Challenges Facing High Power Proton Accelerators

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Introduction

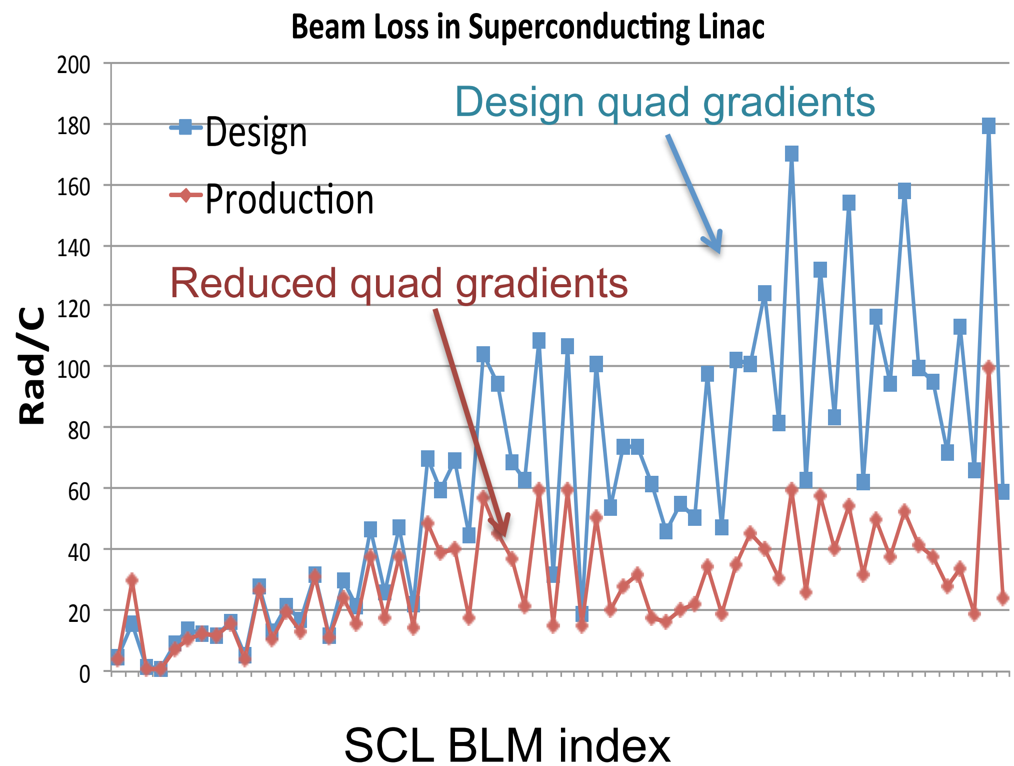
- Many new proton / H^- accelerators are planned and in progress
  - ESS, Project-X, CERN SPL, MYRHHA, CSNS, ADS's in India and China
- Challenges include beam losses, high power RFQs, charge exchange injection
- Many valuable lessons learned from today's high power proton / H^- accelerators that can benefit the new accelerators
  - SNS, J-PARC, PSI, ISIS, LANSCE
  - Most of the new machines mentioned above are based on linacs with superconducting rf cavities
  - SNS has the first and only high power proton / H^- superconducting linac
  - Not included in this talk: SCL tuning methods, SCL trip rates, superconducting RF cavity damage due to errant beams

Outline

- The beam loss challenge
  - Intra-beam stripping, residual gas stripping, H^+ capture and acceleration, dark current
- Beam loss mitigation
  - Low energy scraping, mis-matched beams
- The high power RFQ challenge
  - Gas desorption, fast resonance control
- The charge exchange injection challenge
  - Reflected convoy electrons, vacuum breakdown
- The high power target challenge
- Summary

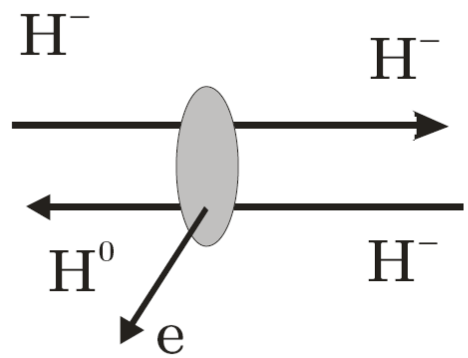
Intra-beam stripping (IBSt)

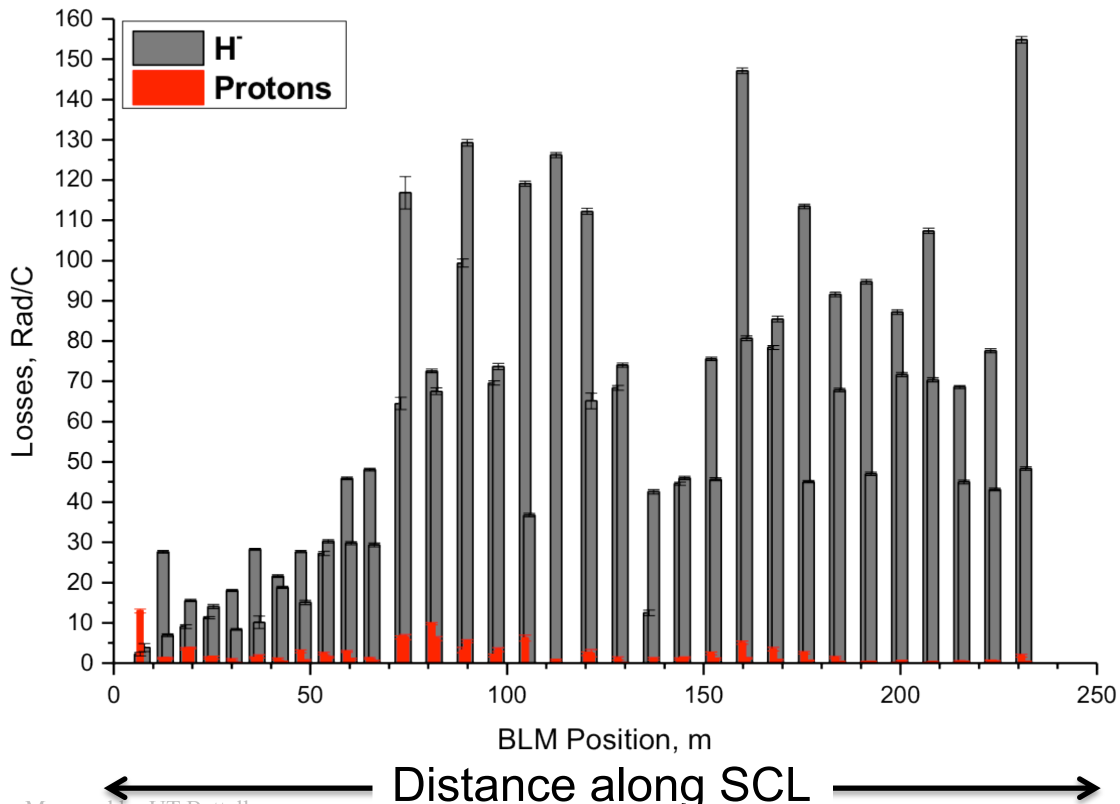
- During the Oak Ridge SNS design phase, the beam loss in the SCL was expected to be negligible
  - Beam pipe aperture is about 10 times rms beam size (76 mm), much larger than upstream warm linac (30 mm)
  - Vacuum pressure very low due to cryogenic pumping
- Found unexpected beam loss and activation during the SNS power ramp up
- Found losses much lower for quad gradients reduced by up to 40%. Also found that normalized loss scales with (peak beam current)^2.



Intra beam stripping (cont.)

