Beam dynamics and beam loss in linacs

by

Michael Plum
ORNL/SNS

USPAS / Joint International Accelerator School: Beam Loss and Accelerator Protection
Newport Beach, California
Nov. 5-14, 2014

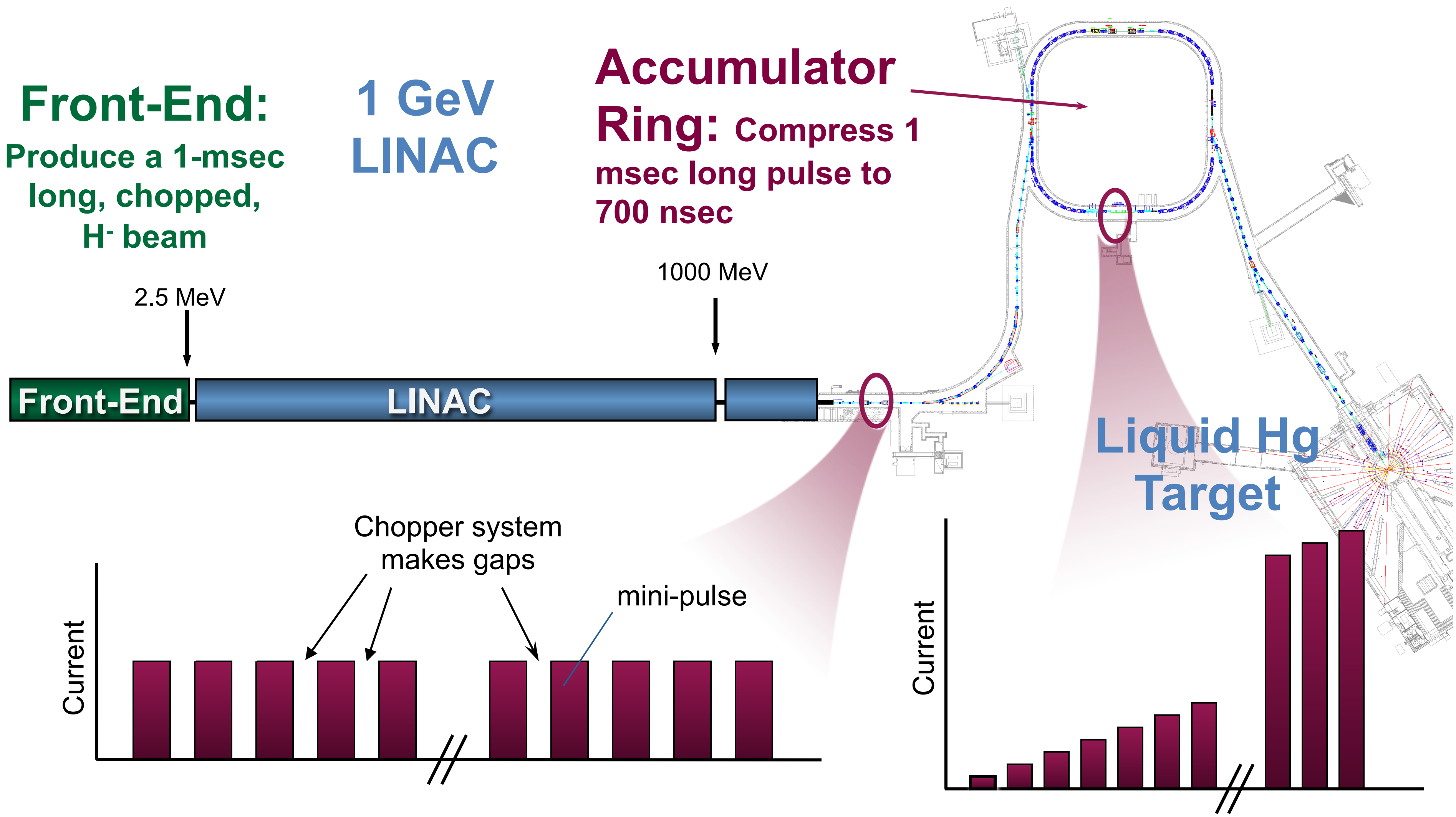
U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

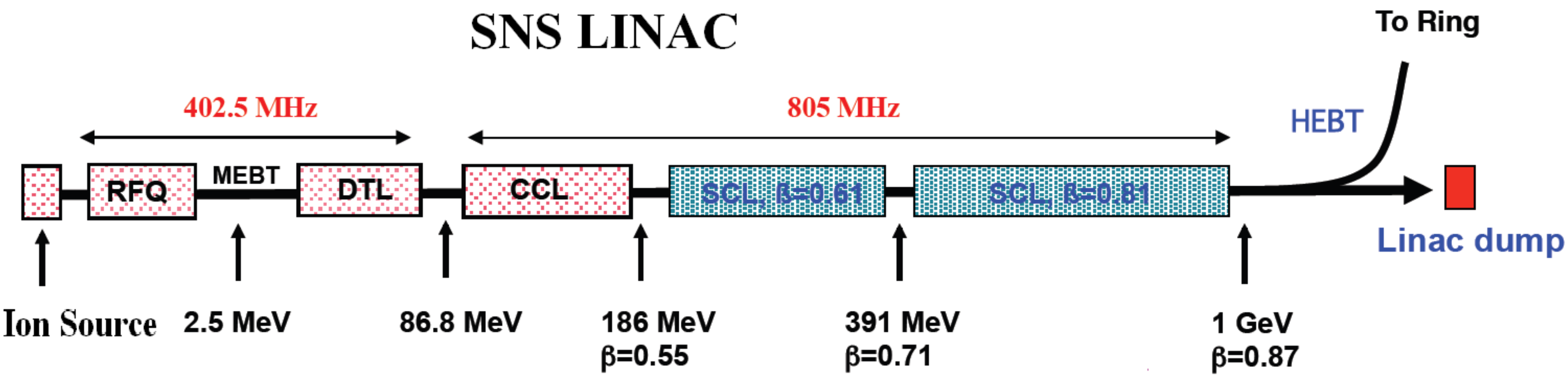
Table of contents

- Beam loss mechanisms
  - Focus on beam loss in linacs
  - Continuous beam loss (e.g. beam halo, residual gas, IBSt, …)
  - Occasional beam loss (e.g. equipment faults)
  - H^- vs H^+ beam loss mechanisms
- Beam loss mitigation
  - Scraping & collimation
  - Equipment modifications (add vacuum pumps, add chicane, …)
  - Tuning
  - Track down the occasional equipment faults

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: 0.85 – 0.975 ms

Average power: 1.2 – 1.4 MW

Why H^- beams

- Low-loss multiple-turn injection into the same RF bucket in storage rings and synchrotrons requires charge-exchange injection
  - Typical beam loss without charge exchange injection is several percent
  - Example: SNS linac beam power is 1.4 MW. If lose 2% of this at injection, you are losing 28 kW !!!
  - Example: SNS ring charge-exchange injection fractional loss is $(1 – 2)\times10^{-4}$, so power loss is 140 – 240 W
- Charge exchange injection also required if want output beam emittance to be less than the sum of the input emittances (Liouville Theorem)
- To accumulate protons and use charge-exchange injection you must accelerate H^- ions

Continuous beam loss

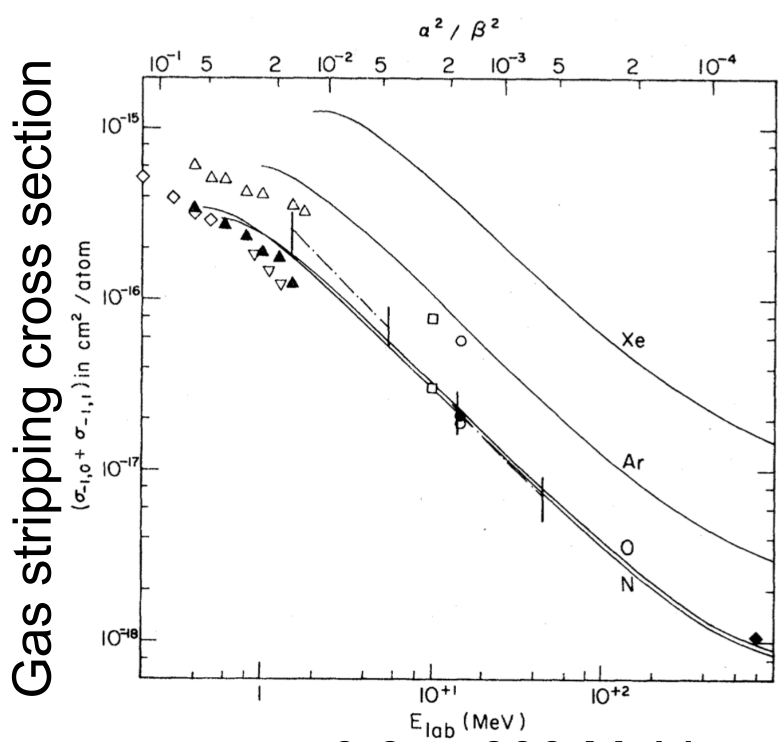
- There are many different and interesting continuous beam loss mechanisms in high-intensity H^+ and H^- linacs
  - Residual gas stripping
  - Intra-beam stripping
  - H^+ capture and acceleration
  - Field stripping
  - Black body radiation stripping

  H^- only

  - Beam halo/tails (resonances, collective effects, mismatch, etc.)
  - RF and/or ion source turn on/off transients
  - Dark current from ion source

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

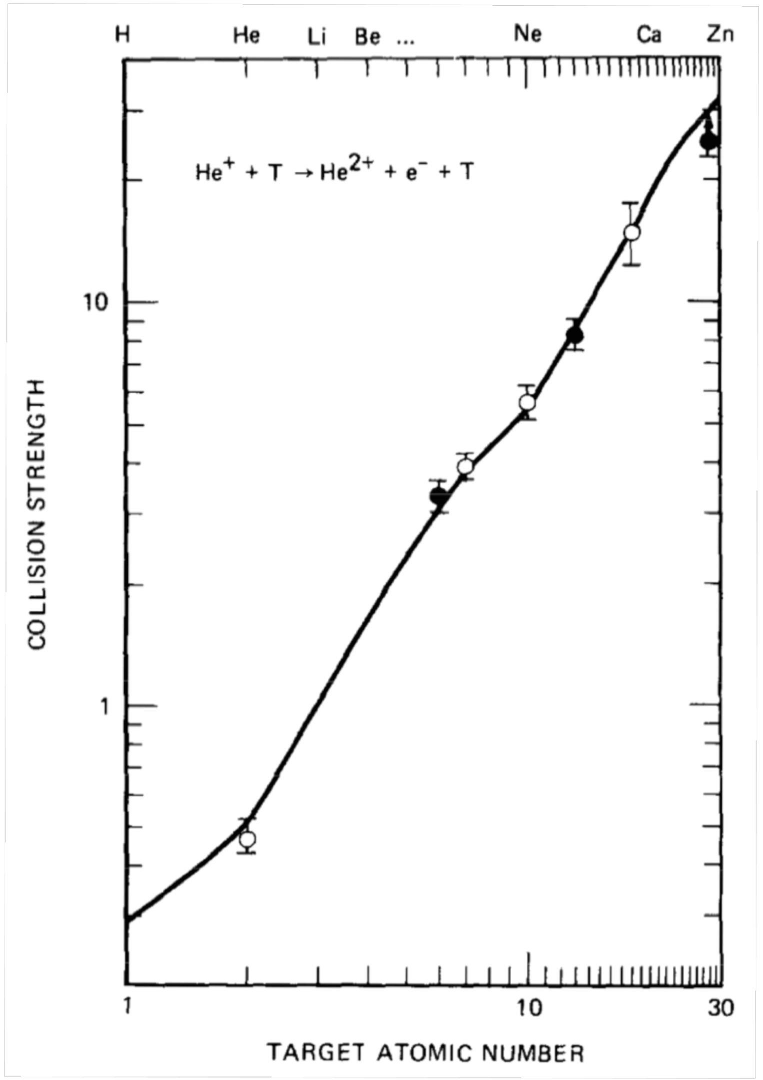


0.6 to 600 MeV

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.)



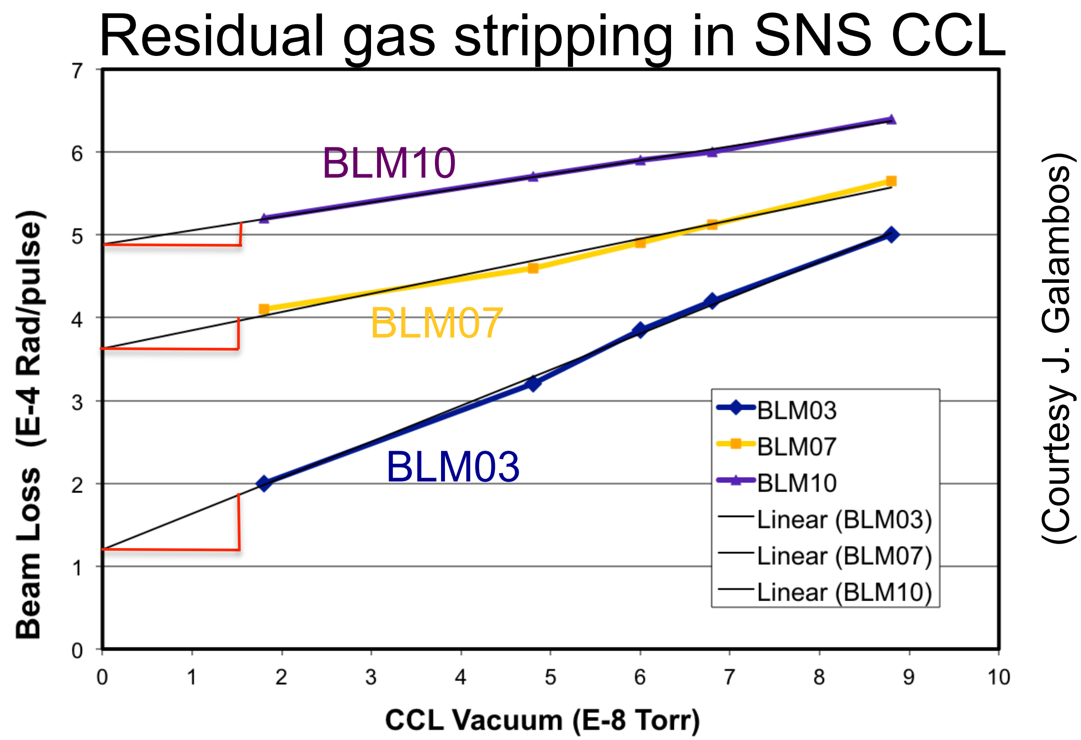
Stripping cross sections scale with atomic number

Good news: Typical gas species in an accelerator: mainly H_2 and H_2O, then some CO and CO_2

G. Gillespie, NIM B2 (1984) 231-234.

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 S-DTL linac (181-MeV)



- 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

Example: Gas stripping calculation

$$\frac{d\sigma}{d\Omega} = \frac{7\cdot 10^{-19}}{\beta^2}\ \mathrm{cm}^2 \quad \text{per atom of nitrogen or oxygen}$$

$$\frac{d\sigma}{d\Omega} = \frac{1\cdot 10^{-19}}{\beta^2}\ \mathrm{cm}^2 \quad \text{per atom of hydrogen}$$

$$\rho = \left(2N_A \frac{p}{22410\cdot 760}\right)\left(\frac{273}{T}\right) \text{ atoms per cm}^3 \quad \text{(diatomic gas at temperature } T \text{ in deg. K, pressure } p \text{ in Torr)}$$

$$P = E_{beam} I_{beam} \frac{d\sigma}{d\Omega}\, \rho\, l \quad \text{beam power lost in length } l$$

Assume 100 MeV, 1 mA H^- beam, in a beam line with 10^{-7} Torr of nitrogen gas at 303 K

