Beam Loss Mechanisms in High Intensity Linacs

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Outline

• There are many different and interesting beam loss mechanisms in high-intensity H\(^+\) and H\(^-\) linacs
  – Intra-beam stripping
  – Residual gas stripping
  – H\(^+\) capture and acceleration
  – Field stripping
  – Black body radiation stripping
  – Dark current from ion source
  – Beam halo/tails (resonances, collective effects, etc.)
  – RF and/or ion source turn on/off transients

H\(^-\) only
SNS Accelerator Complex

**Front-End:**
Produce a 1-msec long, chopped, H⁻ beam

1 GeV LINAC

**Accumulator Ring:**
Compress 1 msec long pulse to 700 nsec

2.5 MeV

1000 MeV

Chopper system makes gaps

mini-pulse

Current

Liquid Hg Target

Injection

Extraction

RF

Collimators

945 ns

1 ms macropulse

Current
SNS Linac Structure

Length: 330 m (Superconducting part 230 m)

Production runs parameters:
Peak current: 38 mA
Repetition rate: 60 Hz
Macro-pulse length: 0.825 ms
Average power: 1 MW
Unexpected Beam Loss at the SCL

- During the SCL design work, it was expected that the SCL would have very little beam loss and very low radioactivation levels
  - Beam pipe aperture is about 10 times rms beam size, much larger than upstream warm linac
  - Vacuum is much better than in DTL, CCL
  - Residual gases hydrogen instead of nitrogen
- Found unexpected beam loss and activation during the SNS power ramp up
Unexpected Beam Loss at the SCL (cont.)

- Loss and activation were empirically reduced by lowering the SCL quad gradients about 40% – counterintuitive
- Intra-beam stripping mechanism (IBSt) proposed as cause of loss by V. Lebedev in 2010. Subsequently verified by experiment.
Intra Beam Stripping (Valeri Lebedev, FNAL)
(Talk at SNS, ORNL, October 2010)

Integral SCL losses estimation: 4x10^{-5} fractional loss

Measured SCL losses (2-7)x10^{-5} fractional loss

\[
dn / dt \propto \sigma \cdot n^2
\]
Signature of IBSt

✔ Beam loss proportional to $n^2$ (loss per Coulomb proportional to beam charge)

✔ Beam loss reduced by increasing beam size

❓ Beam loss much less for proton vs $H^-$ beam – now verified by experiment
Proton beam at the SNS Linac

- A 5 $\mu$g/cm$^2$ carbon foil will suffice, stripping efficiency is $\sim$99.98%.
- 0.6 keV kinetic energy loss for protons (spread is about 12 keV).
- 12% emittance growth expected.
- We can strip up to $\sim$45 $\mu$s 1 Hz beam without damaging the foil – enough to make accurate beam parameter measurements.
Carbon foil used for our measurements

Initially it is covered by a protective layer that we will burn off
Linac Optics for Protons

\[
\frac{dp}{dt} = q \cdot (E + v \times B)
\]

\[
B(E) = B_0(E_0) \cdot \exp(i \cdot w \cdot t + \phi_0)
\]

\[
E = 0
\]

- RF phases shifted by 180 deg.
- Used MEBT quadrupole magnets to match beam into the DTL by switching \(x \leftrightarrow y\) Twiss parameters
- \(H^+\) beam now has same beam dynamics as the \(H^-\) beam!
Beam at the end of SCL

Transverse Profiles of the Beam, HEBT WS04
Production Optics in SCL

Vertical and horizontal profiles are swapped for the proton beam, as expected
Twiss parameters measured at the end of SCL for H$^-$ and Protons

The horizontal and vertical Twiss parameters are swapped for the proton beam, as expected

<table>
<thead>
<tr>
<th></th>
<th>H$^-$ Horizontal</th>
<th>Proton Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{rms, norm}} ,[\text{pi-mm-mrad}]$</td>
<td>0.71</td>
<td>0.80</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>1.8</td>
<td>2.4</td>
</tr>
<tr>
<td>$\beta ,[\text{m}]$</td>
<td>10.0</td>
<td>11.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>H$^-$ Vertical</th>
<th>Proton Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{rms, norm}} ,[\text{pi-mm-mrad}]$</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>-2.2</td>
<td>-2.2</td>
</tr>
<tr>
<td>$\beta ,[\text{m}]$</td>
<td>12.9</td>
<td>12.9</td>
</tr>
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</table>
Two SCL optics for both $H^{-}$ and $H^{+}$

- Low-loss production tune uses quadrupole magnet gradients up to 40% less than the design tune
- Gradients used for the proton optics are almost identical to the $H^{-}$ optics, only adjusted to minimize the proton beam loss
SCL losses protons vs. $H^-$ for 30 mA design case

Proton losses are ~20x less than $H^-$ losses (but not zero)
SCL Losses vs. Peak Current

- $H^-$ beam loss is up to 20 times lower than $H^+$ beam loss
- Normalized $H^-$ beam loss is proportional to ion source current, consistent with IBSt expectations

IBSt also seen at LANSCE

(L. Rybarcyk et al., IPAC2012)
Residual gas stripping

- Beam loss caused by single (H\(^-\) to H\(^0\)) or double (H\(^-\) to H\(^+\)) stripping due to interaction with residual gas
- Can occur anywhere along linac, but cross sections are highest at low beam energies

Cross section for double stripping (H\(^-\) to H\(^+\)) is about 4% of cross section for single stripping (H\(^-\) to H\(^0\))

Residual gas stripping (cont.)

