Oak Ridge National Laboratory

Linac Beam Dynamics & Beam Losses

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USPAS January 30, 2023

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U.S. DEPARTMENT OF ENERGY

Overview

- The Spallation Neutron Source (SNS) linear accelerator (linac)
- 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

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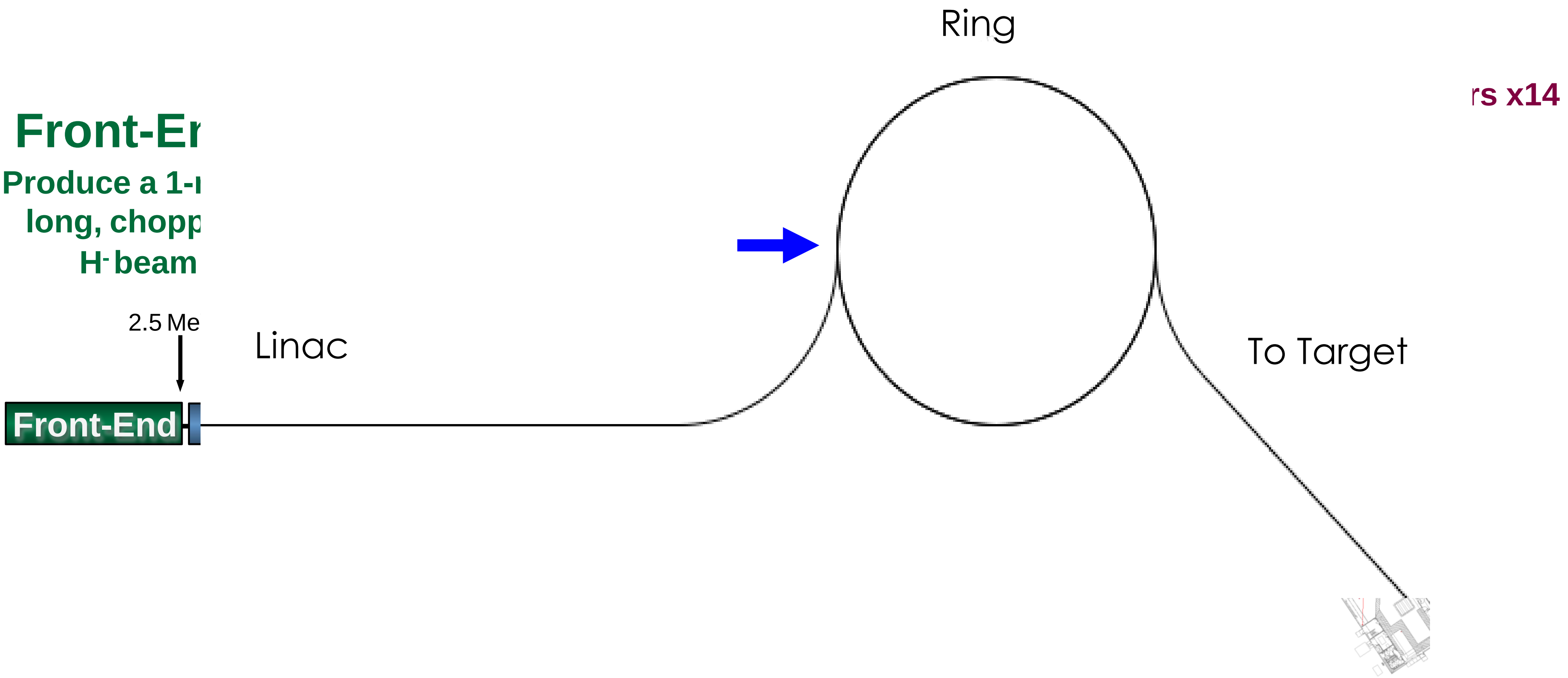
Acronyms

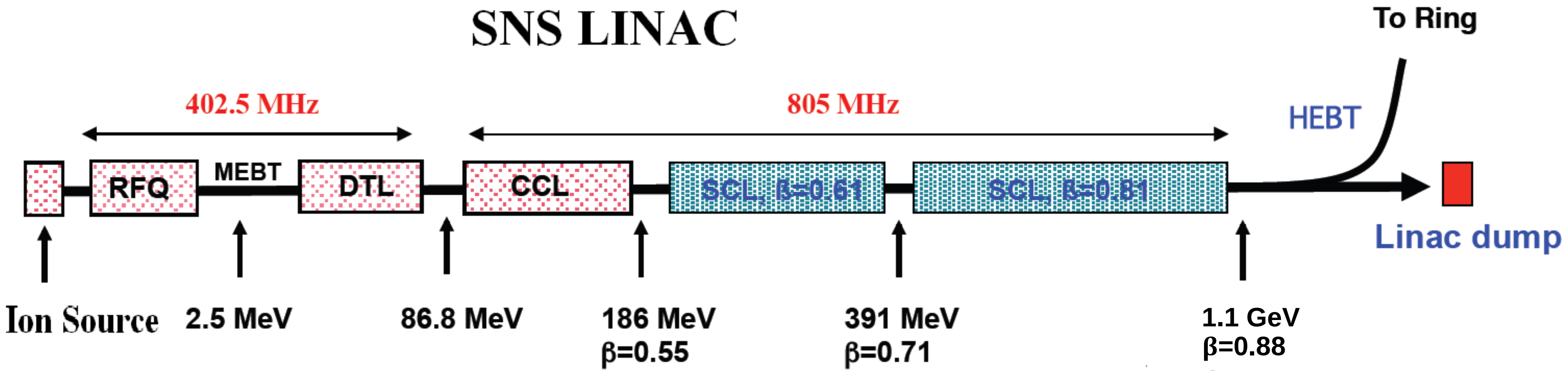
- SNS = Spallation Neutron Source
- MPS = Machine Protection System
- IS = Ion Source
- LEBT = Low Energy Beam Transport
- RFQ = Radio Frequency Quadrupole
- MEBT = Medium Energy Beam Transport
- Linac = Linear Accelerator
- DTL = Drift Tube Linac
- CCL = Coupled Cavity Linac
- SCL = Superconducting Cavity Linac
- SSA = Solid State Amplifier
- FCM = Field Control Module
- HPM = High-power rf Protection Module
- HEBT = High Energy Beam Transport
- RTBT = Ring to Target Beam Transport
- GeV = Giga Electron Volts
- MeV = Mega Electron Volts
- BCM = Beam Current Monitor
- BLM = Beam Loss Monitor
- BPM = Beam Position Monitor
- BSM = Beam Shape Monitor
- HVCM = High Voltage Converter Modulator
- PS = Power Supply
- RF = Radio Frequency
- CW = Continuous Wave
- DF = Duty Factor

SNS Accelerator Complex in Oak Ridge, TN, USA

The SNS machine has over 100,000 control points and cycles ~5.2 million times a day



SNS Linac Structure

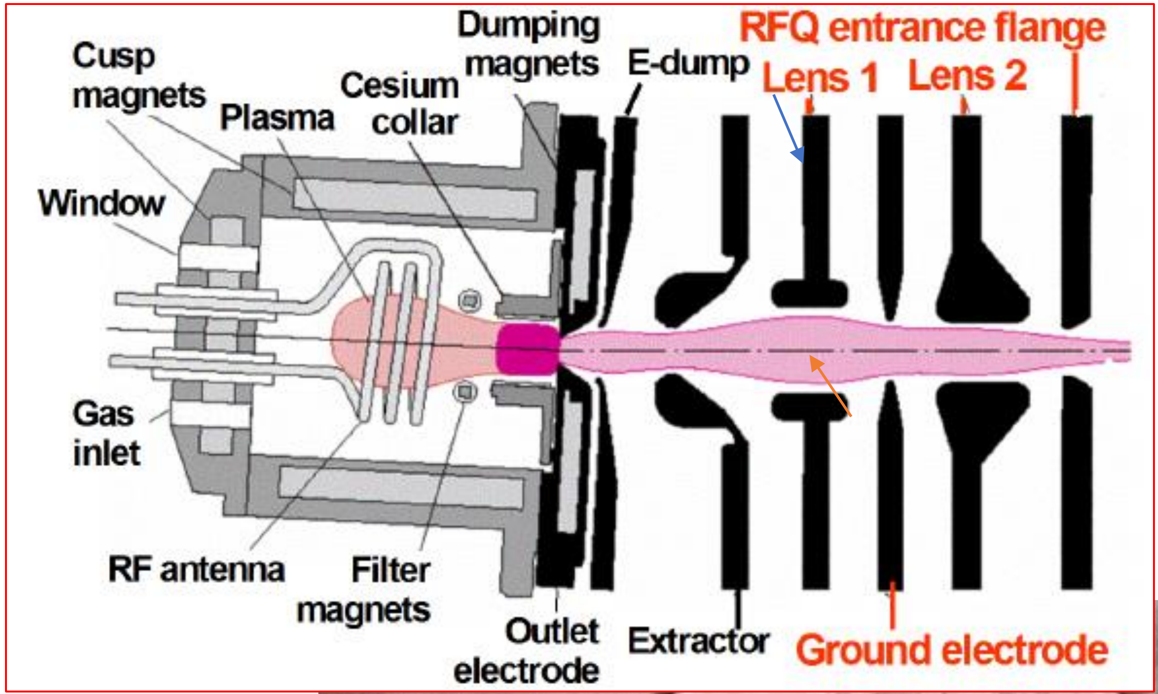


Proton beam energy on target	**1.1**	**GeV**
Proton beam current on target	**1.44**	**mA**
Power on target	**1.55**	**MW**
Pulse repetition rate	60	Hz
Beam macropulse duty factor	6.0	%
Ring fill time	1.0	ms
Protons per pulse on target	1.5×10^{14}	
Proton pulse width on target	695	ns
Linac length	335	m
Total Beamline Length	903	m

Ion Source Prepares Beam for RF Acceleration and Beam Extraction

- Ion source
  - H- species (cesium)
  - 13 MHz CW RF (warming plasma)
  - 2 MHz RF
    - 50 kW peak power
    - Pulse width 1000 µS
    - Repetition rate 60 Hz
  - 65 kV DC
- LEBT
  - Two electrostatic lenses prepare beam for injection into the RFQ
  - Second lens is split into four pieces to provide beam chopping

Top View



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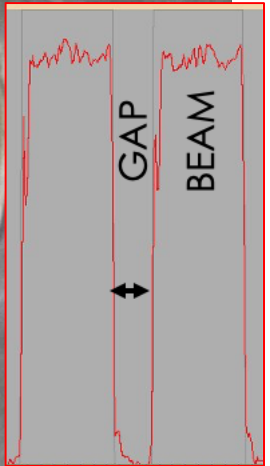

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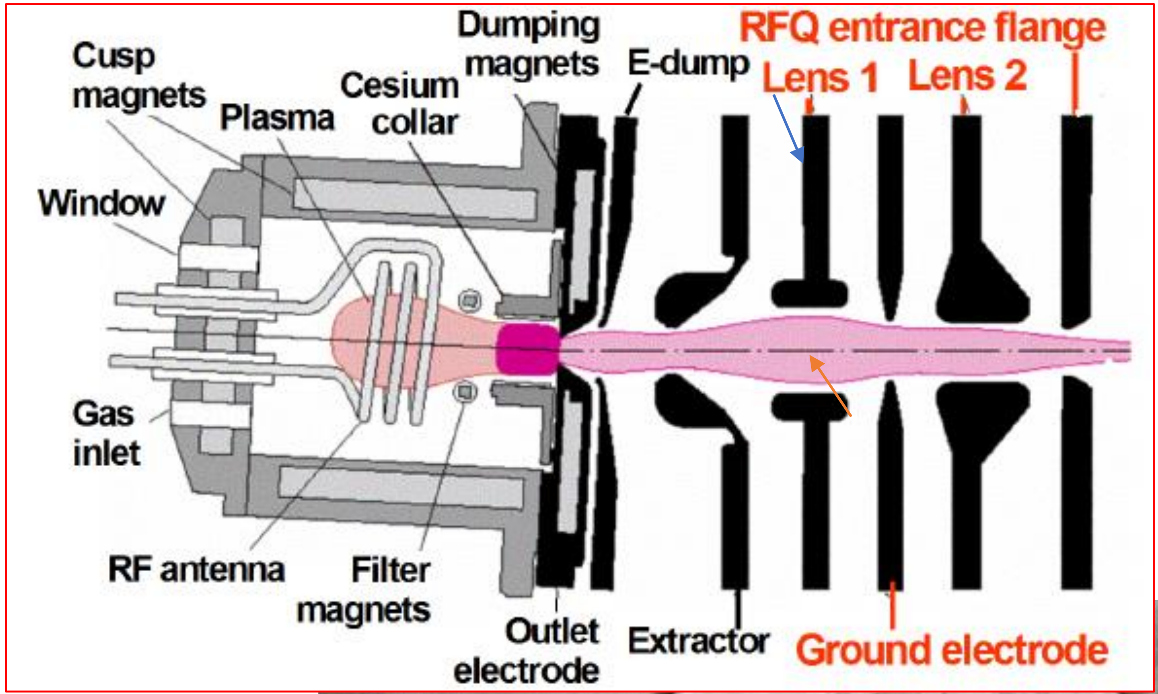

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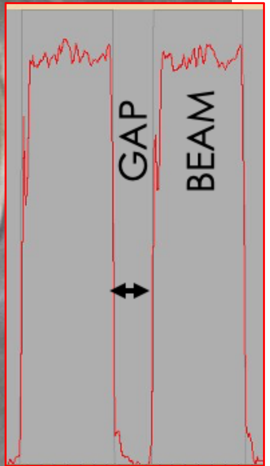

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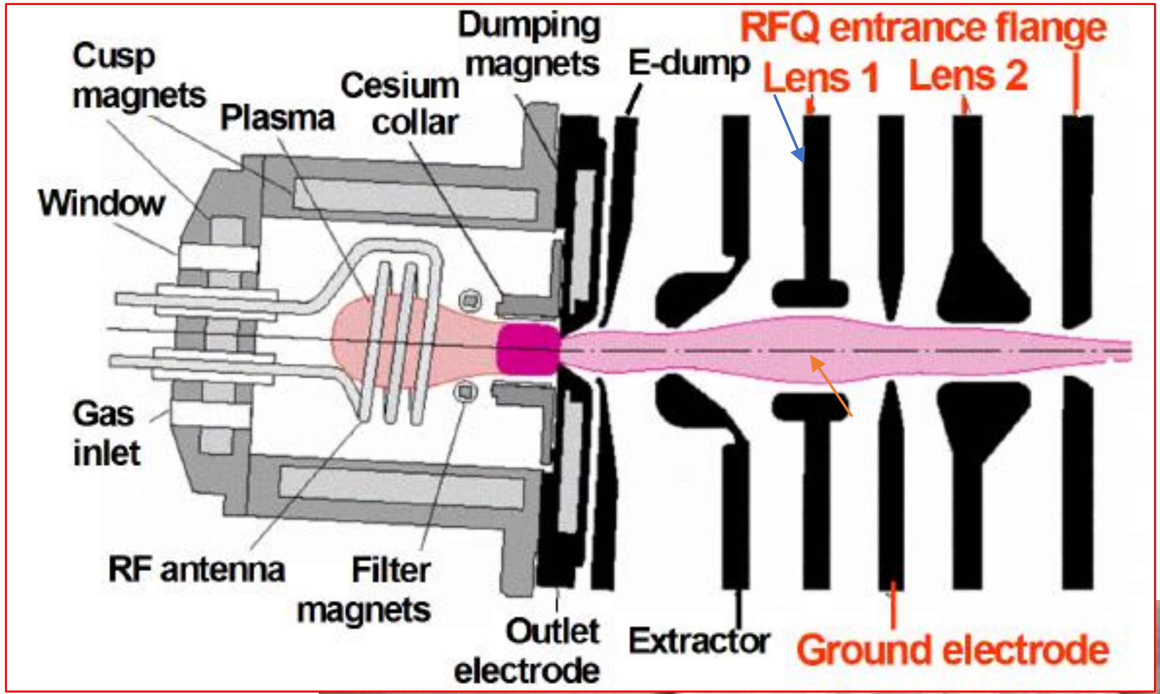

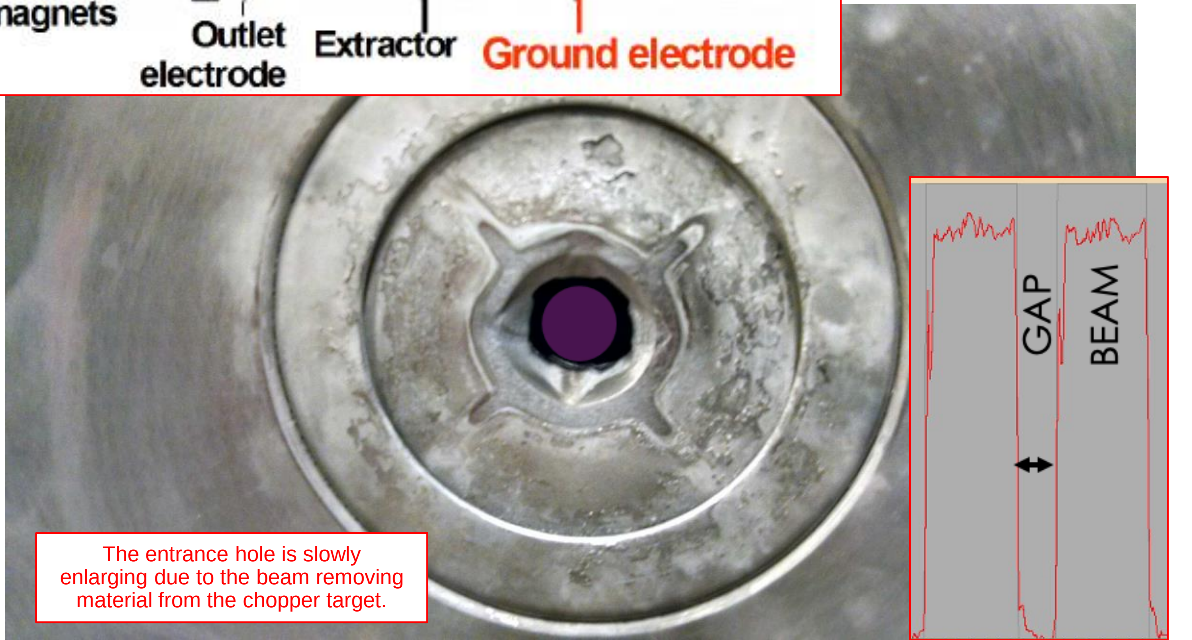

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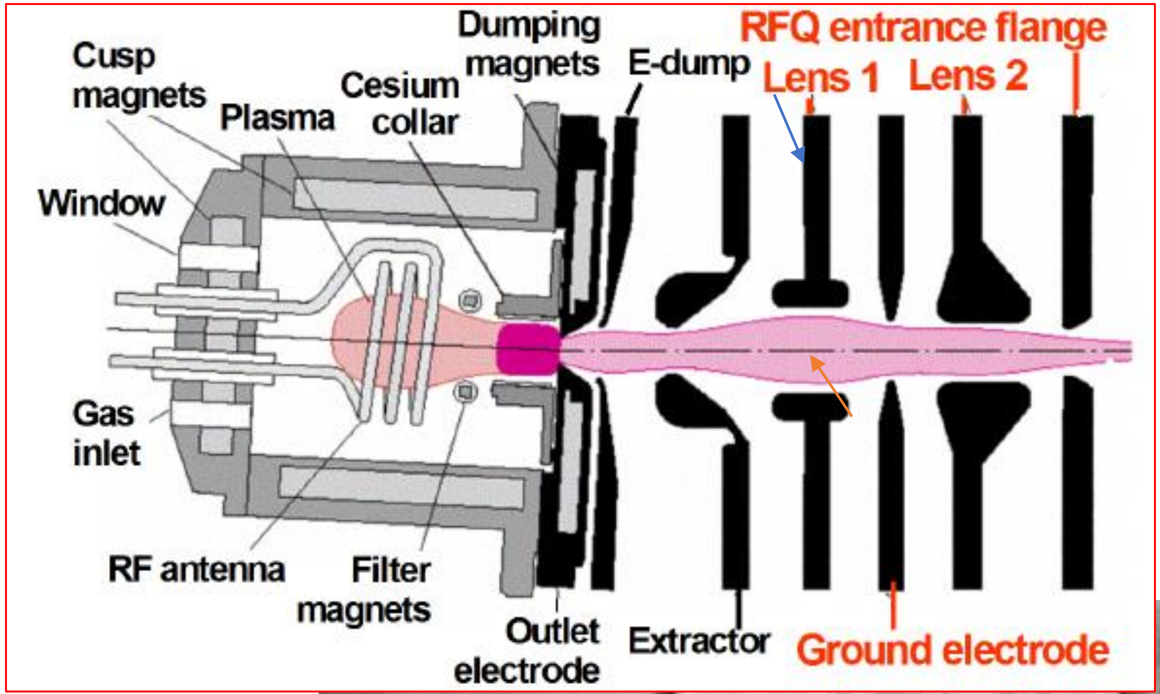

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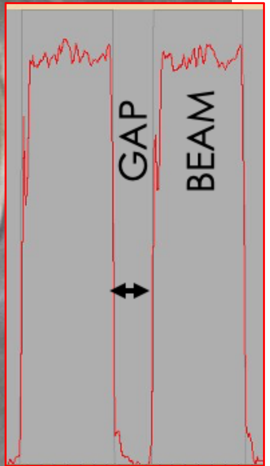

