# Beam Loss Mechanisms in High Intensity Linacs


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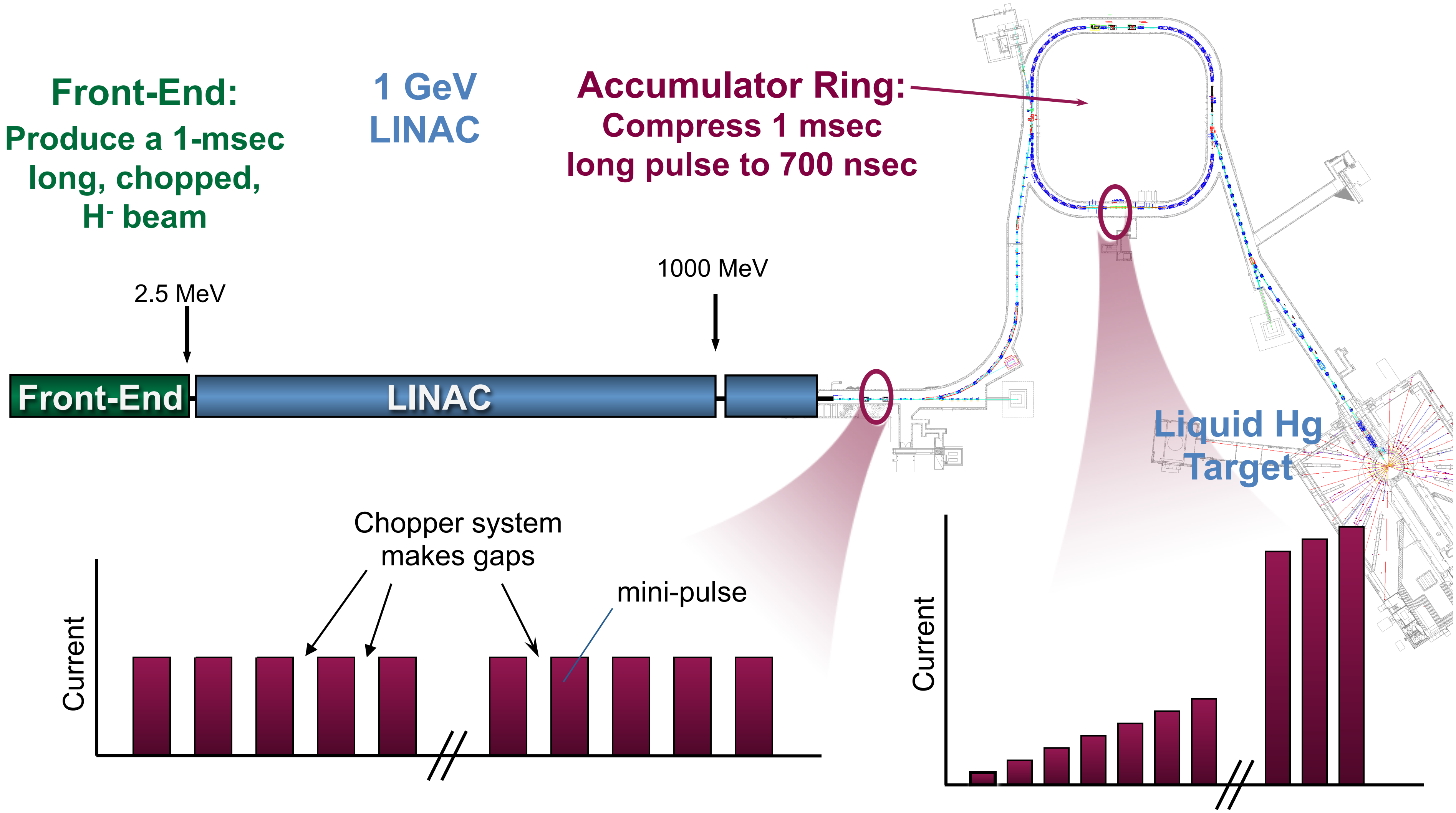
# Outline

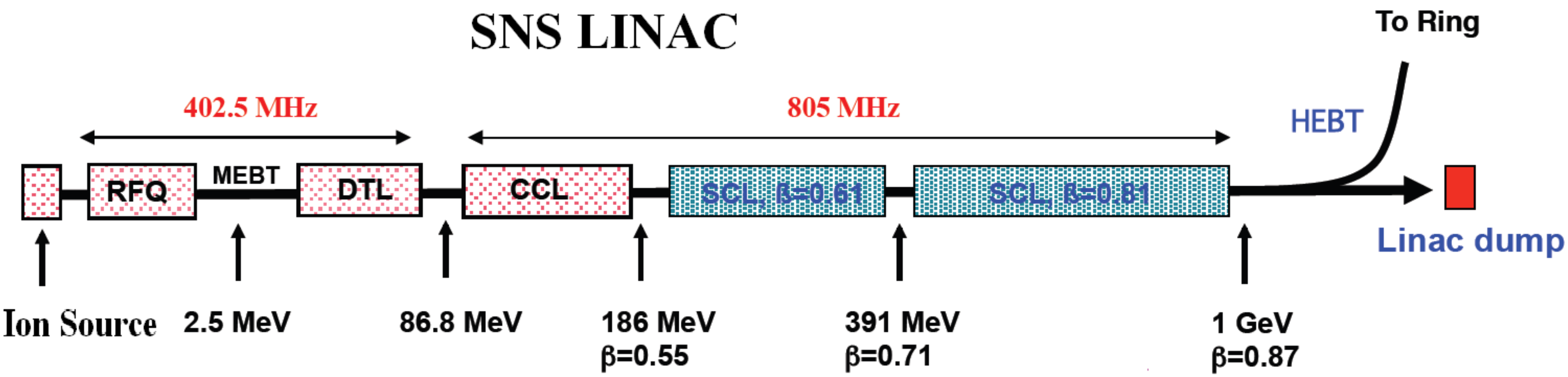
- There are many different and interesting beam loss mechanisms in high-intensity $H^+$ and $H^-$ linacs
  - Intra-beam stripping
  - Residual gas stripping
  - $H^+$ capture and acceleration
  - Field stripping
  - Black body radiation stripping
  - Dark current from ion source
  - Beam halo/tails (resonances,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