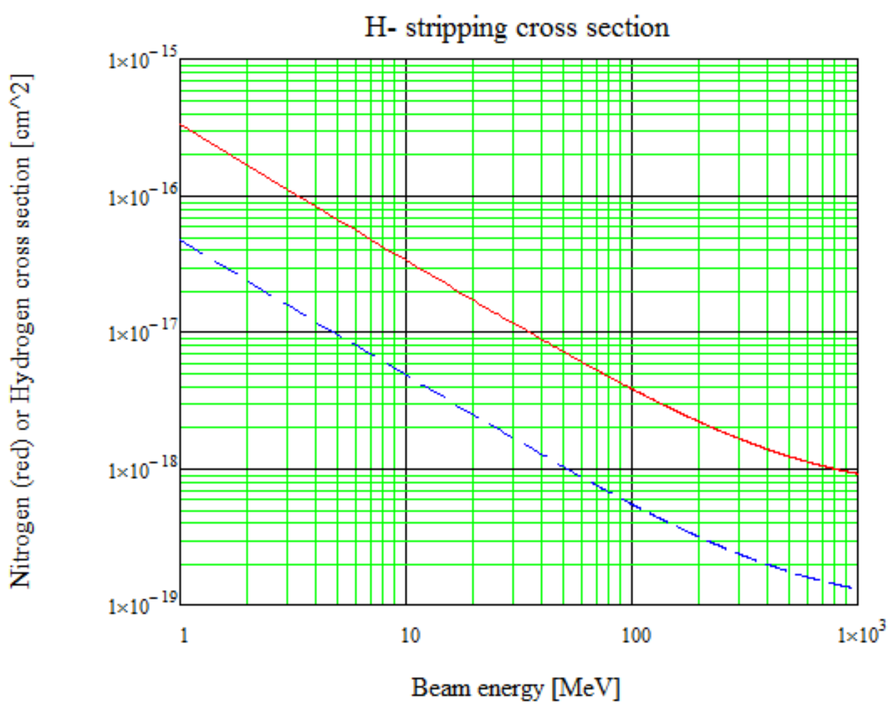
$$P = (10^8\ \mathrm{V})(0.001\ \mathrm{A})\left(\frac{7\cdot 10^{-19}}{0.428^2}\ \mathrm{cm}^2\right)\left(2\cdot 6.022\cdot 10^{23}\frac{10^{-7}\ \mathrm{Torr}}{22410\cdot 760\ \mathrm{Torr}}\ \frac{\mathrm{atoms}}{\mathrm{cm}^3}\right)\left(\frac{273}{303}\right)(100\ \mathrm{cm})$$

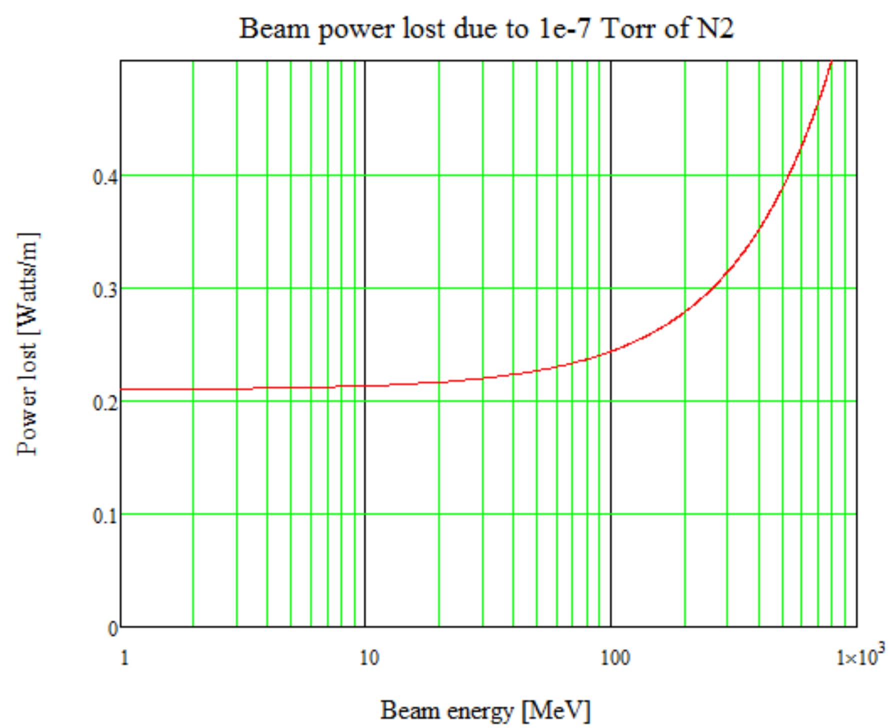
$$P = 0.243\ \mathrm{watts/m}$$

(R. Shafer, TN:LANSCE-1:99-085)

Example: Gas stripping calculation (cont.)

Assume 1 mA H⁻ beam

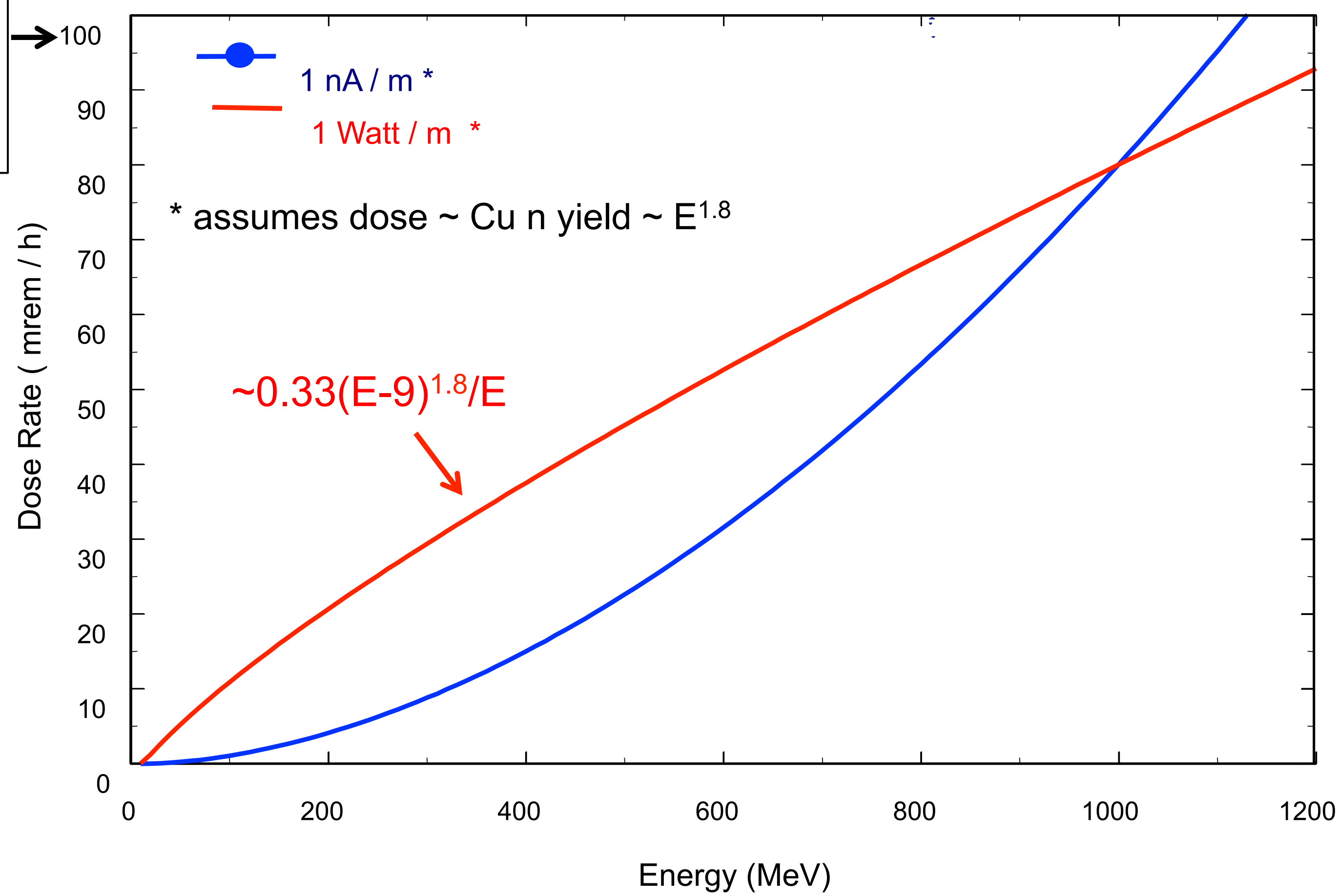




Residual gas stripping causes increasing power loss as beam energy increases

Dose from proton beam loss vs. energy (at 30 cm after 4 Hours)

Typical limit for hands-on maintenance

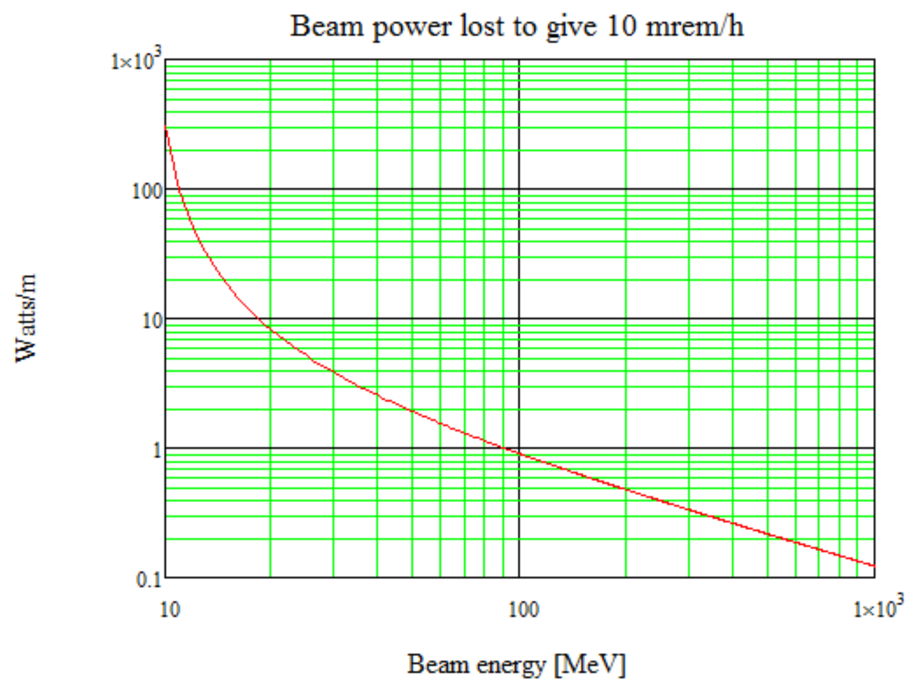


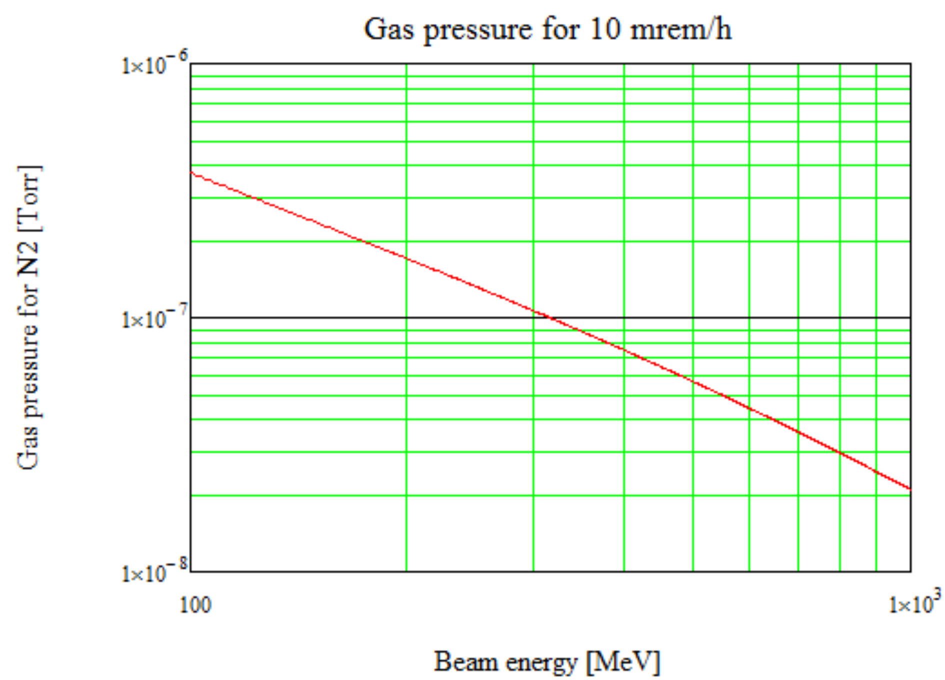
Note: 100 mrem/h = 1 mSv/h

(J. Galambos et al., Snowmass, July 7, 2001)

Example: Gas stripping calculation (cont.)

Assume 1 mA H^- beam, 10 mrem/h (0.1 mSv/h)

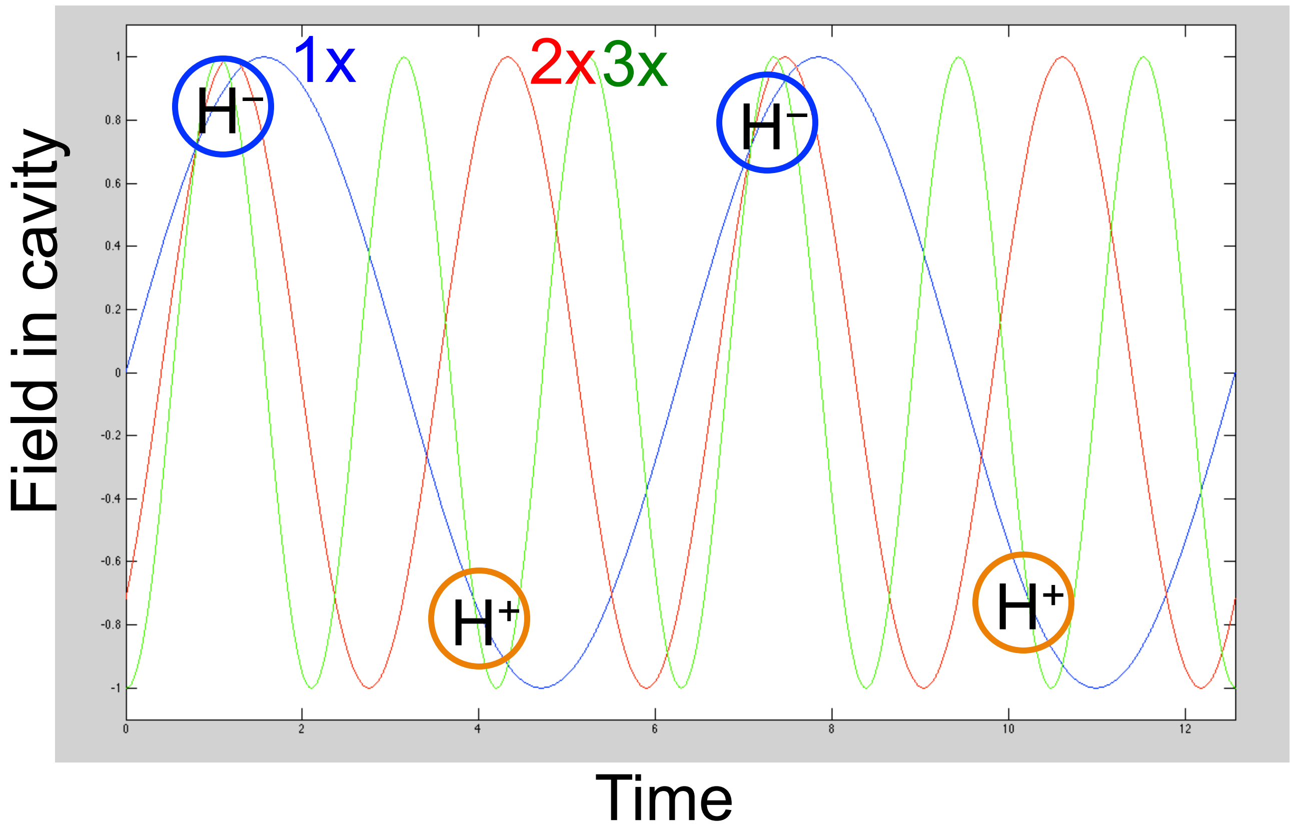




To maintain a constant level of activation caused by residual gas stripping, the allowable gas pressure decreases as the beam energy increases

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.)