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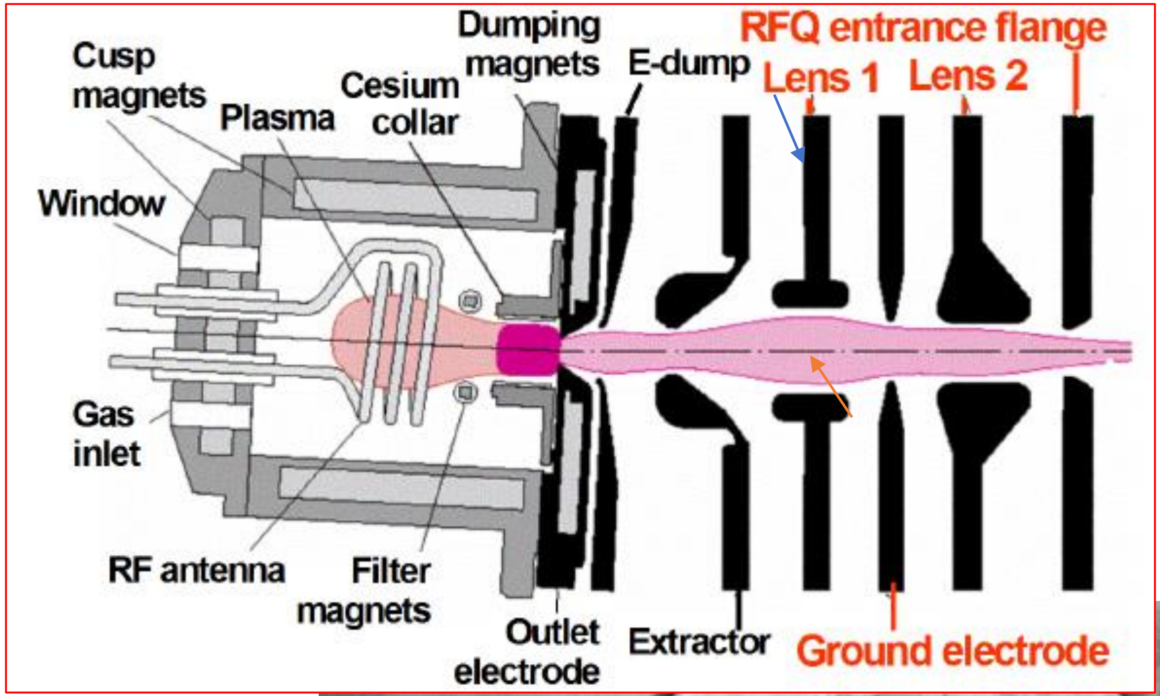

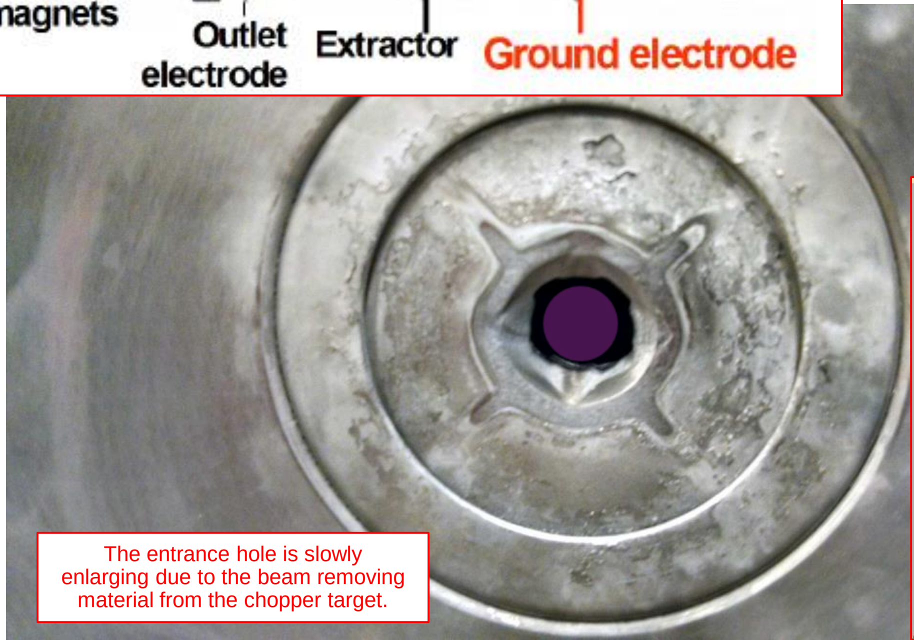

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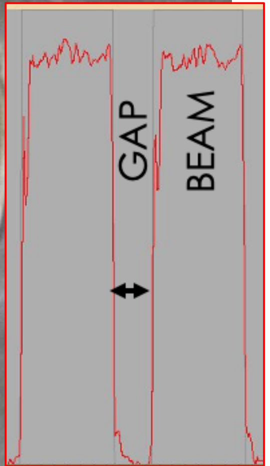

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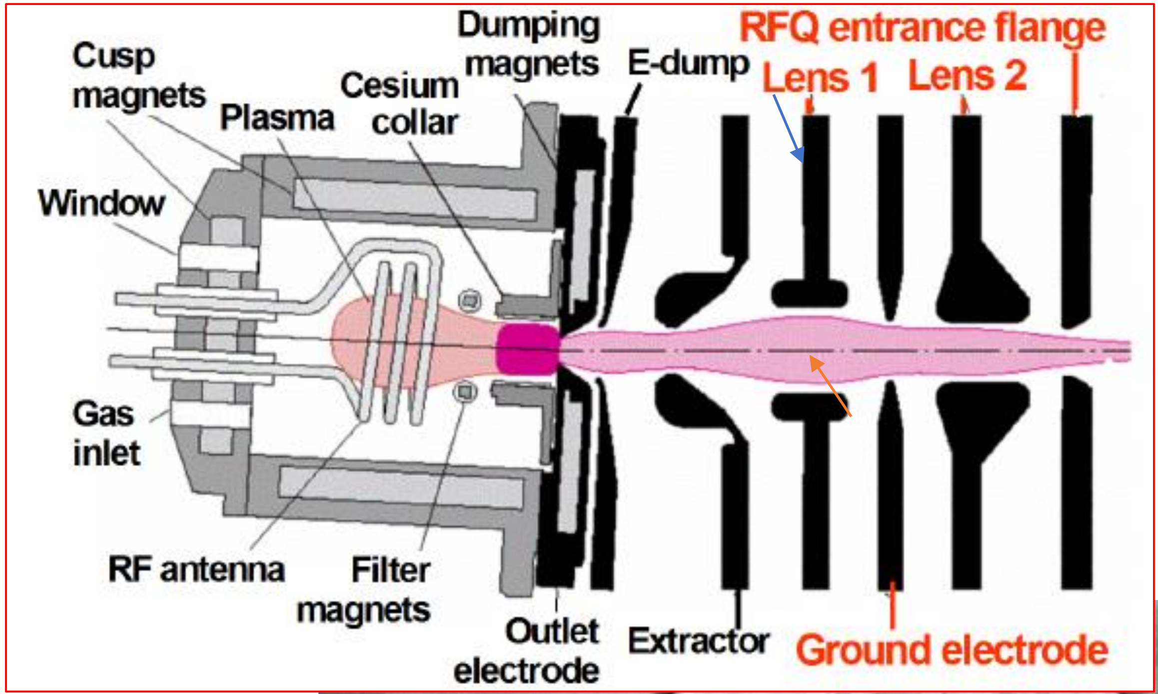

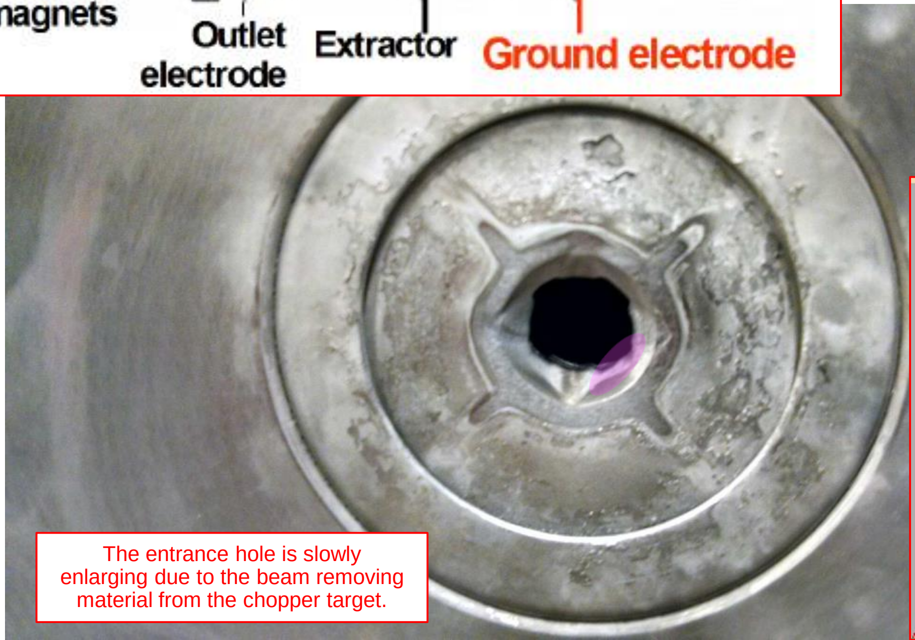
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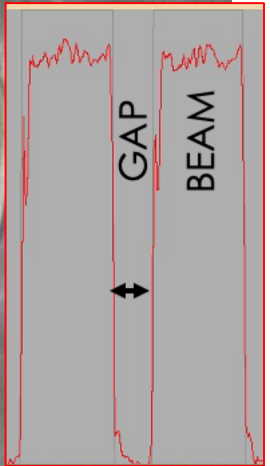

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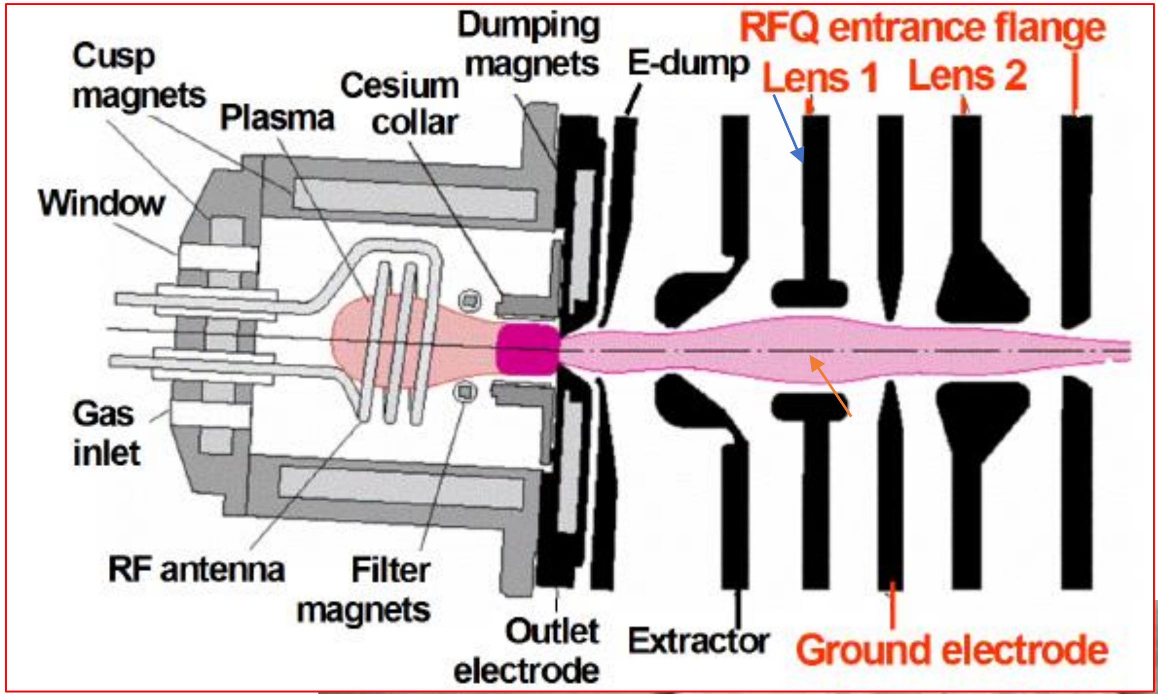

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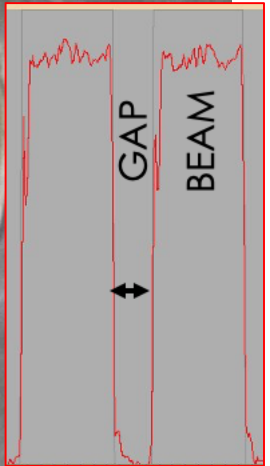

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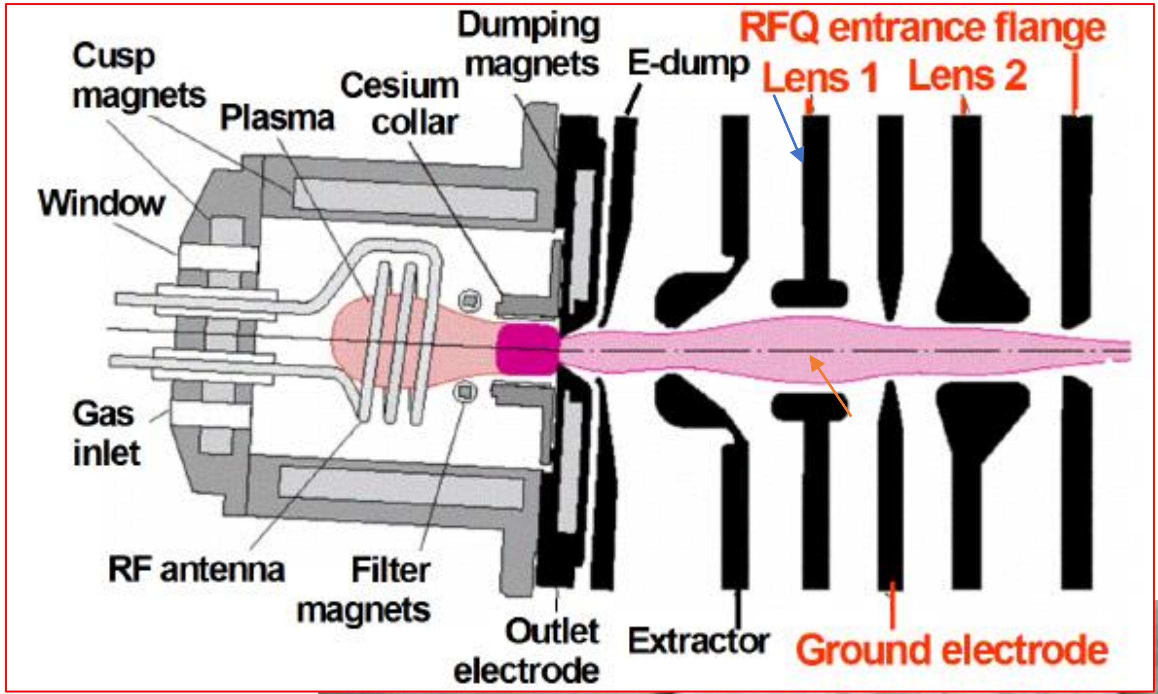

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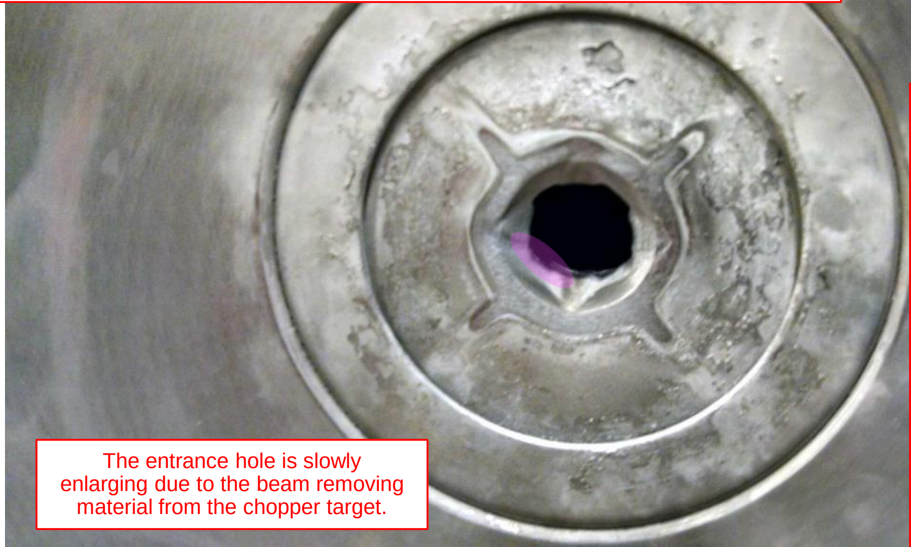

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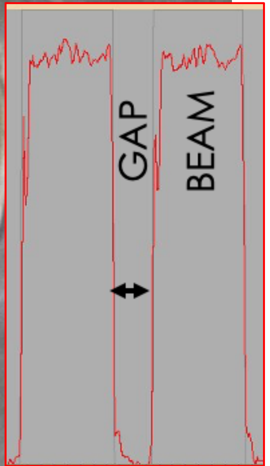

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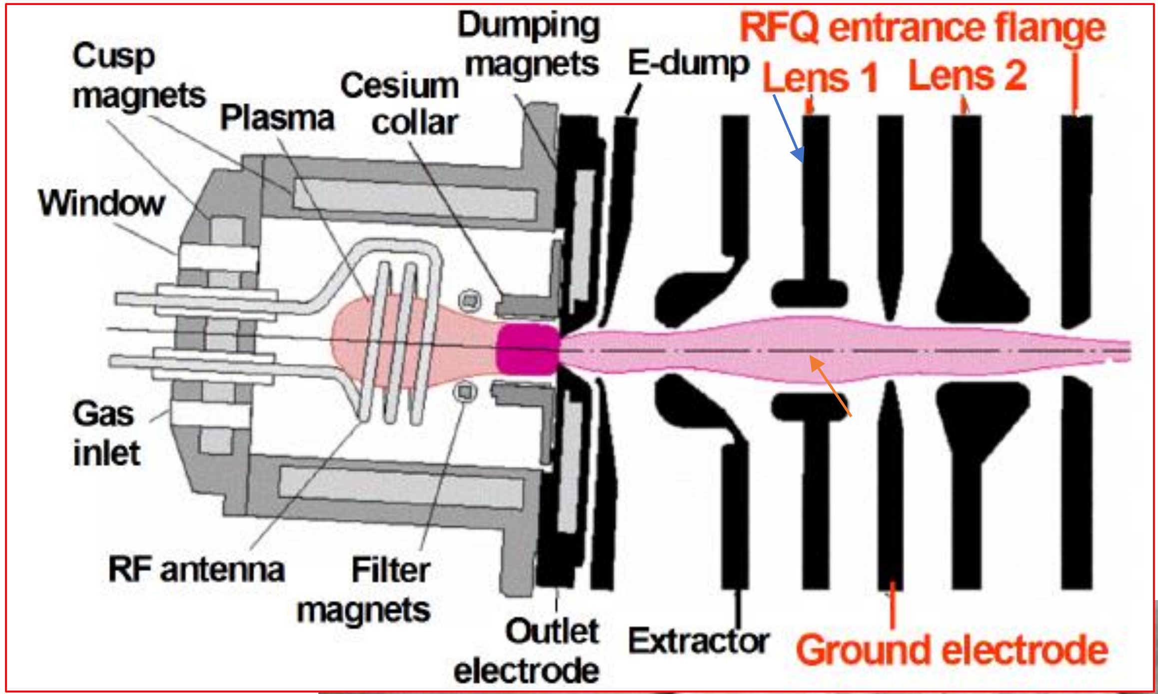

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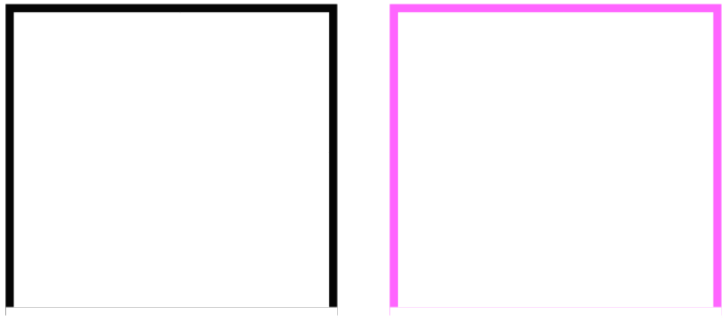
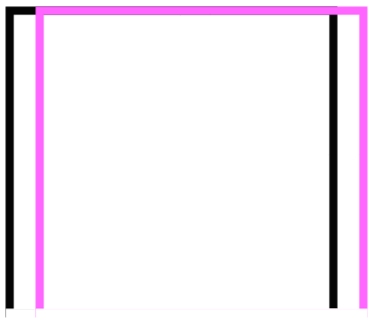
Brief Explanation of SNS Beam Timing

- The ion source is always pulsing for 1000 μseconds 60 times per second
  - This is the beam
- The accelerator is always pulsing for 1000 μseconds 60 times per second
  - This is what accelerates the beam
- Each ion source pulse can be moved in time
  - If an ion source pulse IS NOT ALIGNED with the accelerator pulse then that beam pulse IS NOT ACCELERATED
  - If an ion source pulse IS ALIGNED with the accelerator pulse then that beam pulse IS ACCELERATED