- Observations consistent with IBSt, simple model calculation predicts correct magnitude*
- Best proof is to accelerate protons instead of H^-



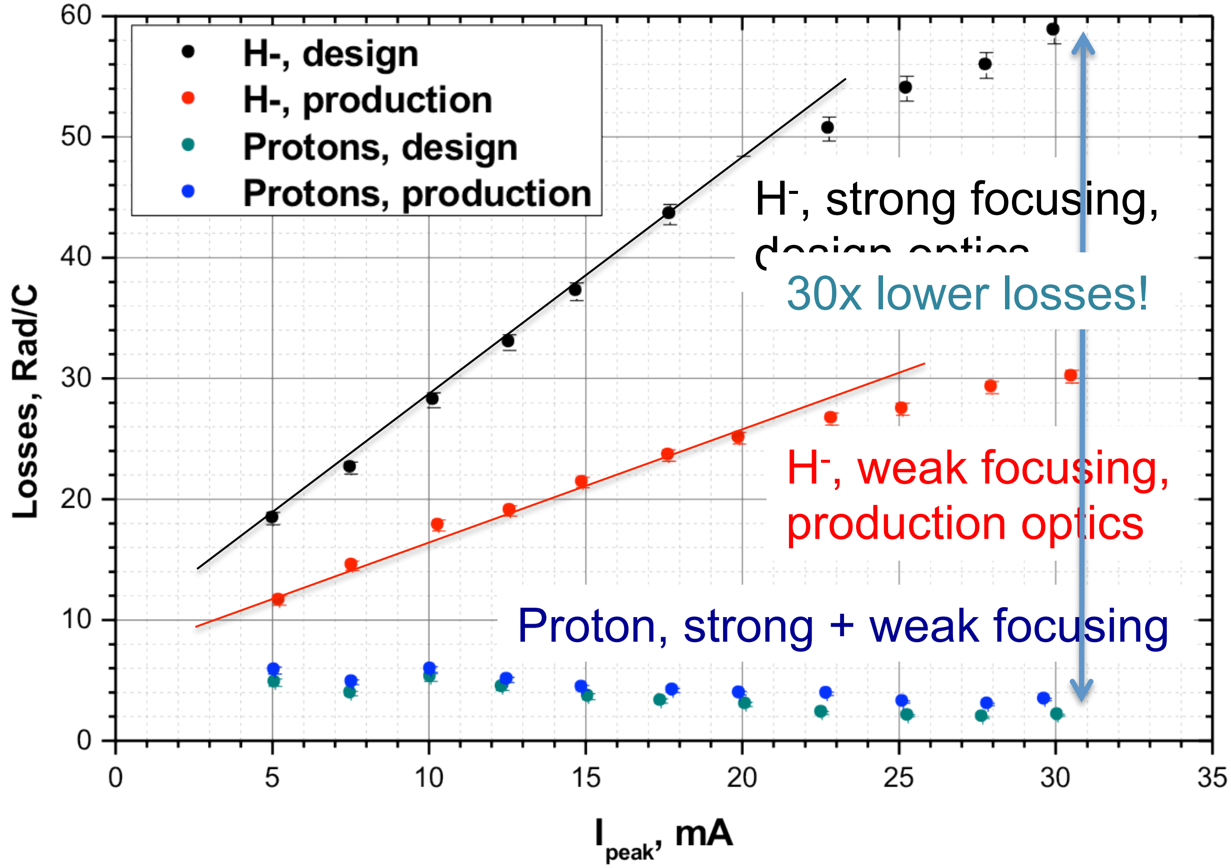


- **Result: Proton losses are ~20x less than H^- losses (but not zero)**

*V. Lebedev et al., Linac2010

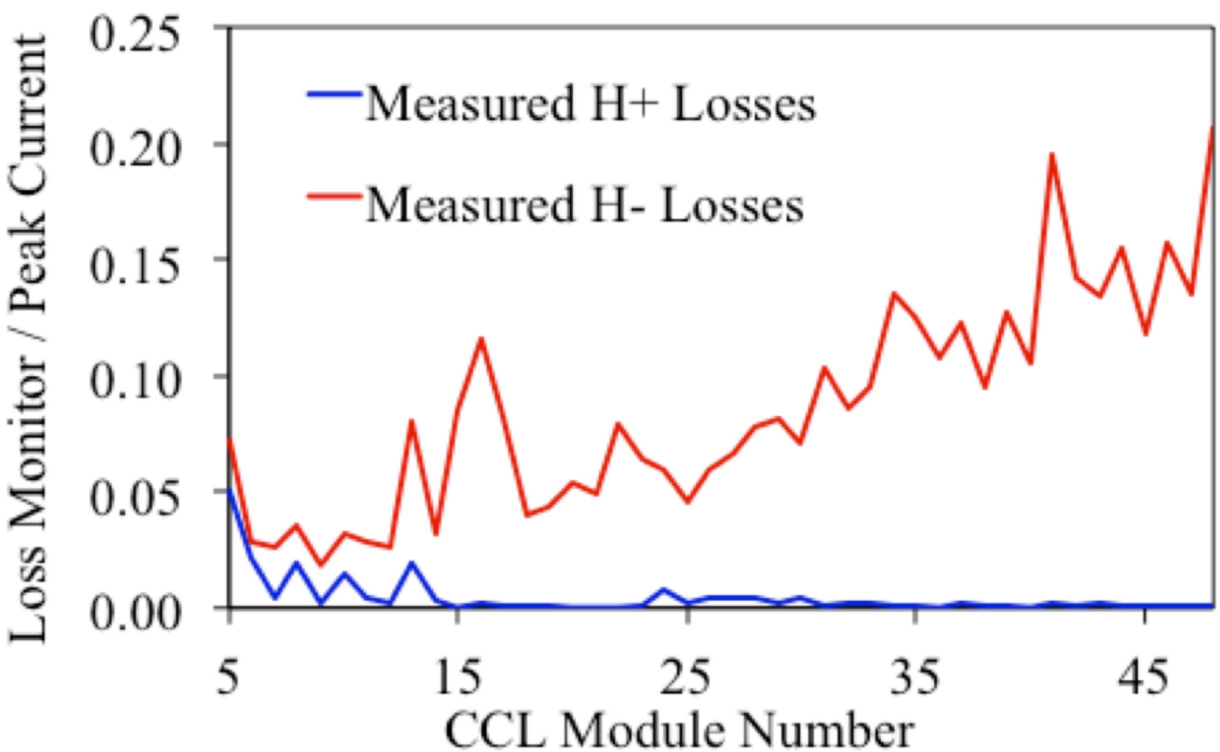
SCL Losses vs. Peak Current

- H^- beam loss is up to 30 times higher than H^+ beam loss
- Normalized H^- beam loss is proportional to ion source current, consistent with IBSt expectations
- H^+ beam loss is very low – good news for proton SCLs like the one planned for ESS



"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

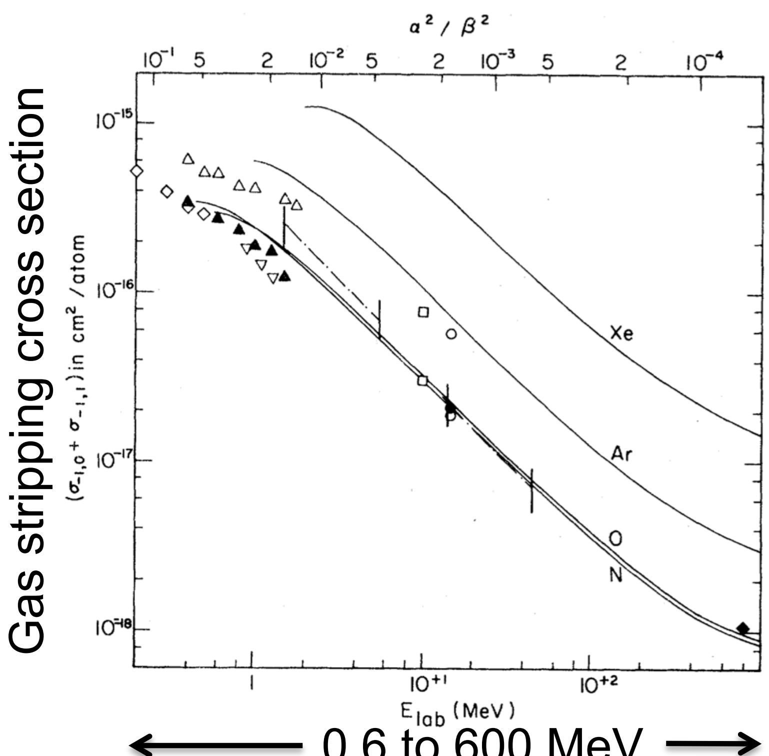


75% of difference due to IBSt, 25% to residual gas stripping

(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 in the accelerator, but cross sections are highest at low beam energies