$H^-$ only

# SNS Accelerator Complex



# SNS Linac Structure



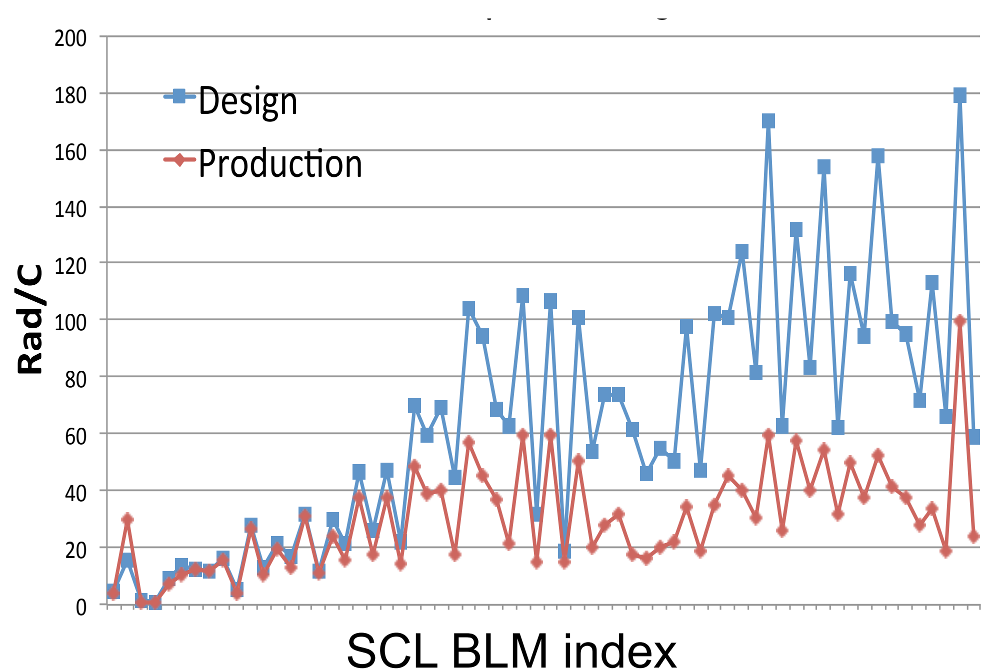

**Length: 330 m (Superconducting part 230 m)**

**Production runs parameters:**

**Peak current: 38 mA**
**Repetition rate: 60 Hz**
**Macro-pulse length: 0.825 ms**
**Average power: 1 MW**

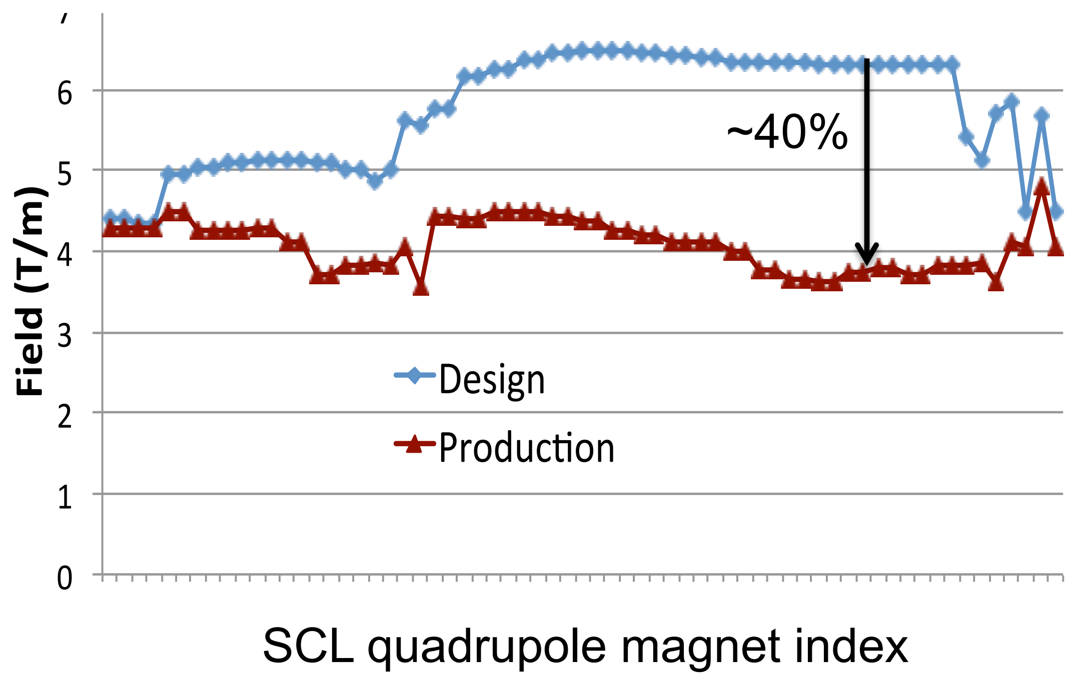
# Unexpected Beam Loss at the SCL

- 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



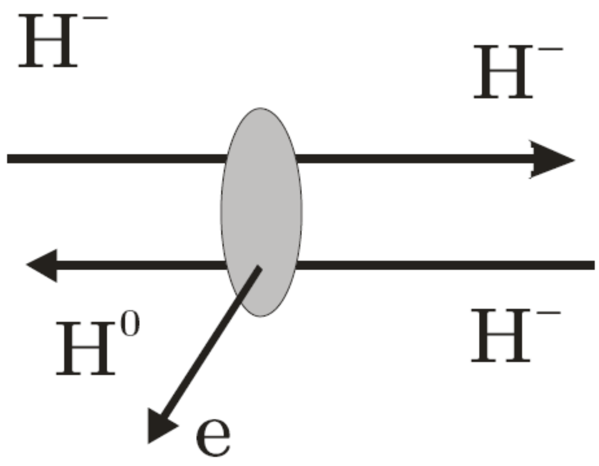
# Unexpected Beam Loss at the SCL (cont.)

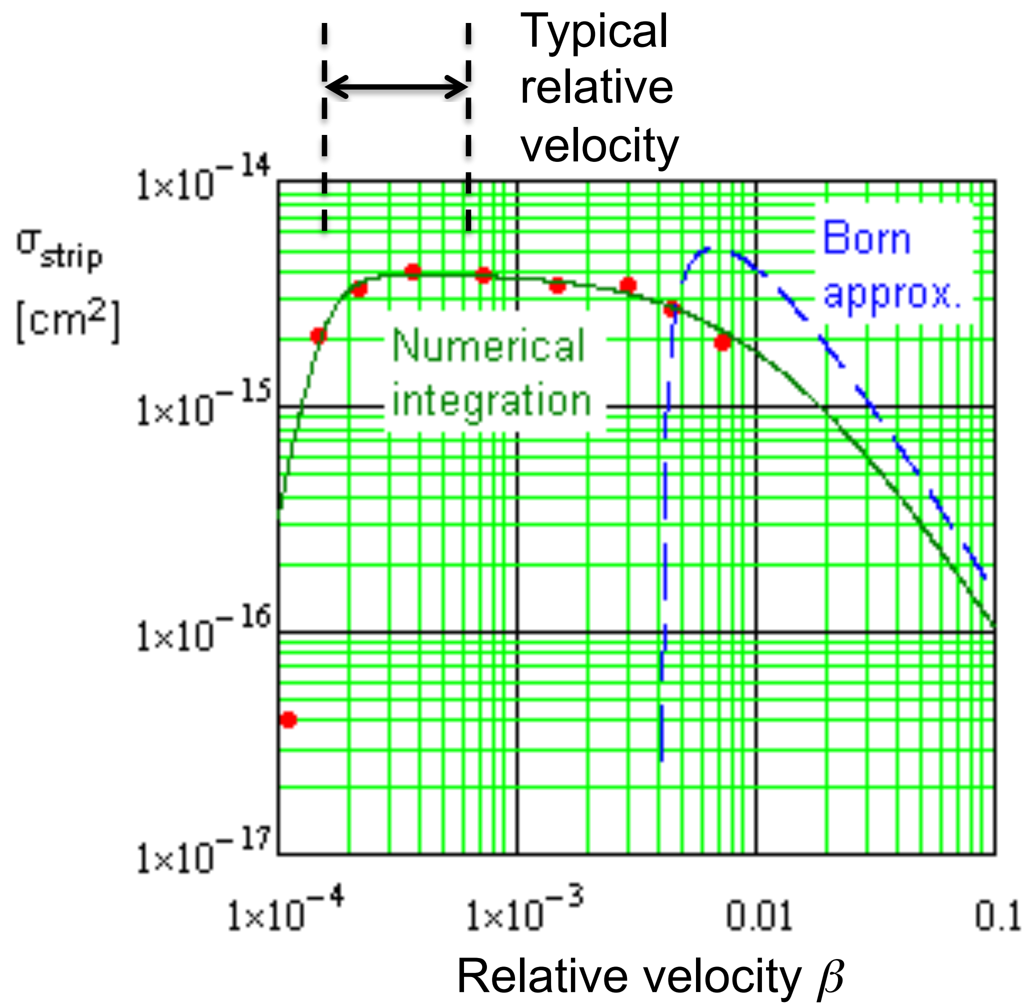
- **Loss and activation were empirically reduced by lowering the SCL quad gradients about 40% – counterintuitive**
- **Intra-beam stripping mechanism (IBSt) proposed as cause of loss by V. Lebedev in 2010. Subsequently verified by experiment.**