Accelerator Ion source



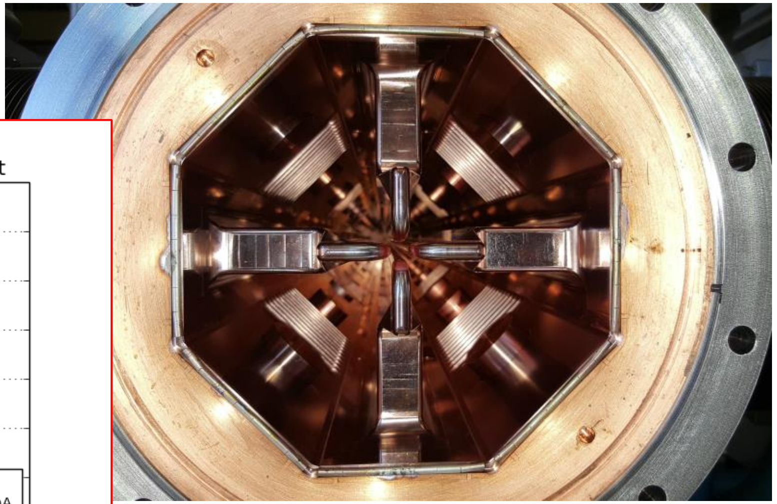
No acceleration
Beam off

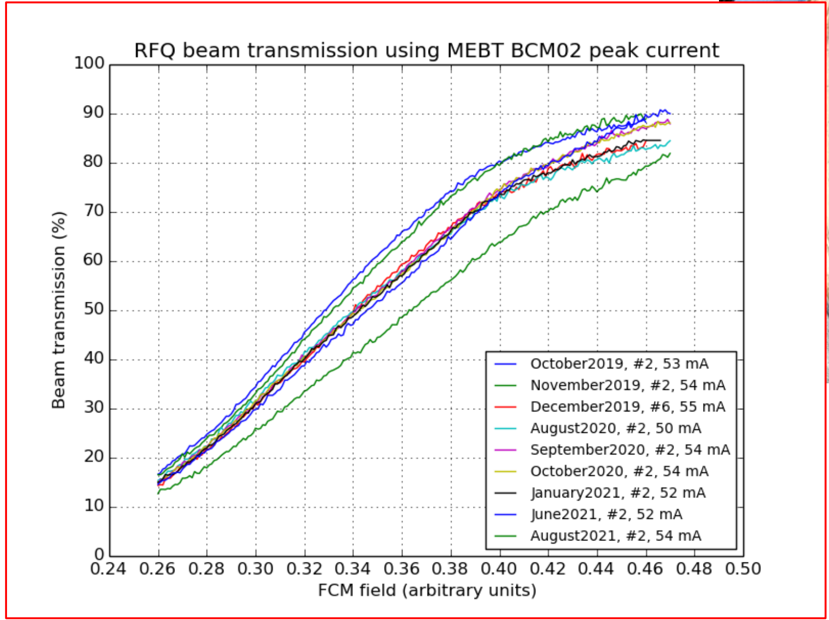


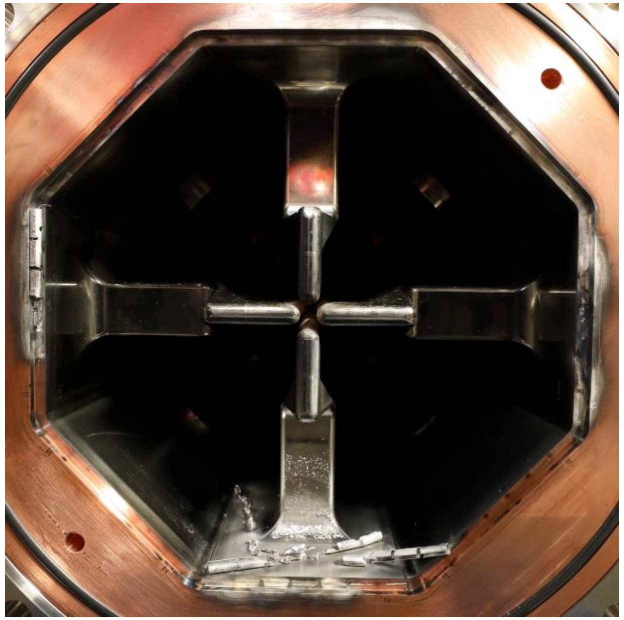
Acceleration
Beam on

RFQ Bunches and Accelerates Beam

- RFQ
  - 402.5 MHz RF
    - 700 kW peak power
    - Pulse width 1035 µS
    - Repetition rate 60 Hz
    - Frequency control with two chilled water systems
      - Chiller 1 for vanes, chiller 2 for walls
    - ≈90% beam transmission with 70 mA input current
    - 1000 kW klystron power
  - Historical issues
    - RFQ1 cooling system inadequate and detuning events decreased beam transmission
    - RFQ2 machining mistake caused damage to RF seals
    - RFQ3 being tested







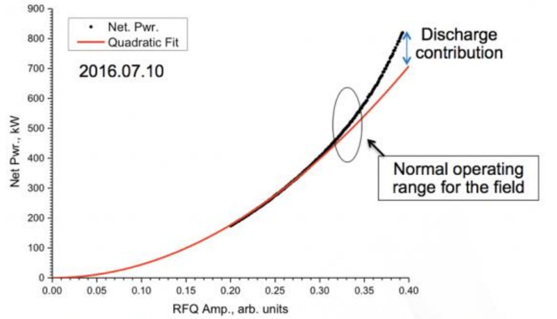


Figure 1. This curve shows the Berkeley RFQ net power deviates from the quadratic relationship between the cavity net RF power (forward - reflected power) and the cavity FCM field.

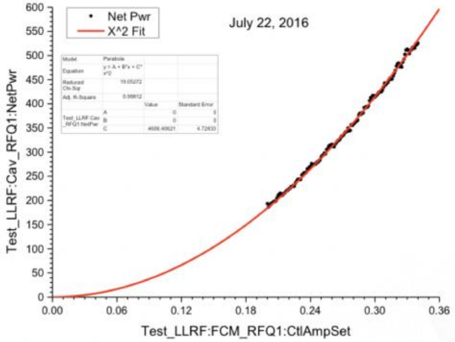


Figure 2. This curve shows the new RFQ net power does **NOT** deviate from the quadratic relationship between the cavity net RF power (forward - reflected power) and the cavity FCM field. The ion source was not running at the time so the heat load was at a minimum. The cavity net power was minimized to lower the probability of damage to the new structure.

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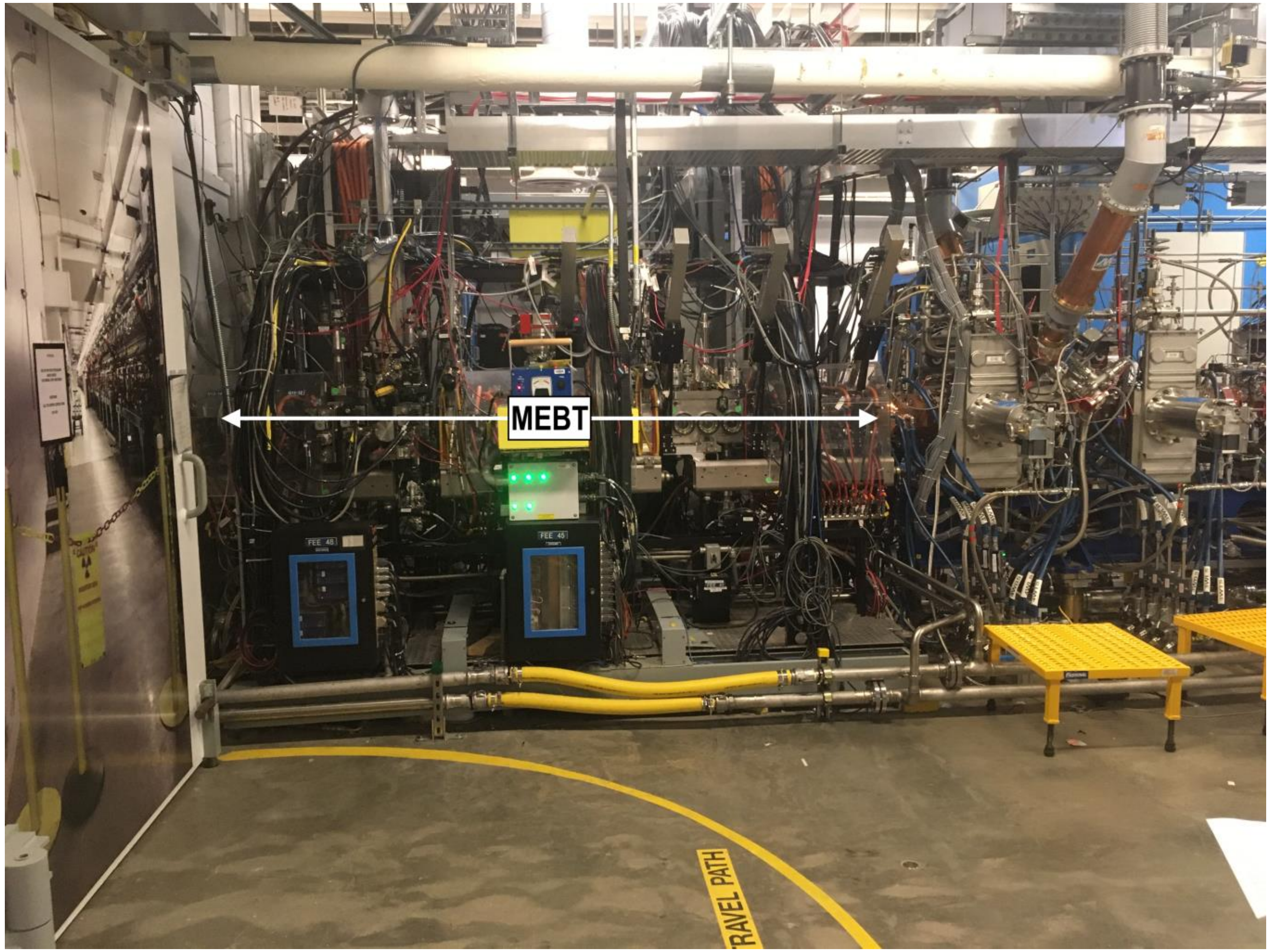
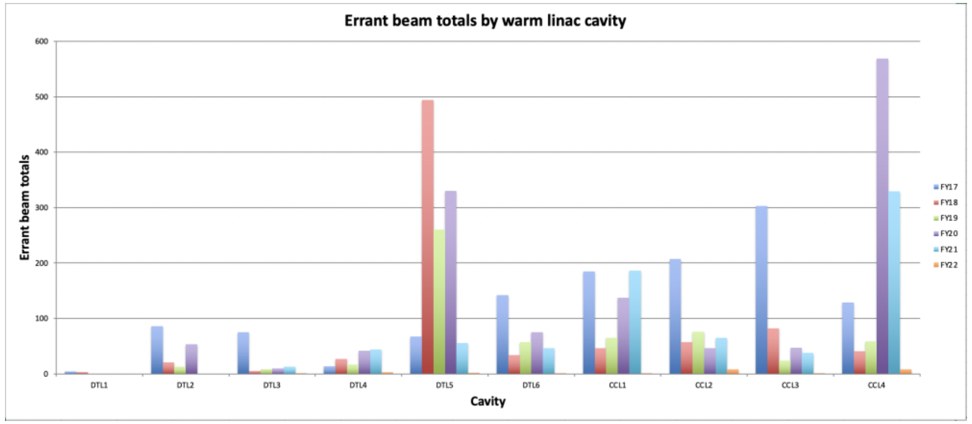
MEBT Re-bunches Beam

- MEBT
  - 4 rebuncher cavities
    - 402.5 MHz RF
    - 5-20 kW peak power
    - Pulse width 1100 µS
    - Repetition rate 60 Hz
    - 25 kW SSA power
  - Magnets
    - Quadrupoles, dipole correctors
  - Diagnostics
    - BCMs (differential interlock)
    - BPMs (ChuMPS)
    - Chopper (not used)
    - Emittance devices (typical and laser)
    - Scrapers
    - Wire scanners

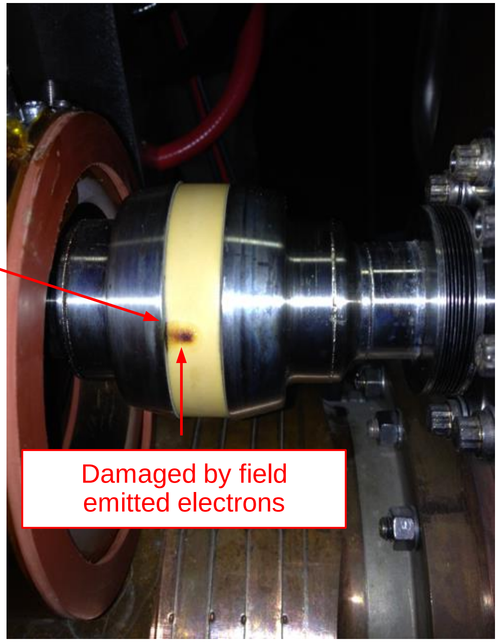


DTL and CCL are the Warm Linac

- DTL 2.5 MeV to 87 MeV
  - 6 cavities
    - 402.5 MHz RF
    - 500-2000 kW peak power
    - Pulse width 1080-1105 µS
    - Repetition rate 60 Hz
    - 2500 kW klystron power each
    - Cooling water maintains resonance
  - Magnets
    - Permanent quadrupoles, dipole correctors
  - Diagnostics
    - BCMs
    - BLMs
    - BPMs
    - Faraday cups
    - Wire scanners



- CCL 87 MeV to 186 MeV
  - 4 cavities
    - 805 MHz RF
    - 3000-4000 kW peak power
    - Pulse width 1060 µS
    - Repetition rate 60 Hz
    - 5000 kW klystron power each
    - Cooling water maintains resonance
  - Magnets
    - Quadrupoles, dipole correctors
  - Diagnostics
    - ~~BCMs~~
    - BLMs
    - BPMs
    - BSMs
    - Faraday cups
    - Wire scanners



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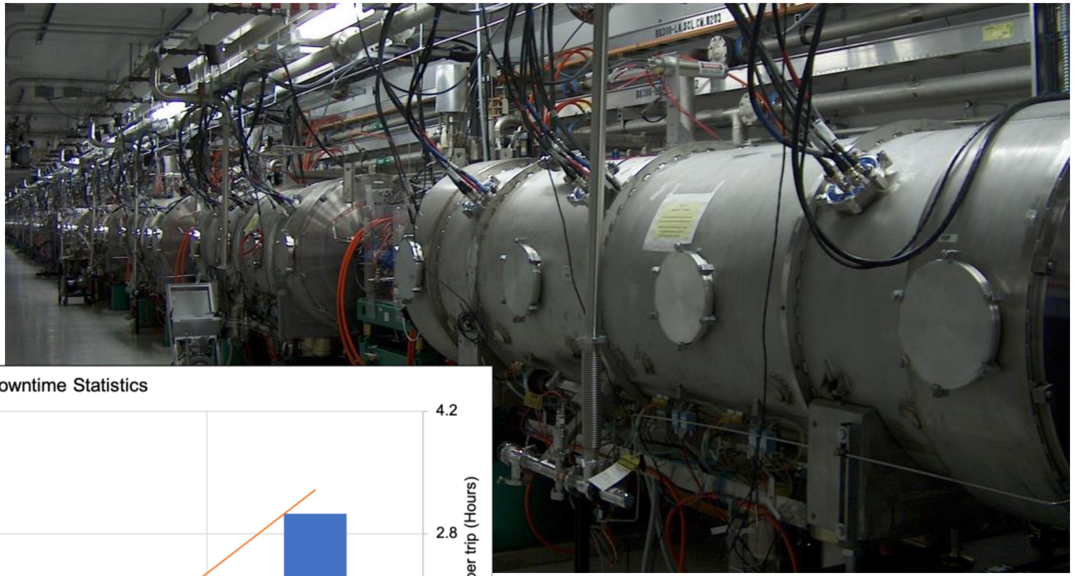
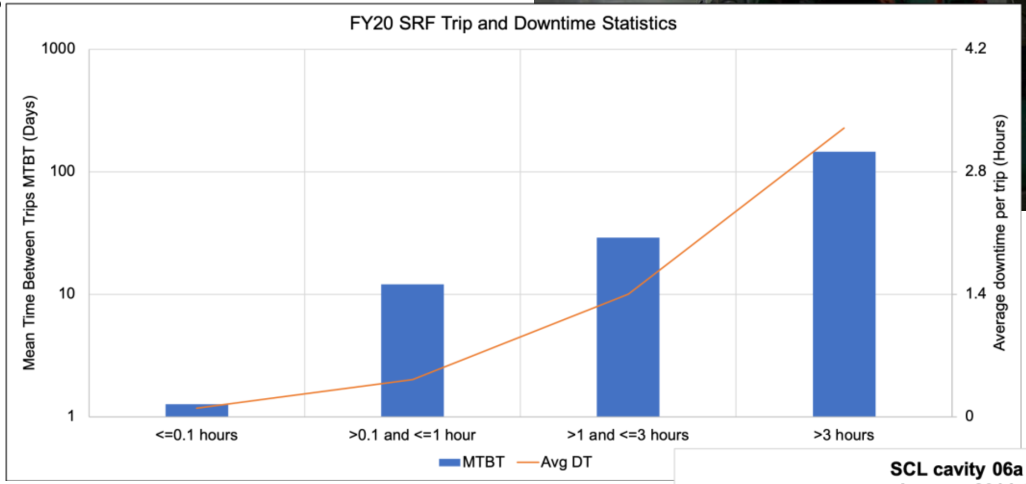
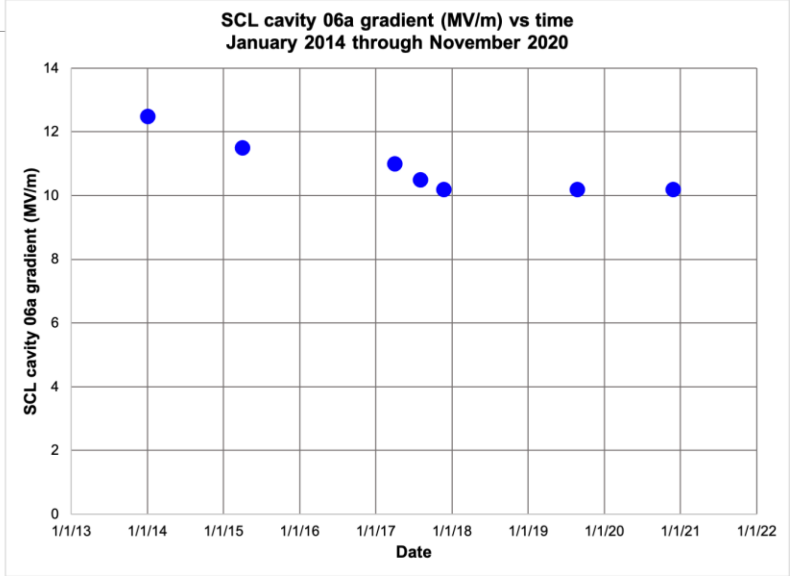
SCL is the Cold Linac

- SCL 186 MeV to 1.1 GeV
  - 89 cavities
    - 33 medium beta in 11 cryomodules
    - 56 high beta in 14 cryomodules
    - 2 Kelvin operating temperature
    - 805 MHz RF
    - 550 kW peak power
    - Pulse width 1265 µS
    - Repetition rate 60 Hz
    - 550-700 kW klystron power each
    - Last cavity on but not accelerating to provide beam energy margin
  - Diagnostics
    - BLMs
    - BPMs
    - Laser wire scanners
  - Highly reliable, very flexible, but sensitive



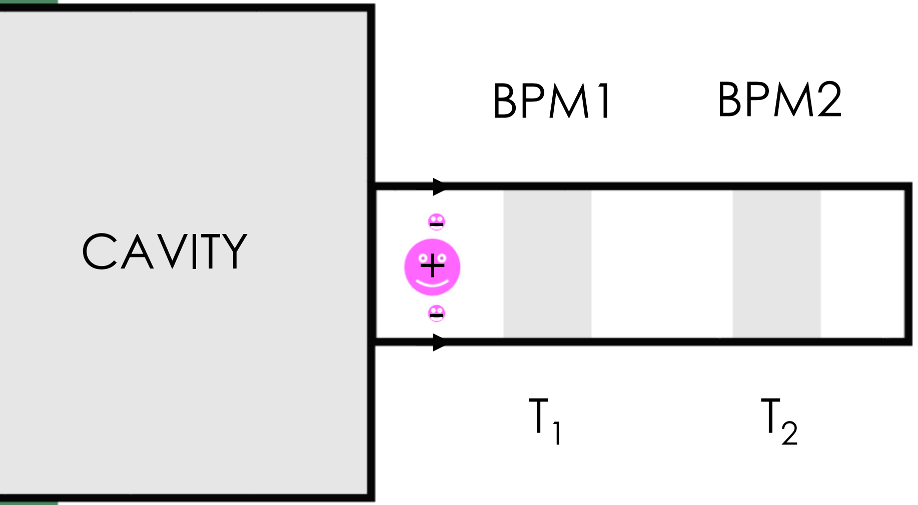




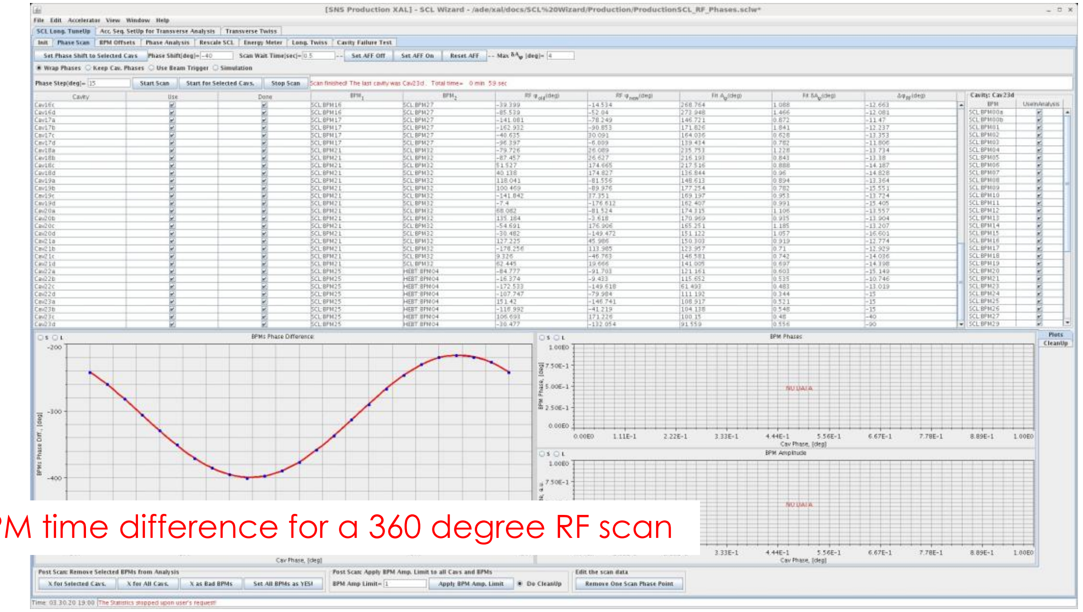
Some cavities are negatively impacted by beam loss

