beam loss, present at the Oak Ridge SNS as well as all other proton and H$^-$ accelerators, is beam halo or long tails on the beam distribution. When the halo / tails intercept the beam pipe apertures the beam is lost. A certain level of halo / tail formation is inevitable, but it is exacerbated by mismatched beams, structure resonances, parametric resonances, etc.

BEAM LOSS MITIGATION

Low-energy Scraping

At the Oak Ridge SNS we have found that beam scraping at low beam energy is an effective method to reduce beam loss due to halo / tails. In 2004-2005 left and right scrapers were added to the 2.5 MeV section of the warm linac, between the RFQ and the first DTL tank. By scraping ~3-4% of the beam we are able to reduce the beam loss in the linac and in the ring injection dump beam line by ~50%. We are now working on adding top/bottom scrapers this summer 2013, to be located nearby the left/right scrapers. Unfortunately there is not sufficient space in the SNS linac to add scrapers at other locations, for example between the warm and cold linac sections, but this may be desirable in the next-generation SCL designs.

Matching

To minimize beam loss, conventional wisdom dictates that the Twiss parameters of the beam should be matched when the beam passes from one lattice section to the next, e.g. from one FODO lattice to another FODO lattice. For a perfect beam distribution this makes good sense because it minimizes the required aperture and prevents phase

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space dilution. However, what if the beam distribution is not perfect, and the Twiss parameters of the core of the beam are different from the tails of the distribution? Perhaps it is better to mismatch the core of the beam to allow better transmission (lower beam loss) for the part of the distribution that causes beam loss (i.e. the tails or halo of the beam).

At SNS the low-loss tune does not have well-matched Twiss parameters for the core of the beam. Setting up the matched core case is a good place to start the beam loss minimization process, but the minimum-loss case can only be found by empirical adjustments to quadrupole gradients and the RF phases and amplitudes. With our present suite of beam instrumentation it is not possible to accurately characterize the parameters of the beam tails / halo because of the limited dynamic ranges of the measurements. Other high power accelerators, including LANSCE, PSI and TRIUMPF have also found that empirical tuning is required to achieve the best beam losses.

RADIO FREQUENCY QUADRUPOLE GAS DESORPTION

All modern high-power proton and H^- linacs use RFQ's for the first stage of acceleration, as opposed to older designs based on Cockcroft-Walton high-voltage generators. ISIS, Fermilab, and CERN have all switched from Cockcroft-Walton generators to RFQ's. The LANSCE linac still uses Cockcroft-Walton generators, but plans to replace the H^+ Cockcroft-Walton with an RFQ in the near future. A key challenge for future high power accelerators is to design more robust and more stable RFQ's.

In the early days of the power ramp up phase at the Oak Ridge SNS, the RFQ would often drift out of resonance, and the resultant large reflected power would trip off the RF system and cause excessive down time. The problem was traced to gas desorption from the copper vanes, which initiates an electric discharge that absorbs enough RF power to overheat the RFQ and throw it out of resonance [7]. The phenomenon is too fast to be controlled by the chilled-water resonance-control cooling system. Our solution at SNS was to extend the RF pulse width enough that it could be rapidly shortened when necessary, under automatic control by the low-level RF system, to stabilize the resonance control during localized micro-discharges. An example is shown in Fig. 4. We also endeavor to minimize the hydrogen gas pressure in the ion source.

The J-PARC RFQ also experienced gas desorption problems, which led to a temporary period of one day of beam-off vacuum conditioning for every two or three days of beam on. The final solution involved additional vacuum pumps, a change from oil-based rotary to oil-free scroll roughing pumps, an orifice in the LEBT to reduce gas flow, and a moisture filter in the hydrogen gas system of the ion source [8].

The gas desorption problem is exacerbated by hydrogen gas from the H^- ion source and by ion beam impingement (which is exacerbated by LEBT chopping). The lessons learned here are that high power RFQs should be designed with ample vacuum pumping; gas loading should be minimized by installing an aperture, as small as practical, between the ion source and the RFQ; and that it is important to test the RFQ together with the ion source. Solenoidal LEBT's, as opposed to electrostatic LEBT's, can help implement these design features.