# Intra Beam Stripping (Valeri Lebedev, FNAL)

(Talk at SNS, ORNL, October 2010)




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

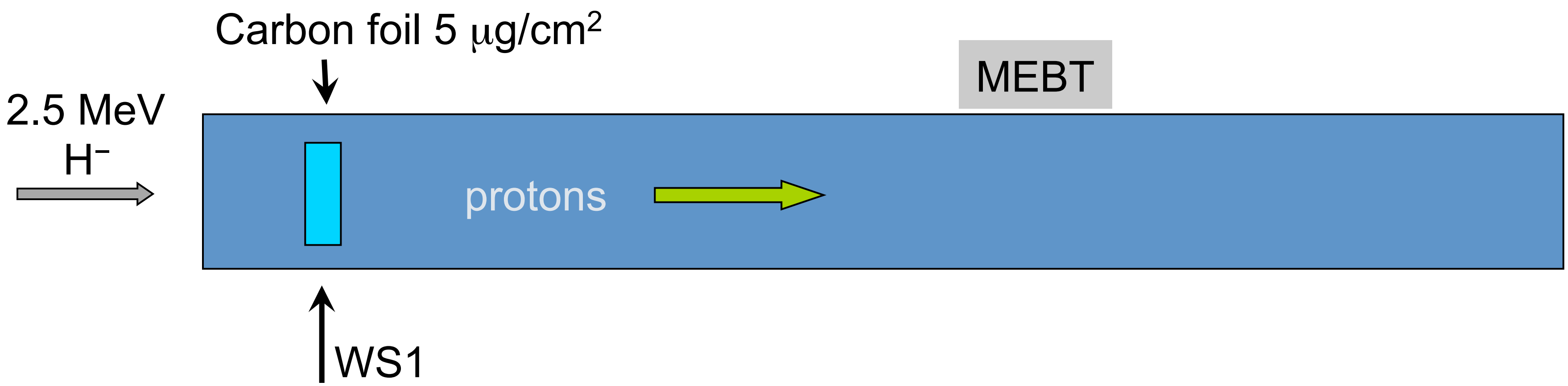
**Measured SCL losses**
**$(2\text{-}7)x10^{-5}$ fractional loss**

$$dn/dt \propto \sigma \cdot n^2$$

# Signature of IBSt

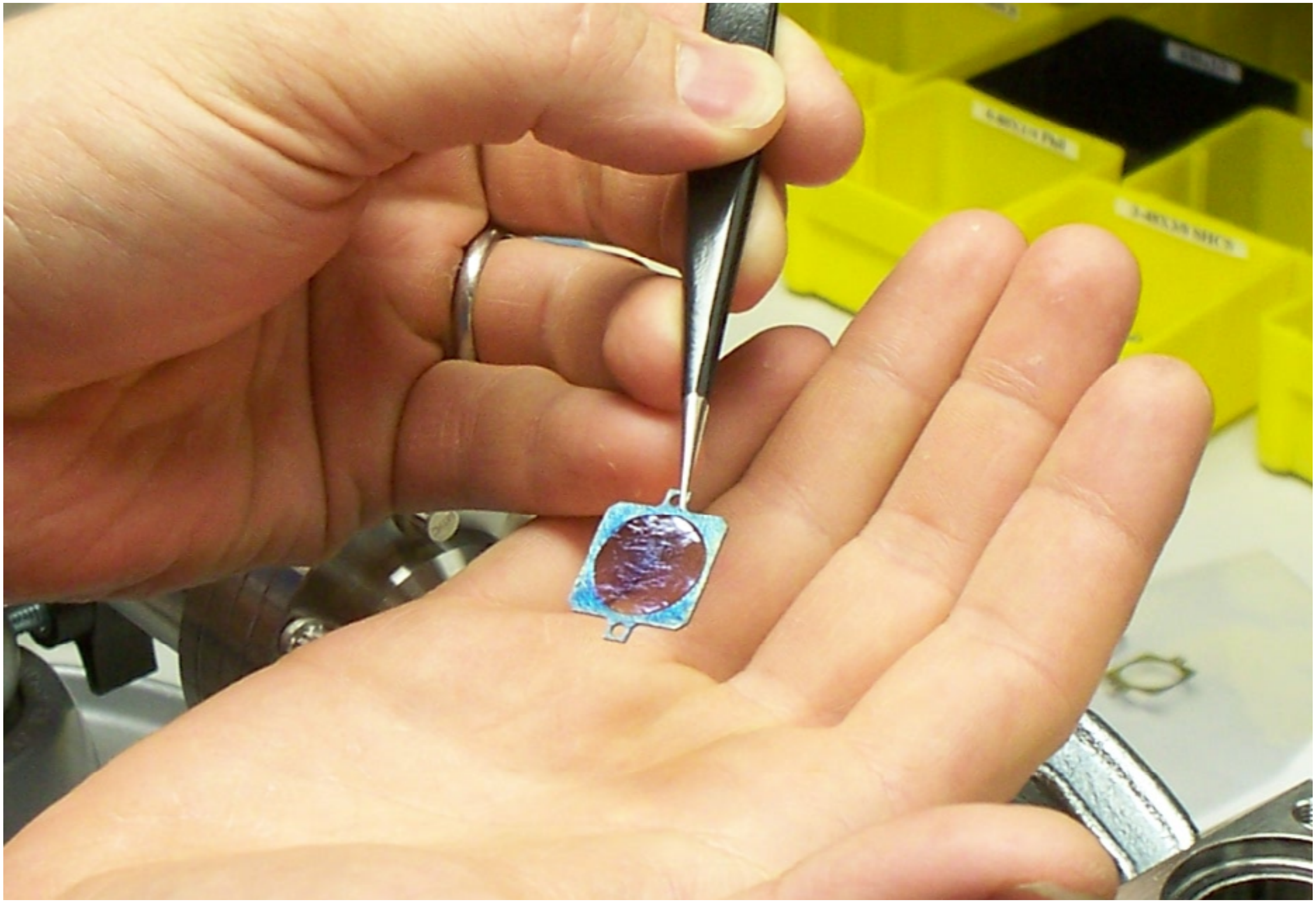
- ✔ Beam loss proportional to $n^2$ (loss per Coulomb proportional to beam charge)
- ✔ Beam loss reduced by increasing beam size
- ? Beam loss much less for proton vs $H^-$ beam – now verified by experiment

# Proton beam at the SNS Linac




- A 5 μg/cm² carbon foil will suffice, stripping efficiency is ~99.98%
- 0.6 keV kinetic energy loss for protons (spread is about 12 keV)
- 12% emittance growth expected
- We can strip up to ~45 μs 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

