The Case of the Lost Beam

Beam on the Loose at SNS

J. Galambos, A. Aleksandrov, M. Plum, A. Shishlo (SNS), E. Laface (ESS), V. Lebedev (FNAL)

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The Spallation Neutron Source (SNS) Superconducting RF Linac

- SNS has a superconducting RF linac for H- acceleration
- Designed to accelerate H- from 186 MeV to 1 GeV
- High power linac (MW)
“As for the superconducting linac, the bore radius aperture is much larger than the nominal beam. Simulations and stripping calculations give a negligible amount of losses. On the other hand, one should be very cautious with our expectations as there is no experience with superconducting proton linacs up to now.”

“Accelerator physics model of expected beam loss along the SNS accelerator during normal operation”

Did the beam have any known enemies?
SNS design stage: The Expectation

- Multi particle simulations did not predict beam loss
  - Maximum extent was far from aperture
Nature of the Beam Loss

- The activation pattern: local hot spots are in warm sections between cryomodules

What did the lost beam look like?

- The activation pattern: local hot spots are in warm sections between cryomodules
SCL Residual Activation Global Distribution

Activation in warm sections along the SCL

• Remarkably uniform!
SCL Activation: The History

- Even at low beam power, we began to measure SCL activation from beam loss
  - Does not limit operational power

When did you first notice the beam was lost?
How much beam is really lost??

It’s difficult to create a simulation that produces similar loss response as production conditions.

Solution: Use available pulsed laser pulses to strip $10^{-6}$ of the beam.

- Implication is that not much beam is lost: $\sim 5 \times 10^{-5}$ throughout the superconducting linac.
How Is Beam Getting Lost ???

• Possible beam loss causes:
  – Longitudinal halo
  – Transverse halo from the source
  – Transverse mis-match
  – $H^-$ stripping
  – Non-linear fields

OK – Round up the usual suspects!
Longitudinal Halo Impact on Beam Loss

- We have measured a long (30-40 deg) longitudinal tail at the SCL entrance.
- Loss is sensitive to warm linac RF setup.

Courtesy Y. Zhang
Transverse halo: MEBT scraping

- 2 horizontal MEBT scrapers at SNS
  - Reduces lattice transition and ring injection dump losses – no uniform reduction throughout the SCL
  - Effectiveness in loss reduction varies from source to source

DTL profile, log scale

MEBT Emittance without scraping

MEBT Emittance with scraping

Courtesy A. Aleksandrov
**H⁻ Stripping Loss Contribution**

- Magnetic stripping, RF field stripping, calculated to have small effect

**Residual gas stripping:**
Measured beam loss sensitivity to upstream vacuum level:

![Graph showing beam loss sensitivity to vacuum level](image)

- Minimal impact on beam loss from residual gas stripping
A clue: reduced transverse focusing lowers beam loss!

- Why does making the beam bigger reduce loss???
The Insight: intra-beam stripping (IBSt)

V. Lebedev’s fortuitous visit to SNS

\[ \frac{dn}{dt} \propto \sigma_{\text{strip}} \times n \]

- Simple estimates of loss rates are consistent with measured loss levels
  - Observed at CERN in 1980’s
- Predicted loss magnitude is right order for SNS
IBSt really seems to make sense, but ...  
Доверяй, но проверяй  (trust, but verify)

So, let’s put a proton beam in the SNS SCL

• Tried to convert an $\text{H}^-$ source to an $\text{H}^+$ source: no luck
• Use an insertable stripper foil upstream of the DTL
  – Use 10 independent focusing power supplies in the transport from RFQ to (permanent magnet) DTL for transverse match
  – Move RF phases 180 degrees
Proton Beam at the SNS Linac

- 5 $\mu g/cm^2$ carbon foil will strip > 99.9% H$^-$
  - 0.6 keV kinetic energy loss for protons
  - ~50 $\mu s$ pulse without damaging the foil
  - 12% emittance growth expected from scattering

Swap H$^-$ and proton Twiss parameters here
Measured Twiss Parameters at the End of SCL for H- and Protons

- **H-**
  - Horizontal: $\varepsilon = 0.71$ mrad, $\alpha = 1.8$ mrad, $\beta = 10.0$ mrad
  - Vertical: $\varepsilon = 0.55$ mrad, $\alpha = -2.2$ mrad, $\beta = 12.9$ mrad

- **Protons**
  - Horizontal: $\varepsilon = 0.80$ mrad, $\alpha = 2.4$ mrad, $\beta = 11.9$ mrad
  - Vertical: $\varepsilon = 0.47$ mrad, $\alpha = -2.0$ mrad, $\beta = 10.3$ mrad

The horizontal and vertical planes are switched for the proton beam – as expected. Transverse profiles at the end of the SCL are also swapped – as expected.
Proton transmission is not 100%
It is peak current dependent
We lose beam in MEBT-DTL

Transmission to SCL, 2011.09.25
Measured SCL Losses Protons vs. H⁻

30 mA, production lattice (weak focusing)

- Significant reduction in loss for the proton beam
Measured SCL Losses Protons vs. H⁻

30 mA, design lattice (strong focusing)

- Even more significant reduction in loss for the proton beam
SCL Losses vs. Beam Current

- H- normalized loss shows linear dependence on current
  - Consistent with IBSt scaling
- Proton normalized loss is independent on intensity
A New H⁻ Beam Loss Mechanism is Identified

- IBSt seems to be the primary contributor to beam loss in the SNS SCL.

- This loss mechanism will be considered in future high power ion accelerators.
  - Situation is good for proton accelerators.

- Direction for SNS:
  - Reduce transverse halo, better match and attempt to make the beam even bigger.
  - Add more transverse scrapers.

Thanks!
Backup
Upstream Halo Scraping Impact Loss at Isolated Locations

- Beam Charge (typically scrape ~3-4% of the beam)
- Warm linac beam loss (~55% lower at this point)
- Ring Injection Dump beam loss (~57% lower at this point)

- The effectiveness of the scrapers varies with the ion source and the machine lattice
MEBT Sizes: Production vs. Optimized

Prediction: Horizontal beam size at the foil will change from about 1.7 mm to 2.6 mm due to the QH01 field change from 34.5 to 2.5 T/m. The vertical size will be almost the same.

Not a problem: the foil is big enough to accommodate this!