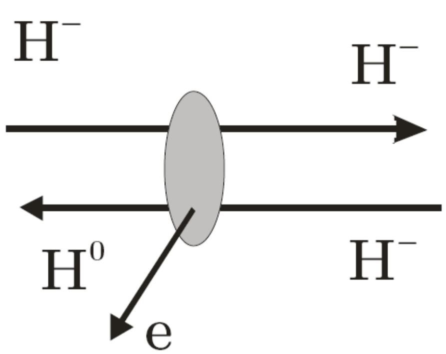
- May be present to a small degree in the SNS linac
  - See loss at 402.5 to 805 MHz frequency jump, but also expect loss due to the lattice transition. Not a problem for 1 MW operations.
- Seen at J-PARC linac
  - Entire linac all at same frequency (until energy upgrade in 2013 – 2014, when new 3rd harmonic section was added), so H^+ was 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

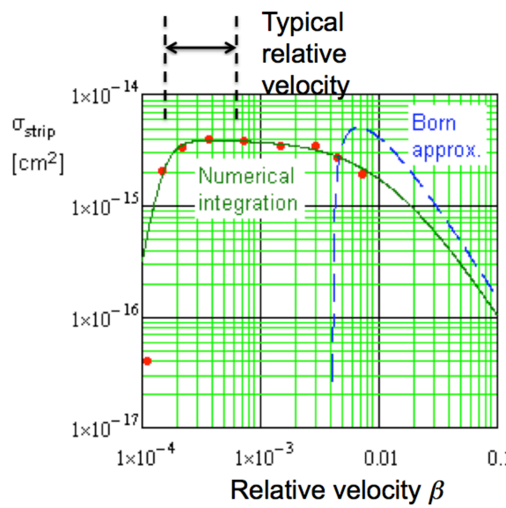
Intra-beam stripping (IBSt) rate

$$\frac{dN}{ds} = \frac{N^2 \sigma_{max} \sqrt{\gamma^2\theta_x^2 + \gamma^2\theta_y^2 + \theta_s^2}}{8\pi^2 \sigma_x \sigma_y \sigma_s \gamma^2} F(\gamma\theta_x, \gamma\theta_y, \theta_s), \quad (1)$$

$$F(a,b,c) \approx 1 + \frac{2-\sqrt{3}}{\sqrt{3}(\sqrt{3}-1)}\left(\frac{a+b+c}{\sqrt{a^2+b^2+c^2}} - 1\right) \quad (2)$$

where N is the number of particles in the bunch, γ is the relativistic factor, $\sigma_{x,y} = \sqrt{\epsilon_{x,y}\beta_{x,y}}$ are the transverse rms bunch sizes, $\theta_{x,y} = \sqrt{\epsilon_{x,y}/\beta_{x,y}}$ are the transverse local rms angular spreads, and σ_s and θ_s are the rms bunch length and the relative rms momentum spread. F is weakly dependent on its variables and ranges between 1 and 1.15.



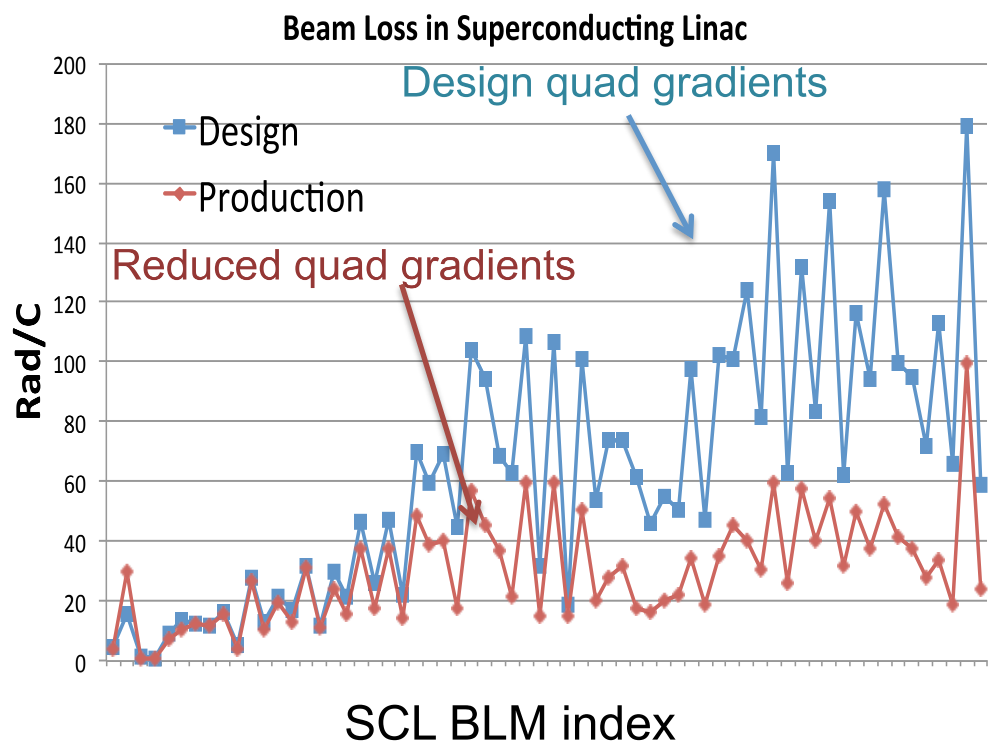


$$\boxed{dN / ds \propto \sigma \cdot N^2}$$

(V. Lebedev et al., LINAC2010, Tsukuba, Japan, p. 929 (2010))

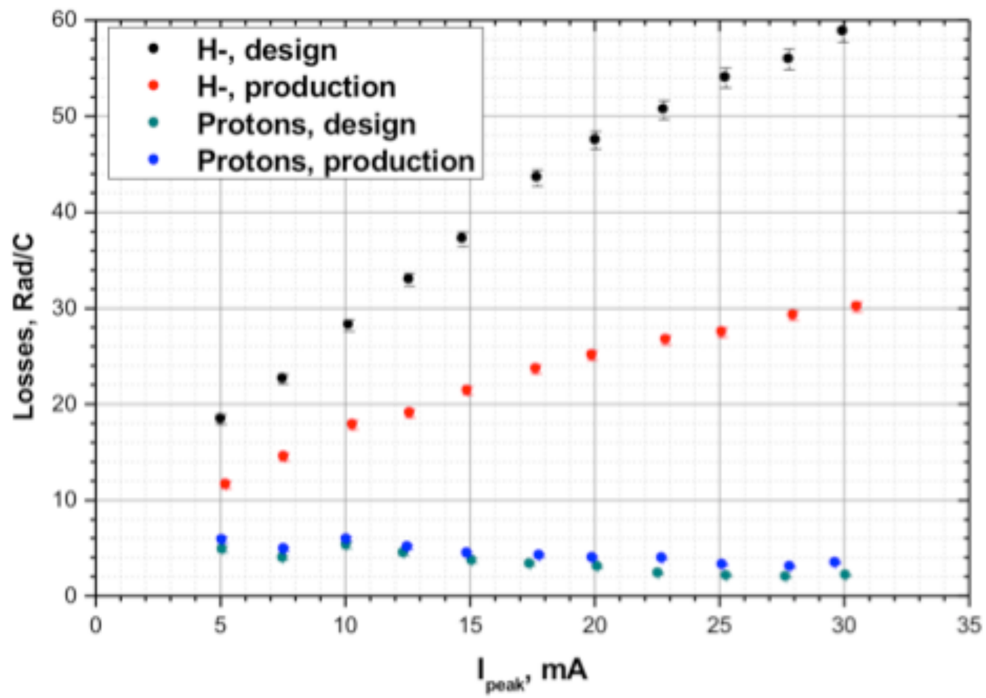
Intra-beam stripping at SNS

- This is the dominant source of beam loss in the SNS SCL
- 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 beam loss scales with (peak beam current)^2.



IBSt – measurement vs. calculation

- We calibrated the SCL BLM system by causing known amounts of beam loss using the laser profile monitor system
- Based on this calibration, and the beam loss signals during normal operation, we estimate a fractional loss of $(2 – 7)\text{x}10^{-5}$ over the entire length of the SCL
- A rough calculation of the expected IBSt loss is $4\text{x}10^{-5}$
- Also measured beam loss for protons, and found much less loss with no intensity dependence

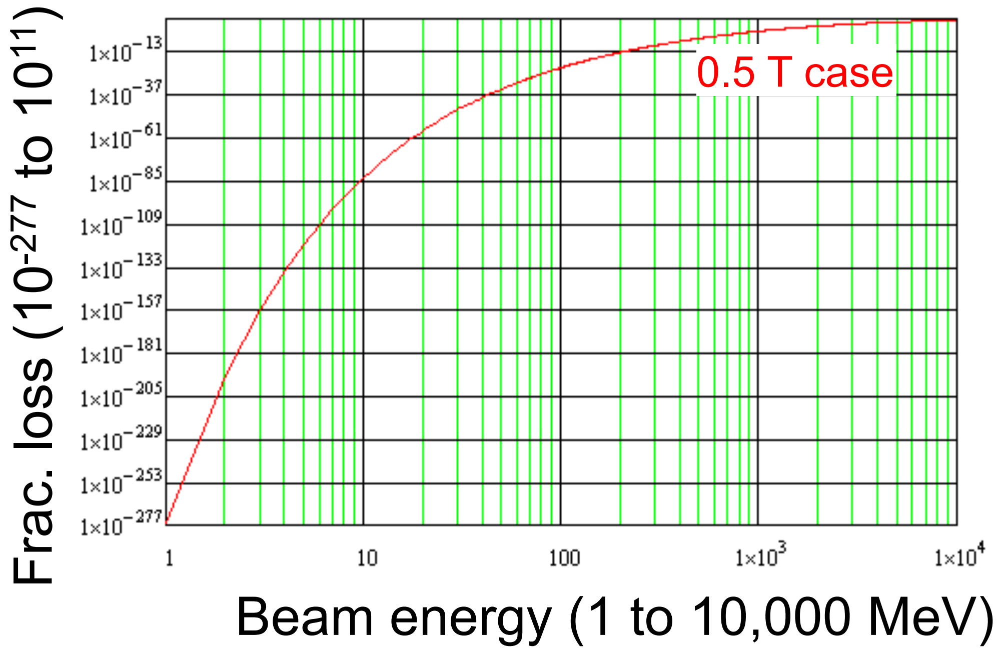


Magnetic field stripping

- Lorentz-transformed magnetic field looks like electric field in rest frame of beam particles E_{ion} [V/m] $= \beta\gamma c B_{lab}$ [T]
- 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
B(s) = magnetic field
β, γ, c = relativistic factors

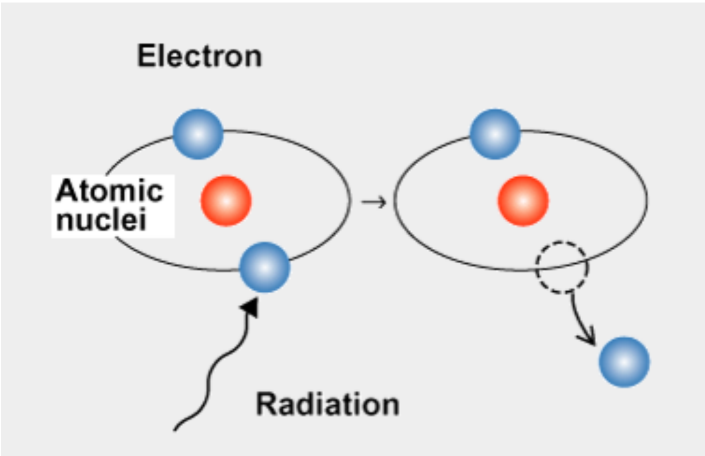


- Seen in ISIS 70 MeV transport line to ring, level of <1%

(A. Jason et al., PAC 1981, p. 2704)

Black body radiation stripping

- Photo-detachment using laser beams is a well-developed method to measure H^- beam profiles and beam emittances, and it is now being developed as a method for charge exchange injection into storage rings and synchrotrons
- Highest H^- beam energy in use today is 1 GeV (at SNS). Doppler-shifted black-body photons are not a problem at this energy.
  - Fractional beam loss caused by room-temperature photons is ~3×10^{-9} per meter
- It will be a problem for high-energy H^- beams, e.g. the 8 GeV beam proposed for FNAL's Project X
  - Fractional loss would be ~8×10^{-7} per meter



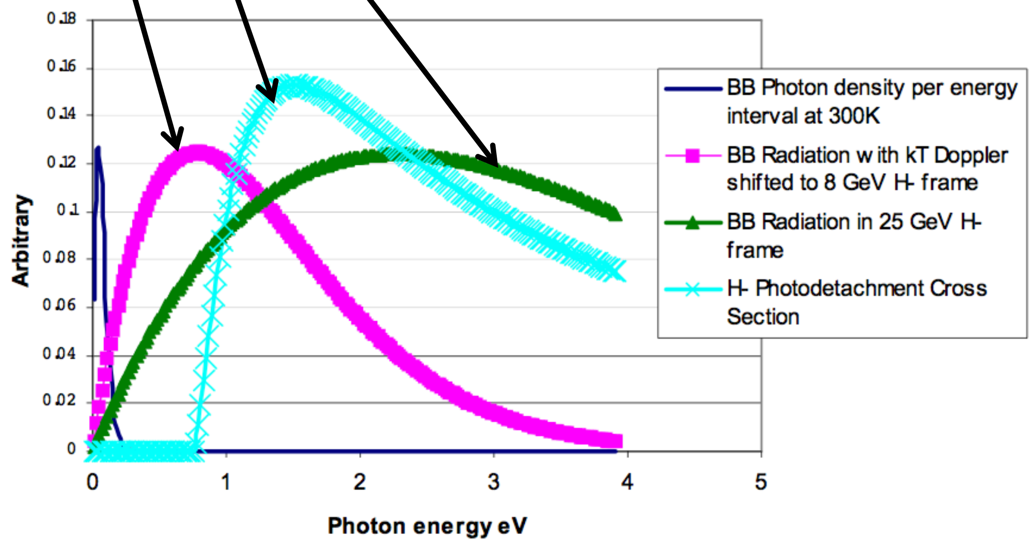
http://ecetutorials.com

Black body stripping vs. beam energy

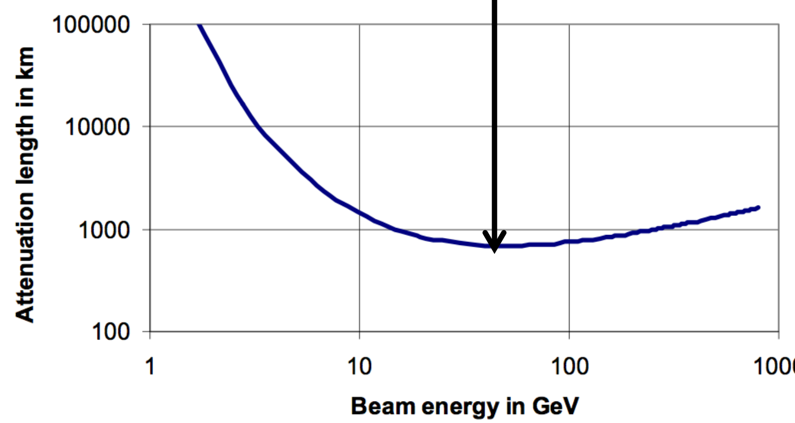
Shifted to 8 GeV H− frame

Shifted to 25 GeV H− frame

Photodetachment cross section



Worst energy for stripping is ~70 GeV



Fractional loss = 1/(Attenuation length)

(H. Bryant and G. Herling, JMO, 2006)

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	Not a problem unless have high beam energy (> about 5 GeV)			

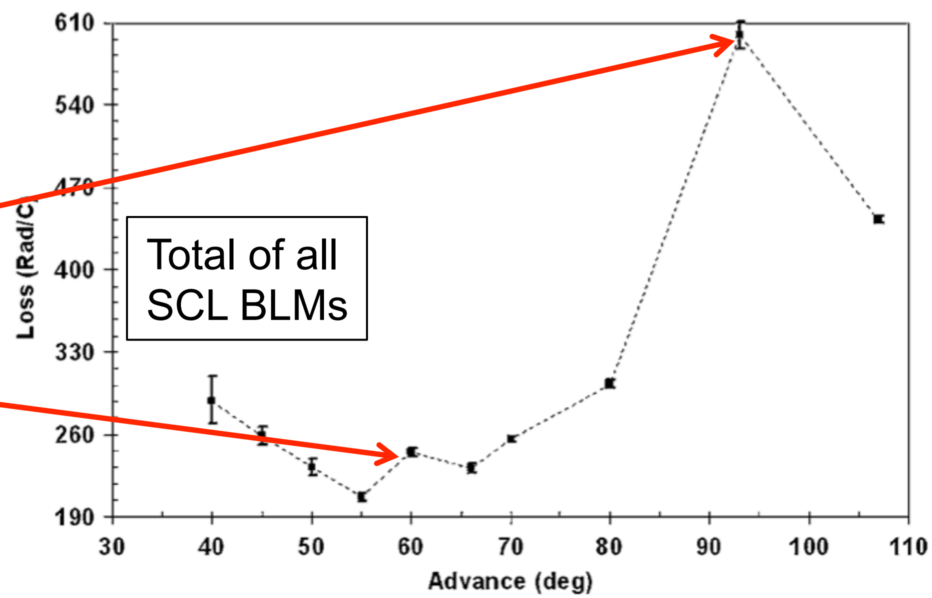
Beam loss in H^+ and H^- linacs

- Beam halo/tails (resonances, collective effects, mismatch, etc.)
- RF and/or ion source turn on/off transients
- Dark current from ion source