At SNS we plan to change from an electrostatic to a solenoid LEBT, in part due to the RFQ gas desorption problem. J-PARC is replacing their RFQ with an improved version with better pumping speed. Project X and other new RFQs are being designed and manufactured with these lessons in mind.

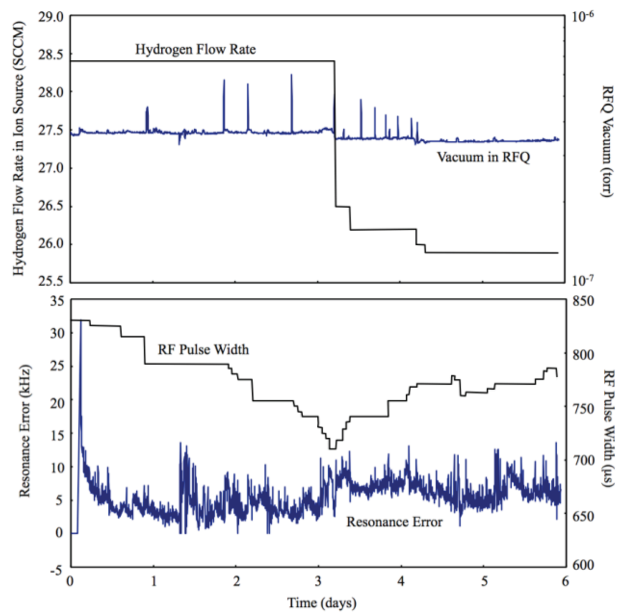

Figure 4: Example of Oak Ridge RFQ resonance error being controlled by automatic RF pulse width adjustments. Top: the hydrogen gas flow rate in the ion source is reduced midway through the plot. Bottom: In response to the drop in flow rate the RF pulse width is automatically increased and the resonance error becomes more stable. (Figure reproduced from ref. [7])

CHARGE EXCHANGE INJECTION

Charge exchange injection is a requirement for high-intensity multi-turn-injection storage rings and rapid-cycling synchrotrons. Compared to non-charge-exchange injection, the fractional beam loss is much lower (several percent for proton injection vs. 0.01% to 0.1% for charge-exchange injection), and it also has the additional advantage that it is possible to paint the beam into a reduced phase space. The LANSCE PSR, ISIS, the Oak Ridge SNS, and the J-PARC RCS all utilize charge-exchange injection. The CERN PS Booster is switching to charge-exchange injection, and the Fermilab Project X will utilize charge-exchange injection. A key challenge for future high power accelerators is to develop charge exchange injection systems that will survive in intense beam environments.

An undesirable side effect of charge-exchange injection is the partially-stripped H^0 excited states. In the cases where the injection beam energy is relatively low (e.g. ISIS, J-PARC), H^0 excited states are not a problem, because the injected beam power is low. But in the higher injection energy cases (e.g. LANSCE PSR, Oak Ridge SNS, Project X), the H^0 excited states can cause substantial beam loss. To manage the beam loss from these excited states the Oak Ridge SNS design places the stripper foil inside the magnetic field of one of the injection chicane dipoles (the Fermilab Project X adopts a similar design). However, the consequences of the stripped electron trajectories were not fully appreciated at the time. By design, the stripped "convoy" electrons circle around the magnetic field lines in a tight 12-mm gyroradius and travel to the bottom of the vacuum chamber where they are ideally captured by a specially designed electron catcher [9]. However, if the relative orientation between the foil and the catcher is not correct within a narrow margin, these convoy electrons are not caught and they can reflect back up to strike the stripper foil and/or the foil mounting bracket, and cause physical damage.