Charge of the particle

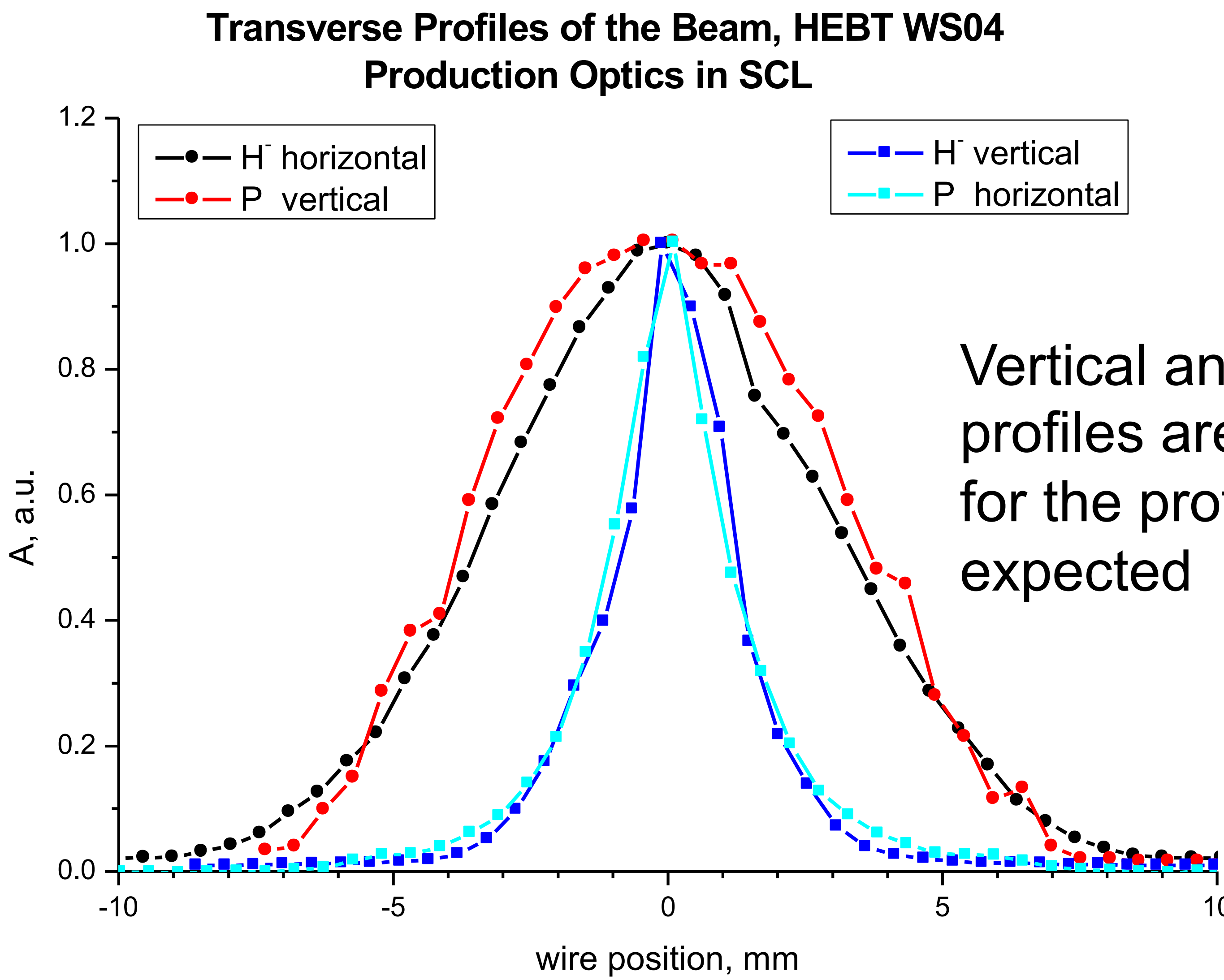
$$d\vec{p}/dt = q \cdot (\vec{E} + \vec{v} \times \vec{B})$$

$$\vec{B}(\vec{E}) = \vec{B}_0(\vec{E}_0) \cdot \exp(i \cdot w \cdot t + \phi_0)$$ **Inside RF Cavities**

$$\vec{E} = 0$$ **Inside quads**

- RF phases shifted by 180 deg.
- Used MEBT quadrupole magnets to match beam into the DTL by switching x⇔y Twiss parameters
- $H^+$ beam now has same beam dynamics as the $H^-$ beam!

# Beam at the end of SCL




Vertical and horizontal profiles are swapped for the proton beam, as expected

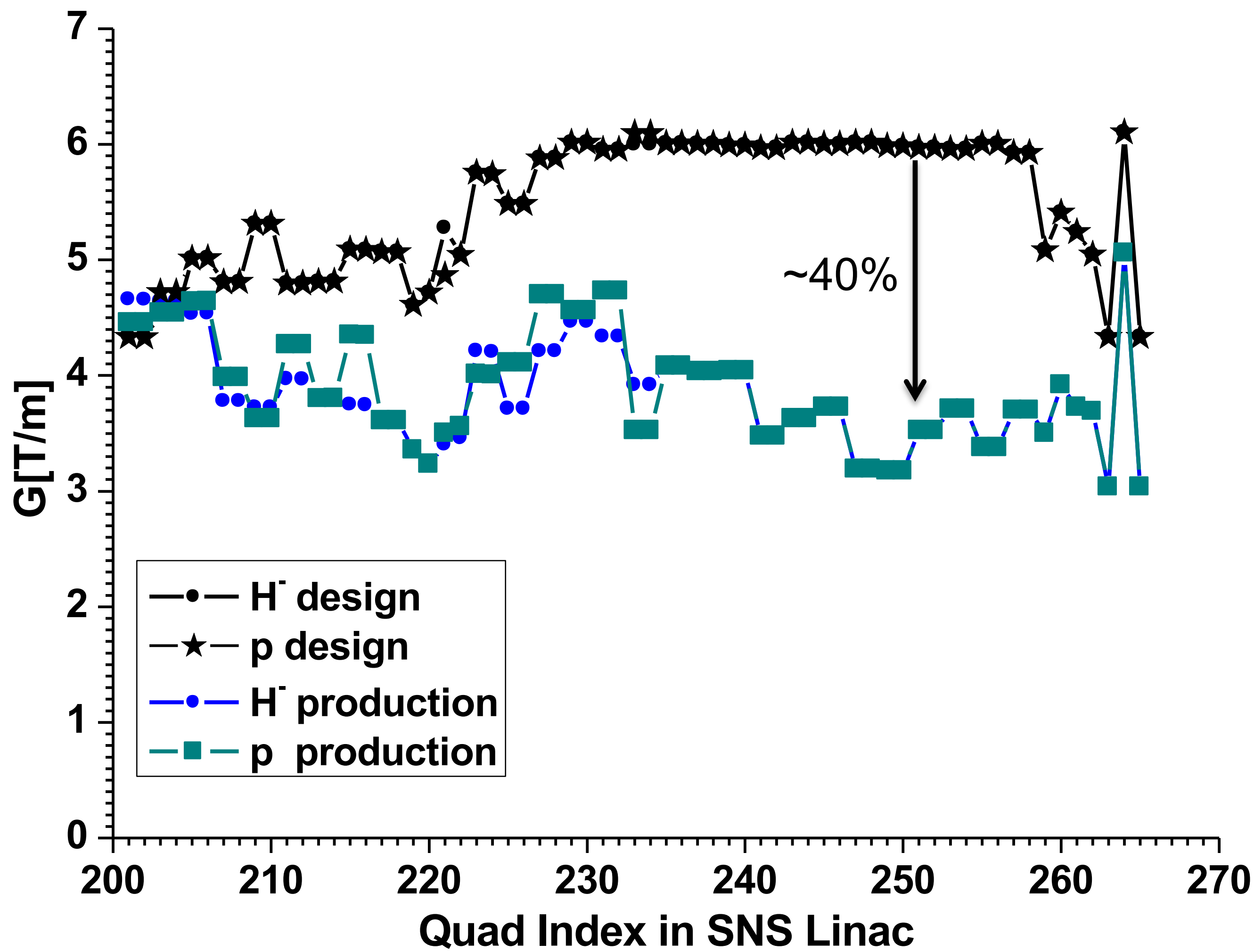
# Twiss parameters measured at the end of SCL for $H^-$ and Protons