Beam loss due to resonances

- Certain phase advances will cause beam loss in linacs and beam transport lines $n\sigma_0$ = 180° or 360°. Resonances drive halo formation.
- The σ_0 = 90° (σ_0 is the transverse phase advance per cell for the zero space charge case) resonance is strong and commonly avoided in all high intensity linacs. Also known as envelope instability.
- Magnet imperfections can cause other resonance-driven losses

Beam loss in the SNS SCL with all RF cavities off



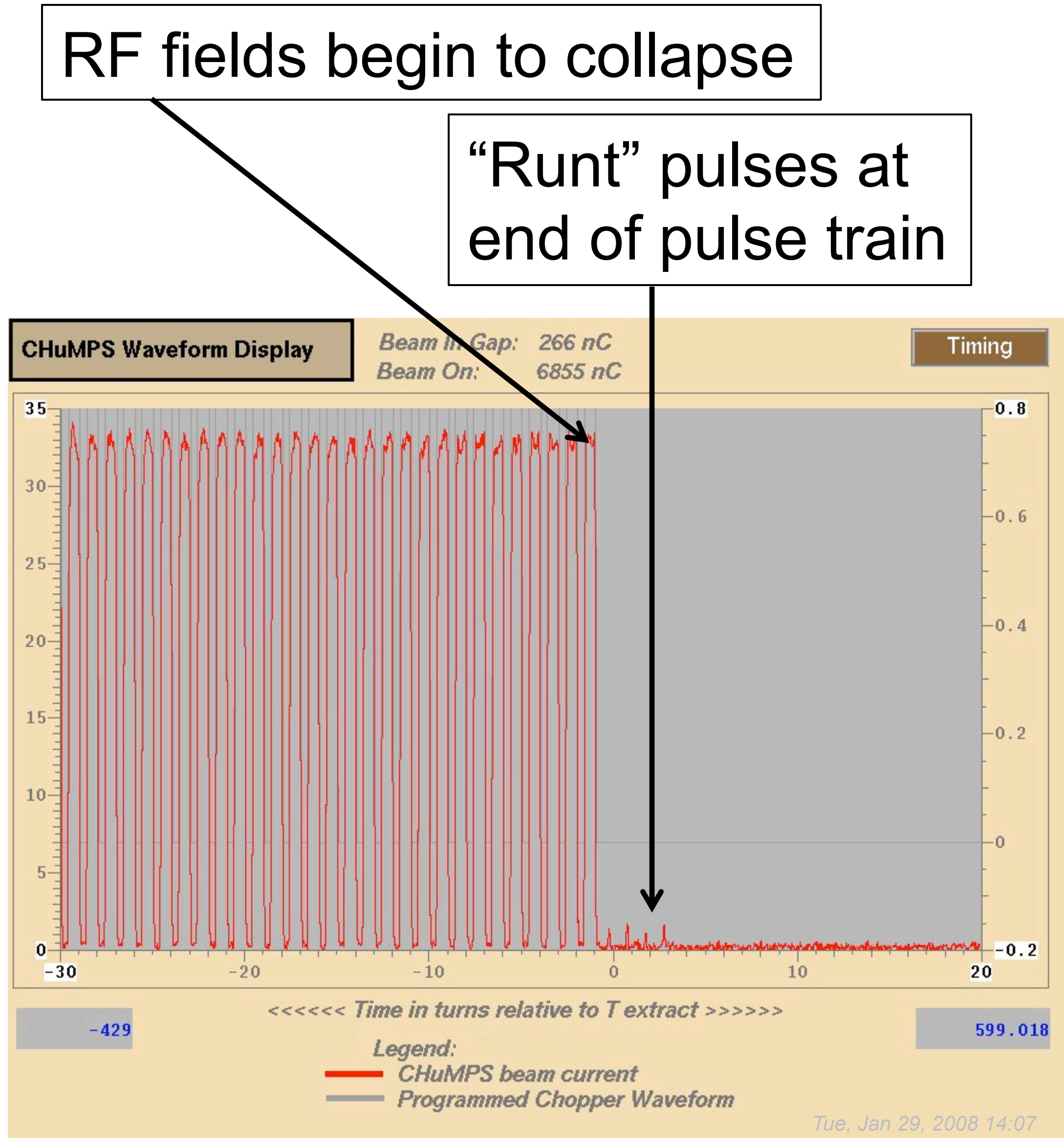
(Y. Zhang et al., PRSTAB 13, 044401 (2010))

Beam loss due to RF turn on / turn off

- Important for accelerators with pulsed RF systems
- Beam that is accelerated while the RF fields are ramping up or ramping down is likely to be lost
- Often solved with a chopper system, located at low beam energy, that blanks the beam during these times
- At SNS the chopper system is not perfect, so we purposely end the RFQ RF pulses ~3 us before the rest of the RF pulses

Beam loss due to RF / chopping

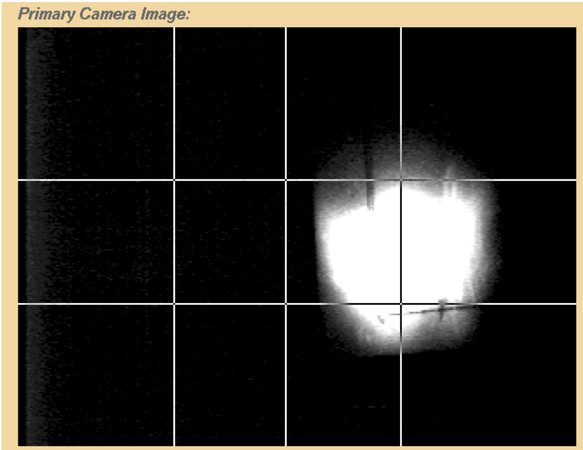
- Example at SNS: small amount of beam at end of pulse train due to poor chopping
- Poorly accelerated during RF field collapse
- Causes beam loss at high energy (in this case downstream of ring in transport to target)
- Mitigated by turning off RFQ ~3 us early



Fast BCM in MEBT

Beam loss due to dark current (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
- This beam is for the most part easily accelerated with very little loss, but…



Dark current seen using a view screen

- A portion of this beam is lost due to RF turn-on and turn-off transients, not detected 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 for the entire duration of the linac RF pulse

Occasional beam loss

- A large amount of beam loss can occasionally occur due to:
  - Response time for RF feed back and feed forward systems
  - RF trips off due to an interlock
  - Fluctuations in the ion source
  - Drifts in the RF system (e.g. due to temperature in klystron gallery)
  - Pulsed magnets miss a pulse or provide only a partial pulse
- The integrated beam power lost may be small compared to the continuous beam loss, but the consequences can be large…

Why occasional beam losses are important

- Example: superconducting linac (SCL) cavity damage
  - Beam hitting RF cavity surface desorbs gas or particulates creating an environment for arcing or low-level discharge
  - RF cavity performance degrades over time
  - At SNS, some cavity fields have been lowered, some cavities have been turned off. Lower fields = lower beam energy.
  - SCL cavities do not trip off with every errant beam pulse, but the probability for a trip increases with time. These trips cause downtime.
  - At SNS, SCL cavity performance degradation from errant beam can usually be restored
    - Requires cavity warm up during a long shutdown and then RF conditioning before resuming beam operation

Beam loss due to RF response time

- RF feed back and feed forward is an important part of beam loss control. The RF system must react to and also anticipate the beam loading caused by high intensity beams.
- Otherwise there will not be a constant accelerating field in the cavity for the duration of the beam pulse, which can cause beam loss
- When the beam is turned back on after a trip, the RF system may have to re-optimize the feed back and feed forward parameters, and beam loss can be higher than normal during this time
- Example: at SNS, after a latched beam-off trip, we slowly increase the average beam current over a period of about 1 minute to give the RF system time to adapt, ramping both the peak current and the rep rate. Beam losses are elevated during this time.

Beam loss due to RF (cont.)

- Also, sudden changes in the beam pulse structure can cause the beam loading to change too fast for the RF system to compensate, which can then cause beam loss
- Similarly, if an RF system trips off in mid-pulse, the collapsing field in the cavity will only partially accelerate the beam, and cause beam loss in the downstream portion of the linac or beam transport lines
  - Due to the response time of the MPS system (15 - 20 us at SNS), the ion source will continue to inject beam into the linac, only to be lost downstream of the affected cavity

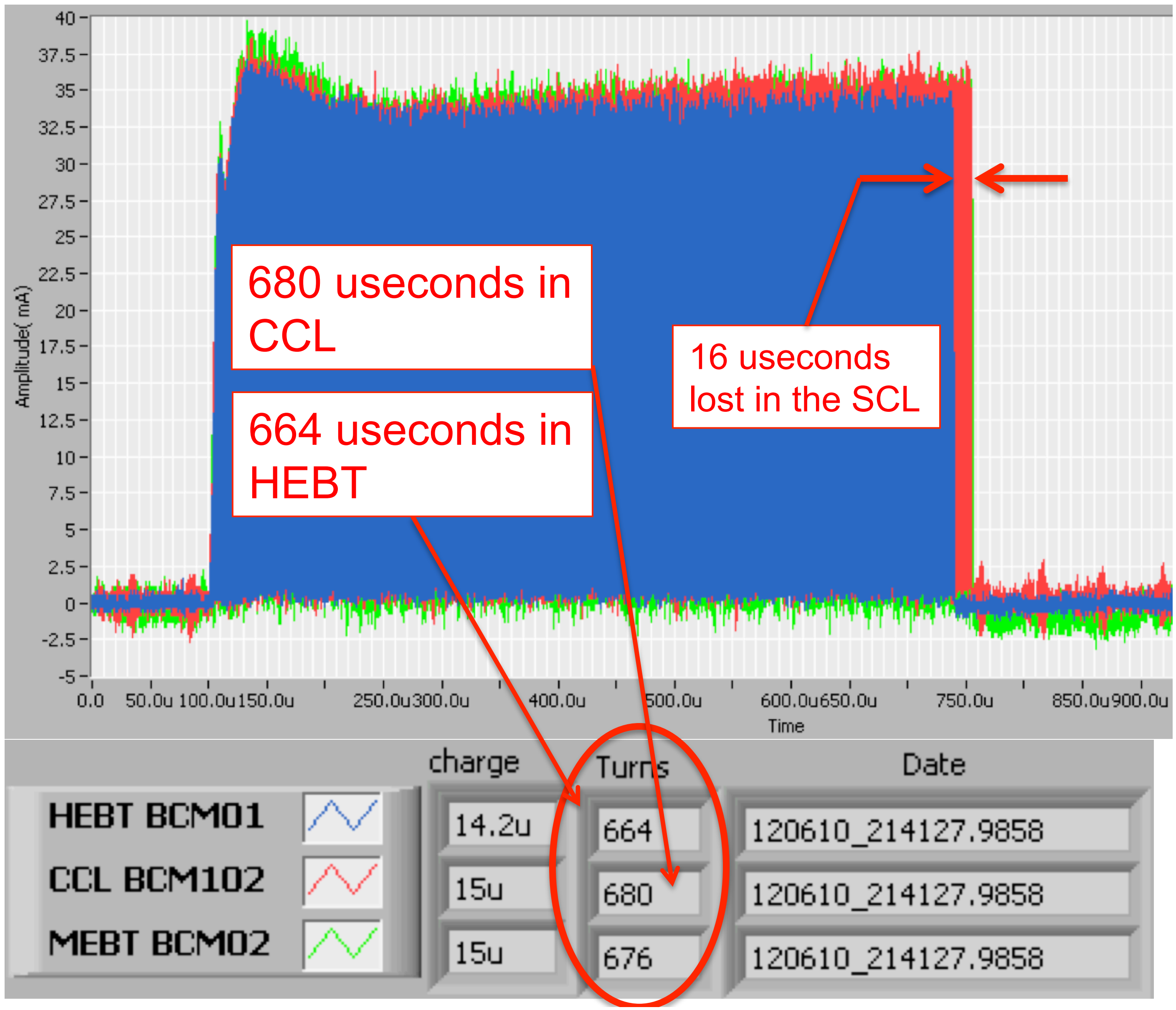
Capturing the occasional beam loss events in the SNS linac

- Differential Beam Current Monitor (BCM) systems
  - Use BCMs in the MEBT, CCL, and HEBT to see how much beam is lost in the SCL
- BLM systems
  - 76 ion chamber detectors along the SCL
- Automated report system
  - SCL BLM trip occurs, or BCM system detects abnormal signal
    - Record BCM waveforms, BLM waveforms, BLM signal level
    - Send data to a webserver for immediate viewing

How much beam is lost

16 useconds
End of DTL = 30 J
End of CCL = 66 J
End of SCL = 350 J

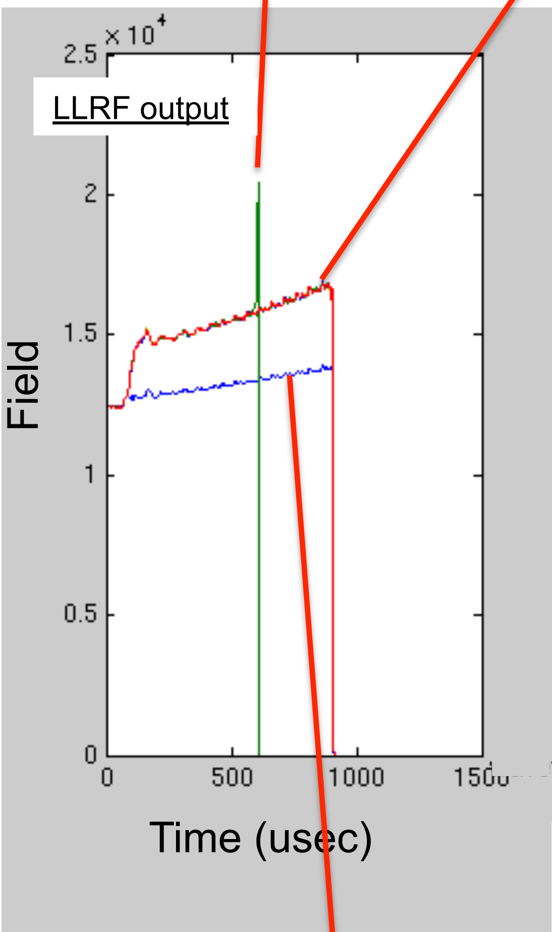
- Differential BCMs showed different types of faults
  - Average 15-20 usec of beam lost in the SCL