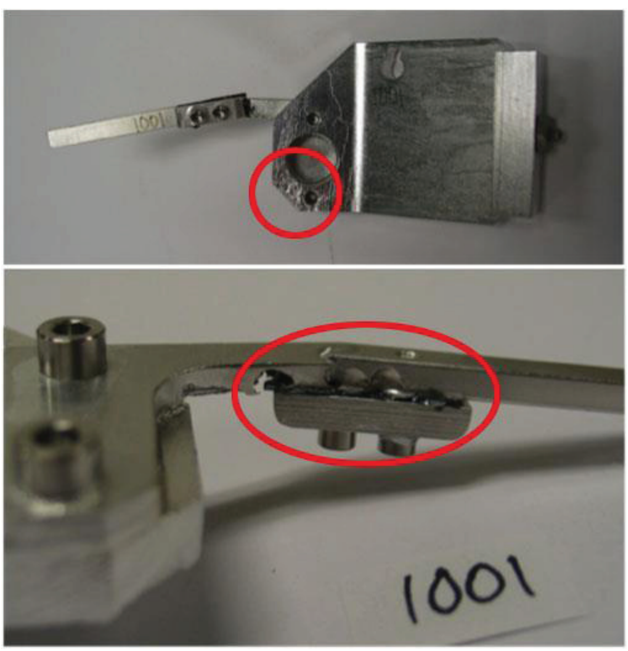

Figure 5: Photos of a failed stripper foil bracket showing reflected convoy electron damage (top) and arcing damage (bottom). (Photos reproduced from Ref. [10])

At SNS the relative orientation between the foil and the collector was well outside the acceptable margin, due to a combination of fabrication and installation errors, and also because the injection point was moved during commissioning [10]. As a result the convoy electrons reflected back up and damaged the foil brackets enough to cause the brackets to melt and fail, as shown in Fig. 5. Today we still have these reflected convoy electrons, but the foil bracket material has been changed from aluminum to titanium, which can withstand the convoy electron impact. An upgrade is planned to replace the electron collector with a new design that has a larger acceptance and that will be properly positioned.

Another interesting foil damage mechanism seen at SNS is due to the foil charging up from secondary electron emission. Although the SNS foil has good electrical connection to the foil mounting bracket and then to ground, the foil itself it is made of nanocrystalline diamond, which has poor electrical conductivity and is therefore more likely to charge up. The charge on the foil creates a high electric field between the foil (anode) and the bracket (cathode), and then sharp points on the bracket can become hot due to field emission, which initiates an arcing phenomenon known as cathode-spot in-vacuum breakdown. This type of arcing can occur even in a perfect vacuum. The arcing erodes the bracket supporting the foil and over time it can fatally damage the bracket, as shown in Fig. 5. To mitigate this foil failure mechanism the brackets are polished smooth to minimize the sharp points that initiate the process. The change to a titanium bracket also helped with the arcing problem due to its higher melting temperature.

Stripper foil arcing was also observed at the LANSCE PSR during experiments with a "postage stamp foil" that was supported only by carbon fibers stretched across a frame. The only path to ground was through the very thin fibers that had only poor electrical contact with the foil. Once this was discovered the PSR foil mounting method was changed to have one edge of the foil extend all the way to the mounting frame.

SUMMARY

The future is bright for high power proton and H^- accelerators. New machines with ever-higher beam powers are now moving from the design stage to construction. Thanks to good international cooperation the experiences gained and the lessons learned from today's machines are being applied to make the new machines better than ever.

REFERENCES

[1] A. Shishlo et al., Phy. Rev. Lett. 108, 114801 (2012).
[2] L. Rybarcyk et al., IPAC2012, New Orleans, Louisiana, USA, p. 3892 (2012).
[3] R. McCrady et al., LINAC2010, Tsukuba, Japan, p. 908 (2010).
[4] K. Hasegawa, LINAC2010, Tsukuba, Japan, p. 449 (2010).
[5] A. Miura et al., LINAC2010, Tsukuba, Japan, p. 587 (2010).
[6] A. Lechford, private communication, August 2012.
[7] S. Kim et al., PRST-AB 13, 070101 (2010).
[8] K. Hasegawa et al., IPAC2010, May 2010, p. 621 (2010).
[9] L. Wang et al., PRST-AB 8, 094201 (2005).
[10] M. Plum et al., PRST-AB 14, 030102 (2011).

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