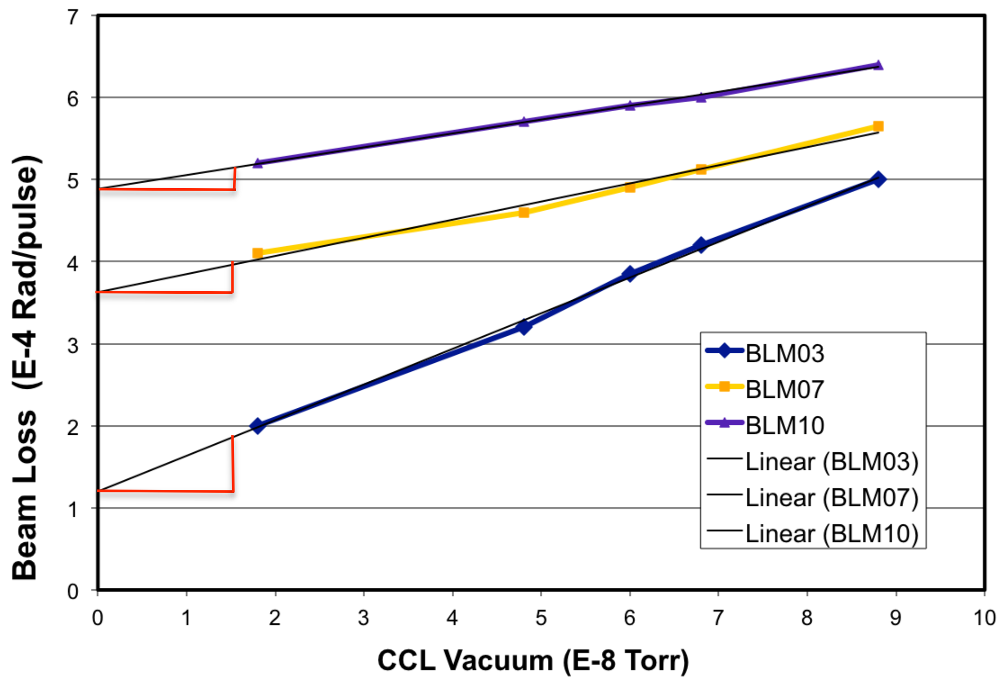


Cross section for double stripping (H^- to H^+) is about 4% of cross section for single stripping (H^- to H^0)

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

Residual gas stripping (cont.)

- SNS
  - Stripping in warm linac 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 at end of warm linac

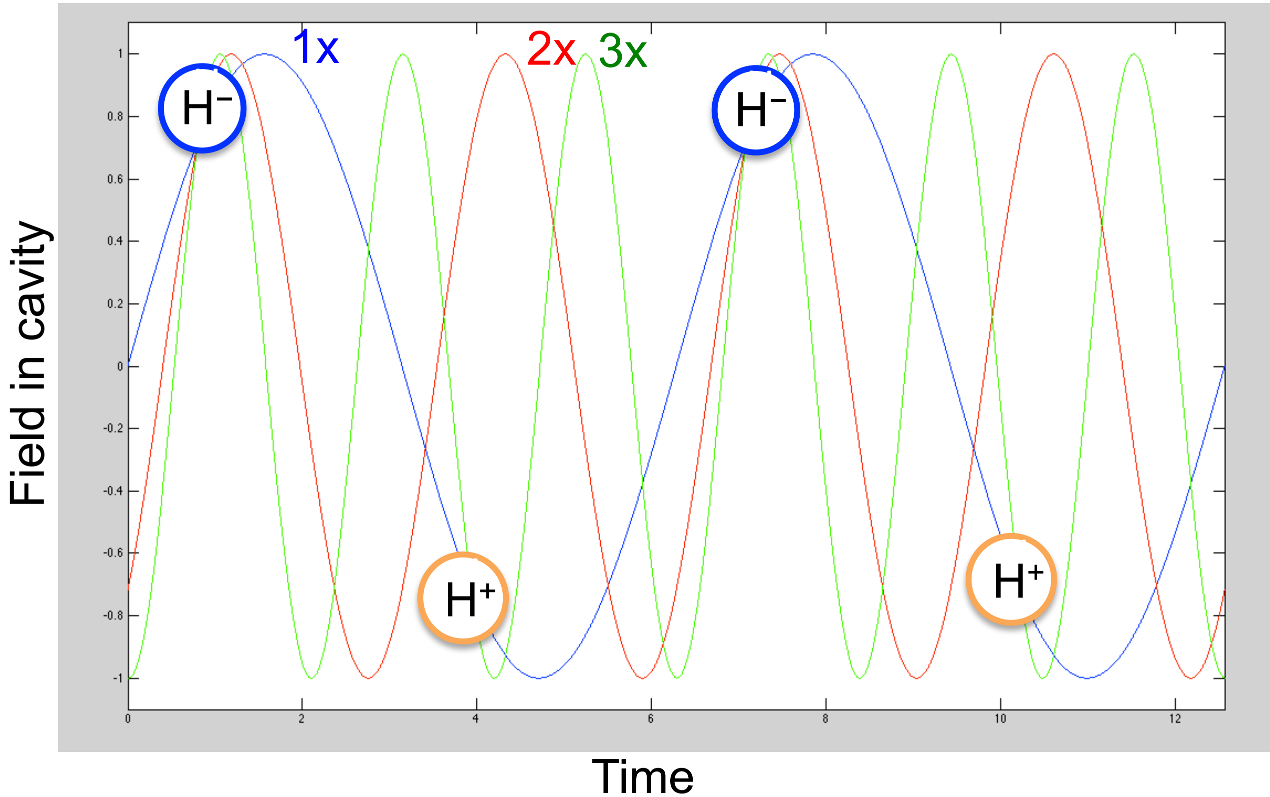


(Courtesy J. Galambos)

- 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). H^+ is captured and accelerated in linac, then lost.
- Stopped by even (e.g. 2, 4, etc.) frequency jumps in linac RF



H^+ capture and acceleration (cont.)

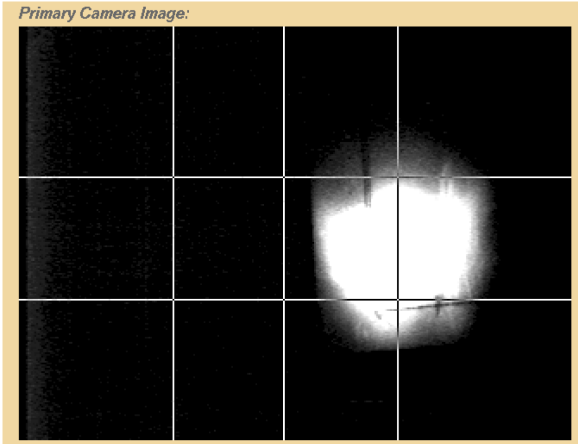
- May be present to a small degree in the SNS linac
  - See loss at 402.5 to 805 MHz frequency jump, but also expect loss due to the lattice transition. Not a problem for 1 MW operations.
- Seen at J-PARC linac
  - Entire linac all at same frequency (until energy upgrade later this year), so H^+ is accelerated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