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

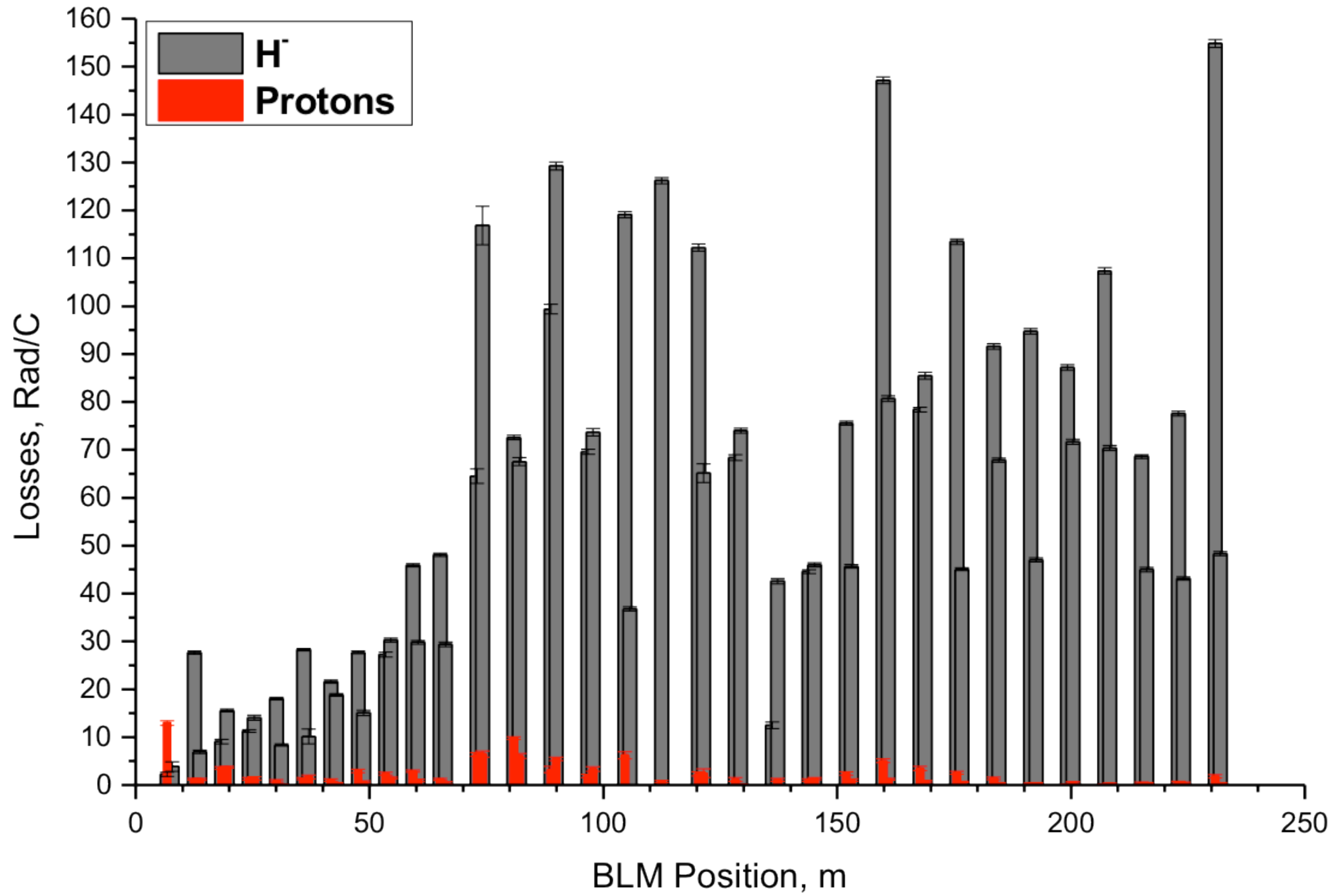
| | $H^-$ Horizontal | Proton Vertical |
|---|---|---|
| $\varepsilon_{rms,\ norm}$ [pi-mm-mrad] | 0.71 | 0.80 |
| $\alpha$ | 1.8 | 2.4 |
| $\beta$ [m] | 10.0 | 11.9 |
| | | |
| | $H^-$ Vertical | Proton Horizontal |
| $\varepsilon_{rms,\ norm}$ [pi-mm-mrad] | 0.55 | 0.55 |
| $\alpha$ | -2.2 | -2.2 |
| $\beta$ [m] | 12.9 | 12.9 |

# 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



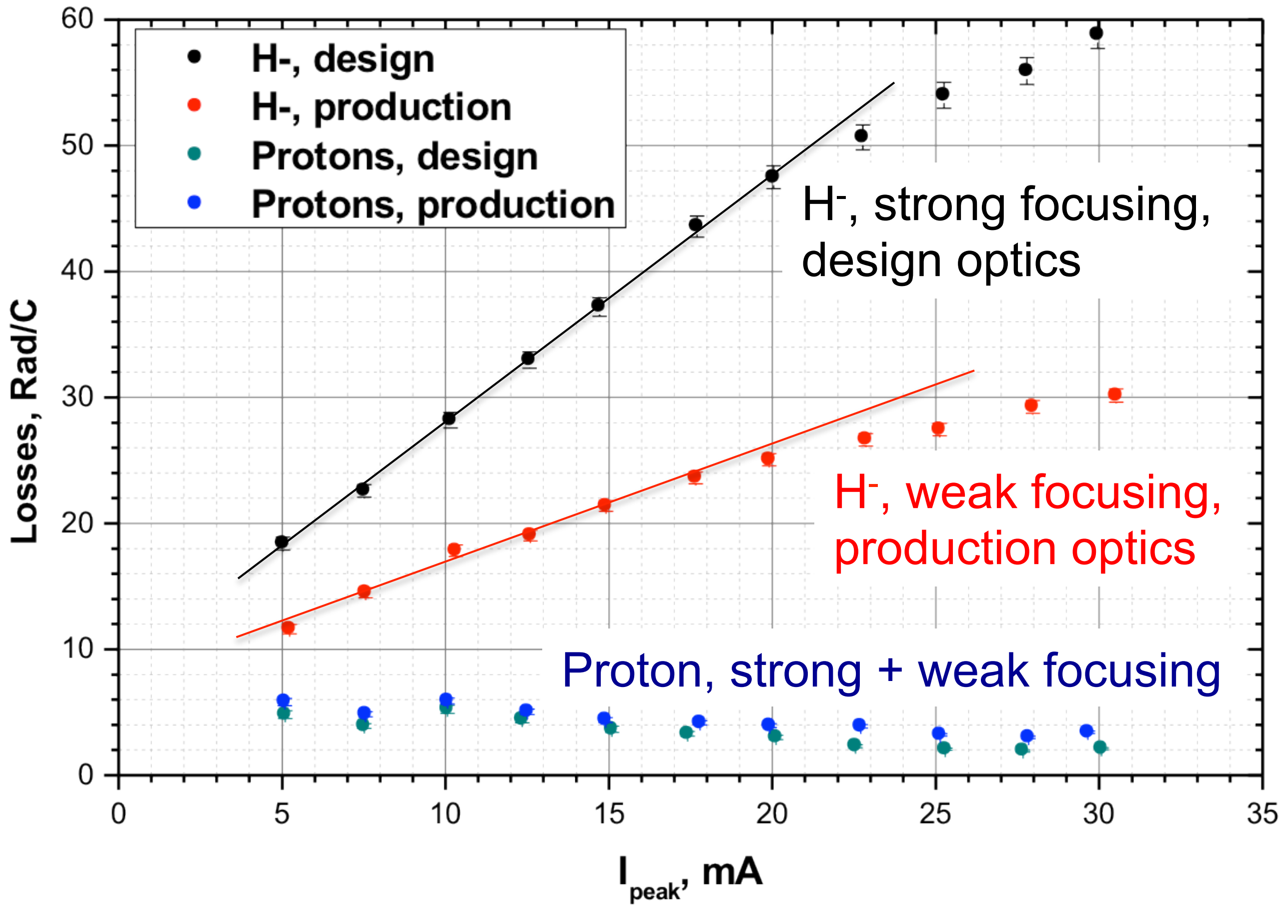
# SCL losses protons vs. $H^-$ for 30 mA design case