- **SNS**
  - Stripping in CCL causes loss in the SCL
  - Hot spot in transport line to ring is likely due to gas stripping

- **J-PARC**
  - Was a cause of significant loss in linac, in early days
  - Fixed by adding pumping to S-DTL and future ACS section

- **LANSCE**
  - Measured to cause about 25% of the $H^-$ beam loss along linac

- **ISIS**
  - Not significant when vacuum is good, but can be significant if there are vacuum problems

(Courtesy J. Galambos)
**H⁺ capture and acceleration**

- Due to double-stripping (H⁻ to H⁰ to H⁺) usually at low beam energy (where cross sections are highest and where capture into RF buckets is more likely)

- Stopped by even (e.g. 2, 4, etc.) frequency jumps in linac RF
H\(^+\) capture and acceleration (cont.)

- May be present to a small degree at SNS
  - See loss at 402.5 to 805 MHz frequency jump, but also expect loss due to the lattice transition. Not a problem for 1 MW operations.

- Seen at J-PARC linac
  - Entire linac all at same frequency (until future energy upgrade), so H\(^+\) is accelerated and transported to the end of the linac, and lost in arc leading to ring
  - Cured by adding chicane magnets in MEBT

- Seen at LANSCE
  - Significant source of beam loss if there is a vacuum leak in the LEBT
Field stripping

- Lorentz-transformed magnetic field looks like electric field in rest frame of beam particles
- Loosely-bound electrons on H\(^-\) particles can be stripped off

\[
\frac{df}{ds} = \frac{B(s)}{A1} e^{-A2/\beta\gamma cB(s)}
\]

\(A1 = 2.47E-6\) V sec/m
\(A2 = 4.49E9\) V/m

- Seen in ISIS 70 MeV transport line to ring, level of <1%
# Beam loss in H⁻ linacs

<table>
<thead>
<tr>
<th>Beam loss mechanism</th>
<th>SNS</th>
<th>J-PARC</th>
<th>ISIS</th>
<th>LANSCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intra-beam stripping</td>
<td>Yes, dominant loss in linac</td>
<td>Not noted as significant</td>
<td>Not noted as significant</td>
<td>Yes, significant, 75% of loss in CCL</td>
</tr>
<tr>
<td>Residual gas stripping</td>
<td>Yes, moderate stripping in CCL and HEBT</td>
<td>Yes, significant, improved by adding pumping to S-DTL and future ACS section</td>
<td>Yes, not significant when vacuum is good, but can be significant if there are vacuum problems</td>
<td>Yes, significant, 25% of loss in CCL</td>
</tr>
<tr>
<td>H⁺ capture and acceleration</td>
<td>Possibly, but not significant concern</td>
<td>Yes, was significant, cured by chicane in MEBT</td>
<td>Not noted as significant</td>
<td>Yes, significant if there is a vacuum leak in the LEBT</td>
</tr>
<tr>
<td>Field stripping</td>
<td>Insignificant</td>
<td>Insignificant</td>
<td>Yes, &lt;1% in 70 MeV transport line, some hot spots</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Black body radiation stripping</td>
<td>Would be a problem if FNAL project X goes with the 8 GeV H⁻ beam option</td>
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Dark current beam loss at SNS

- Very low H\(^-\) beam current is emitted continuously by the SNS ion source due to the 13 MHz CW RF used to facilitate the plasma ignition

- A portion of this beam is lost due to RF turn-on and turn-off transients, not seen by BLMs due to cavity x-ray background auto-subtraction

- In early days of SNS this caused excessive end group heating in the SCL cavities

- Cured by reversing phase of first DTL tank when beam is turned off, and by using the chopper to blank the head and tail of the beam

- RF turn-on and turn-off transient losses present for any pulsed linac without chopper, H\(^+\) or H\(^-\)
Beam halo / tails is another significant cause of beam loss, low energy scraping is a big help

- The effectiveness of the scrapers varies with the ion source and the machine lattice
- We are working to reduce tails/halo by optimizing the match of the beam into the DTL, CCL, SCL, and HEBT

Beam Charge (typically scrape ~3-4% of the beam)

Warm linac beam loss (~55% lower loss at this location)

Ring Injection Dump beam loss (~57% lower loss at this location)

Scrapers out

Scrapers in

time

Courtesy J. Galambos
Summary

• We measured the beam loss for H− and H+ beams in the SNS SCL
  – The H+ loss is significantly less than H− loss, due to intra-beam stripping (IBSt)
  – Most of the SCL H− beam loss at SNS is caused by the IBSt
  – IBSt also seen at LANSCE

• Other interesting beam loss mechanisms seen in high intensity linacs include:
  – Residual gas stripping
  – H+ capture and acceleration
  – Field stripping
  – Dark current from the ion source
  – Beam halos / tails
Summary (cont.)

• At SNS we plan to use our flexible lattice and extensive suite beam instrumentation to explore the linac design “rules” to minimize beam loss, like $\sigma_{0t}$ and $\sigma_{0l}$ always $<90^\circ$ and never cross, continuous $k_{0t}$ and $k_{0l}$, equipartitioning, ...

• SNS is a great place to benchmark simulation codes, and we welcome your involvement

• This talk focused on beam loss in the linac. The ring is another story…
• Backup slides
Example: beam tails are created in DTL

Semi-log scale

Horizontal

Mismatched production tune
Better matched beam

Vertical

Start of DTL
(7.5 MeV)

Beam tails improved but still present

End of DTL
(86 MeV)

Courtesy C. Allen