Linac RF Beam Setup

- RF phases are set by beam time of flight measurements using Beam Position Monitors (BPMs)
  - BPMs measure the up/down/left/right position of the beam AND the arrival time of the beam

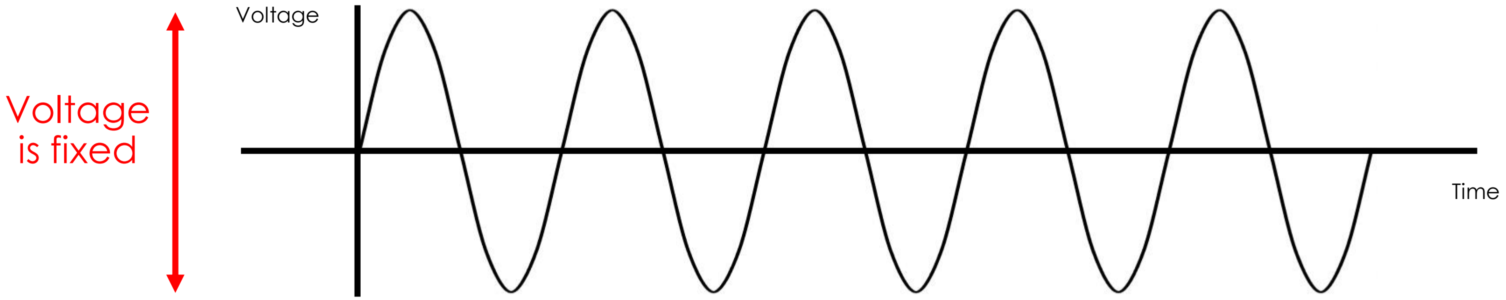


Implementation: Jython + OpenXAL



BPM time difference for a 360 degree RF scan

App changes the phase of the cavity RF waveform, measures the time difference between the two BPMs, and sets the cavity RF phase to the minimum time difference



RF sine wave

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 1.55 MW. If 2% is lost at injection, you are losing 31 kW !!
  - Example: SNS ring charge-exchange injection fractional loss is (1 – 2)x10^{-4}, so power loss is 140 – 240 W and residual activation is 1.2 Rem
- Charge exchange injection also required if want output beam emittance to be less than the sum of the input emittances
- 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
  - Beam halo/tails (resonances, collective effects, mismatch, etc.)
  - RF and/or ion source turn on/off transients
  - Dark current from ion source

H^- only (applies to the first four items)

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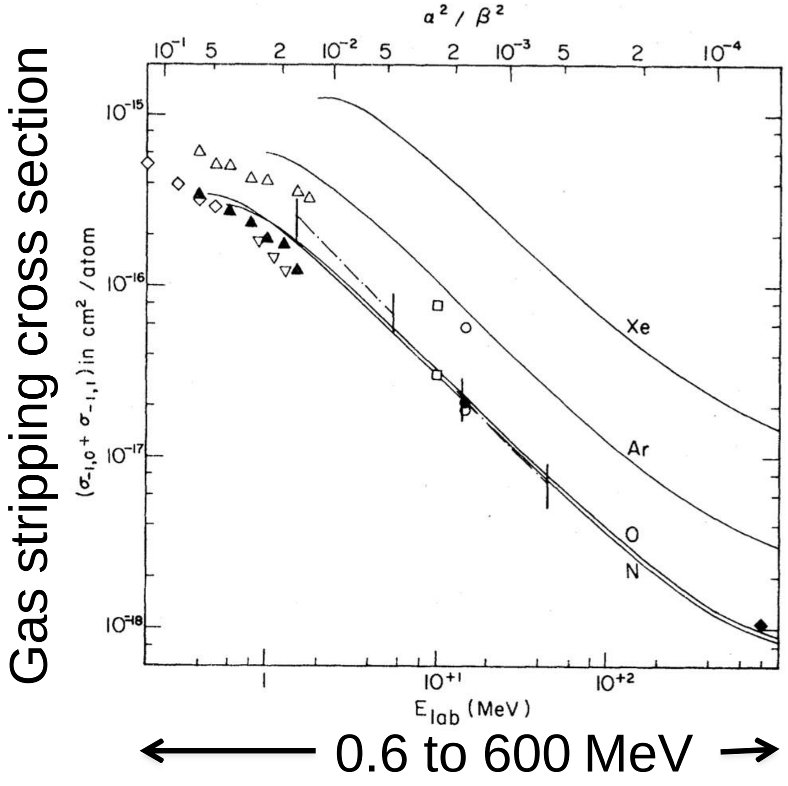
Residual gas stripping

- 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

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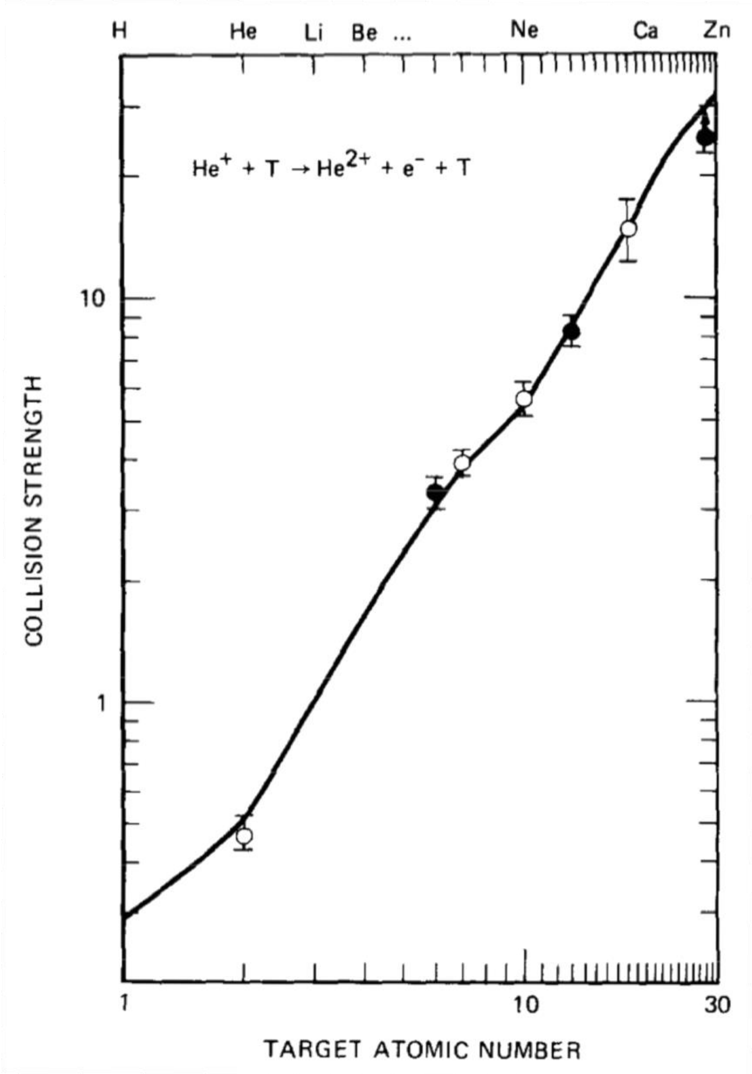
Residual gas stripping (cont.)



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.

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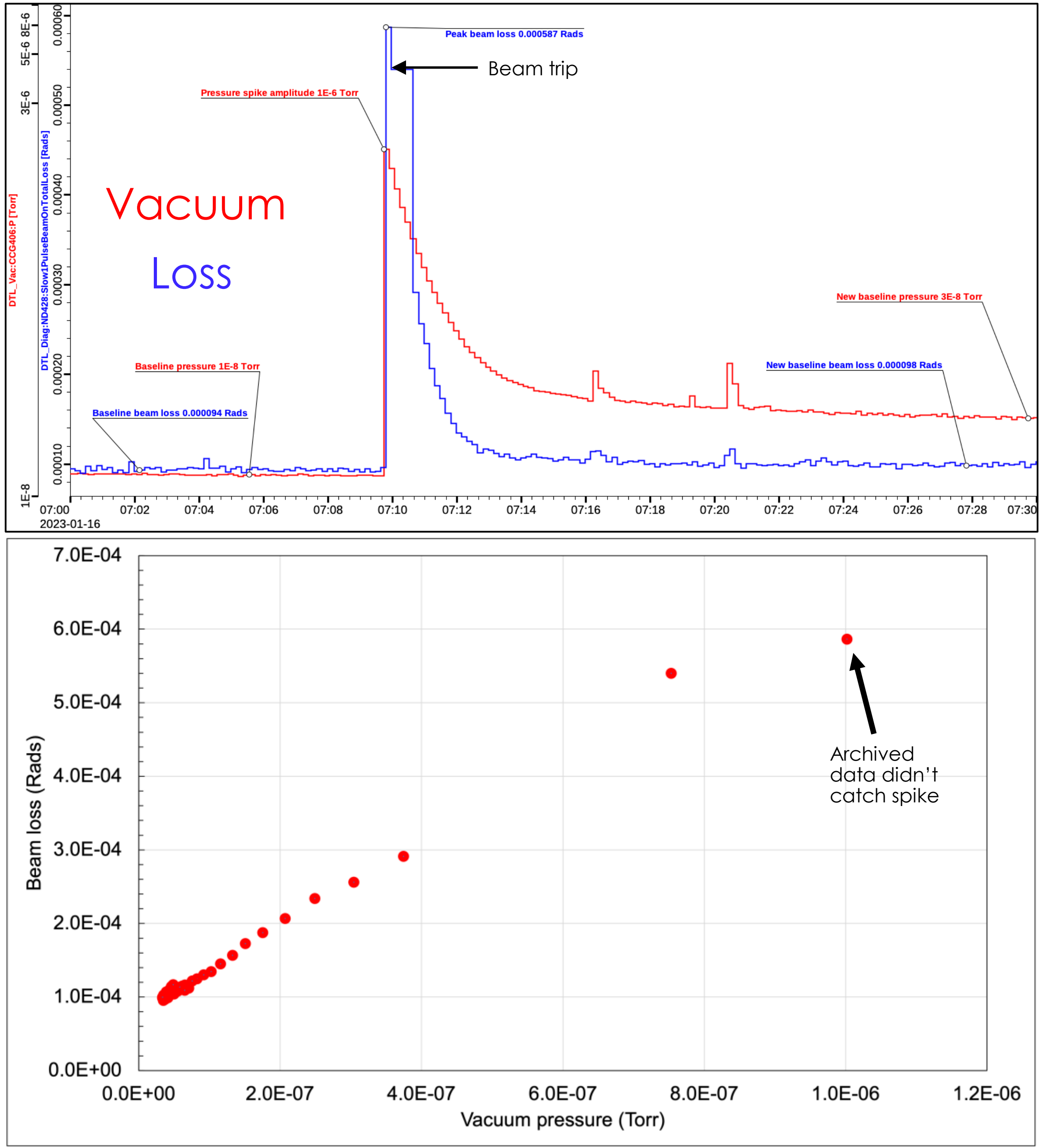
Residual gas stripping (cont.)

- SNS
  - Biggest impact to residual activation is from stripping upstream of RFQ
  - Hot spot in transport line to ring is likely due to gas stripping
- LANSCE
  - Measured to cause about 25% of the H^- beam loss along linac

Example of residual gas stripping in SNS DTL



Example: gas stripping calculation

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

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

$\rho = (2NA)\left(\frac{\mathrm{p}}{22410\, ml\cdot 760}\right)\left(\frac{273}{T}\right)$ per atoms cm^3

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

Assume 50 MeV, 1.44 mA H^- beam, in a beam line with 10^{-8} Torr of nitrogen gas at 303 K, β = 0.314

$$P = (5x10^8\ \mathrm{V})(1.44\mathrm{mA})\left(\frac{7\cdot 10^{-19}}{0.314^2}\, cm^2\right)\left(2\cdot 6.022\cdot 10^{23}\, \frac{10^{-8} Torr}{22410\cdot 760\, Torr}\, \frac{atoms}{cm^3}\right)\left(\frac{273}{303}\right)(100\ cm)$$

P = 0.0326 watts/m

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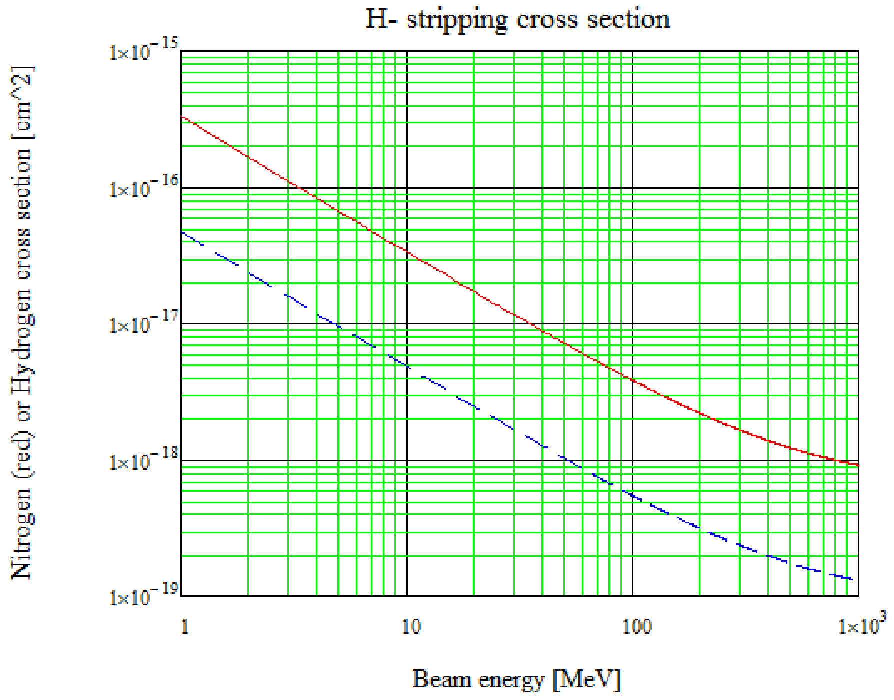
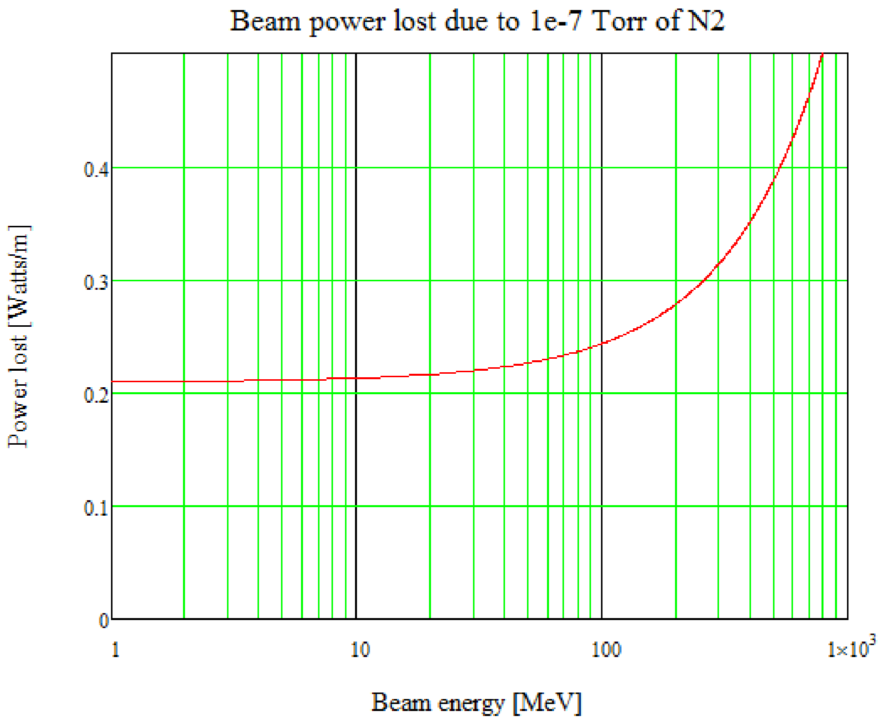
Example: Gasstripping calculation (cont.)

1 mA H^- beam

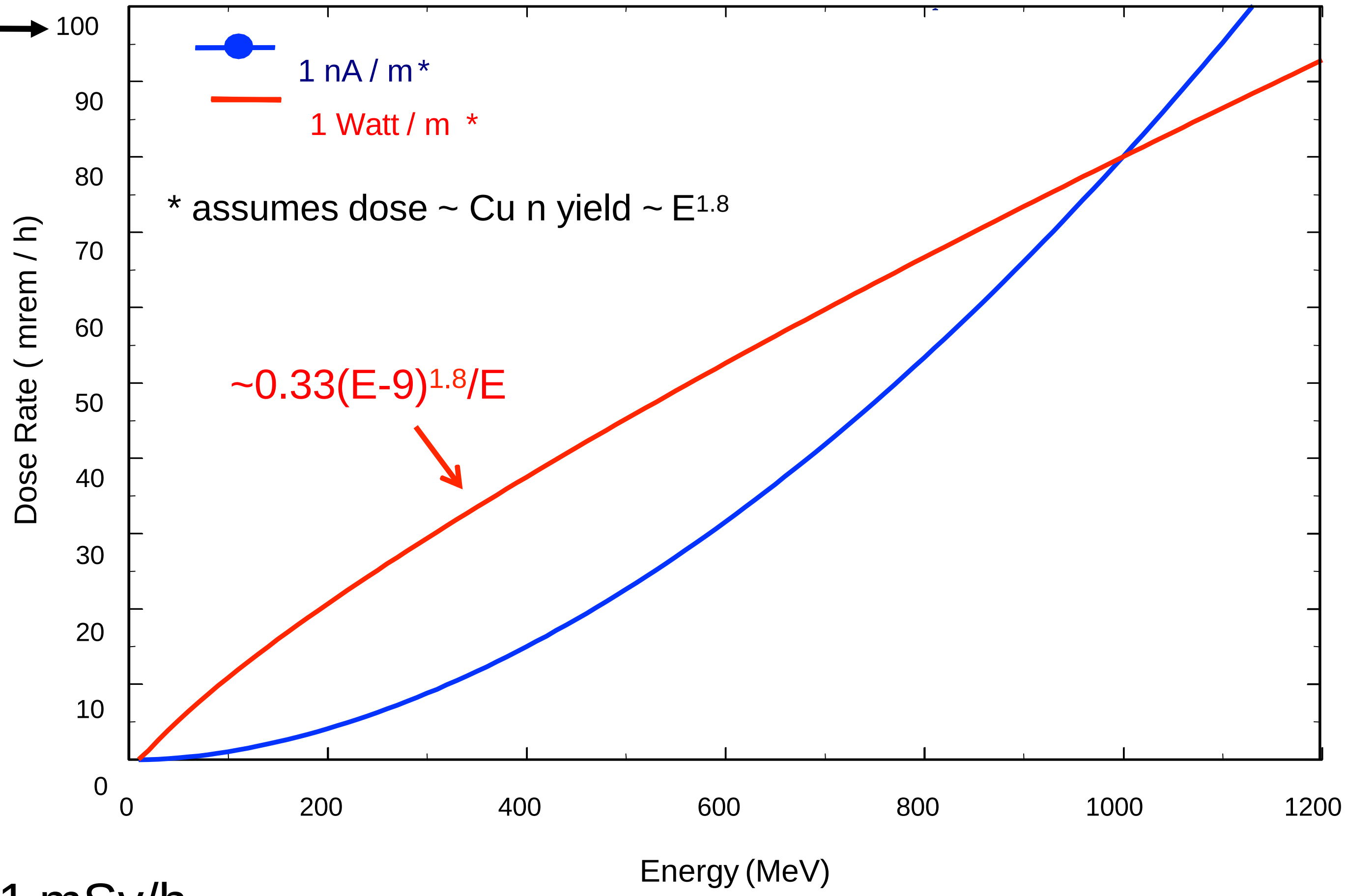




Residual gas stripping causes increasing power loss as beam energy increases

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)