Beam loss in H^- accelerators

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

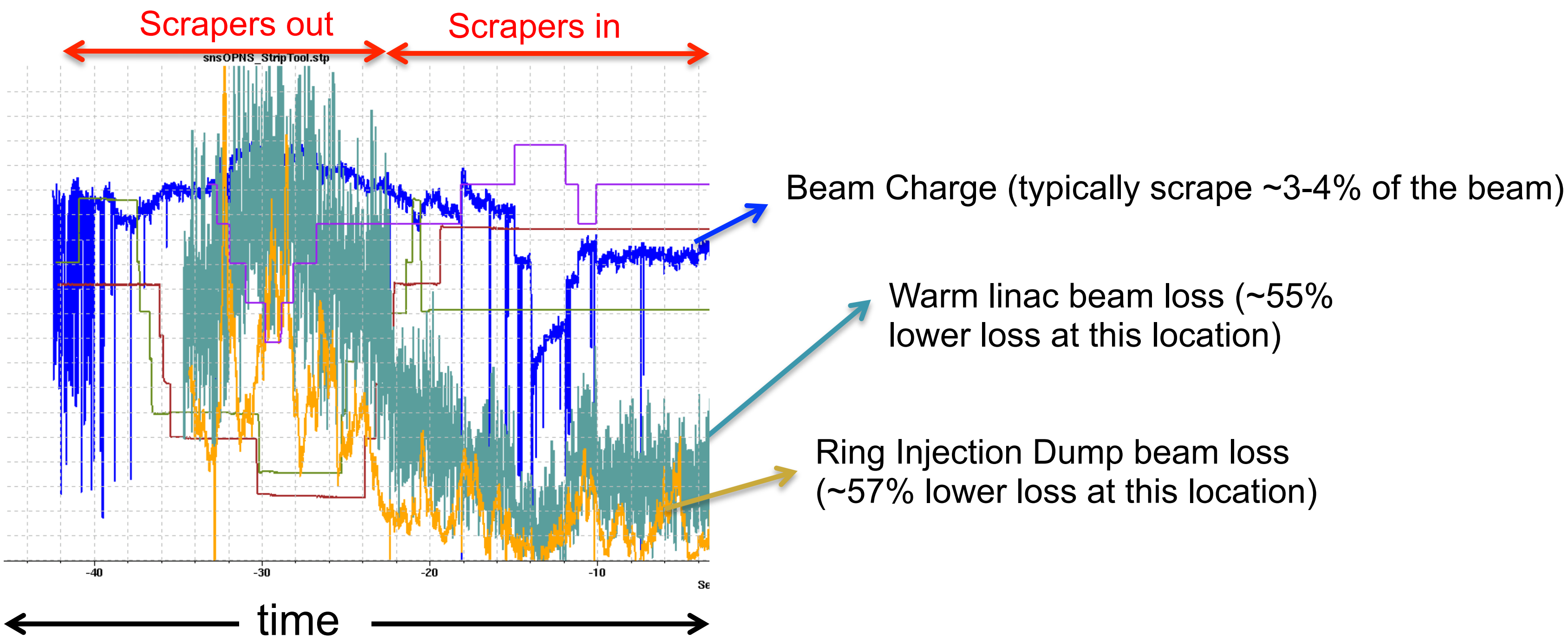
- Very low (~3 uA peak) H^- beam current is emitted continuously by the SNS ion source due to the 13 MHz CW RF used to facilitate the plasma ignition
- A portion of this beam is lost due to RF turn-on and turn-off transients, not seen by BLMs due to cavity x-ray background auto-subtraction



Dark current seen using a view screen

- 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 for the entire duration of the linac RF pulse
- RF turn-on and turn-off transient losses present for any pulsed linac without chopper, H^+ or H^-

Beam loss due to halo / tails, mitigated by low energy scraping



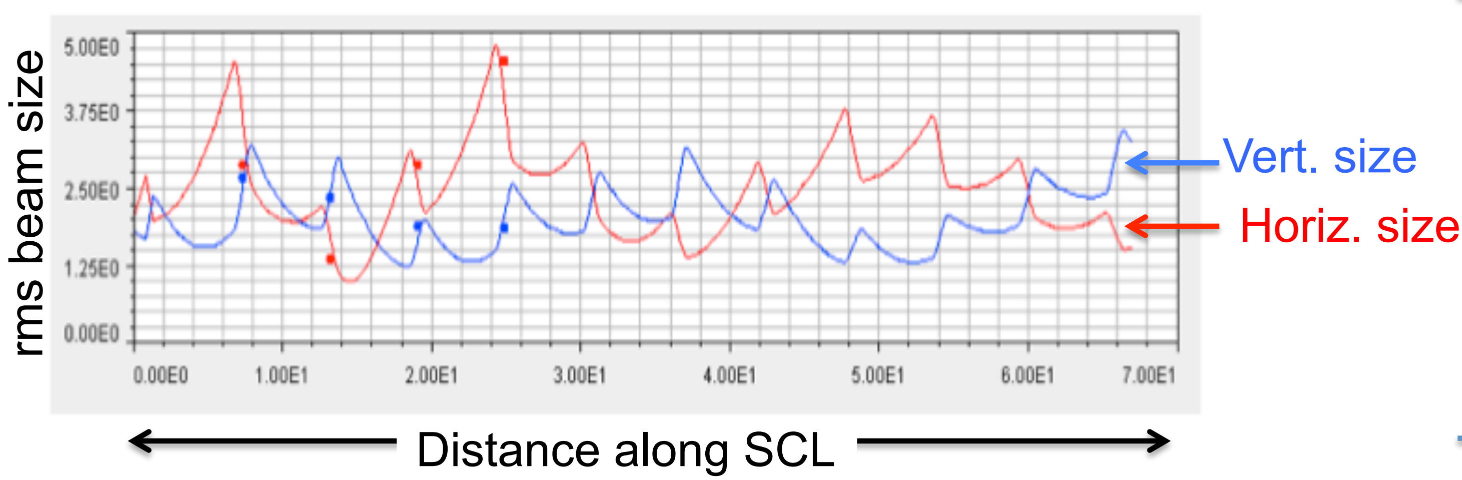
- At SNS we have had good results from scraping the left/right tails of the beam in the 2.5 MeV MEBT
- Up to 57% loss reduction by scraping 3-4%
- Top / bottom scraper installation is planned for this summer

(Courtesy J. Galambos)

Beam loss mitigation: matching

- Conventional wisdom: It is best to match the beam Twiss parameters at the lattice transitions (e.g. one FODO lattice to another)
- Good advice for perfect beam distributions – but what about distributions that have different Twiss parameters for the core and the tails of the beam?
- Initial set up using the design parameters is a good place to start, but need empirical adjustments to, e.g., quad magnets and RF phase and amplitudes to minimize the beam loss (SNS, LANSCE, PSI, TRIUMPF)