Proton losses are ~20x less than $H^-$ losses (but not zero)

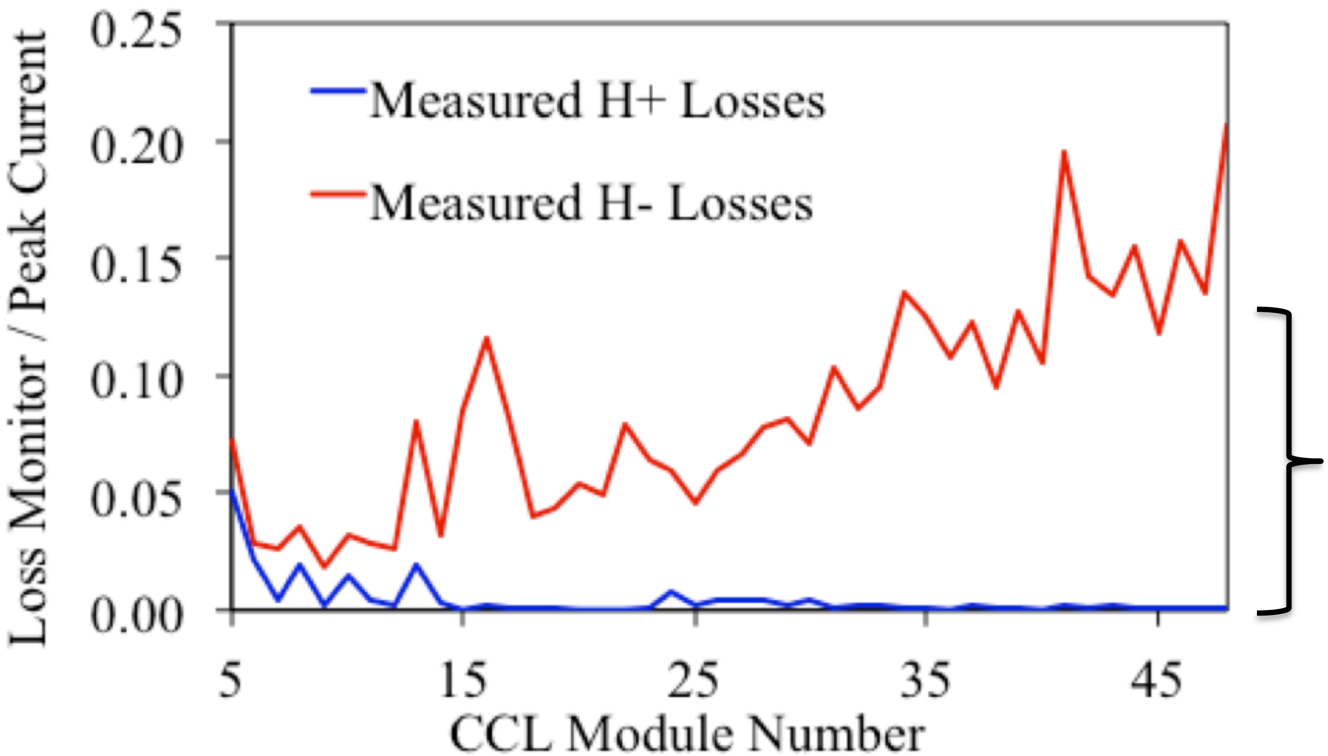
# SCL Losses vs. Peak Current

- $H^-$ 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




"First Observation of Intrabeam Stripping of Negative Hydrogen in a Superconducting Linear Accelerator," A. Shishlo, J. Galambos, A. Aleksandrov, V. Lebedev, and M. Plum, Phys Rev Letters 108, 114801 (2012).