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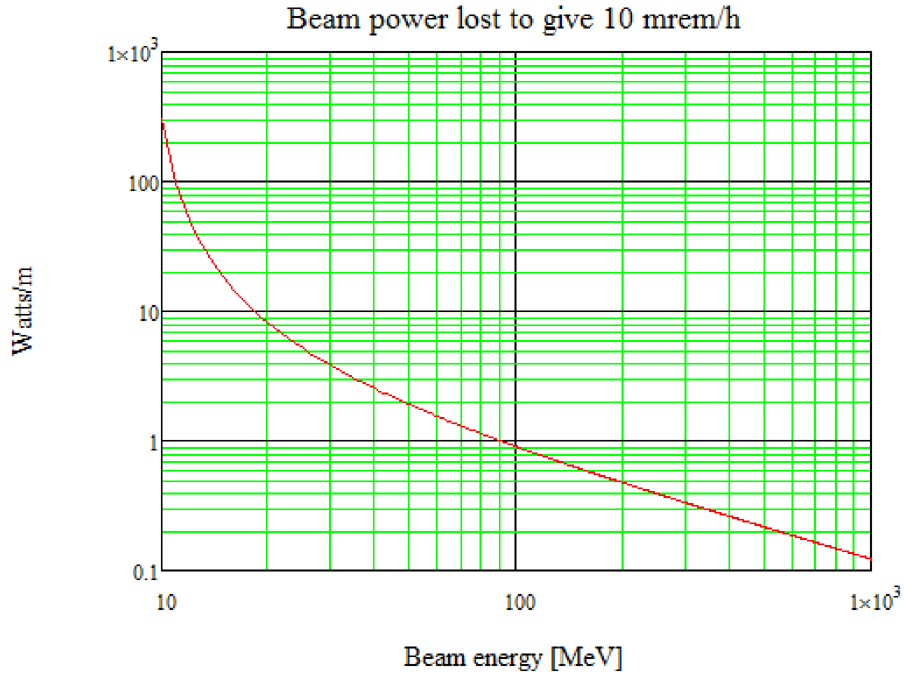
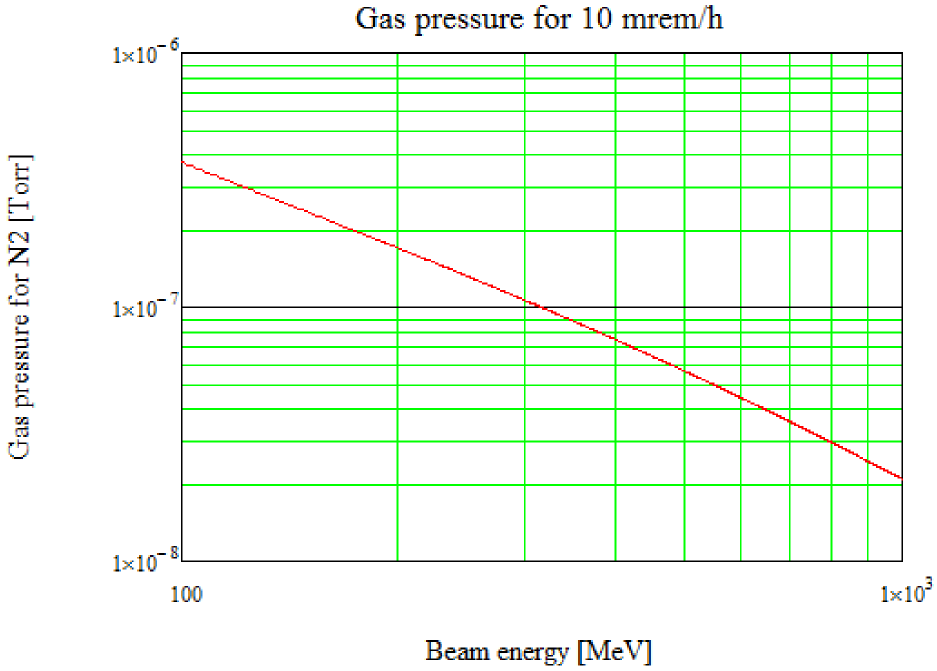
Example: Gasstripping calculation (cont.)

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

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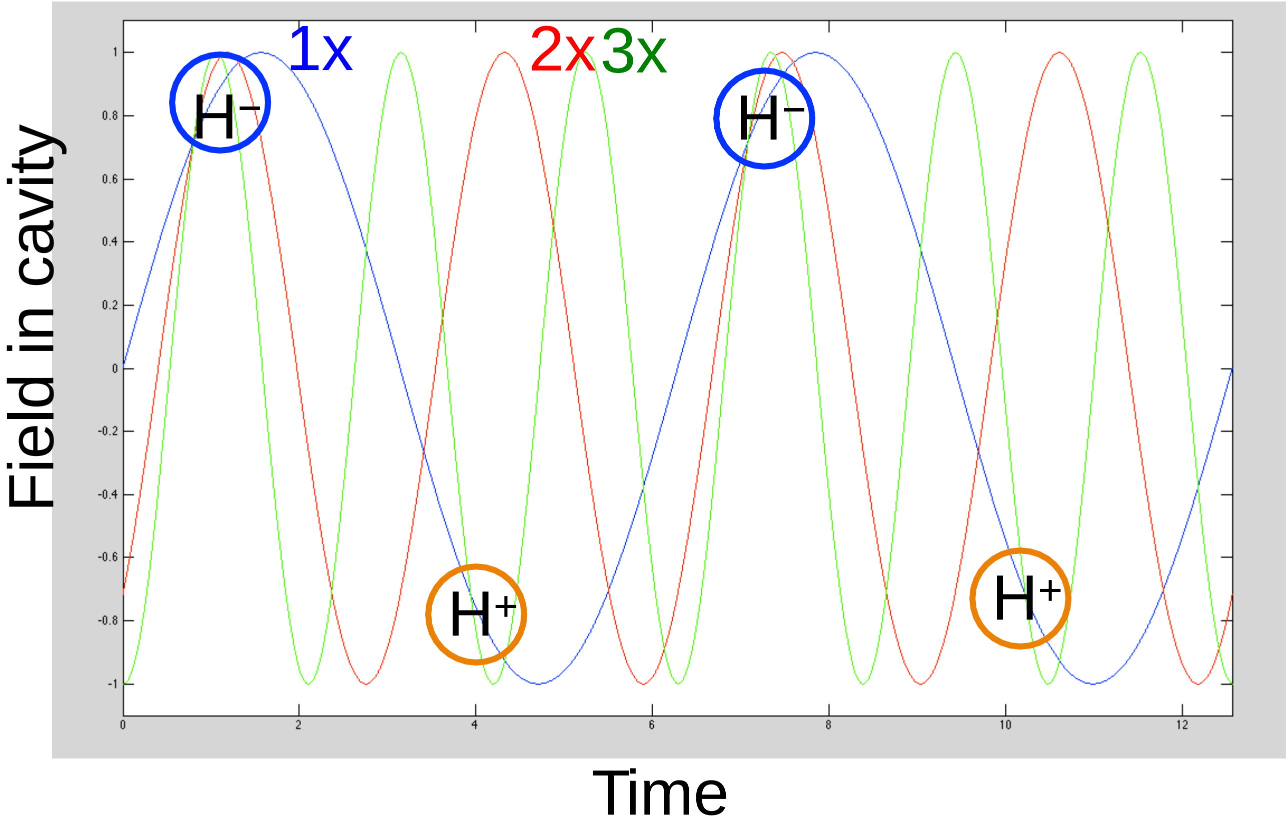
H^+ capture and acceleration

- 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.
- Debunched by even (e.g. 2, 4, etc.) frequency jumps in linac RF



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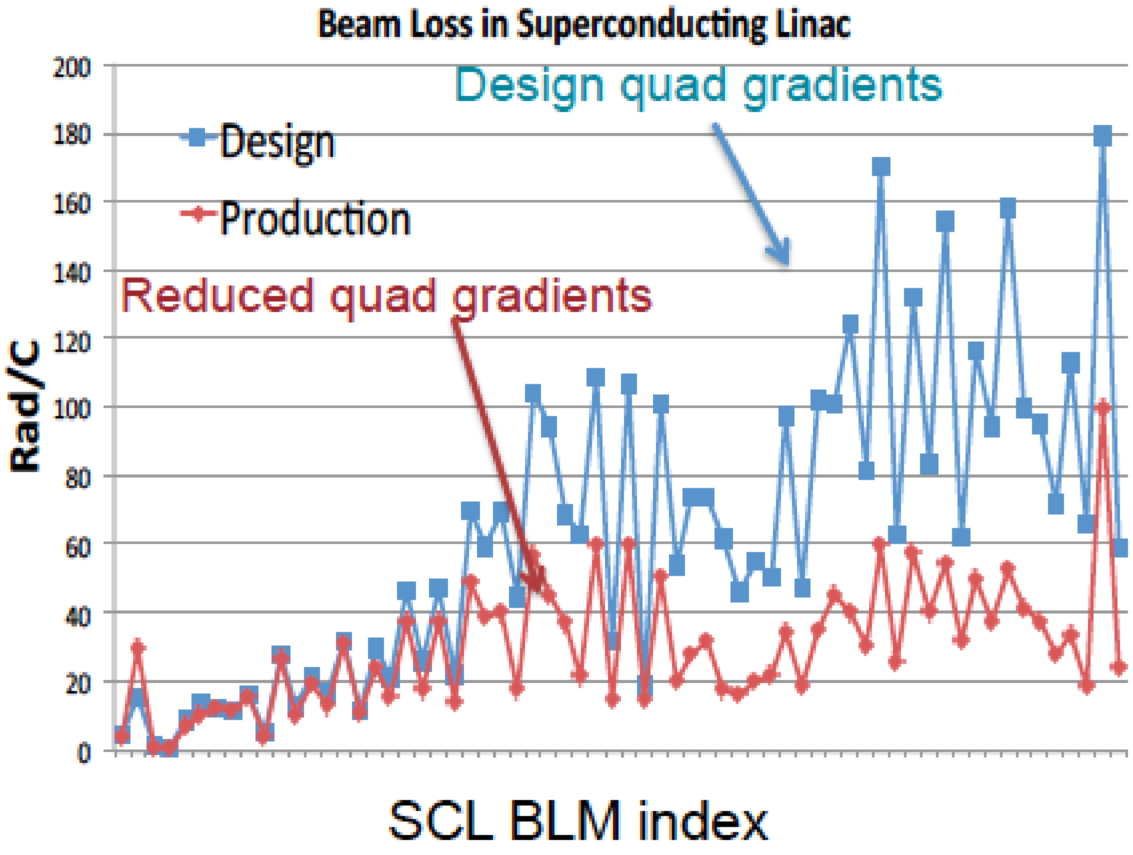
H^+ capture and acceleration (cont.)

- Present in the SNS linac with biggest impact at the beginning of the SCL
  - See loss in the first 3 cryomodules of the SCL with possible losses further downstream. Not a major issue for 1.55 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 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.

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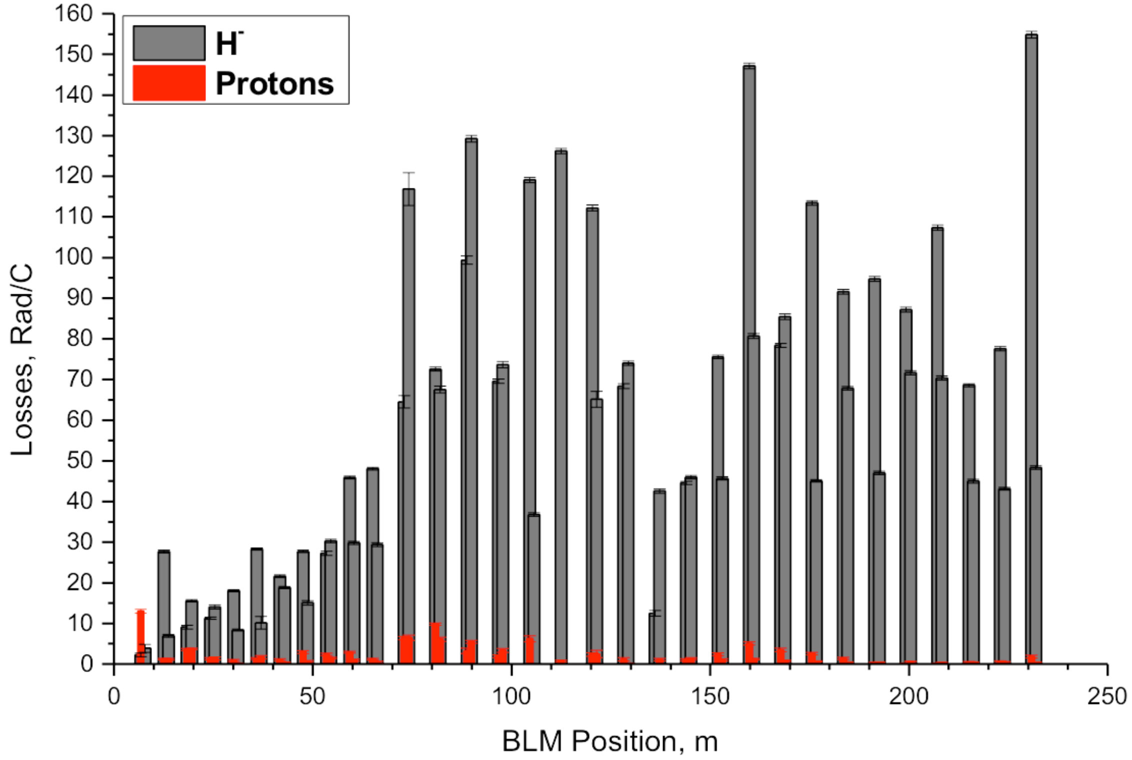
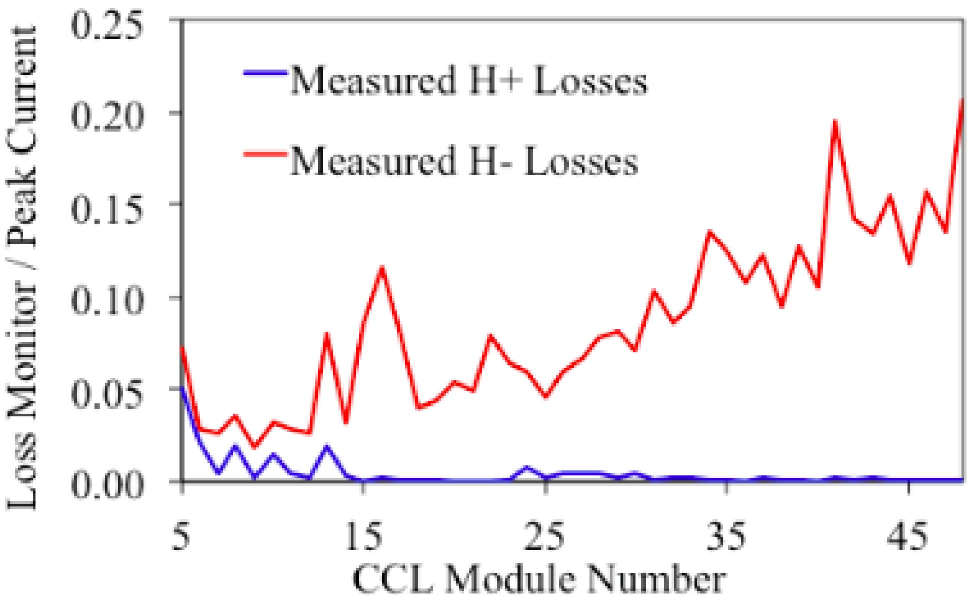
Intrabeam stripping (cont.)

- 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)



Distance along SCL



Measured at LANCE

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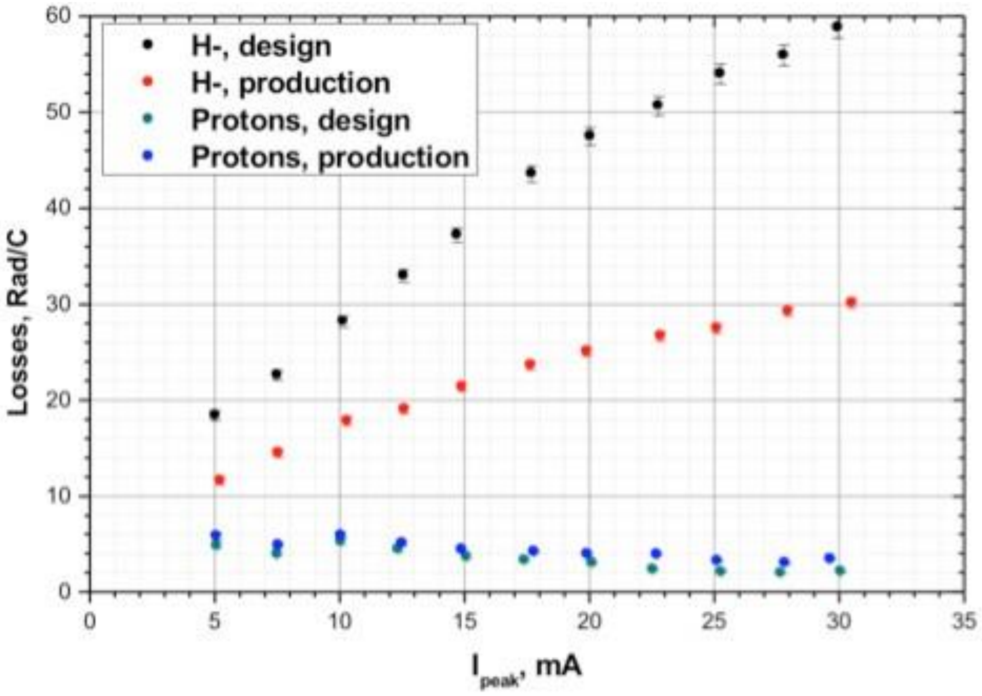
IBSt – measurement vs. calculation

- 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)x10^{-5} over the entire length of the SCL
- A rough calculation of the expected IBSt loss is 4x10^{-5}
- Also measured beam loss for protons, and found much less loss with no intensity dependence



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Magnetic field stripping

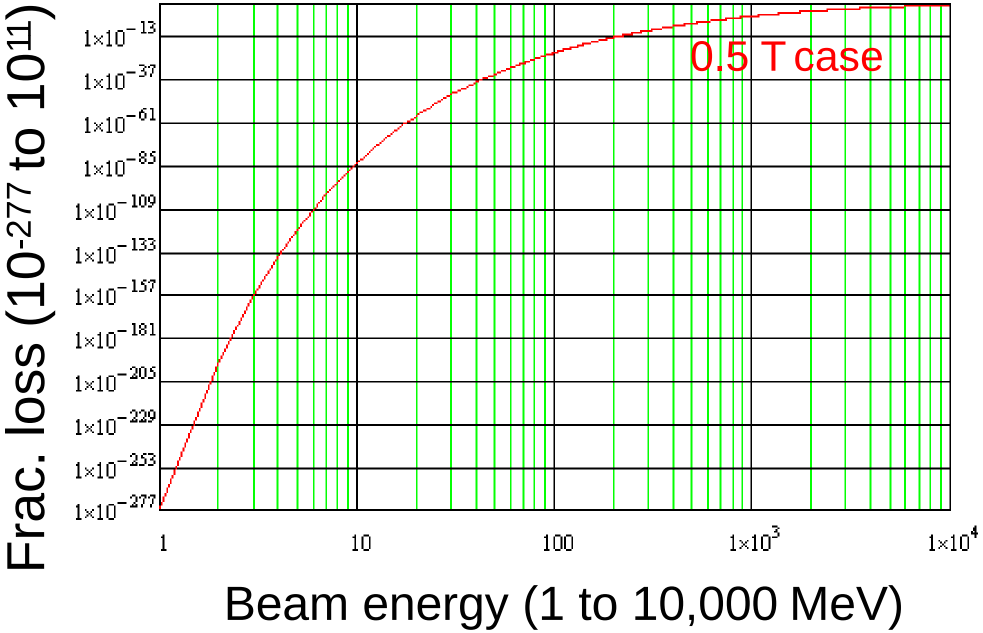
- Lorentz-transformed magnetic field looks like electric field in rest frame of beam particles

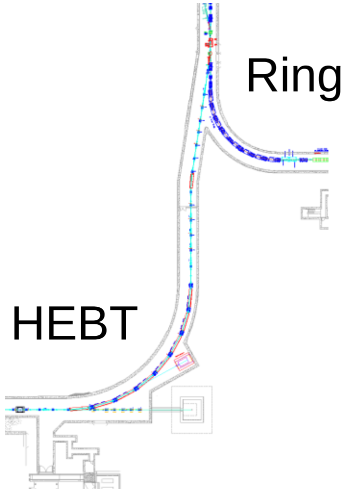
E_{ion} [V/m] = ®©cB_{lab} [T]

- Loosely-bound electrons on H^- particles can be stripped off

$$\frac{df}{ds} = \frac{B(s)}{A1} e^{A2/®©cB(s)}$$

$A1$ = 2.47E-6 V sec/m
$A2$ = 4.49E9 V/m
B(s) = magnetic field
®, ©, c = relativistic factors





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

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

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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 at low energy	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	Yes, 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 at 1.1 GeV	Insignificant	Yes, <1% in 70 MeV transport line, some hot spots	Insignificant