Low-loss tune is mis-matched at beginning of SNS SCL



This is a doublet lattice

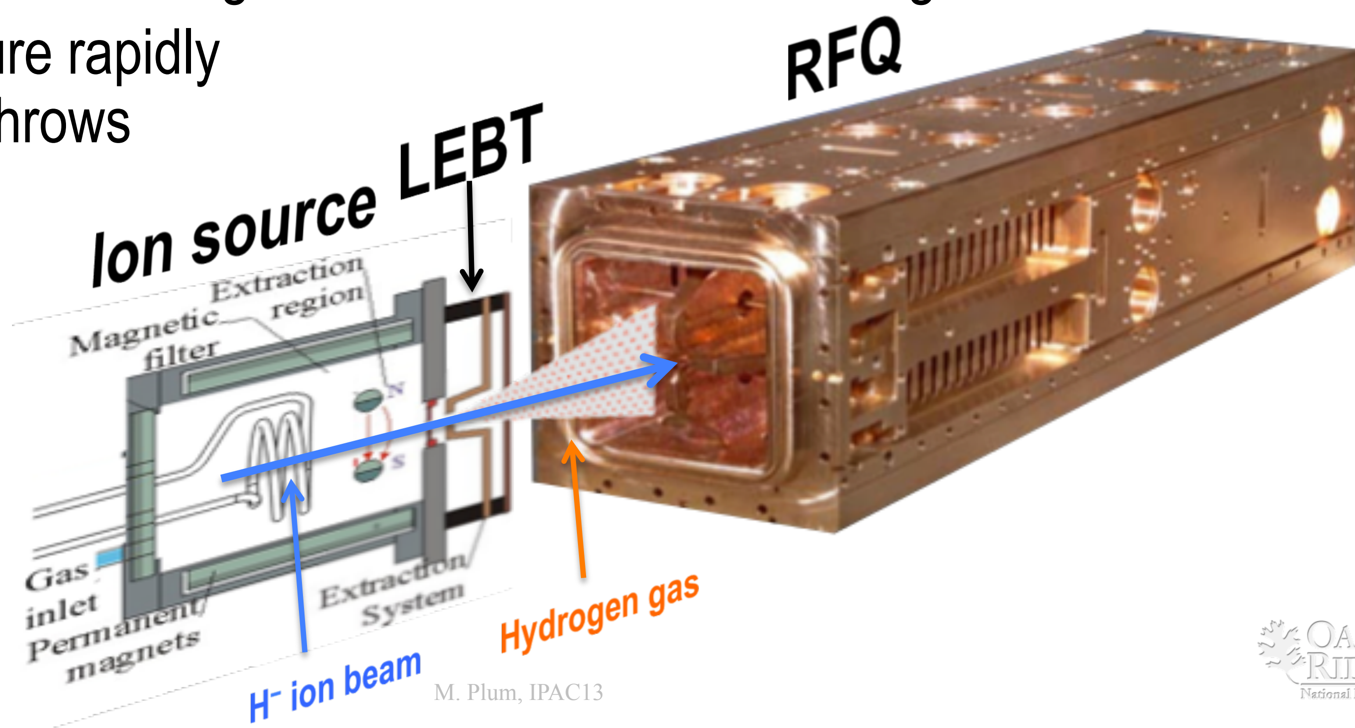
The low-loss tune is mis-matched

The high power RFQ challenge

- All modern high power linacs use RFQs. FNAL, ISIS, CERN have changed from Cockroft-Walton generators to RFQs.
- Both SNS and J-PARC experienced resonance control and electrical discharge problems with their RFQ's
- Hydrogen gas from ion source is absorbed by copper vanes in RFQ
- Lesson learned: The ion source can strongly impact RFQ performance
  - Minimize gas flow from source to RFQ (minimize ion source gas pressure, use orifice between ion source and RFQ)
  - Design the RFQ for high pumping speed and ensure adequate pumping
  - Magnetic LEBT's can help
  - Pre-installation testing should include the ion source and LEBT

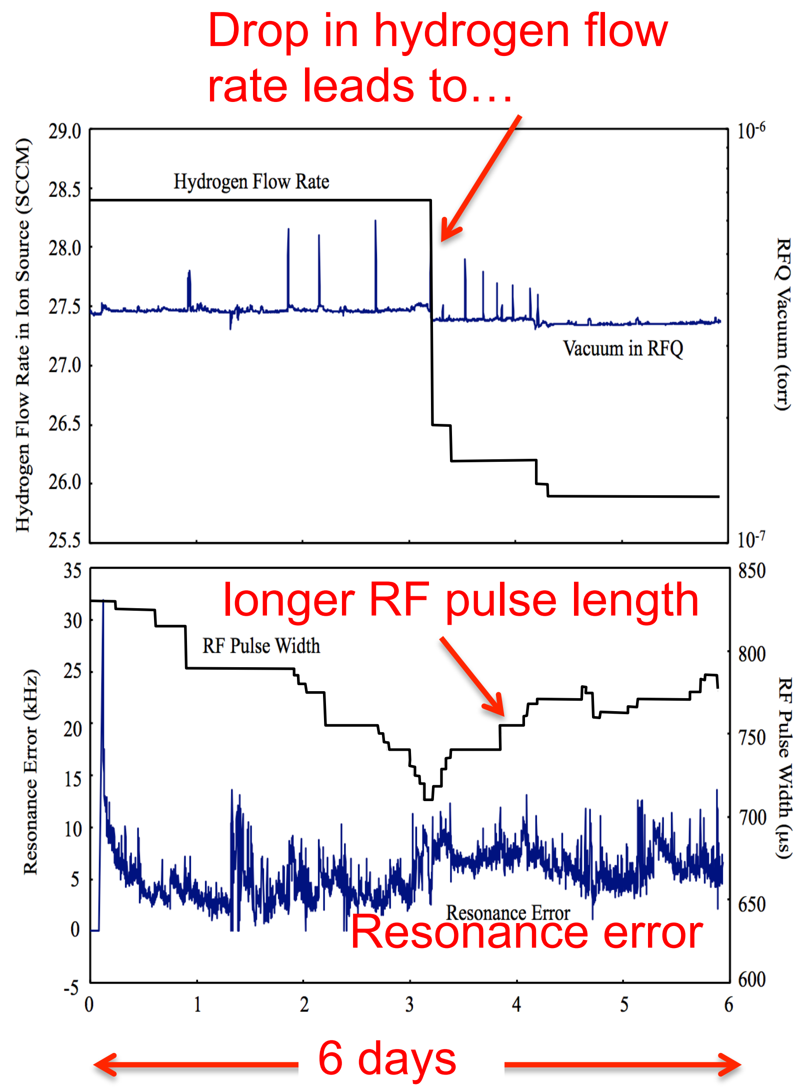
RFQ instability due to gas desorption

- Gas from ion source is absorbed by copper in RFQ, especially by the vanes
- Gas desorption (or lack of more absorption), possibly helped by ion beam striking the vanes
- A mild electric discharge is started, driven by the RF power
- Klystron power is increased to maintain field
- More RF power >> more gas released >> more discharge
- Vane temperature rapidly increases and throws RFQ out of resonance



SNS RFQ instability control

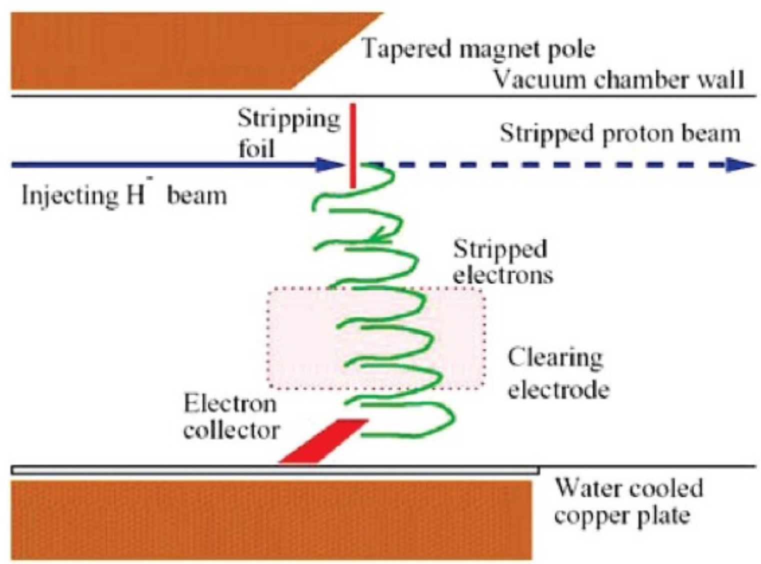
- RFQ resonance is normally controlled by cooling water temperature
- To control the gas desorption instability at SNS a control loop was added for the RF pulse length
- The RF pulse length is typically up to 40 us longer than the beam pulse length, and it is adjusted to rapidly compensate for additional heating caused by the electric discharge



(Courtesy S. Kim)