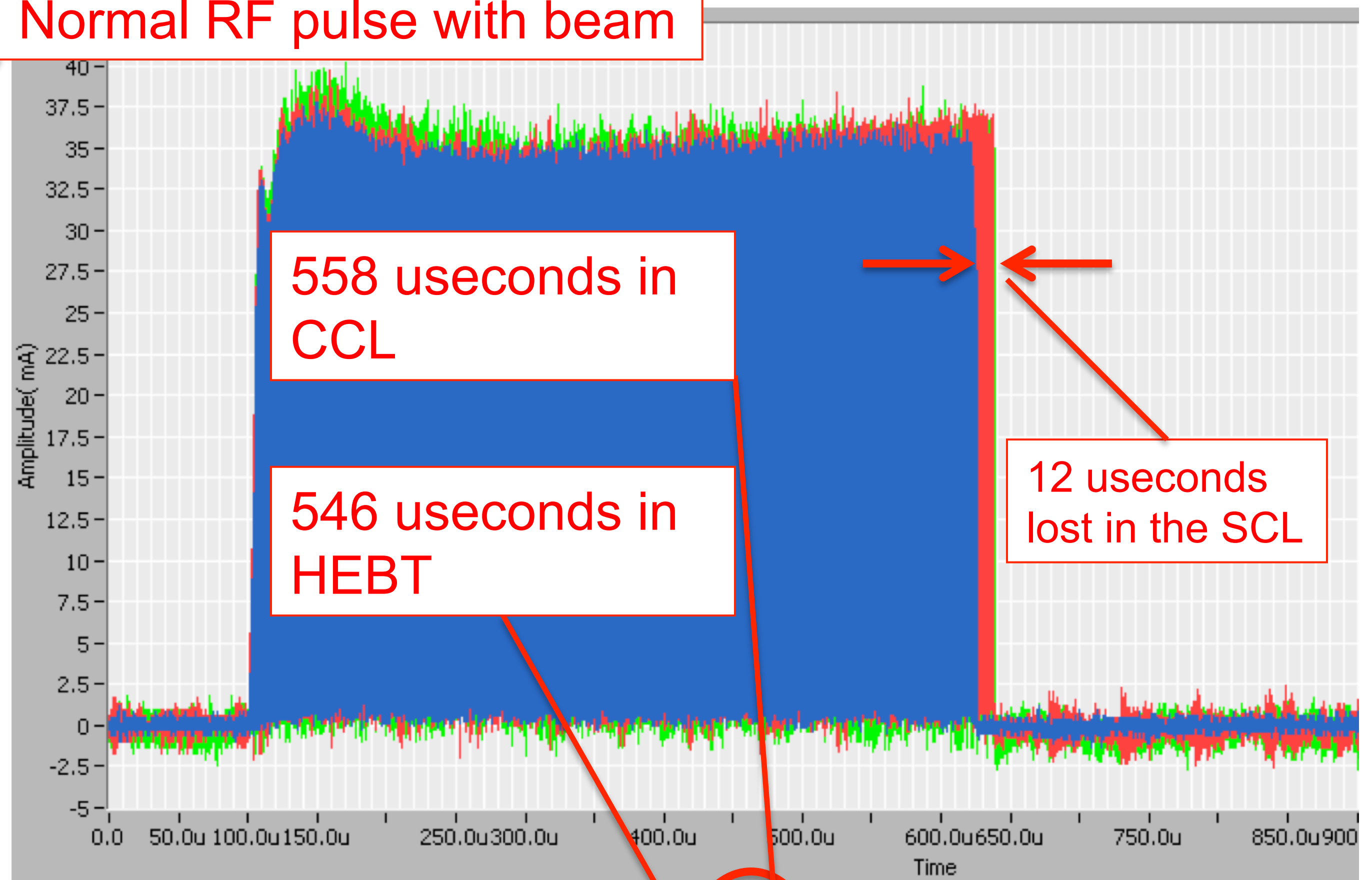


Beam loss due to warm linac RF

Abnormal RF pulse with beam

Normal RF pulse with beam





558 useconds in CCL

546 useconds in HEBT

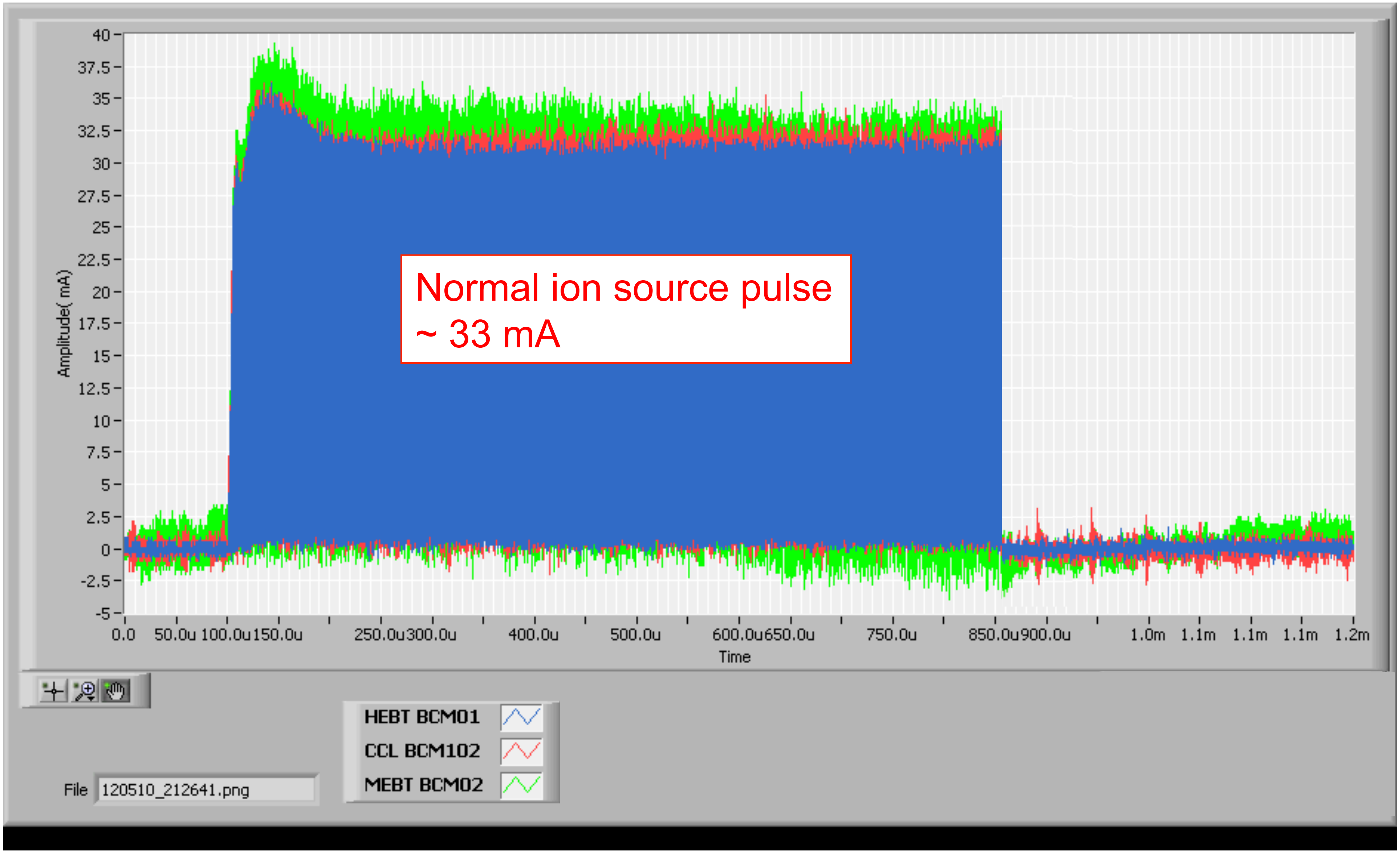
12 useconds lost in the SCL

		charge	Turns	Date
HEBT BCM01		11.9u	546	120612_190535.8754
CCL BCM102		12.5u	558	120612_190535.8754
MEBT BCM02		12.6u	555	120612_190535.8754

Normal RF pulse with no beam

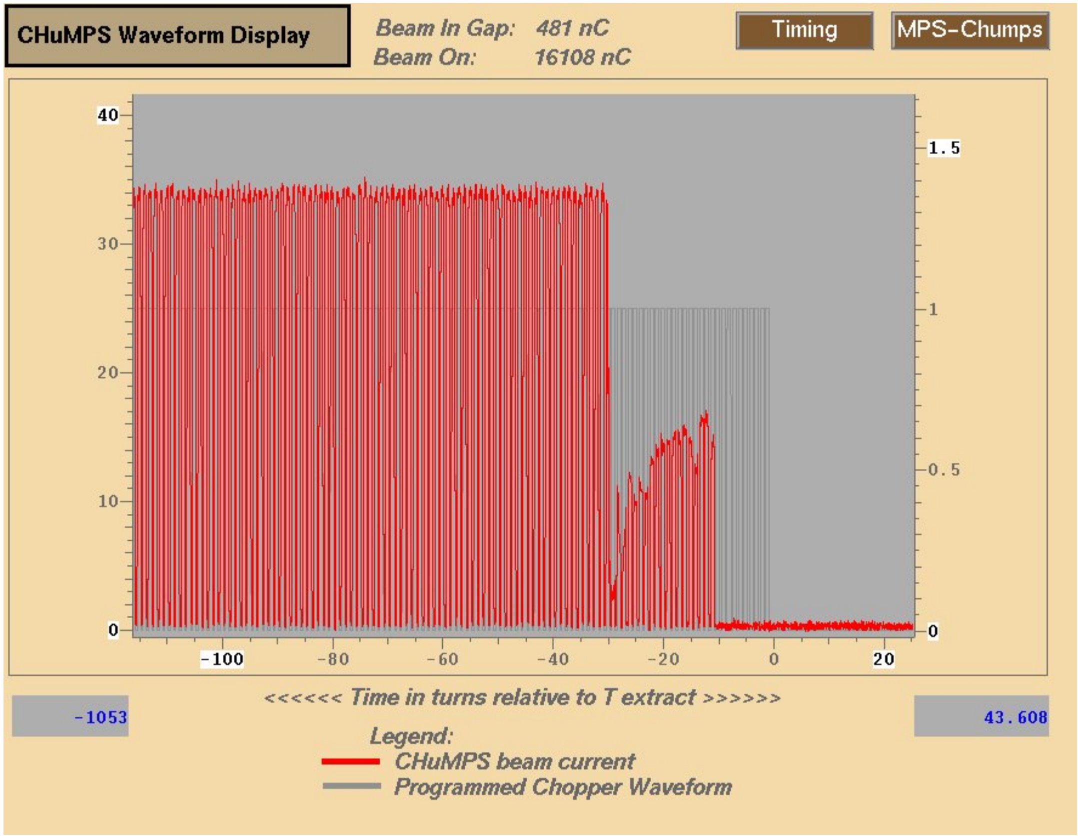
(Courtesy C. Peters)

Beam loss due to ion source/LEBT



Beam loss due to ion source

- Abrupt beam loss caused by sudden changes in the ion source



Fast beam current monitor in MEBT

At SNS, the majority of trips originate in the warm linac

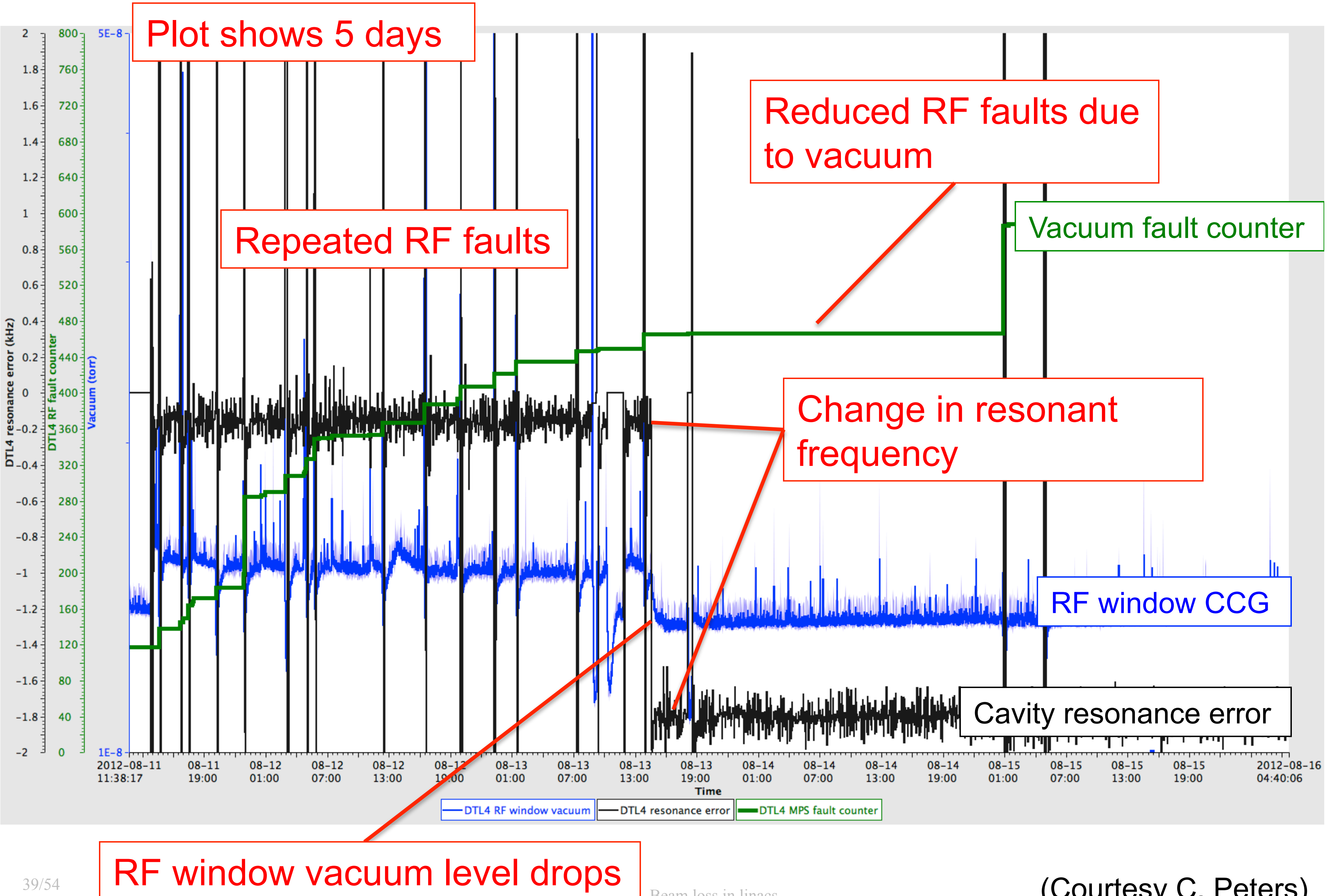
- < 10% of BLM trips were due to the Ion source/LEBT
  - Most ion source induced BLM trips occur during the first week of a new source installation
    - High voltage arcing
- > 90% of BLM trips were due to Warm Linac RF faults
  - RF faults occur at different times during the pulse
    - Faults during the RF fill had reproducible times
    - Faults during the RF flattop were random
  - Focused on improving warm linac operation

RF fill faults can be reduced

- Adjust the RF field
  - Move below or above multipacting band
- Adjust RF fill time
  - Ramp speed through multipacting bands
- Change cavity resonant frequency
  - Move multipacting band
- Vacuum maintenance
  - Maintain low vacuum near RF window

DURING BEAM OPERATION

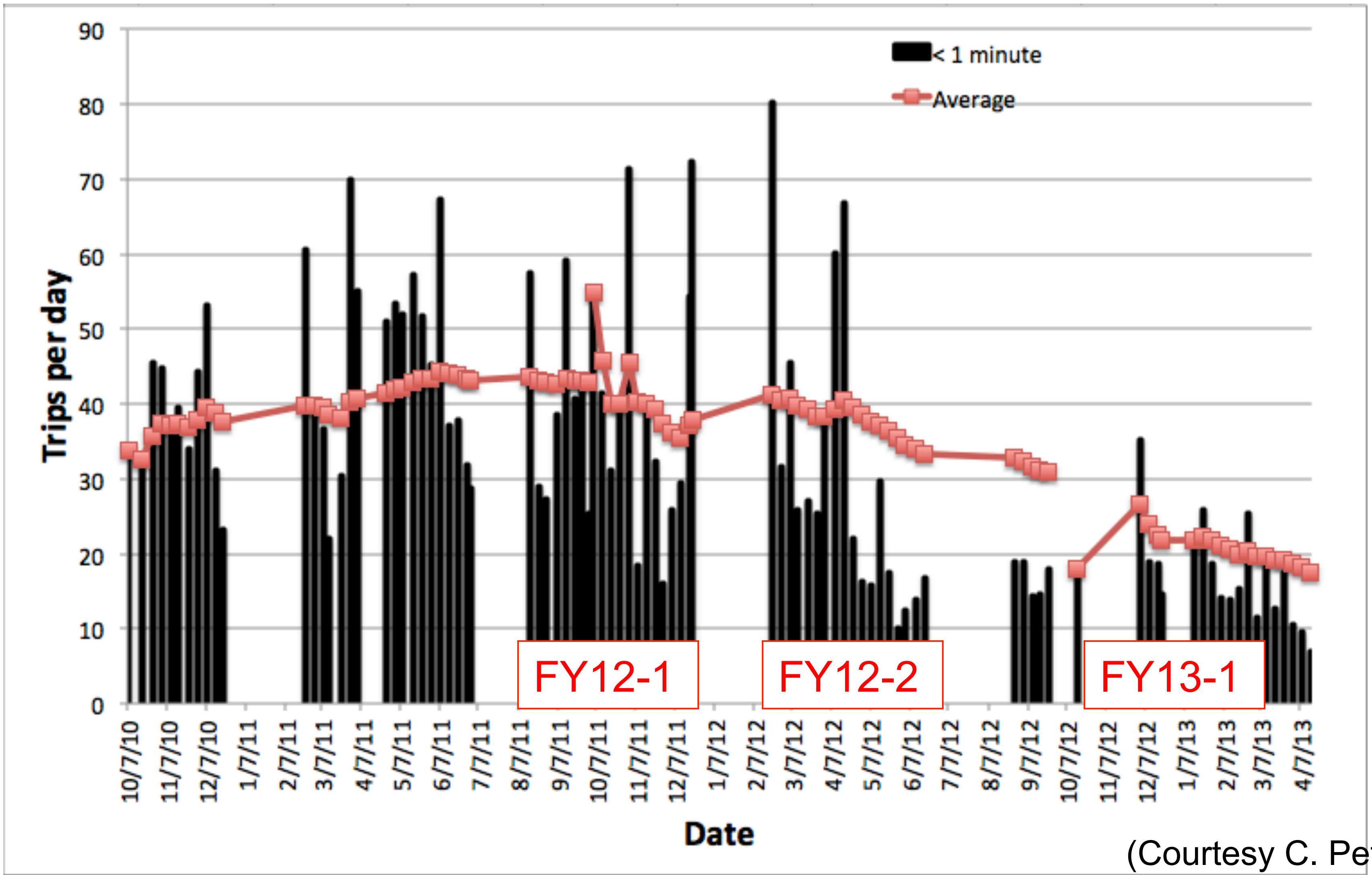
Resonant frequency change improves trip rate