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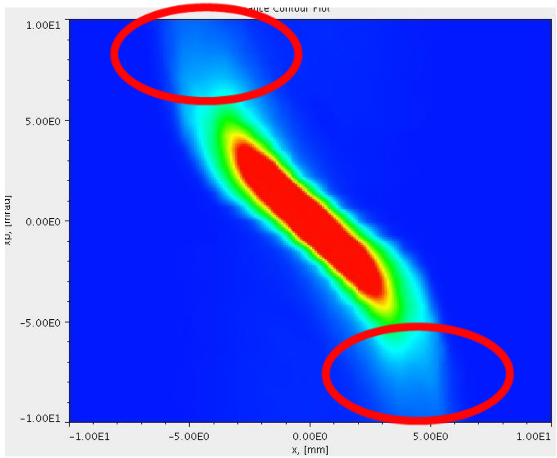
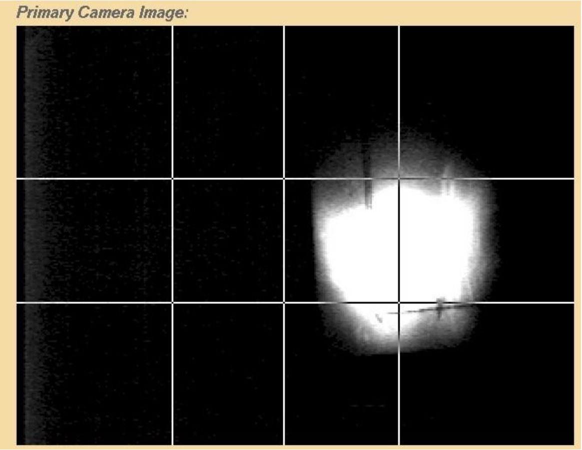
Beam loss in H^+ and H^- linacs

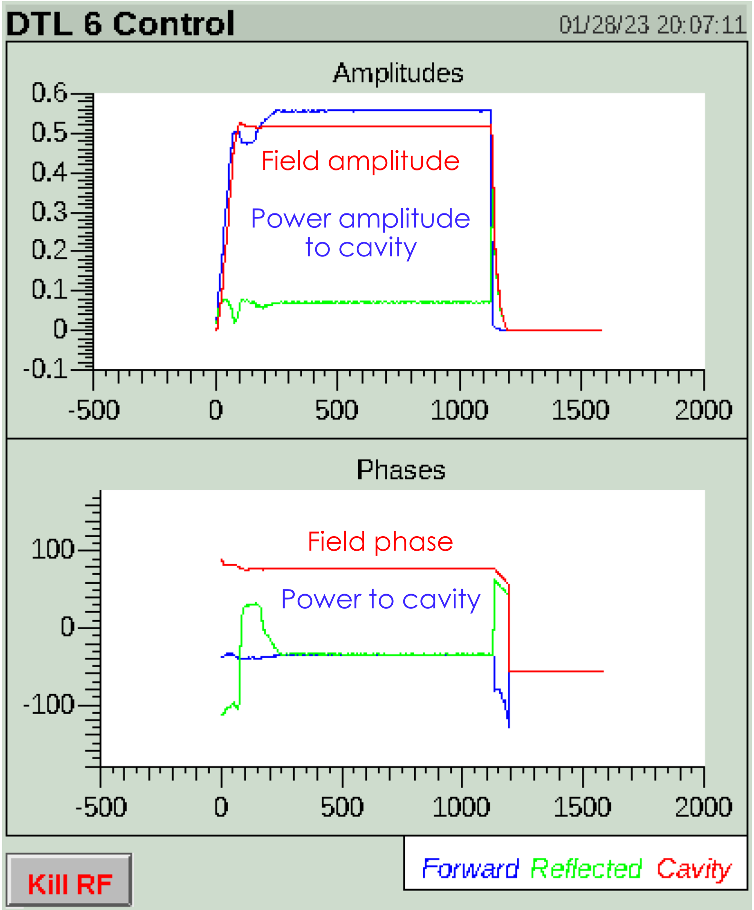
- Beam halo/tails (large emittance from IS, RF mismatch, etc.)
- Dark current from ion source
- RF feedback control
- RF and/or ion source transients (errant beam)



Beam emittance
Beam halo



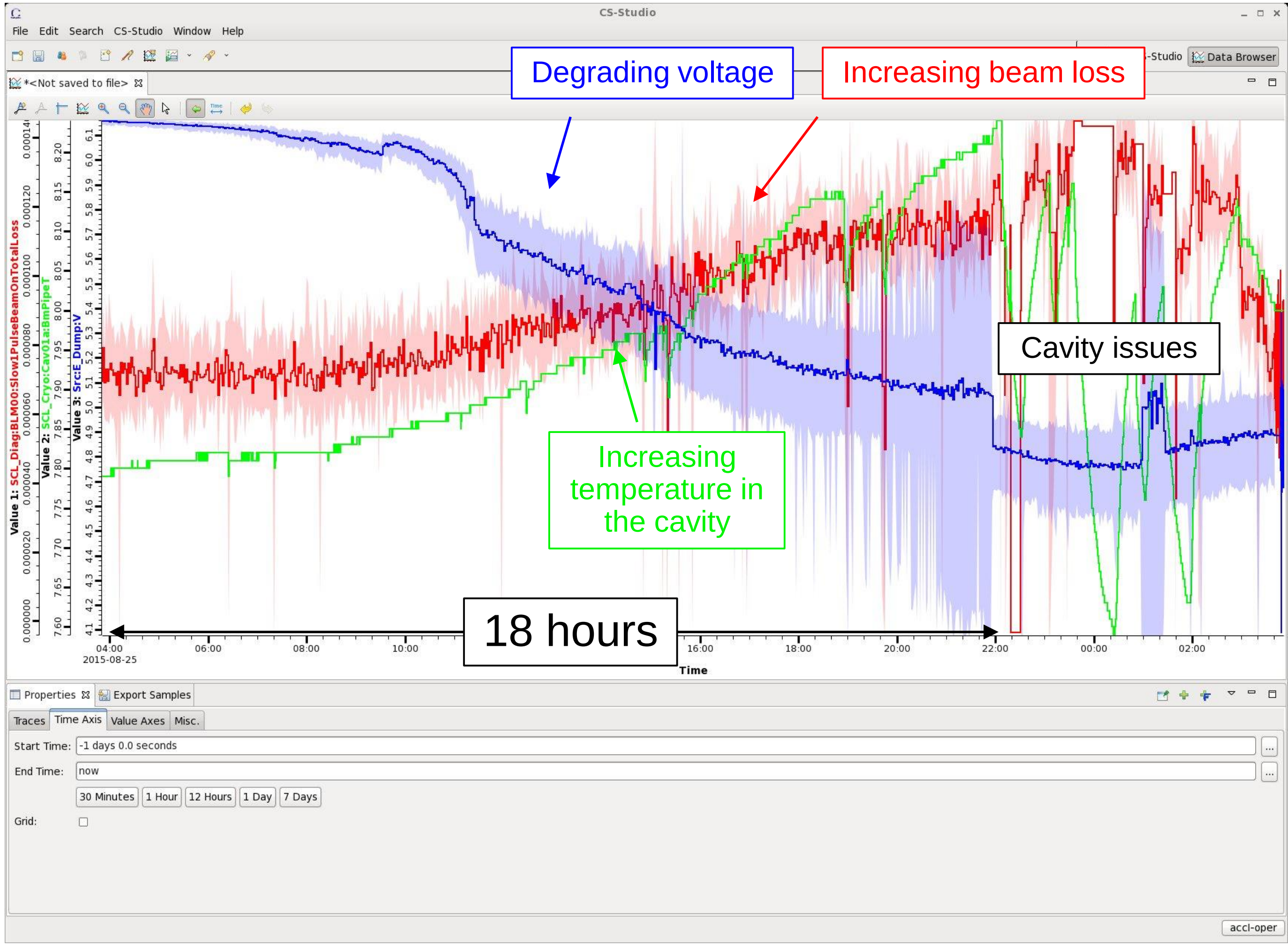
Dark current



RF cavity amplitude and phase control

Beam halo can degrade cavity performance

- An ion source extraction electrode was unable to maintain the appropriate voltage
- As the voltage decayed beam loss began to occur in the first SCL cavity
  - An upstream Beam Loss Monitor (BLM) increased by about 30% over 18 hours
  - Beam pipe temperature within the cavity increased from 7.8 K to 8.25 K
- Eventually the cavity could not run reliably and the gradient had to be reduced
  - Adjustments were made in the ion source, but the cavity gradient needed to remain reduced



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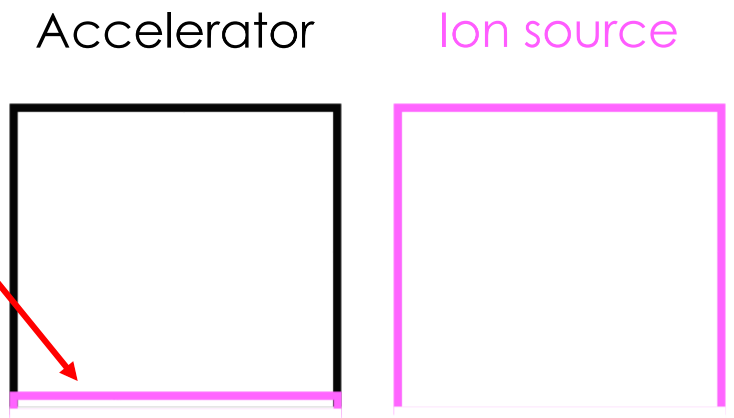
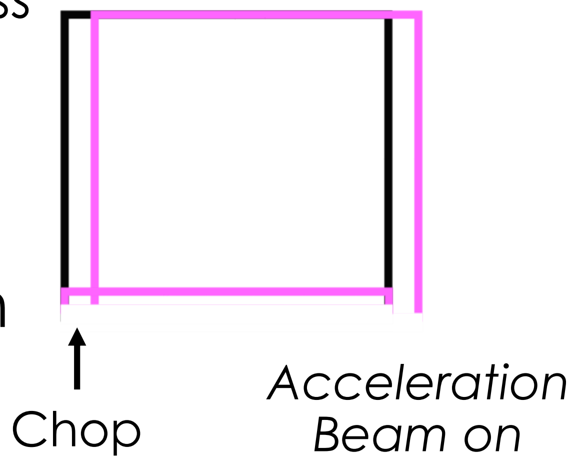
Explanation of Dark Current

- The ion source warming plasma is always on
  - This is the dark current
- The accelerator is always pulsing for ≈1000 μseconds 60 times per second
  - This is what accelerates the dark current
- Chopper duty factor too high to chop both accelerator and ion source pulse during beam off
  - No chopped gap for dark current so there will be beam loss in ring
  - If a system is off downstream all the dark current will be lost in a localized spot
- Not a major issue during normal beam acceleration
  - Dark current gets chopped appropriately



Dark current accelerates with every RF pulse



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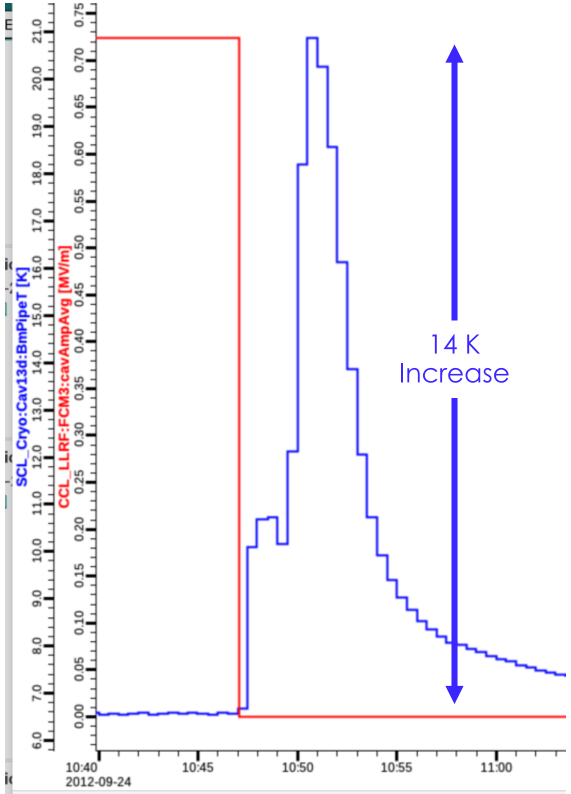
Dark Current Bad During Beam Off

- Beam Power = Pulse Width x Current x Rep Rate x Beam Energy
  - Dark Current = 1035 microseconds x 3 microamps x 60 Hz x 2.5 MeV = 0.5 W — End of RFQ
  - Dark Current = 1035 microseconds x 3 microamps x 60 Hz x 87 MeV = 15.7 W — End of DTL
  - Dark Current = 1035 microseconds x 3 microamps x 60 Hz x 186 MeV = 33.5 W — End of CCL
  - Dark Current = 1035 microseconds x 3 microamps x 60 Hz x 1100 MeV = 198 W — End of SCL

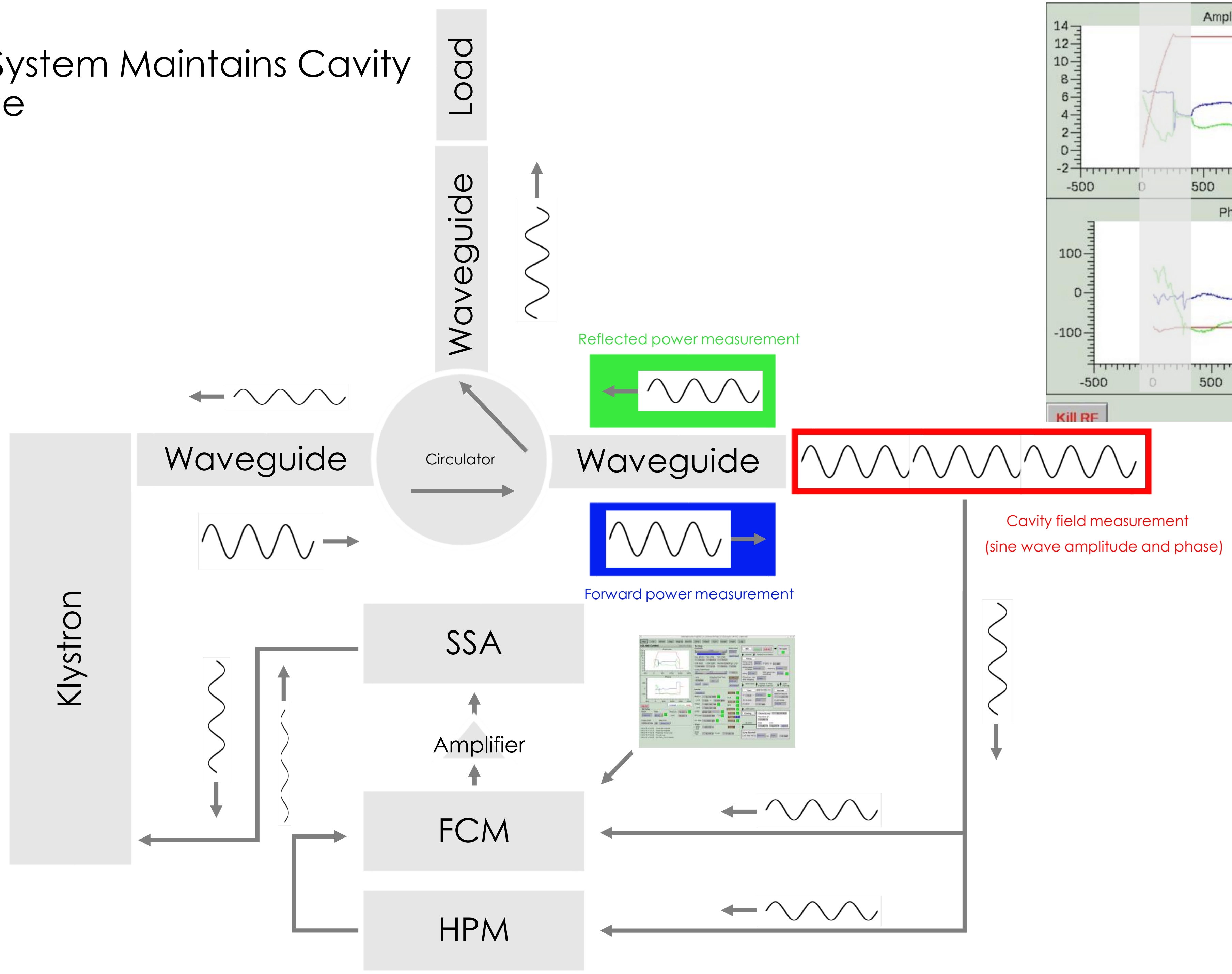
- Impact eliminated by reversing phase of first DTL tank during beam off
  - Plot to the right shows the impact of dark current during beam off with a downstream cavity off
    - Heating in the SCL is immediate

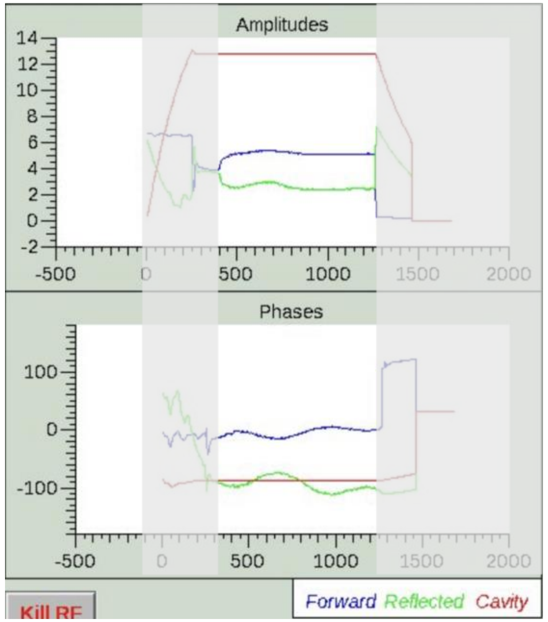


CCL cavity status

Temperature in SCL cavity

RF Feedback System Maintains Cavity Field and Phase





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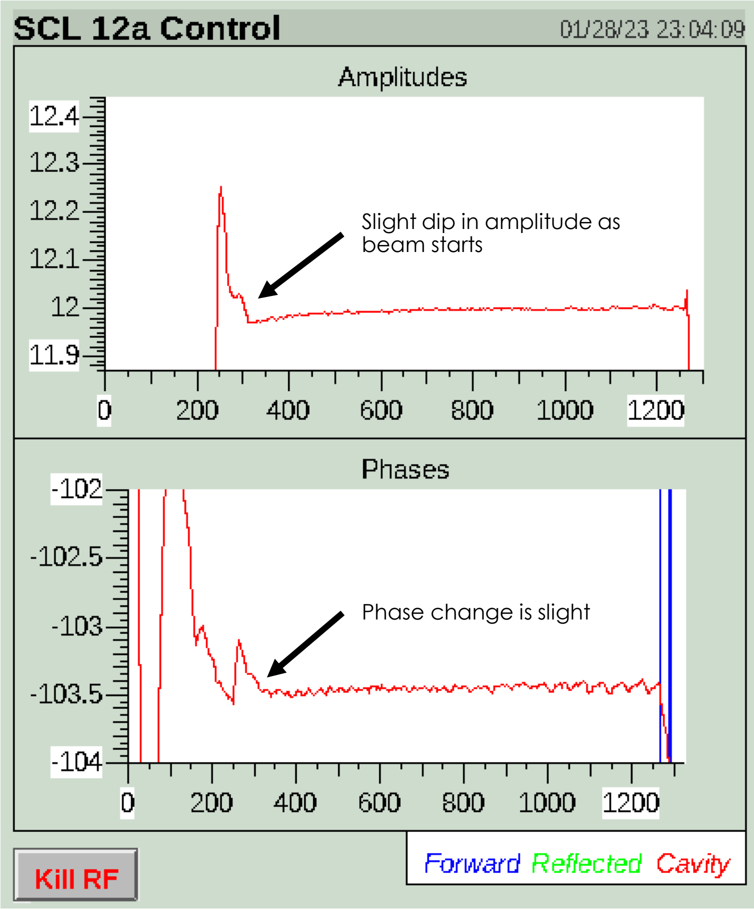
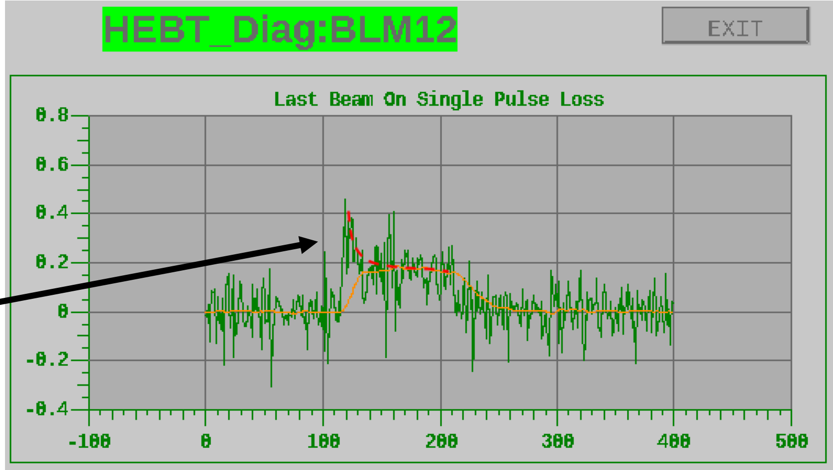
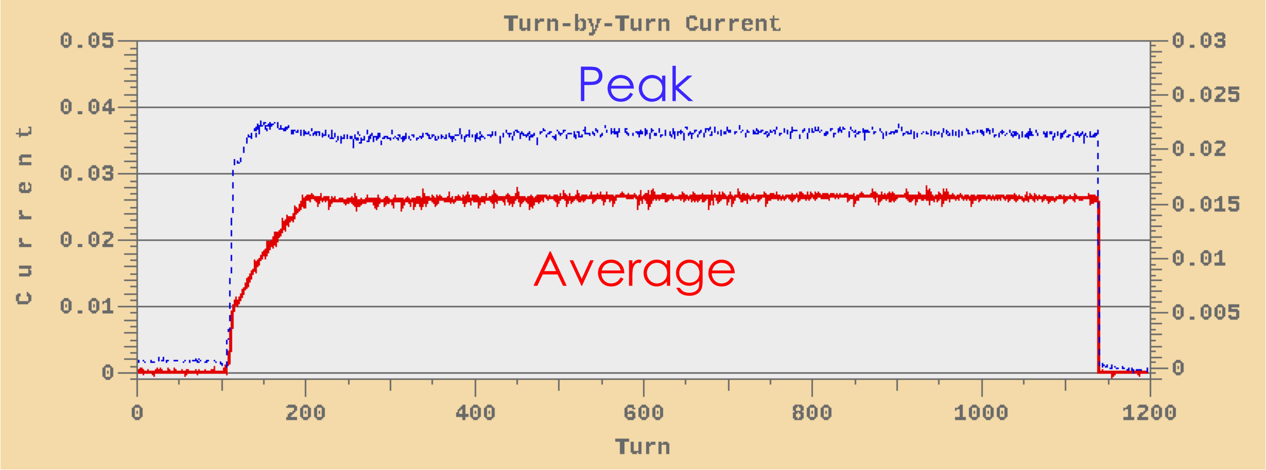
RF Field Amplitude and Phase Errors Cause Beam Loss