# IBSt also seen at LANSCE

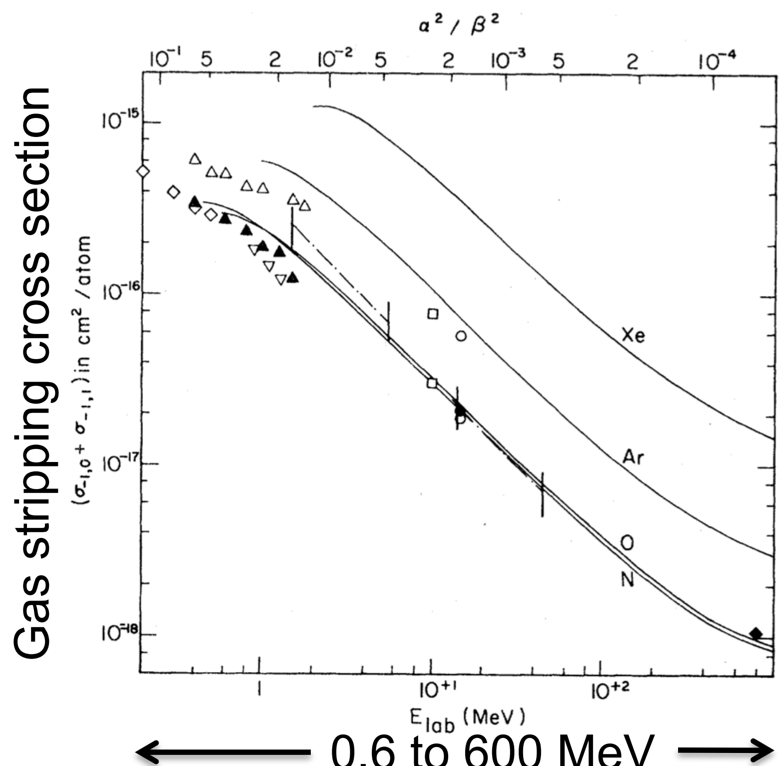



75% of difference due to IBSt, 25% to residual gas stripping

*(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**

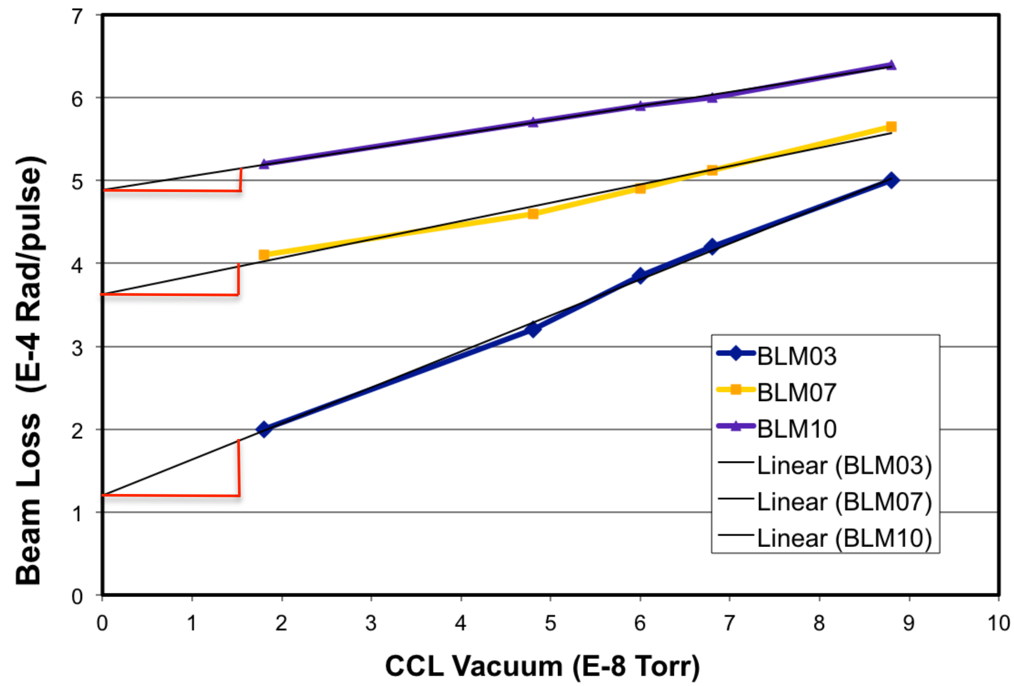



Cross section for double stripping ($H^-$ to $H^+$) is about 4% of cross section for single stripping ($H^-$ to $H^0$)

*G. Gillespie, Phys. Rev. A 15 (1977) 563*
*G. Gillespie, Phys. Rev. A 16 (1977) 943*

# 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

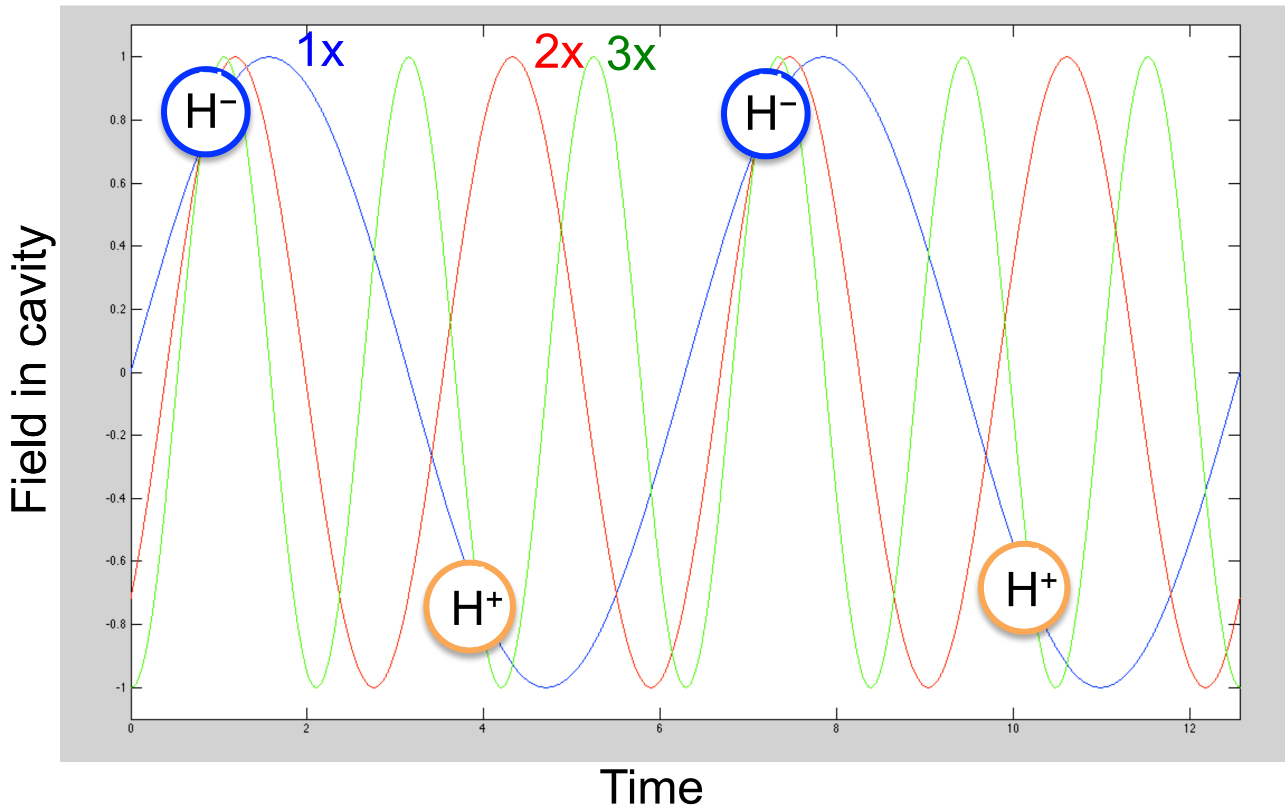



(Courtesy J. Galambos)

- 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

# $H^+$ capture and acceleration

- Due to double-stripping ($H^-$ to $H^0$ 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.)

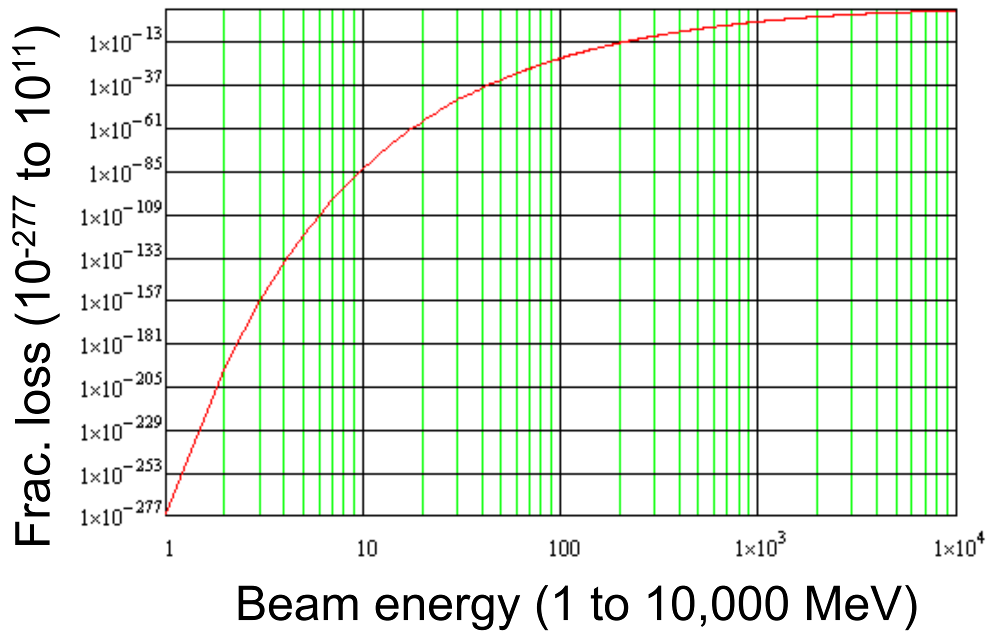
- May be present to a small degree at SNS
  - See loss at 402.5 to 805 MHz frequency jump, but also expect loss due to the lattice transition. Not a problem for 1 MW operations.
- Seen at J-PARC linac
  - Entire linac all at same frequency (until future energy upgrade), so $H^+$ is accelerated and transported 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