(Courtesy C. Peters)

Errant beam trips reduced

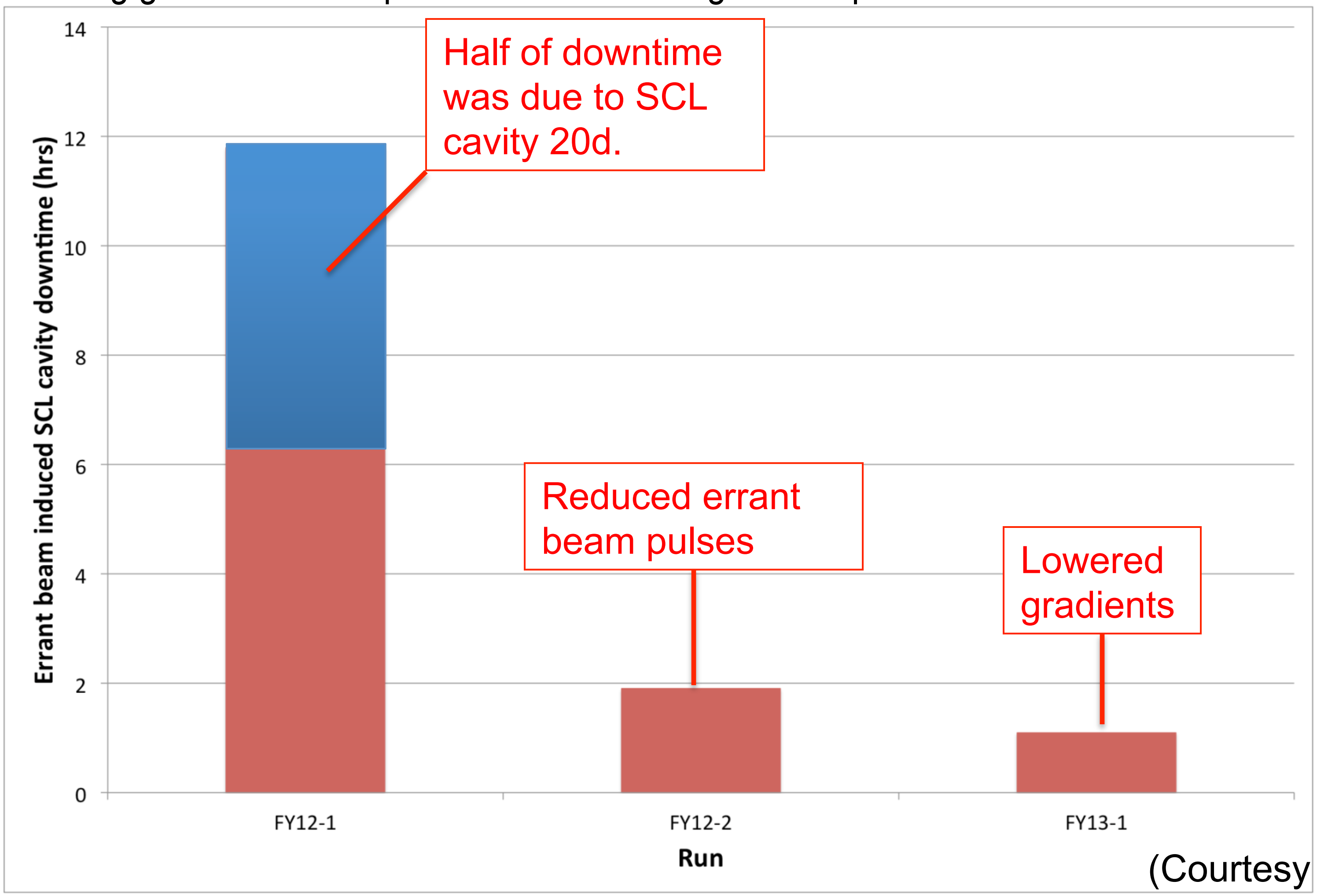
- From over ~40 to less than ~15 errant beam pulses per day



(Courtesy C. Peters)

SCL cavity downtime reduced 6x

- Reducing errant beam pulses reduced errant beam induced SCL cavity downtime by factor of 3
- Lowering the gradient on problematic cavities reduced downtime by factor of 2
  - Lowering gradients a few percent is done during beam operation



(Courtesy C. Peters)

Beam loss mitigation

Cause of beam loss	Mitigation
Beam halo – both transverse and longitudinal*	Scraping, collimation, better matching from one lattice to the next, magnet and RF adjustments
Intra beam stripping*	Increase beam size (both transverse and longitudinal)
Residual gas stripping	Improve vacuum
H^+ capture and acceleration	Improve vacuum, add chicane at low energy
Magnetic field stripping	Avoid by design
Dark current from ion source	Deflect at low energy, reverse (phase shift) RF cavity field when beam is turned off
Off-normal beams (sudden, occasional beam losses)	Turn off beam as fast as possible, track down troublesome equipment and modify to trip less often

Beam loss reduction by scraping

Example: SNS

Most effective

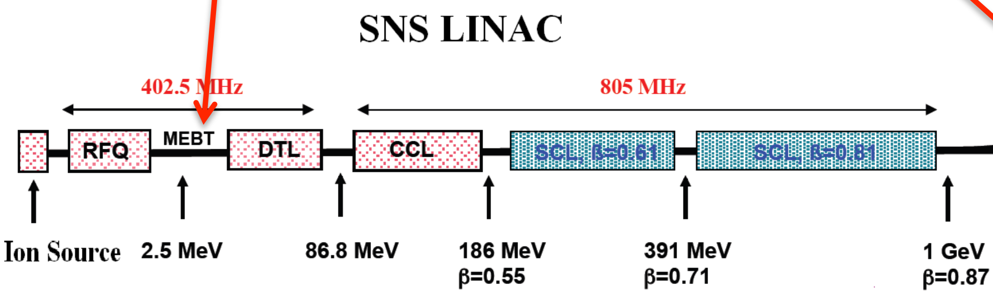
In MEBT:
Left-right scrapers
Top-bottom scrapers

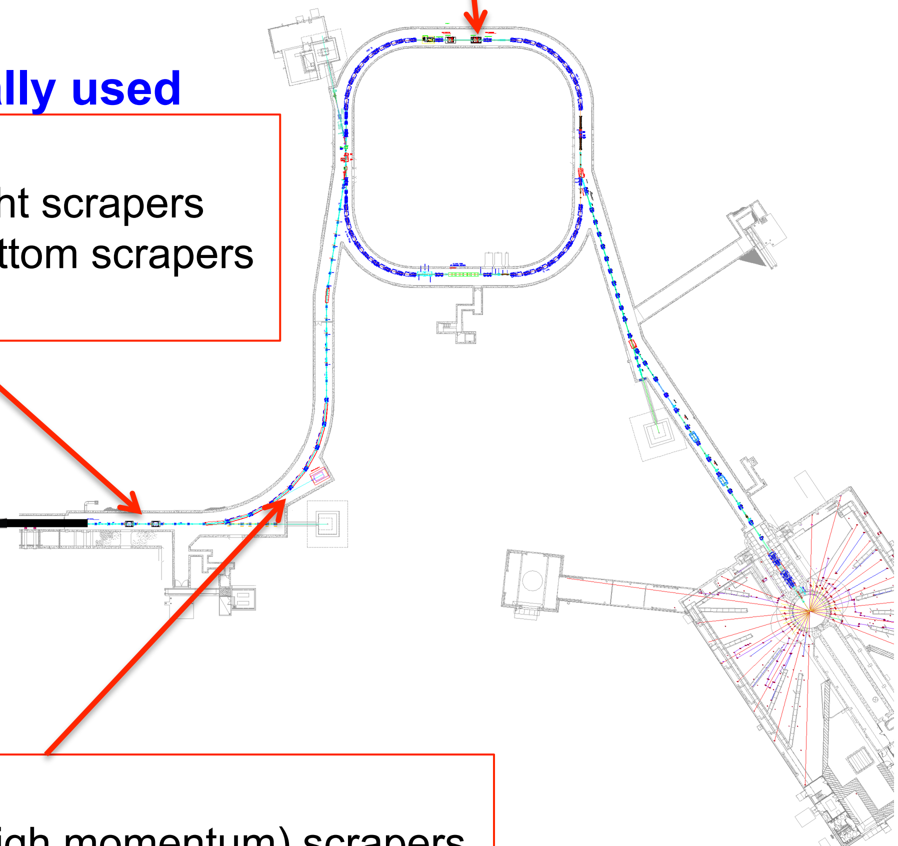
Almost never used

In Ring:
Four scrapers (0, 45, 90, 135 deg.)
Three collimators

Occasionally used

In HEBT:
Two pairs of left-right scrapers
Two pairs of top-bottom scrapers
Two collimators





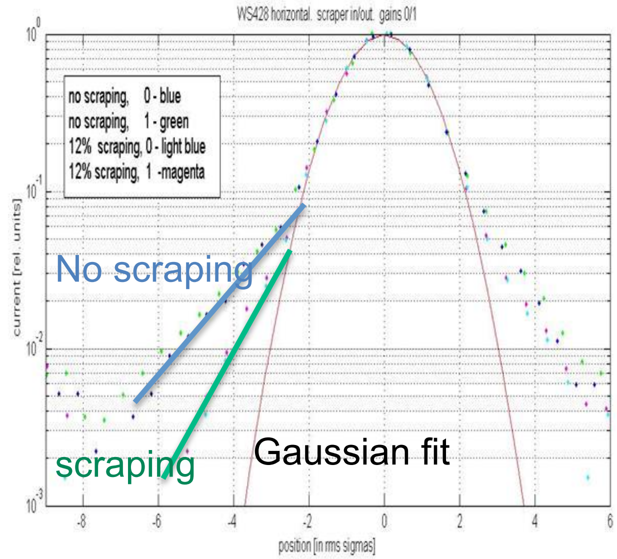
Rarely used

In HEBT:
Left-right (low and high momentum) scrapers
Followed by beam dump

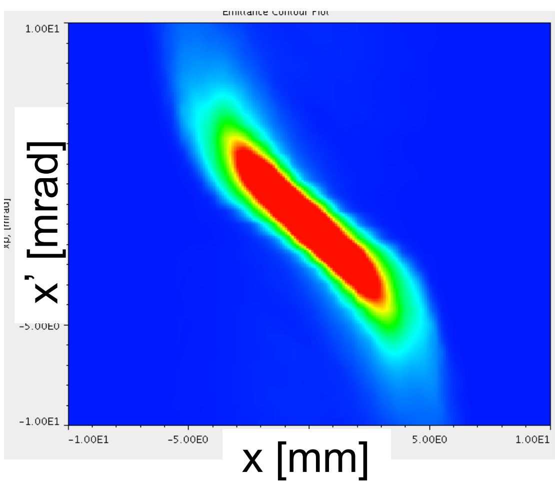
MEBT Scraping

- 2 horizontal and 2 vertical MEBT scrapers
  - Standard part of production
  - Reduces linac and injection dump losses by up to ~60%
  - Effectiveness in loss reduction varies from source to source

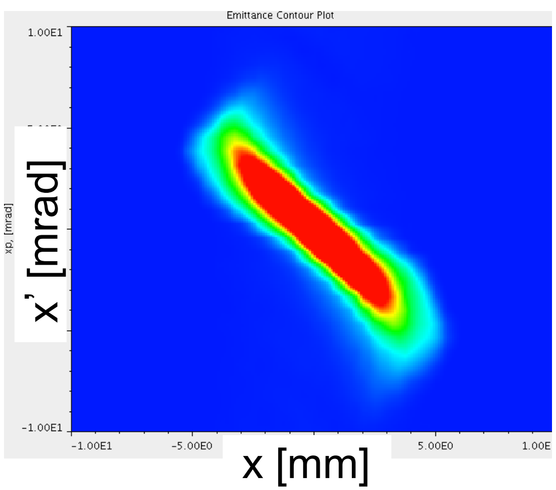
DTL profile, log scale



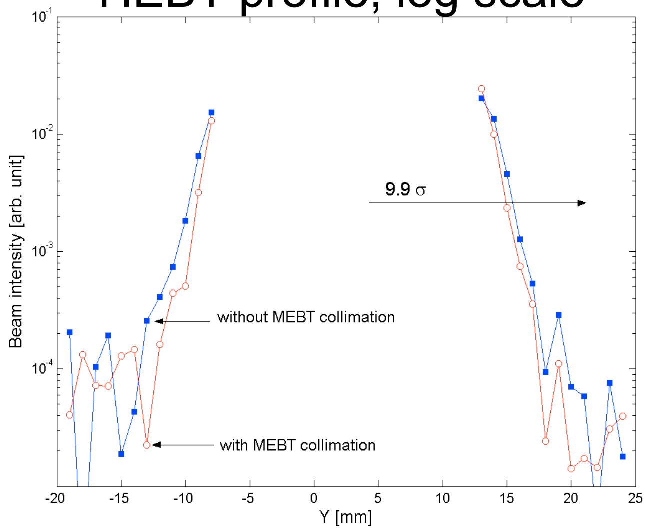
MEBT Emittance without scraping



MEBT Emittance with scraping

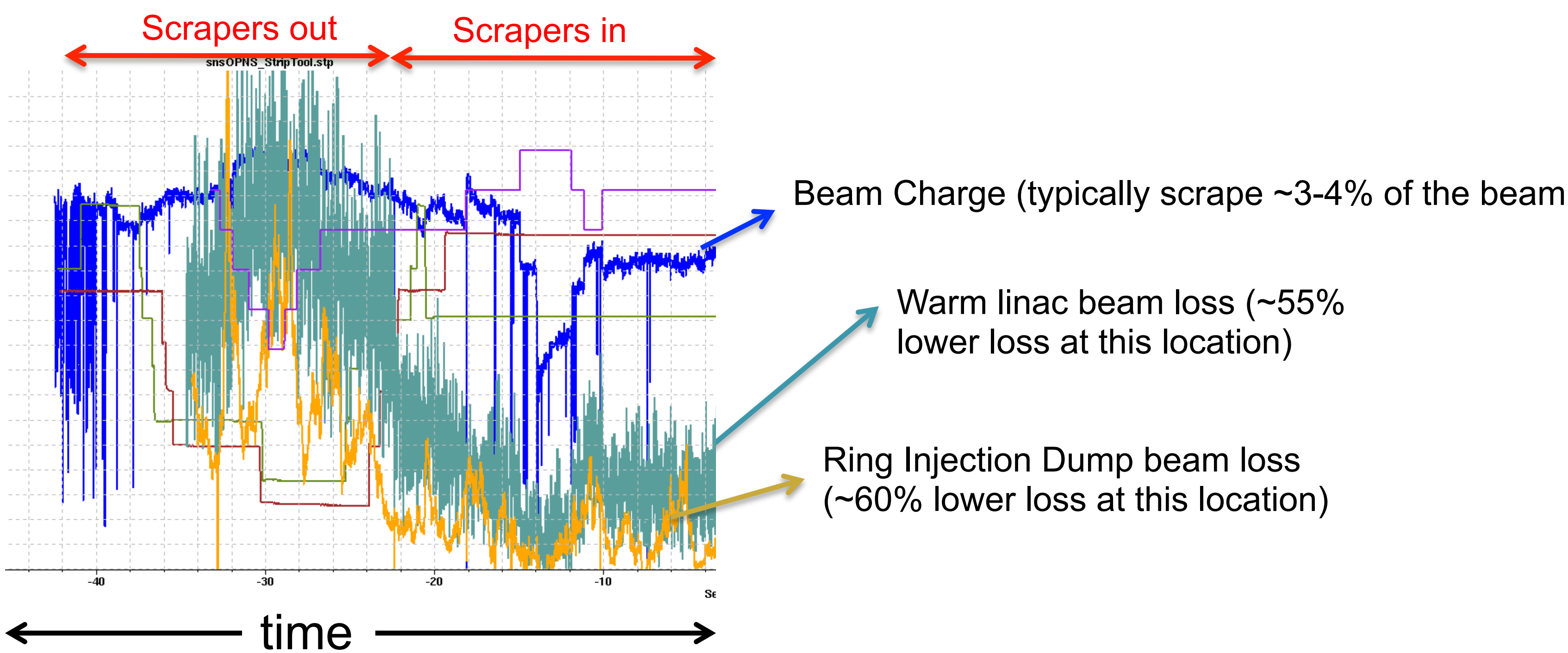


HEBT profile, log scale



(Courtesy A. Aleksandrov)