- Field amplitude dips as beam enters cavity and feedback attempts to correct



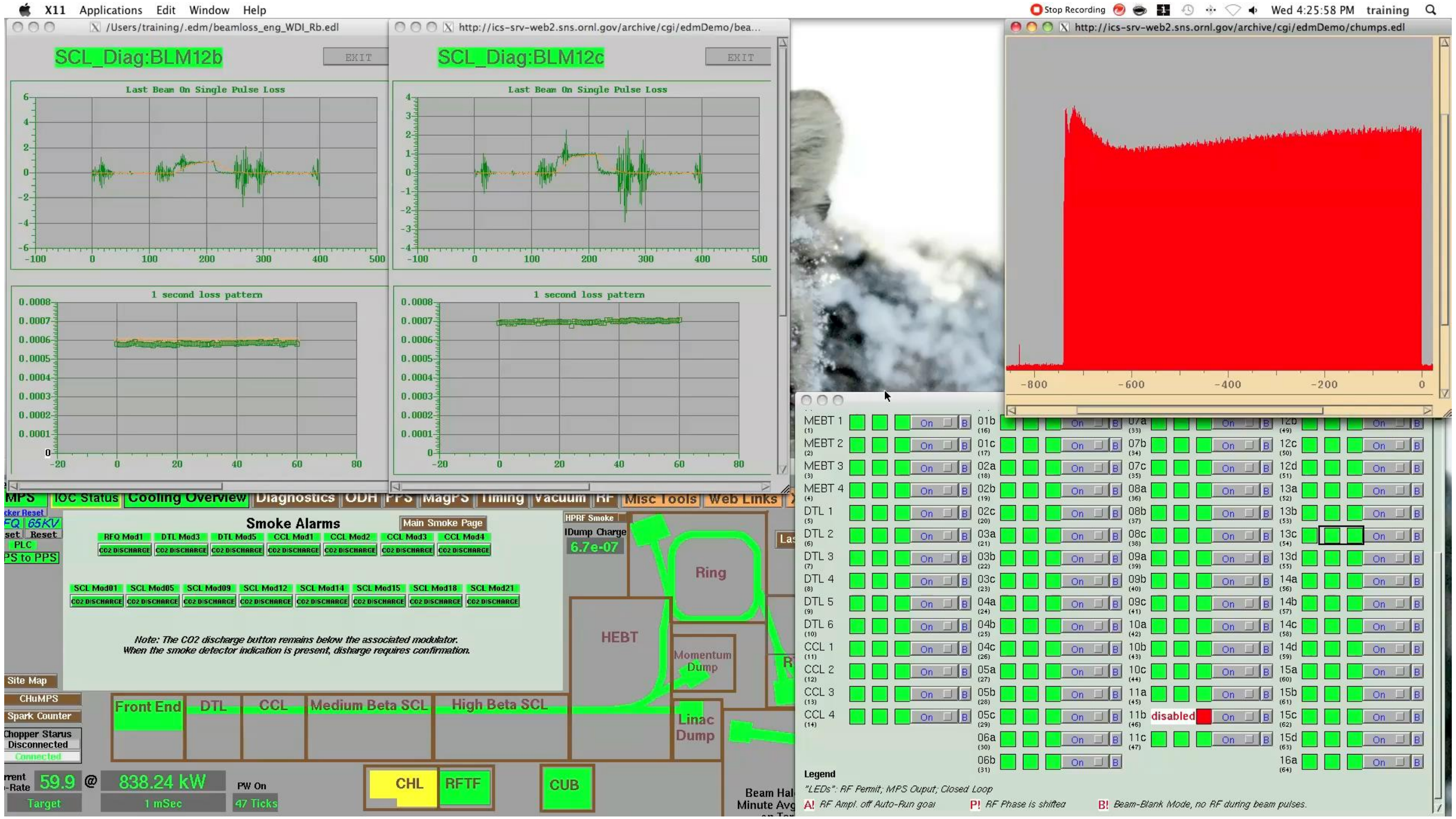
- SNS has 104 cavities so errors add up along the linac



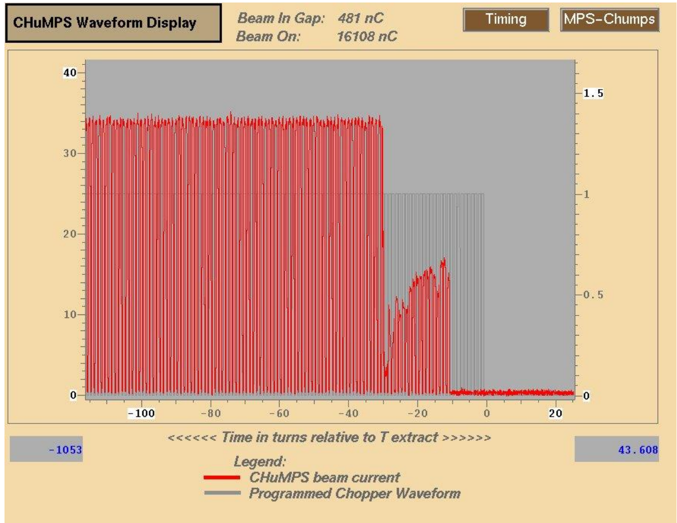


- Impact is minimized by slowly increasing average beam current

Errant beam is uncontrolled beam loss in the SCL



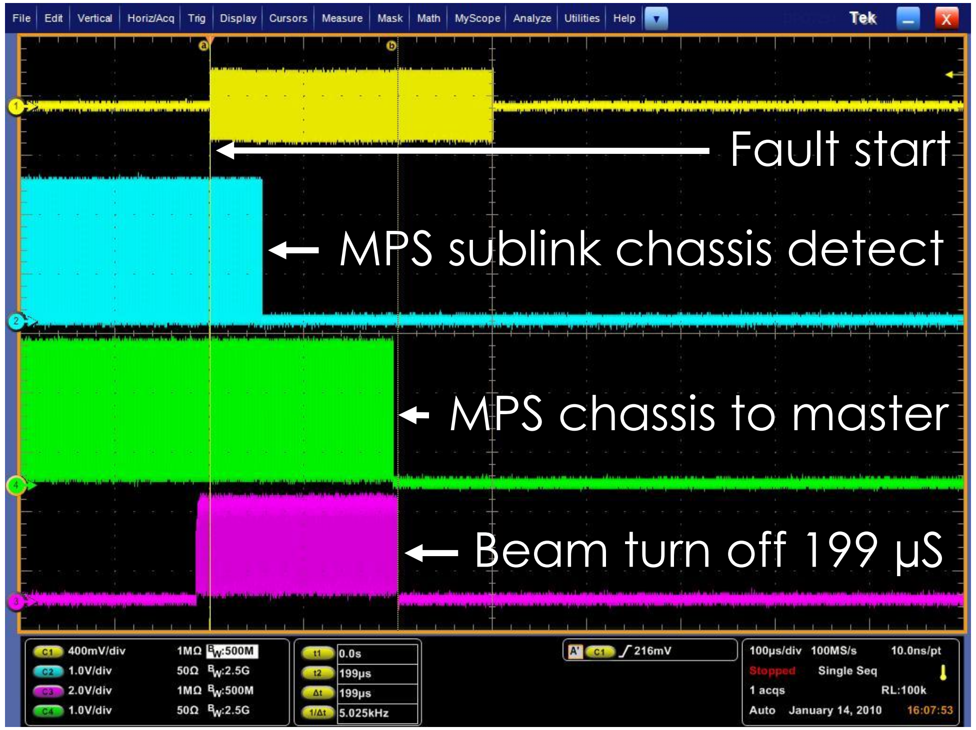
Example of a CCL RF cavity fault



Example of ion source high voltage malfunction

SCL cavities are very sensitive to beam loss

- In 2009 a correlation was found between beam loss events and SCL cavity reliability issues
  - MPS delay issue was found and design change implemented
- After the MPS fix there were continued correlations between beam loss events and SCL cavity reliability issues



Operations
20-Nov-2015 13:47

Re: CCL 2 HPM fault tripped SCL cavities - Charles Peters

It looks like 16.3 turns lost. We made some adjustments yesterday that may have moved the dumping place for **CCL**2 faults.

(1)

Event: 20-NOV-2015 13:32

Operations
20-Nov-2015 13:41

CCL 2 HPM fault tripped SCL cavities - Geoffrey Milanovich

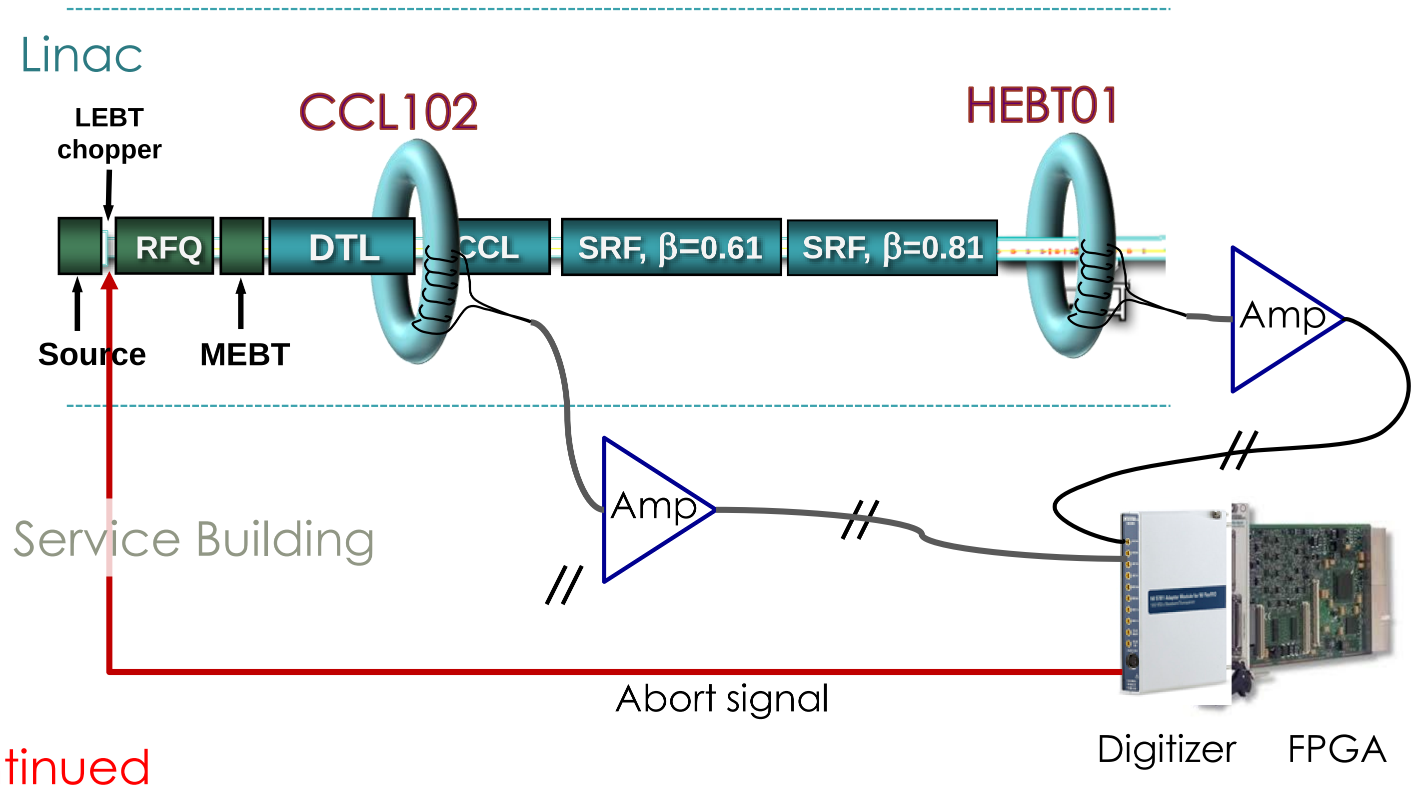
Looks like a fault of **CCL** 2 sent enough bad beam through the linac to trip cavities and close valves. Recovering..

(6)

Event: 20-NOV-2015 13:32

Implementation of DCM for RF faults

- Most errant beam losses come from the DTL and CCL RF systems which results in total beam loss in the SCL
- To minimize the impact a single differential BCM with current measurement at the beginning of the CCL and after the SCL was implemented
  - Uses the PXI Platform with LabVIEW Real-time and FPGA
  - Connects directly to the LEBT chopper which then connects to the MPS
  - Beam turn off time of 8 μs
    - FPGA needs about 1-2 μs to decide
    - Signal and beam propagation and chopper timing, adds 5-6 μs

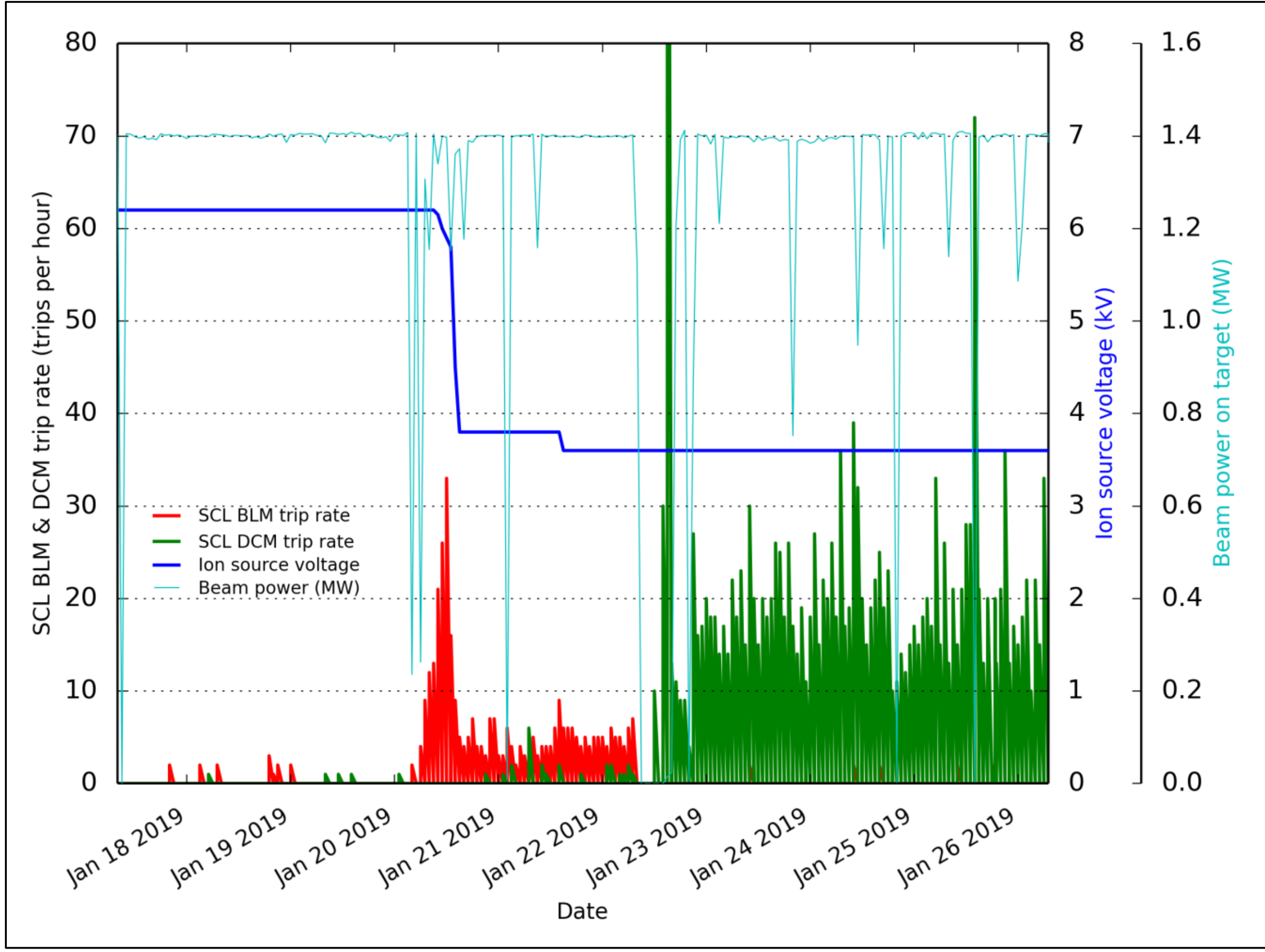


Differential Current Monitor

SCL cavity reliability issues continued

Implementation of DCM for ion source faults

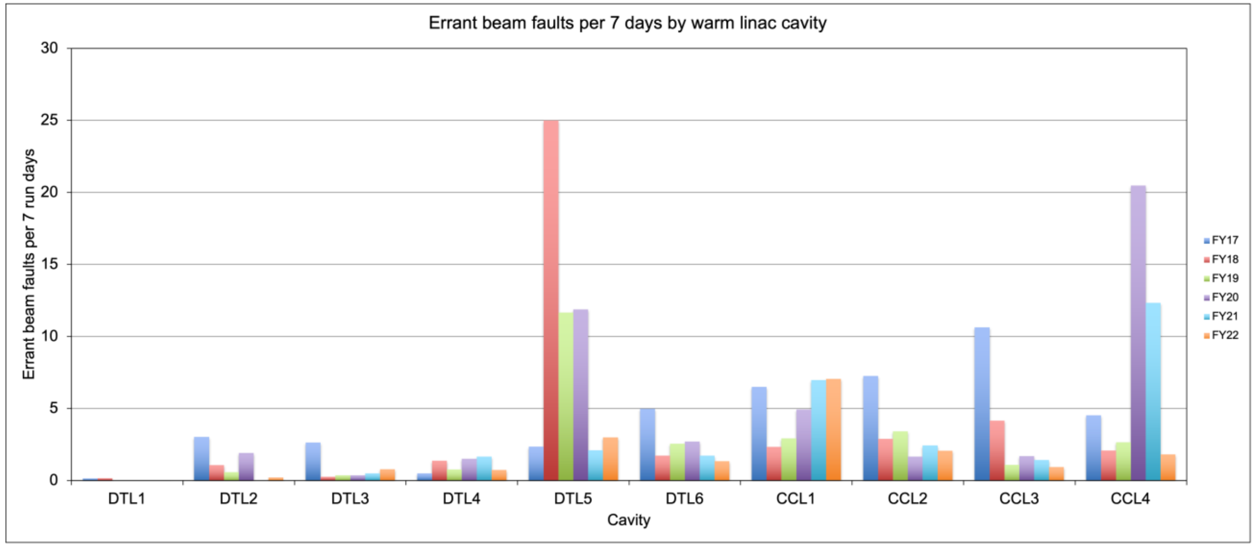
- Errant beam losses also come from the ion source and cause partial beam loss in the SCL
- Ion source high voltages are not monitored by the MPS which means malfunctions that cause abnormal beam pulses are not detected by downstream systems other than BLMs
- The DCM system compares the charge along the beam pulse to the previous pulse and aborts if the difference is above a threshold
  - Same beam detection and turn off time of 8 μs