$$\frac{df}{ds} = \frac{B(s)}{A1} e^{-A2/\beta\gamma c B(s)}$$

$A1 = 2.47\text{E-6 V sec/m}$
$A2 = 4.49\text{E9 V/m}$




- Seen in ISIS 70 MeV transport line to ring, level of <1%

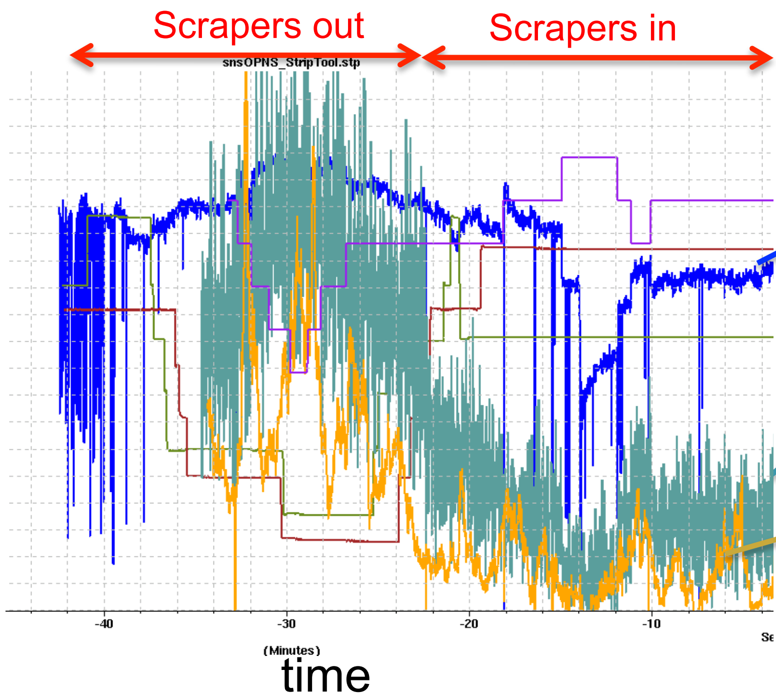
# Beam loss in $H^-$ linacs

| Beam loss mechanism | SNS | J-PARC | ISIS | LANSCE |
|---|---|---|---|---|
| **Intra-beam stripping** | Yes, dominant loss in 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 |
| **Black body radiation stripping** | Would be a problem if FNAL project X goes with the 8 GeV $H^-$ beam option | | | |

# 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




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)

- **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**



Courtesy J. Galambos

# Summary

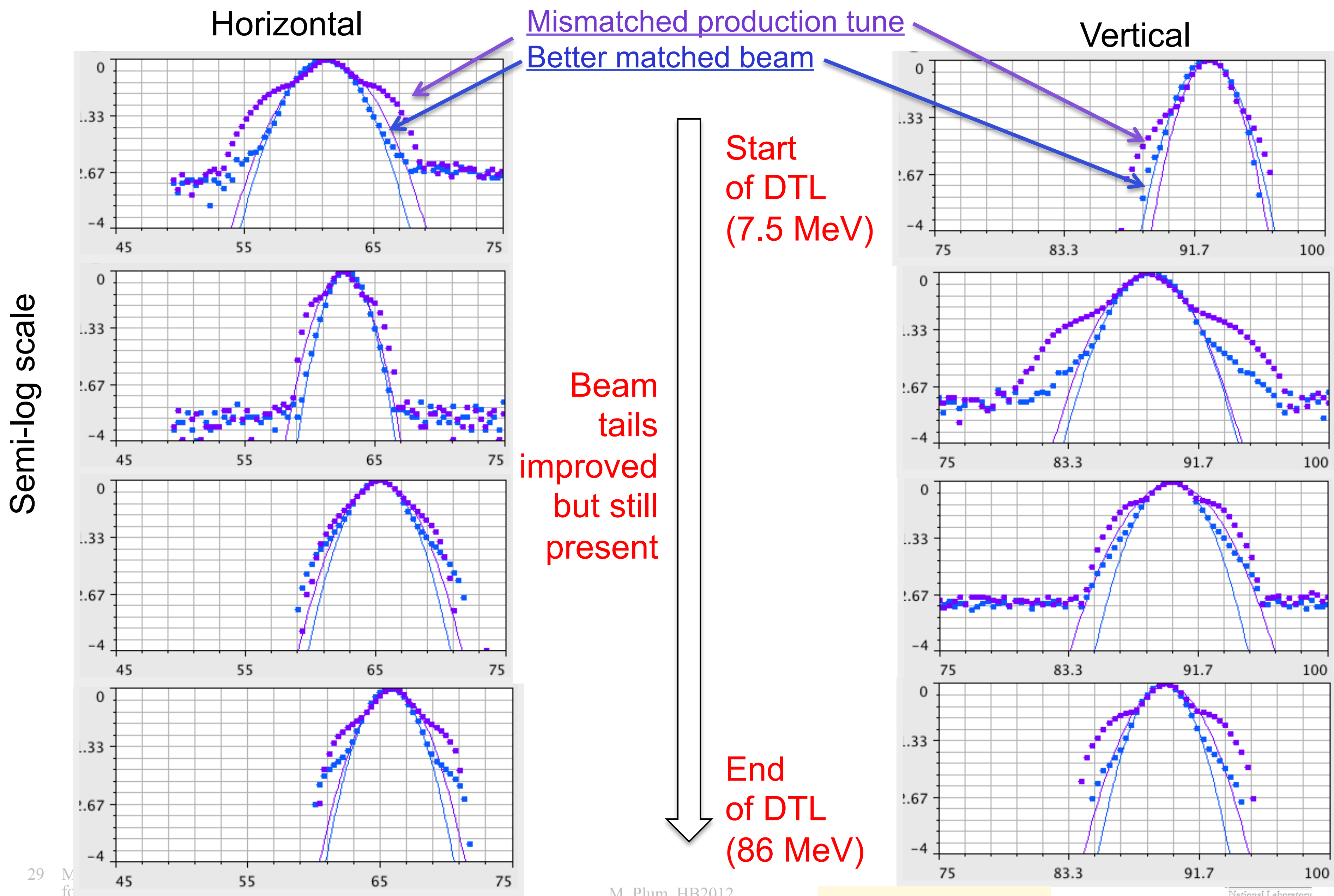
- We measured the beam loss for $H^-$ and $H^+$ beams in the SNS SCL
  - The $H^+$ loss is significantly less than $H^-$ loss, due to intra-beam stripping (IBSt)
  - Most of the SCL $H^-$ beam loss at SNS is caused by the IBSt
  - IBSt also seen at LANSCE
- Other interesting beam loss mechanisms seen 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 <90º and never cross, continuous $k_{0t}$ and $k_{0l}$, equipartioning, …
- 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




Courtesy C. Allen