Beam loss reduction 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 ~60% loss reduction by scraping 3-4% of the beam

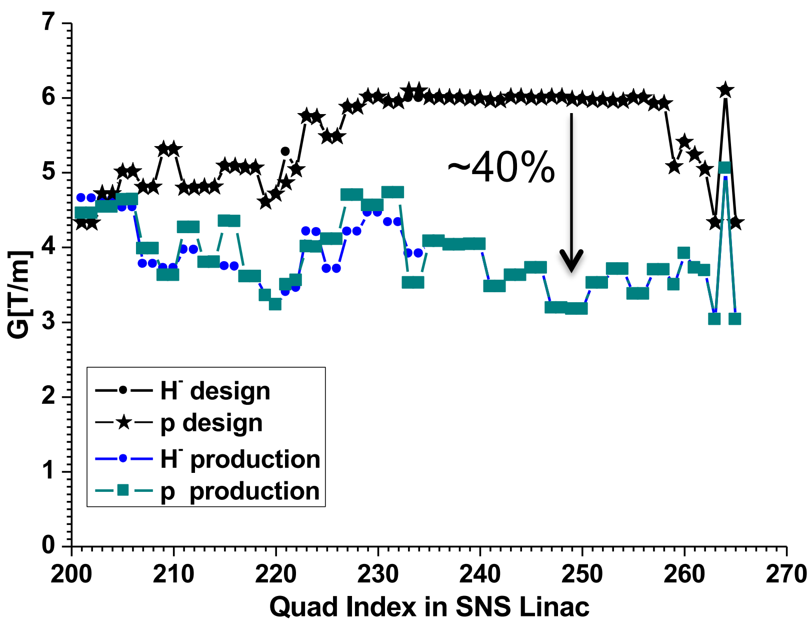
(Courtesy J. Galambos)

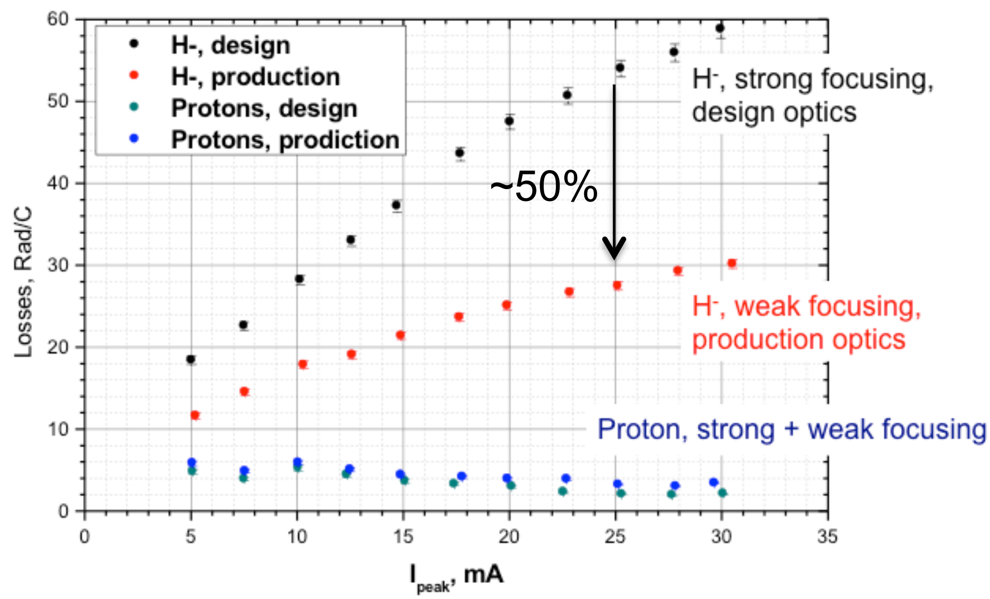
Beam loss reduction by collimation

- Collimators are often found in transfer lines and rings, but not so much in linacs
- There may be some unintended collimation at low energy, where beam loss is not easily detected.
  - Example: Drift tubes in DTL linacs make good collimators
  - We may have some of this at SNS

Beam loss reduction by increasing the beam size in the SNS SCL

- Most of the beam loss in the SCL is due to intra-beam stripping ($H^- + H^- \rightarrow H^- + H^0 + e$)
- IBSt reaction rate is proportional to (particle density)^2

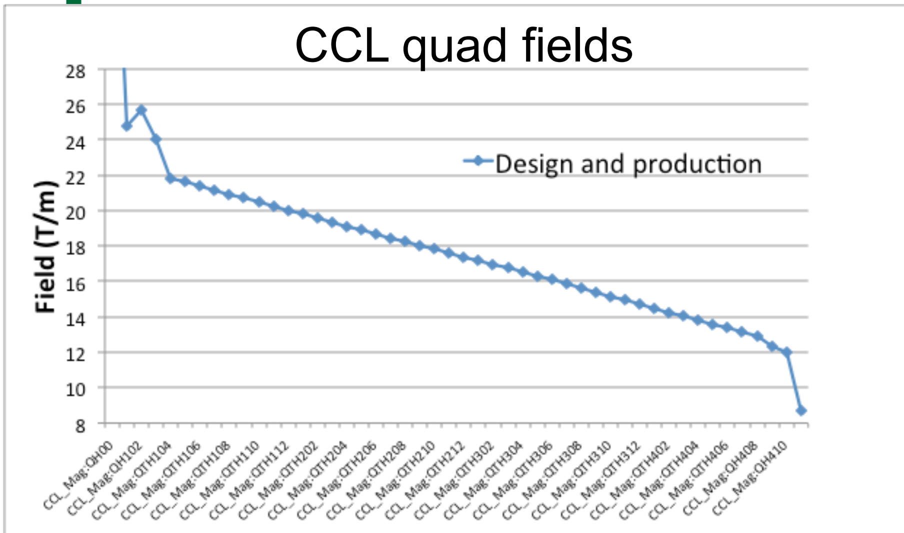


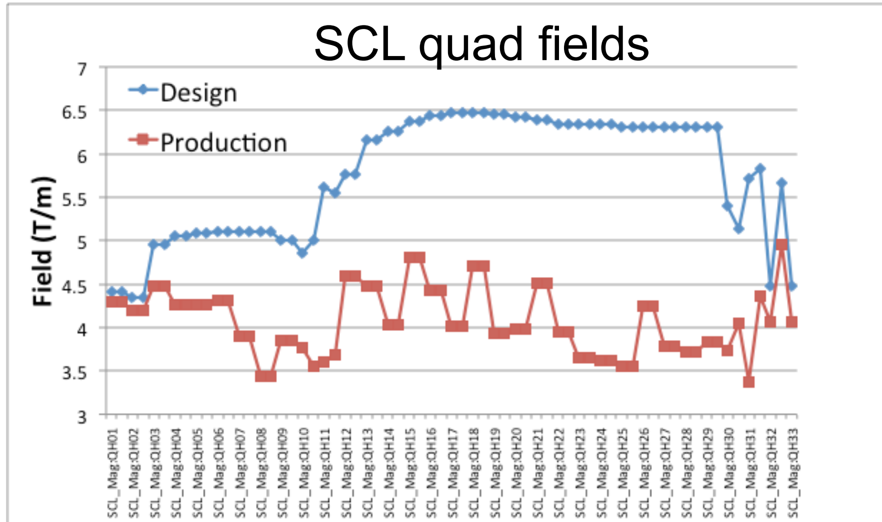


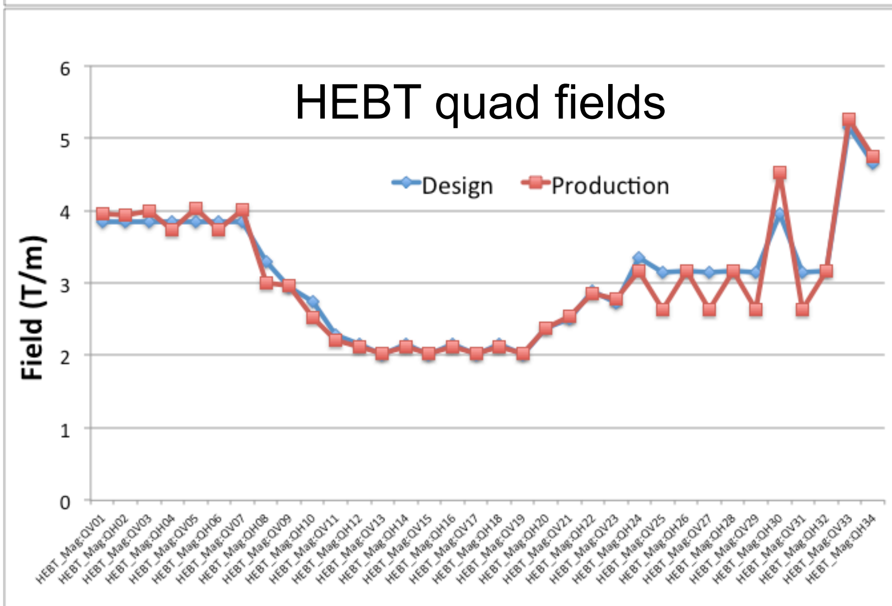
Beam loss reduction by empirically adjusting magnets and RF phase

- Best beam loss is obtained by empirical tuning. This is done at all high power accelerators.
- Empirical tuning sometimes results in beam that is transversely mismatched at lattice transitions (e.g. CCL to SCL, SCL to HEBT)
- RF phases may also need adjustment - simulation codes may not give the best beam loss
  - Example: At SNS, biggest deviation from simulations are at entrance to SCL
  - One degree phase change can approx. double the beam loss at some places
  - Typical phase changes are 1 to 10 deg.

SNS Linac Transverse Lattice: Design vs. Operation

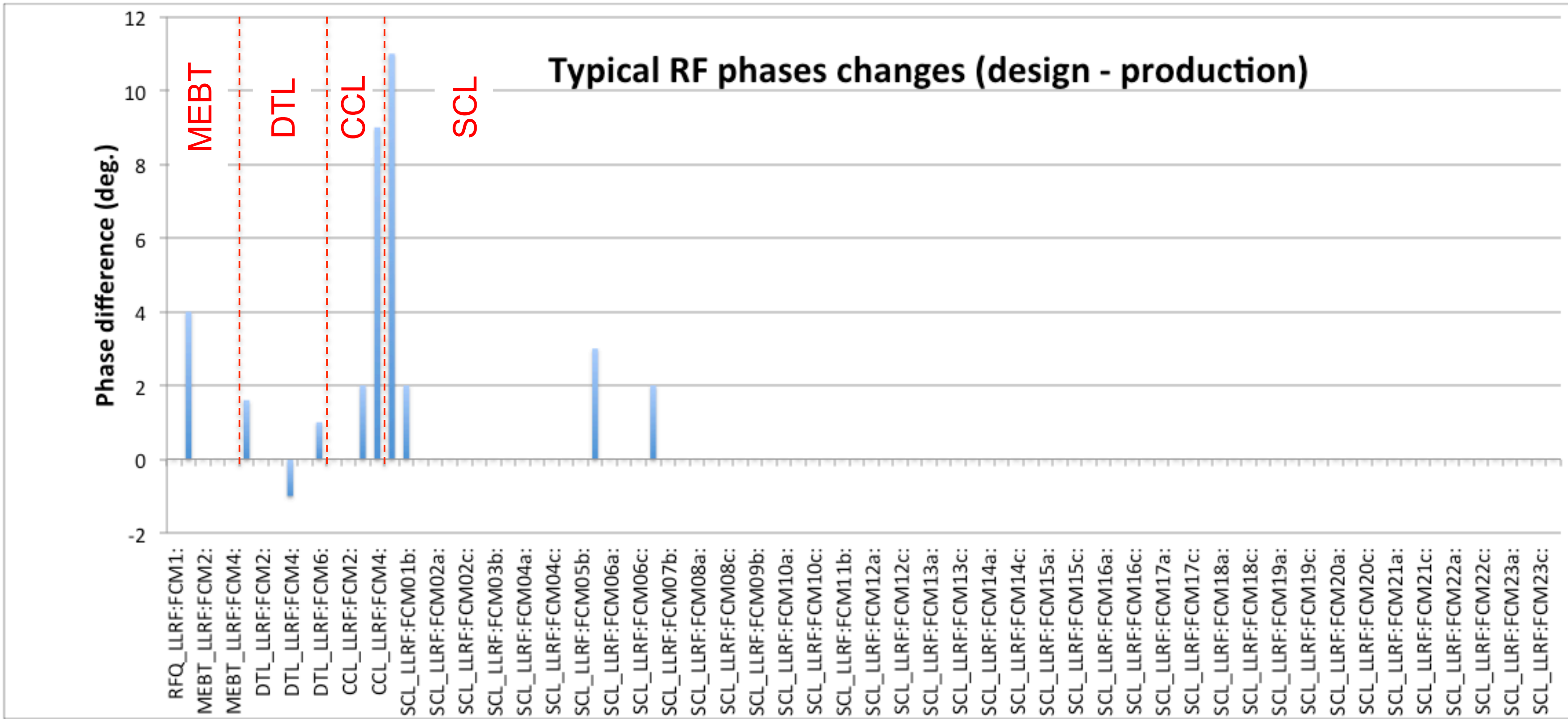






- Warm linac CCL quads are equal to design
- SCL quads run much lower than design
- HEBT is run close to design

SNS Linac RF phases design vs production

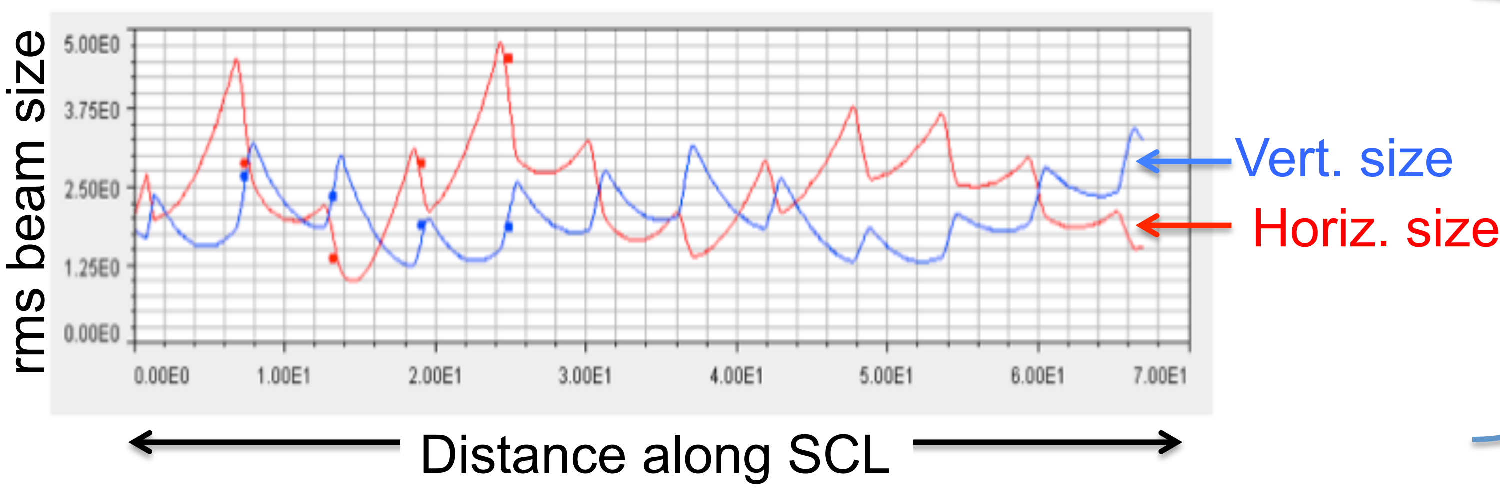


Some RF phases must be empirically adjusted to achieve the low-loss tune

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)