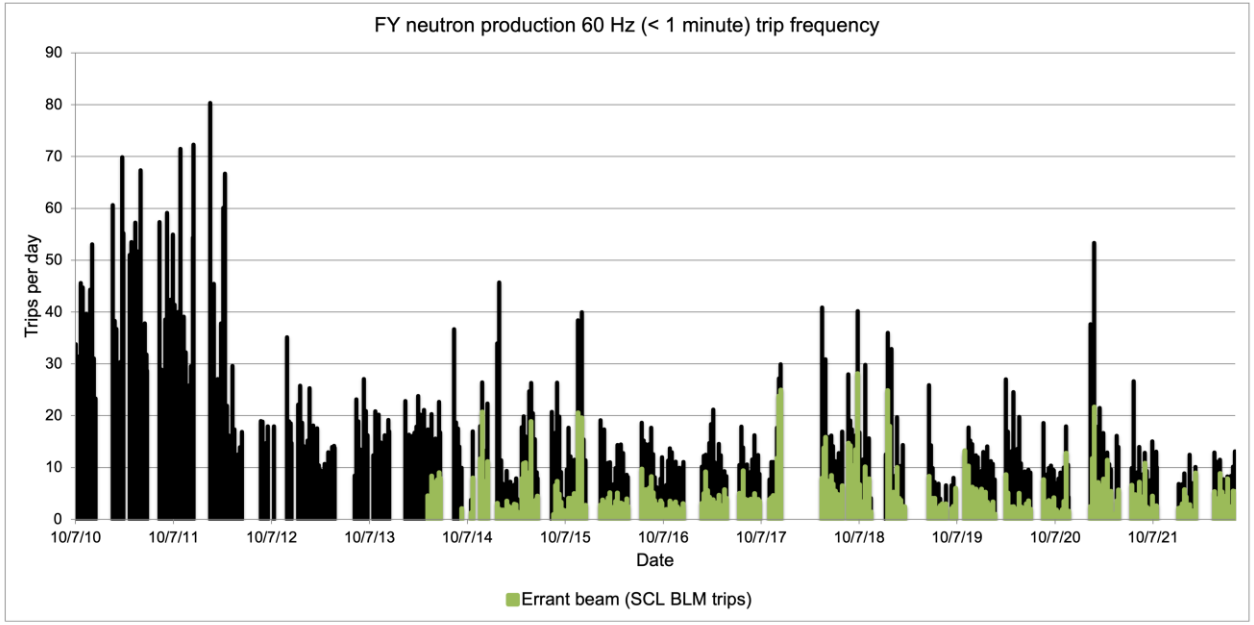


SCL cavity reliability issues continued though significantly reduced

It is not possible to eliminate ion source and RF faults

- Monitoring fault frequencies allows tracking of health but is postmortem
  - Planned upgrades will increase beam current by about 20%
- Anticipating faults based on slow trends has been done by setting alarm thresholds
- Working on a machine learning system to predict faults and tell MPS not to send beam





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 or scrapers 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

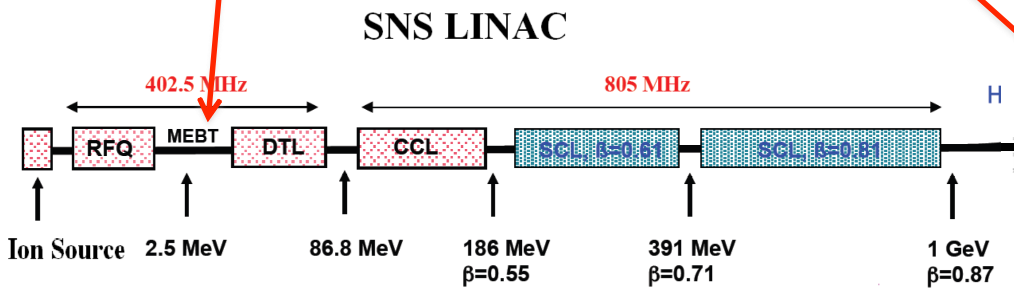
In MEBT:
Left-right scrapers
Top-bottom scrapers

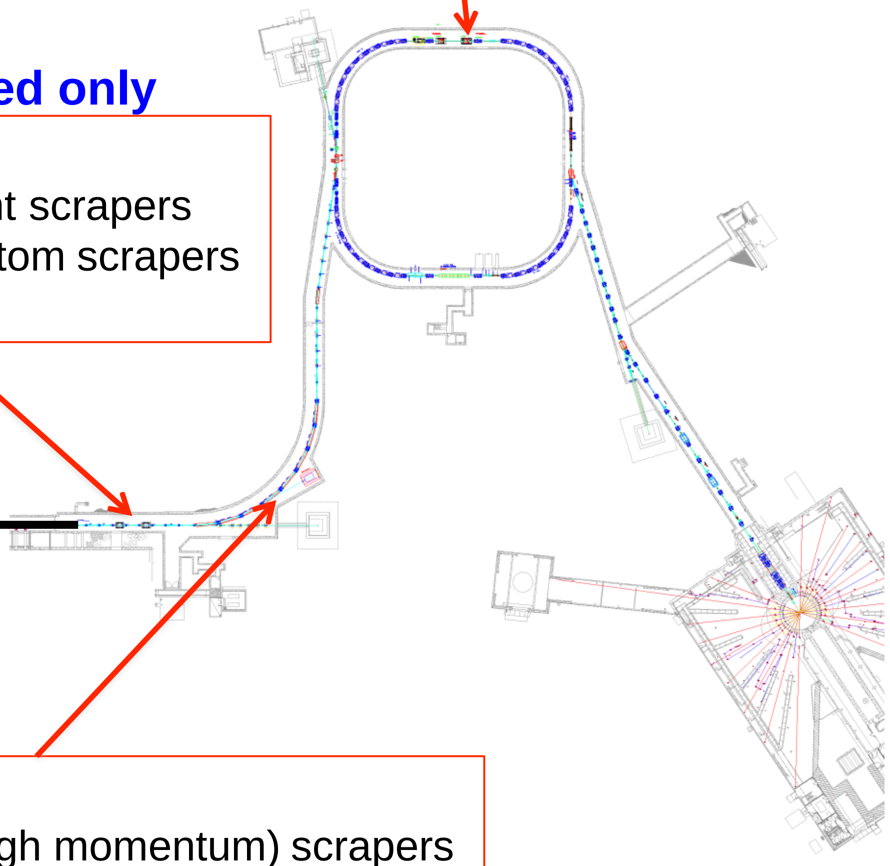
Never used

In Ring:
Four scrapers
Three collimators

Vertical used only

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





Never used

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

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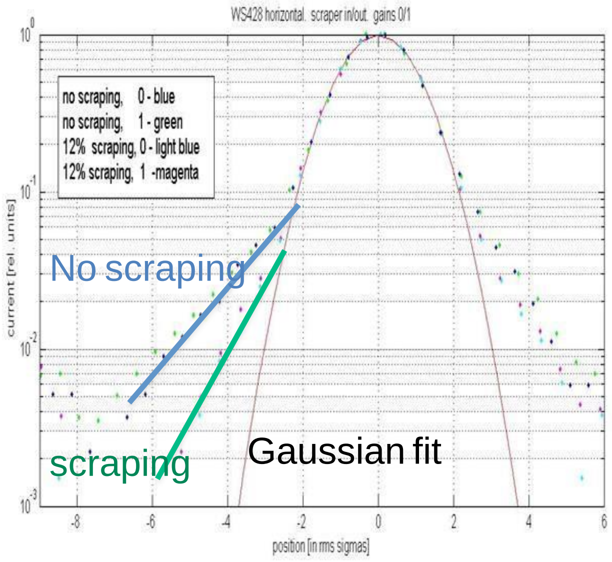
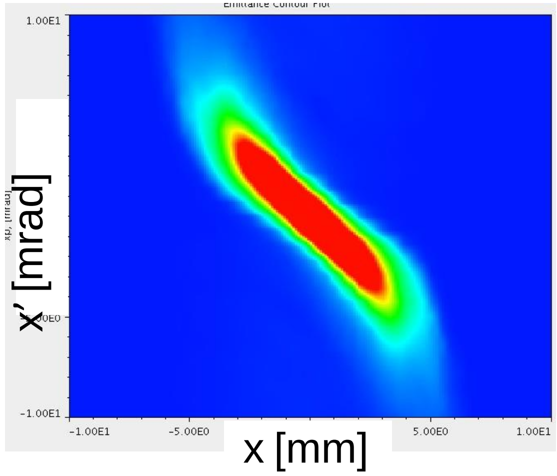
MEBT Scraping

- 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

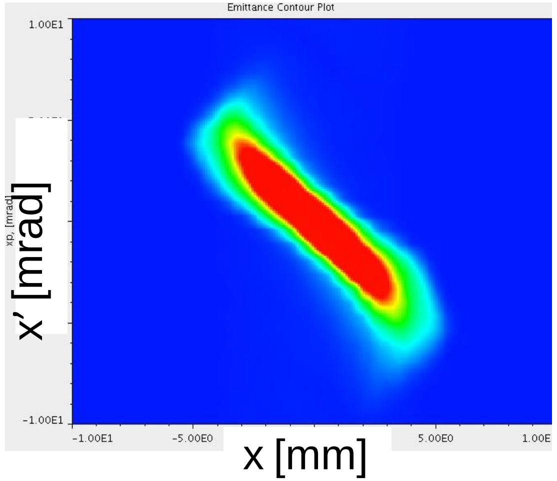
DTL profile, log scale



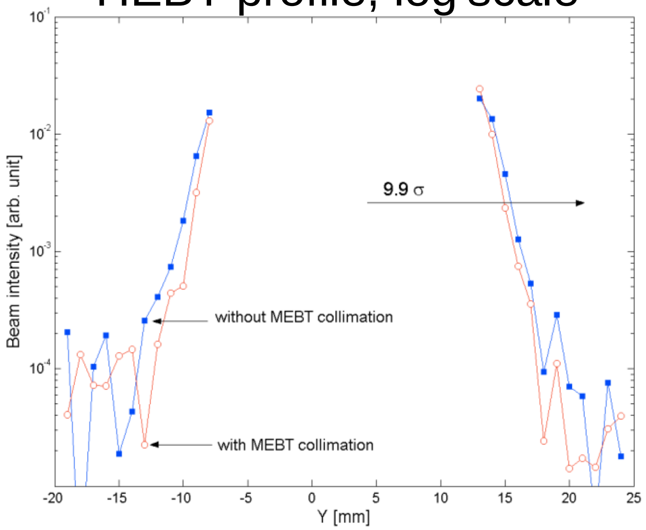
MEBT Emittance without scraping



MEBT Emittance with scraping

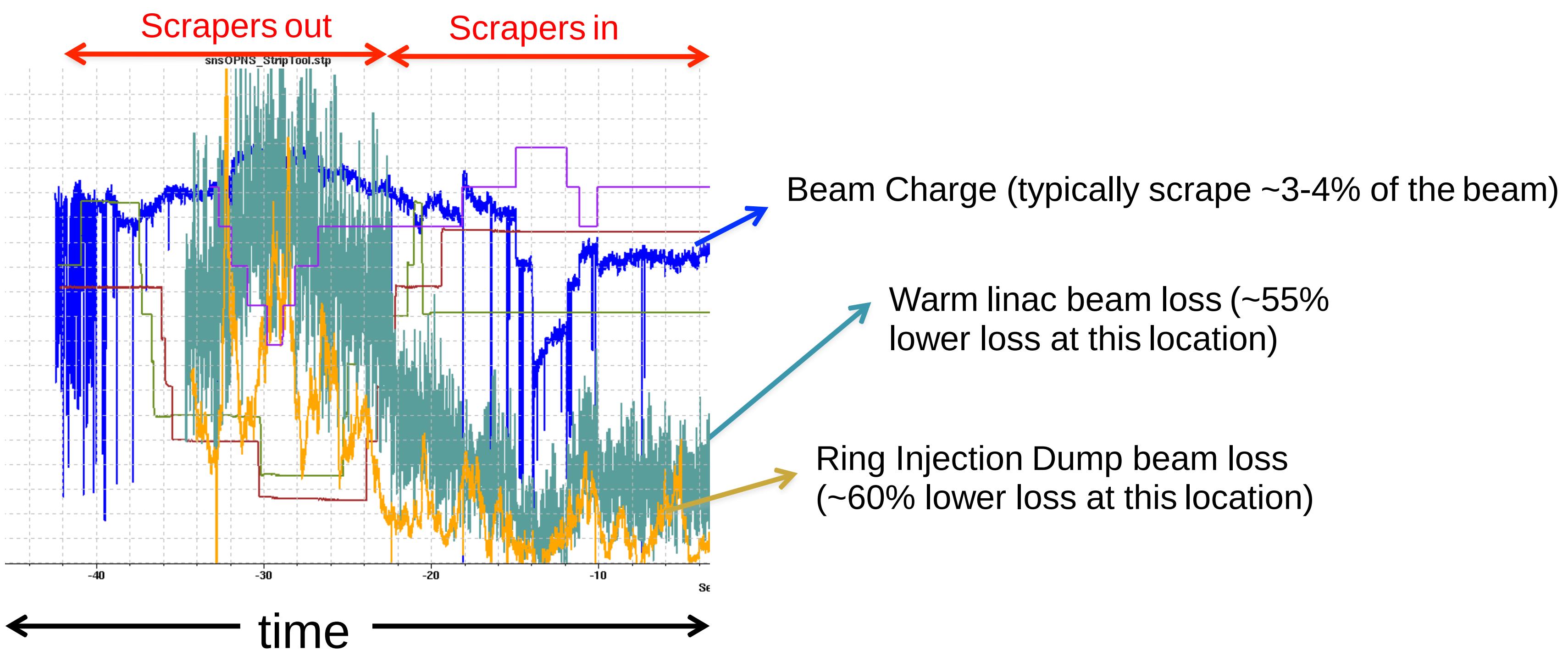


HEBT profile, log scale



(Courtesy A.Aleksandrov)

Beam loss reduction by low energy scraping

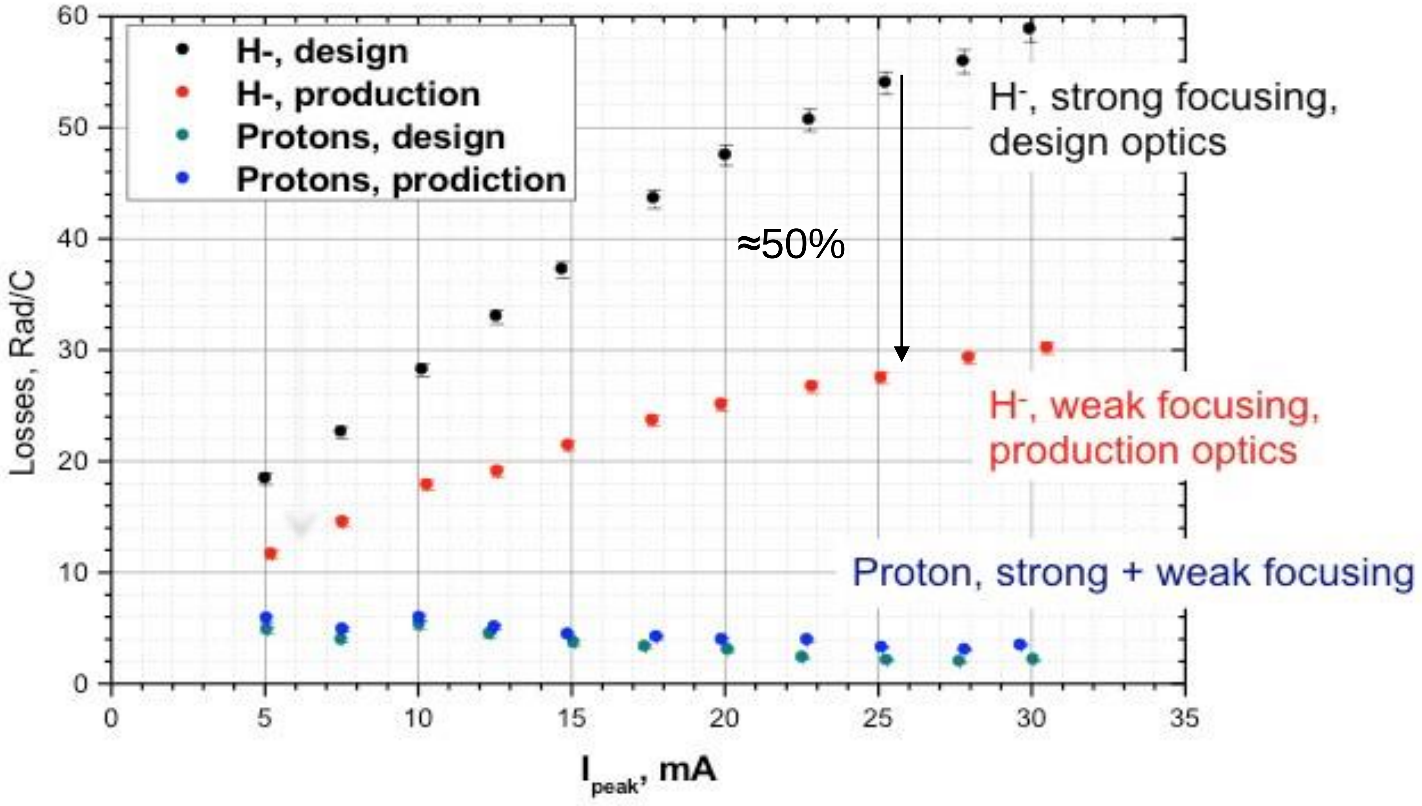


- At SNS we have had good results from scraping the left/right tails of the beam in the 2.5 MeV MEBT
- Up to ~60% loss reduction by scraping 3-4% of the beam

(Courtesy J. Galambos)

Beam loss reduction by 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



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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 approximately double the beam loss at some locations
  - Typical phase changes are 1-2 degrees in the warm linac and 1-5 degrees in the SCL.

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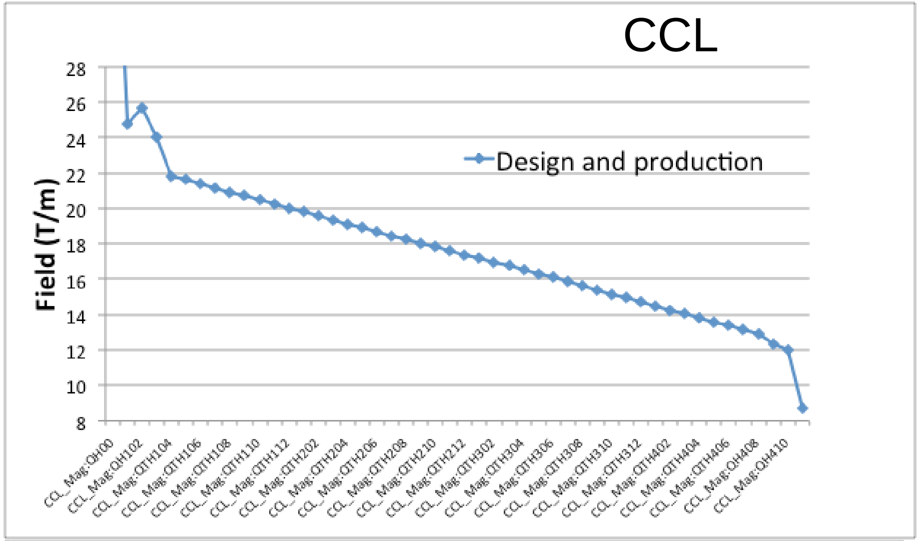
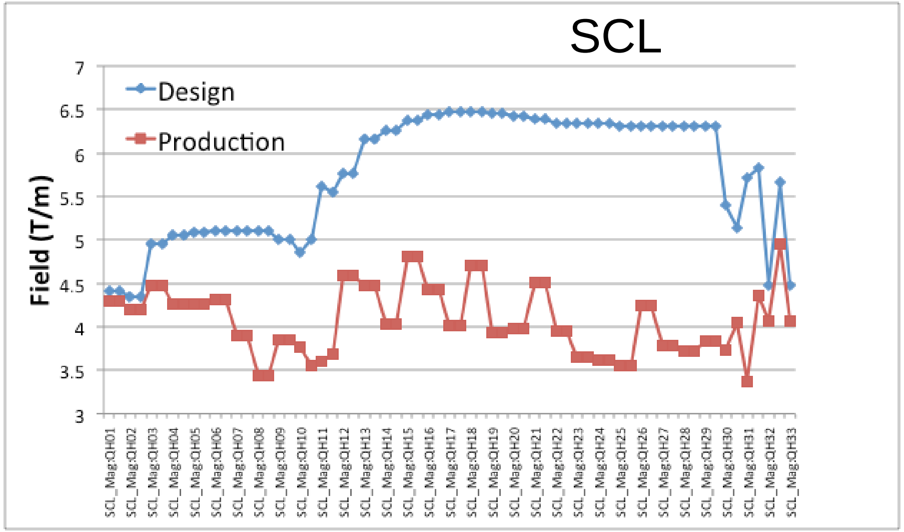
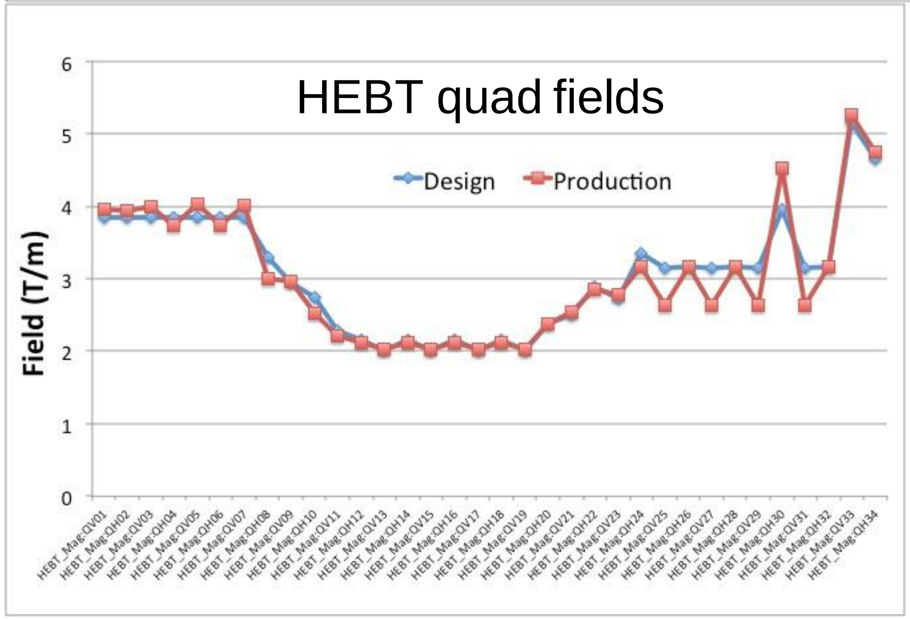
SNS Linac Transverse Lattice: Design vs. Operation







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

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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