The charge exchange injection challenge

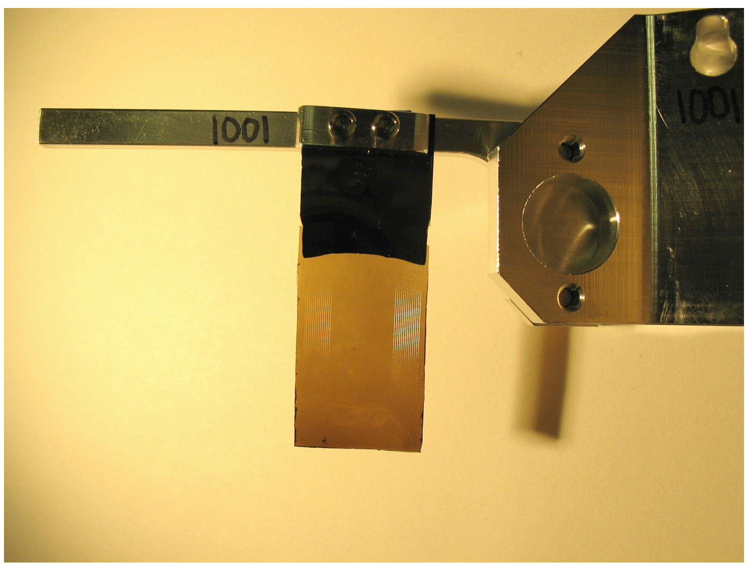
- Charge exchange injection is required for low-loss multi-turn injection into storage rings and synchrotrons
- The only practical option today is stripper foils
- The SNS stripper foil is located inside one of injection chicane magnets to mitigate beam loss from H^0 excited states (Project X has similar strategy)
- This leads to problems from the convoy electrons stripped off the incoming H^- beam



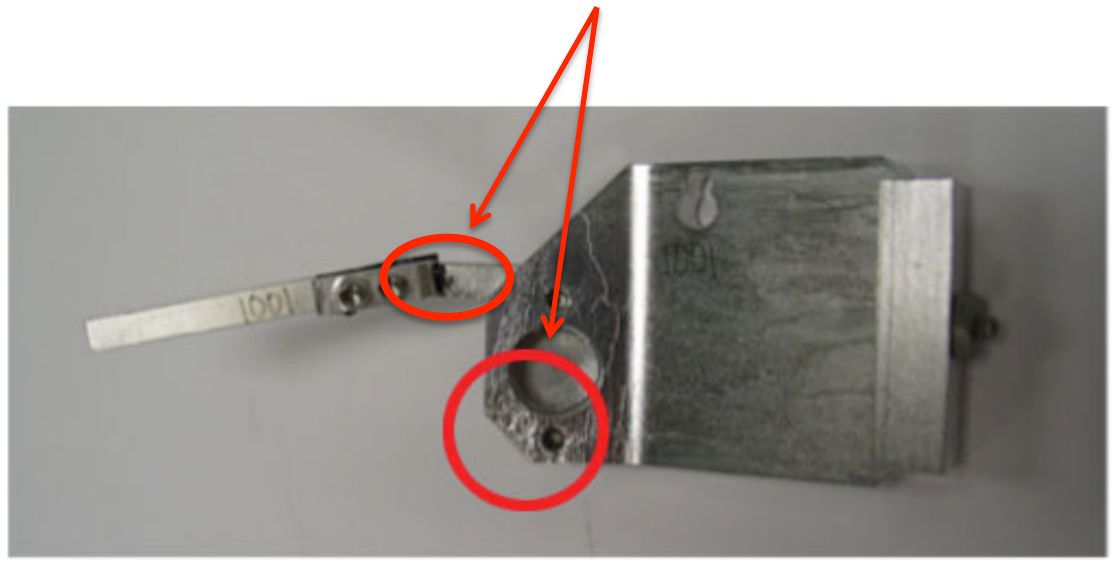
Damage due to convoy electrons

- If the convoy electrons are not properly captured by the electron collector at the bottom of the vacuum chamber, they are reflected back up, and they can strike the foil bracket

New foil

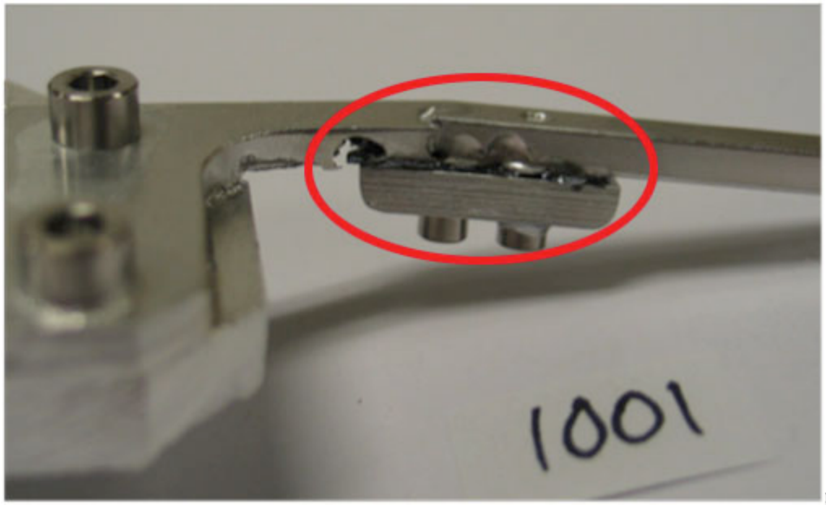


Melting damage



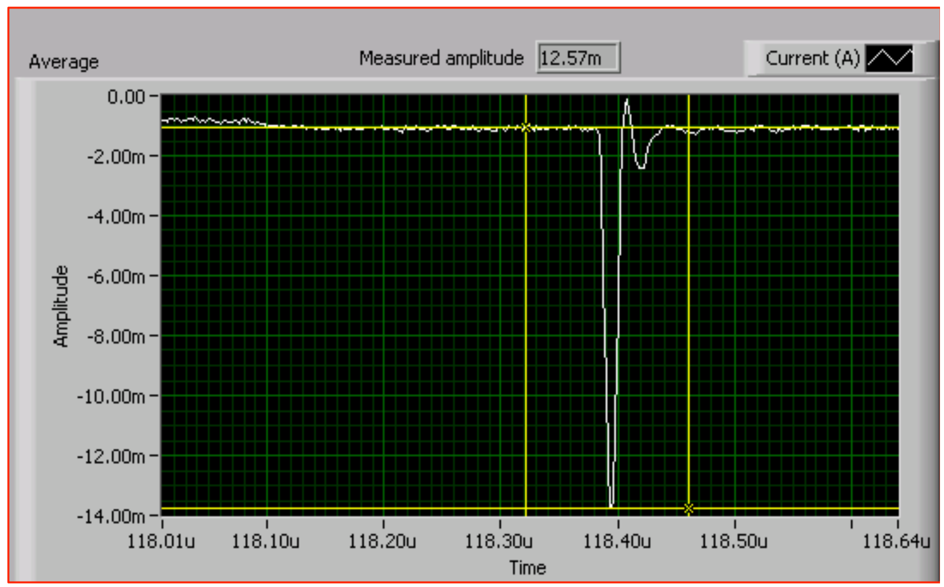
Damage due to arcing

- The SNS foils are made from nanocrystalline diamond. Their electrical conductivity is poor.
- The foil charges up due to secondary electron emission
- The electric field created between the foil and sharp points on the bracket initiate cathode-spot in-vacuum breakdown (can occur even in a perfect vacuum)
- The arcing erodes the bracket arm, eventually leads to failure



Laser stripping

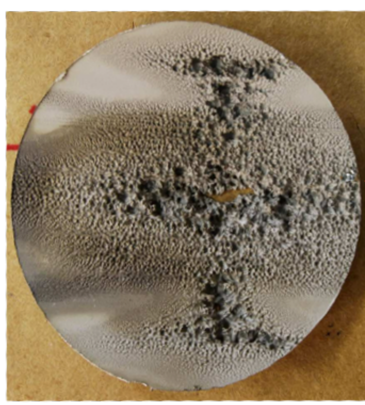
- Ultimate solution to the many issues with charge exchange injection is laser stripping
- Proof of principle demonstrated at SNS in 2006, 90% stripping efficiency for ~7 ns
- At SNS we are now working on demonstrating stripping for ~10 us (>1000 times longer)