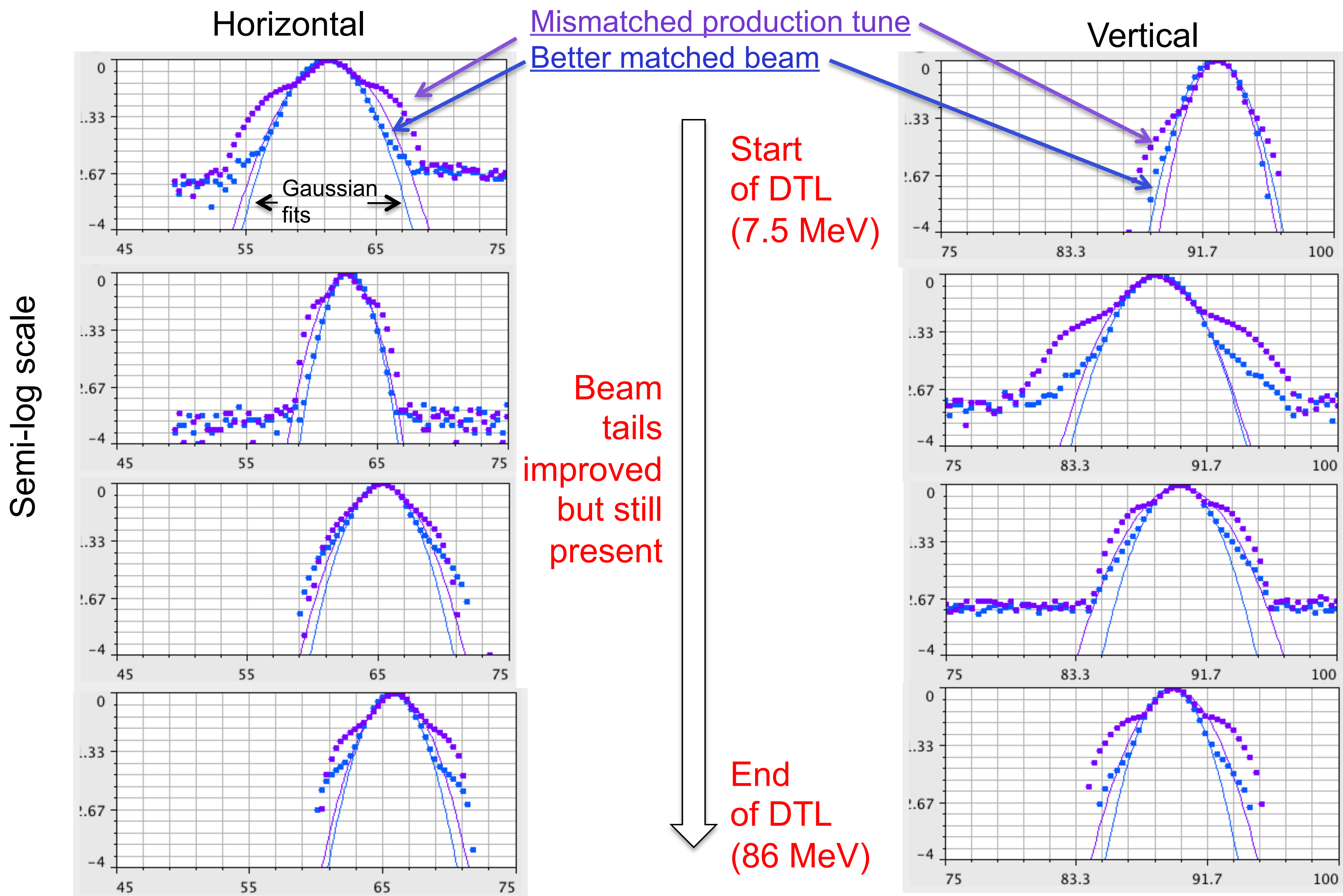
Low-loss tune is mis-matched at beginning of SNS SCL



This is a doublet lattice

The low-loss tune is mis-matched

Example: beam tails in SNS DTL



(Courtesy C. Allen)

Hypothesis

- The empirically-derived low-loss tune shows a mis-matched core throughout the linac and transport lines
- Beam halos/tails are what cause the beam loss, and they are present at the 0.01% to 30% level
- Due to space charge effects, ion source effects, etc., the Twiss parameters of the tails are different than the core of the beam
- The low-loss tune is the one which best transports the halos/tails of the beam, and which may cause strange results (e.g. mis-matched) for beam-core measurements

Summary

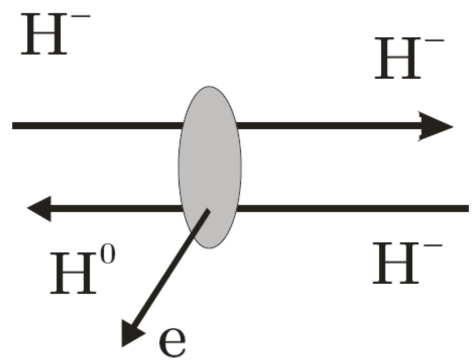
- There are many causes of beam loss. In general there are more causes of H^- beam loss than for H^+ beam loss.
- Two basic categories: continuous vs. occasional
- Methods of mitigation vary from magnet and RF adjustments to adding vacuum pumps to adding beam line components like collimators and chicanes

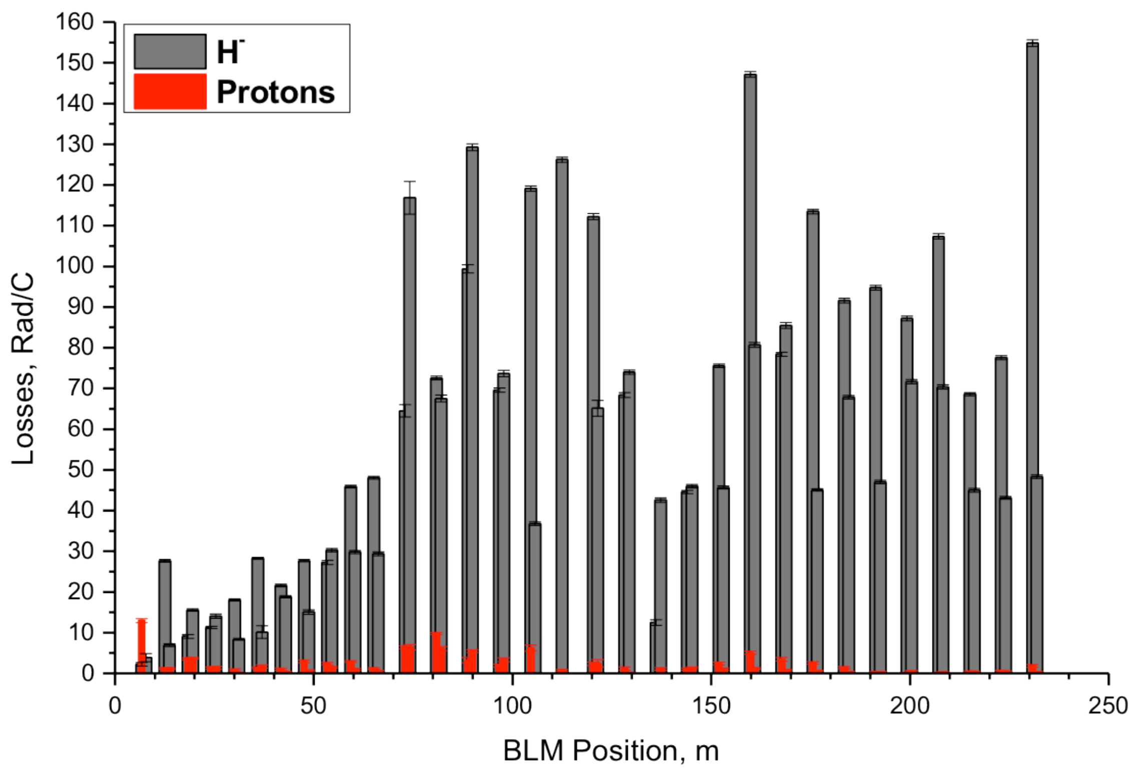
Thank you for your attention!

Back up slides

Intra beam stripping (cont.)

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



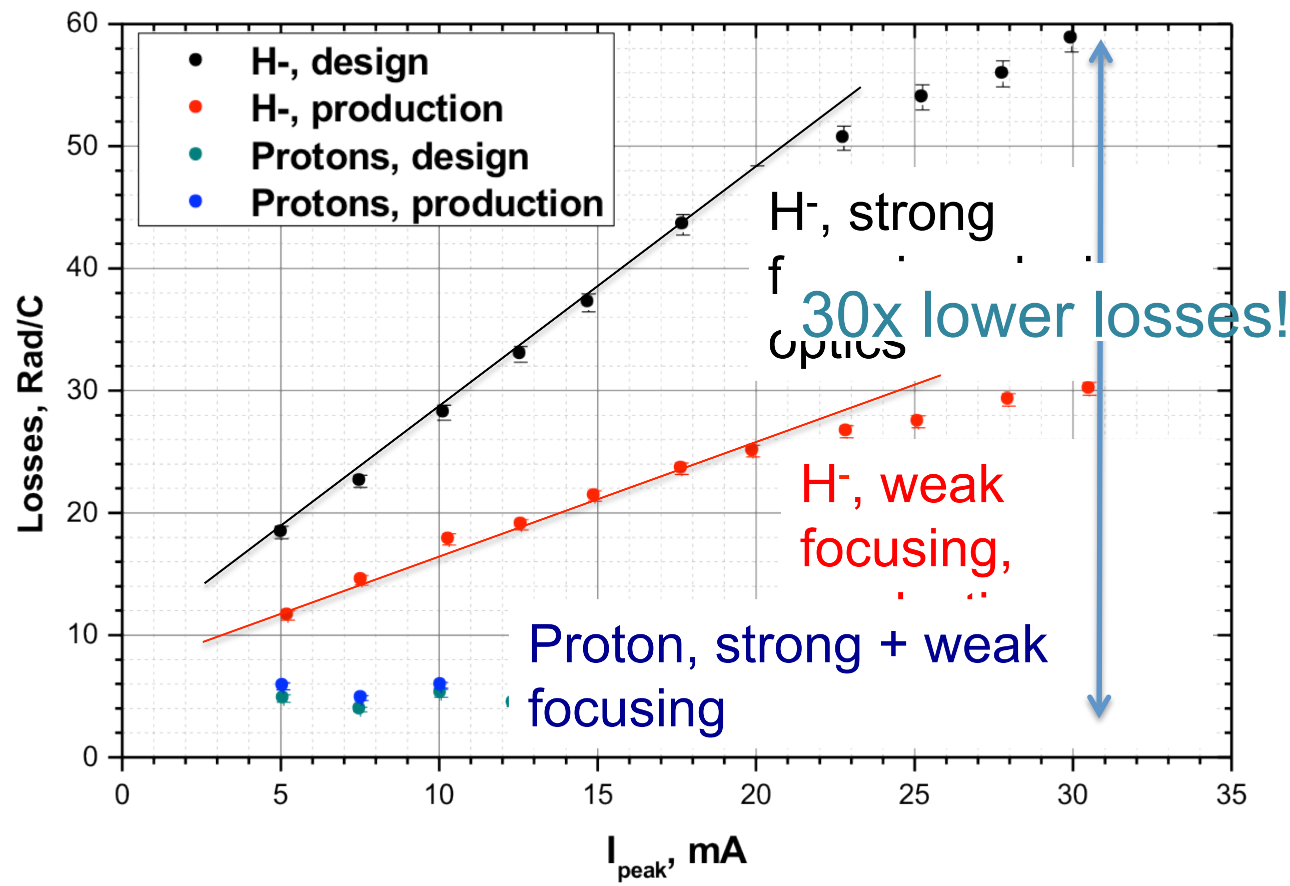


- **Result: Proton losses are ~20x less than H^- losses (but not zero)**

*V. Lebedev et al., Linac2010

SCL Losses vs. Peak Current

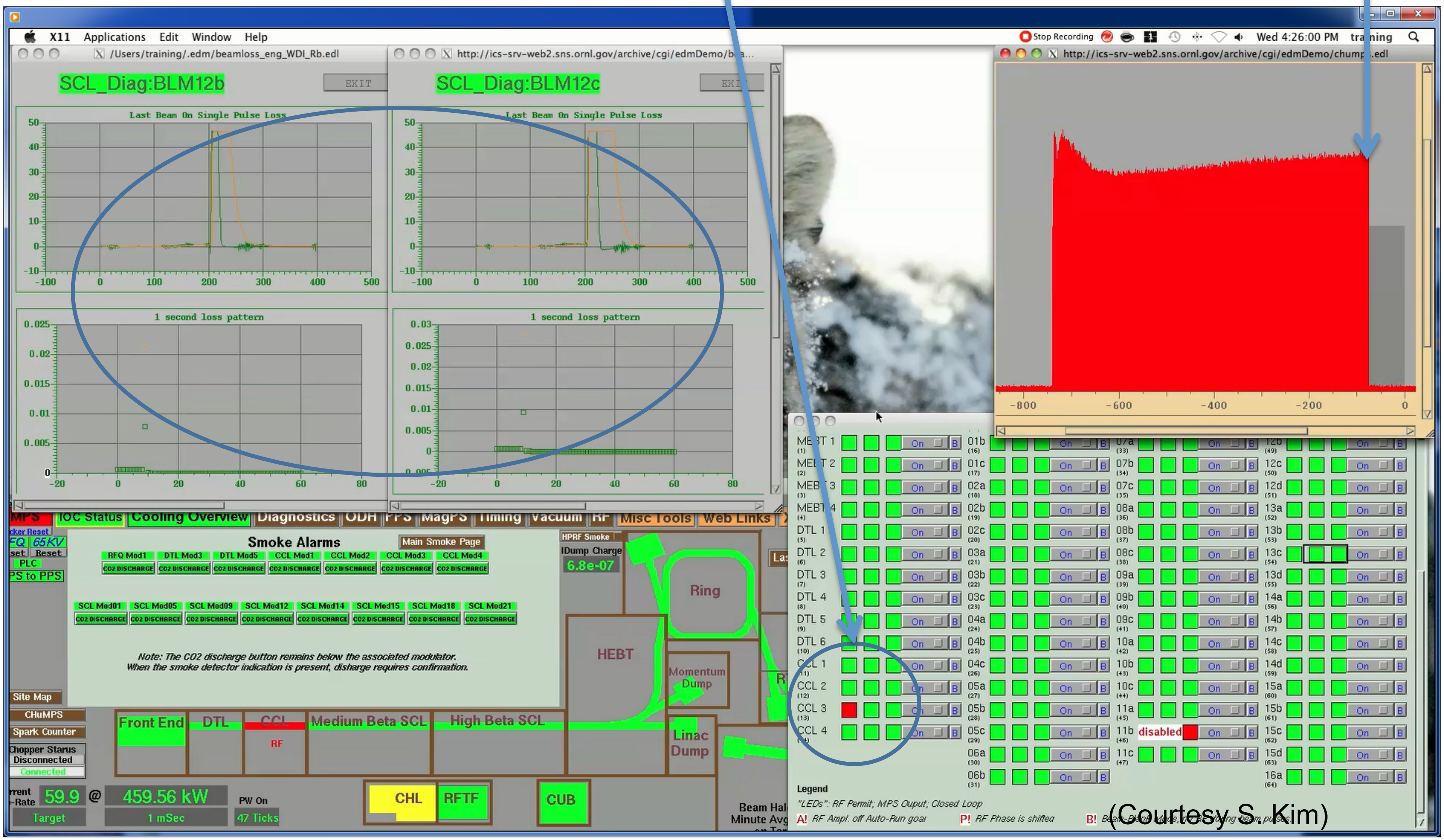
- H^- beam loss is up to 30 times higher than H^+ beam loss
- Normalized H^- beam loss is proportional to ion source current, consistent with IBSt expectations
- H^+ beam loss is very low – good news for proton SCLs like the one planned for ESS



"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).

Example of loss due to RF cavity

- At MPS trip



(Courtesy S. Kim)

Example of loss due to drop in beam current drop