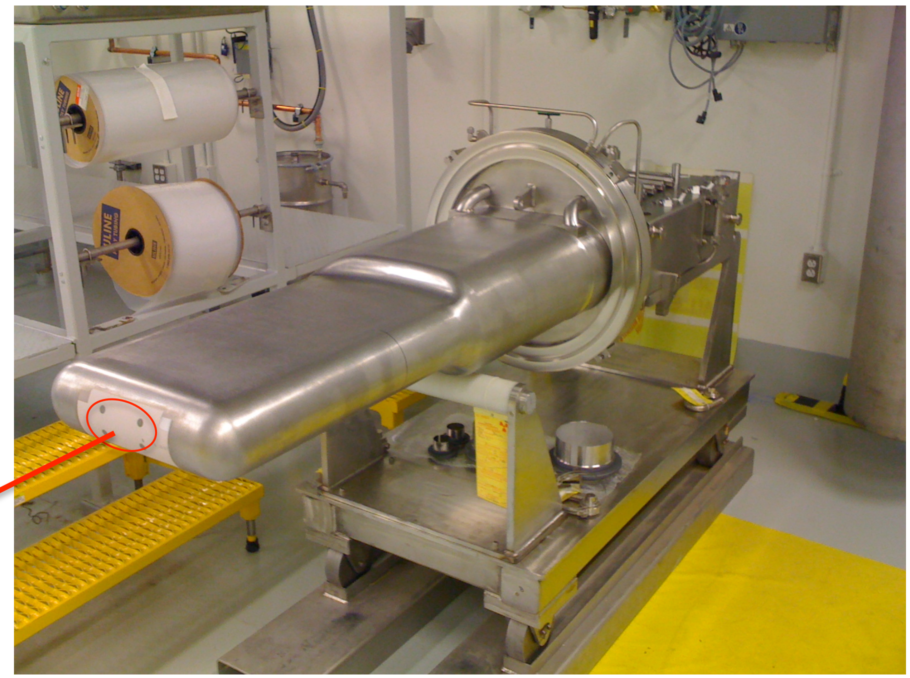
90% stripping efficiency demonstrated for ~7 ns

The high power targets challenge

- After accelerating and creating all that beam power the target must be strong enough to stand up to it!
  - New target system designs are needed that will last longer at higher beam powers
  - The SNS accelerator power is restricted today by the targets
  - The beam power has been lowered from 1 MW to 850 kW until target supply issues are resolved



Sample removed from mercury containment vessel on spent target



The SNS target

Summary

- There are many important lessons learned from the recent experiences at SNS, J-PARC, PSI, ISIS, and LANSCE
- Beam loss mechanisms:
  - Intra-beam stripping
  - Residual gas stripping
  - H^+ capture and acceleration
  - Field stripping
  - Dark current from the ion source
  - Beam halos / tails
- SNS accelerator beam power is not limited by beam loss
- Scraping at low beam energy can make significant reduction in high-energy beam loss

Summary (cont.)

- RFQ instability due to hydrogen gas from ion source
  - At SNS this is managed by rapid automatic adjustments to the RF pulse length
  - RFQ design for high vacuum pumping speeds is crucial
- Stripper foil issues
  - Reflected convoy electrons can damage foil brackets
  - Vacuum breakdown due to foil charging up can also damage brackets
- High power accelerators need high power targets
- Not discussed here but information is available on:
  - SCL trip rates, impact of errant beams on SCL cavities, methods to quickly set SCL cavity phases, RFQ mechanical fabrication issues, reliability statistics …

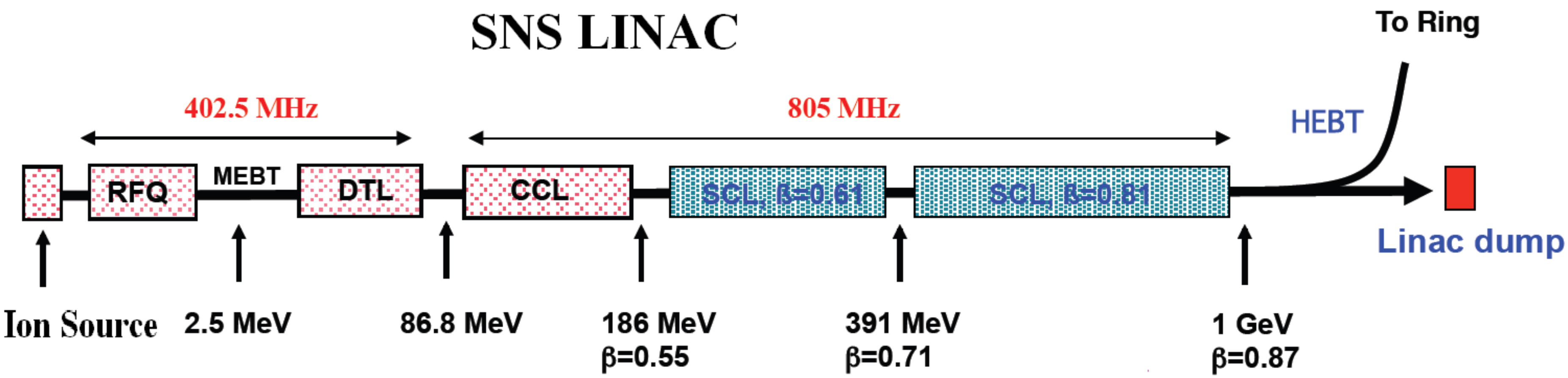
Summary (cont.)

- The linac design rules challenge: which rules should be followed to minimize the cost of a high power low loss linac?
- At SNS we plan to use our flexible lattice and extensive suite of beam instrumentation to explore the linac design "rules" to minimize beam loss, like σ_{0t} and σ_{0l} always <90^o and never cross, continuous k_{0t} and k_{0l}, equipartioning, …
- SNS is a great place to benchmark simulation codes, and we welcome your involvement

Thank you for your attention!

- **Backup slides**

SNS Linac Structure



Length: 330 m (Superconducting part 230 m)

Production runs parameters:

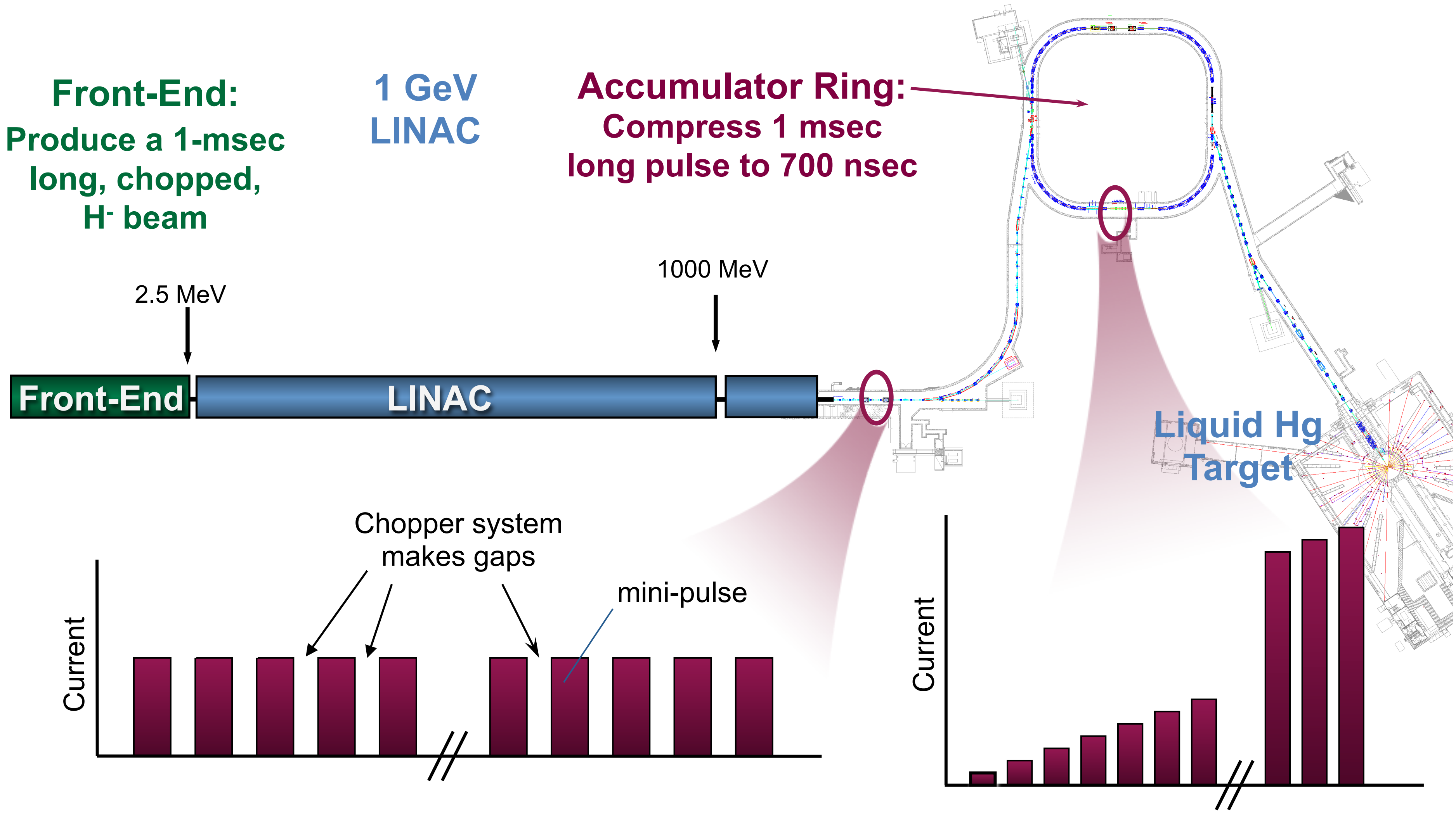
Peak current: 38 mA

Repetition rate: 60 Hz

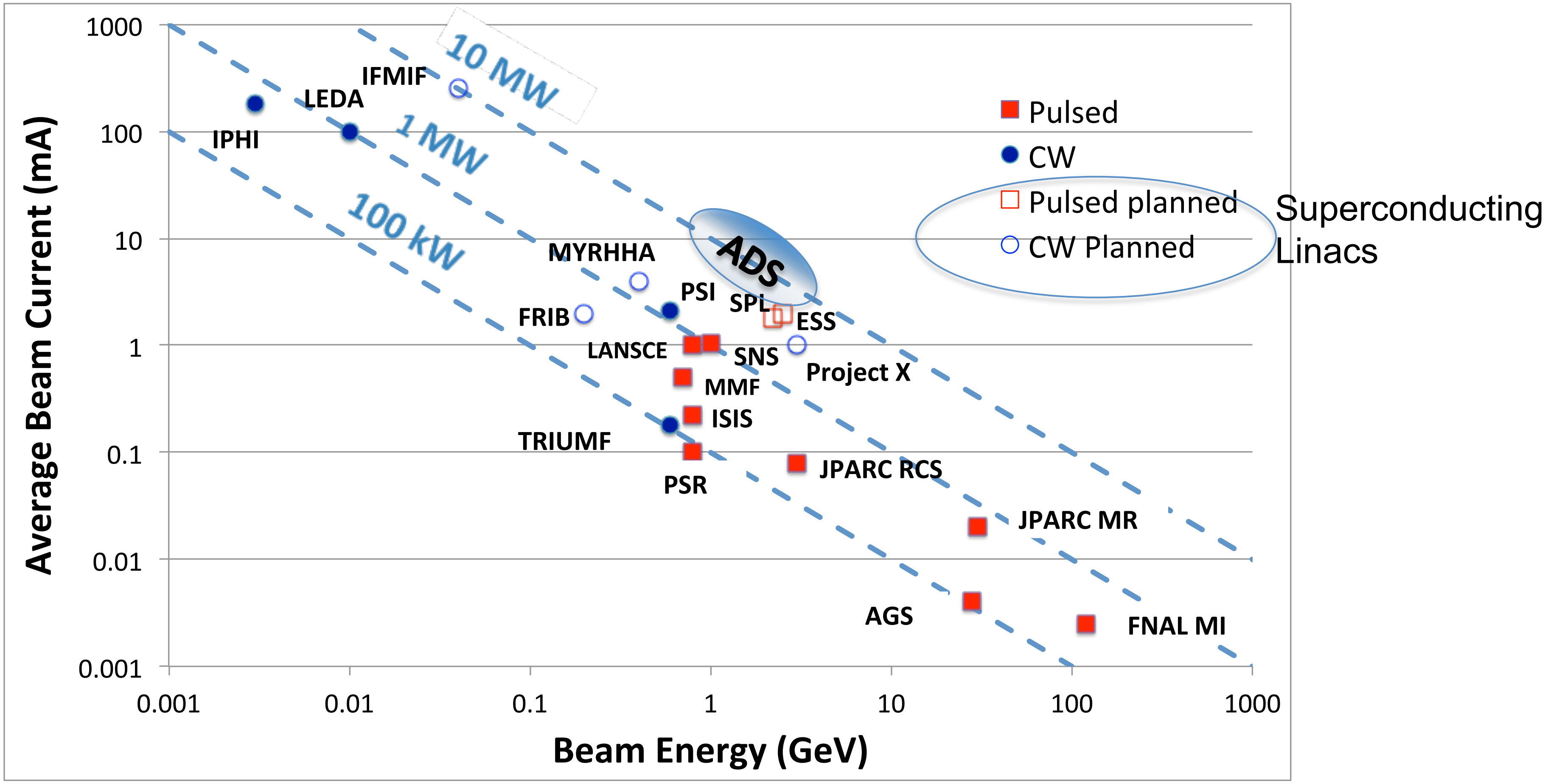
Macro-pulse length: 0.825 ms

Average power: 1 MW

SNS Accelerator Complex



High Power Accelerator History



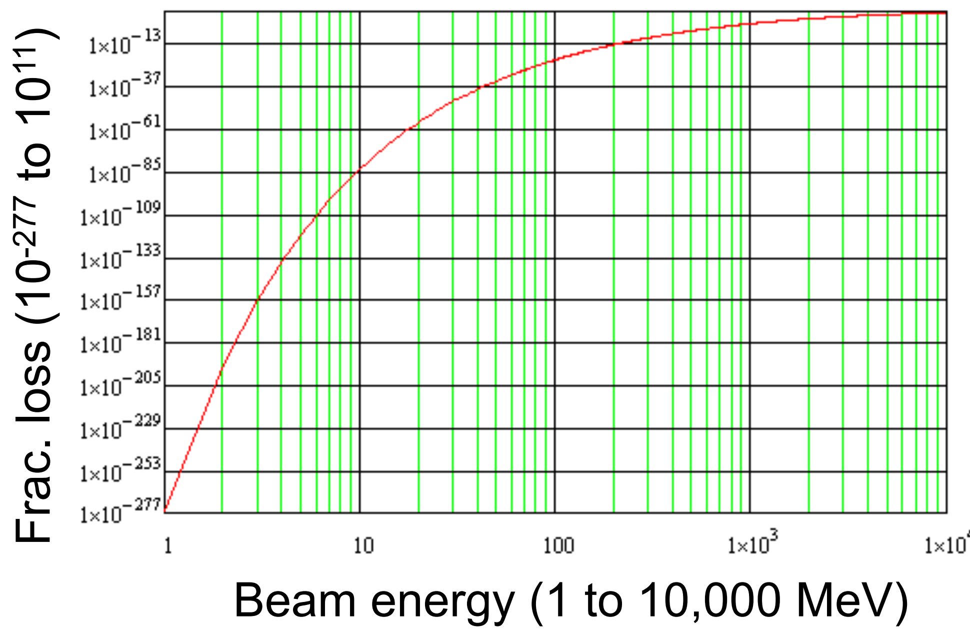
- **Relevant accelerators with ~ MW beam experience**
  - **PSI: 600 MeV cyclotron, 1.3 MW**
  - **SNS 925 MeV superconducting linac , 1 MW**
  - **LANSCE: 800 MeV copper linac, 800 kW**

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

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

$A1$ = 2.47E-6 V sec/m
$A2$ = 4.49E9 V/m



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