SNS Stripper Foils

by
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SNS Accelerator Physics and Technology Forum
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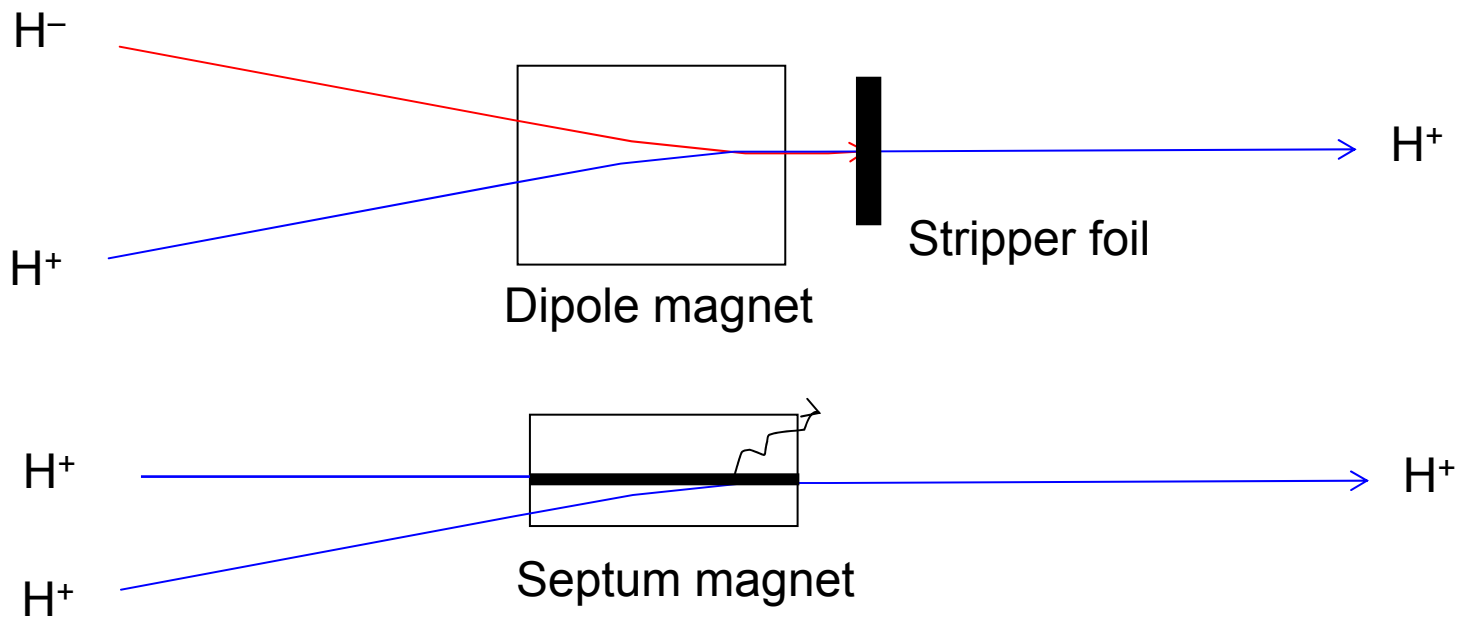
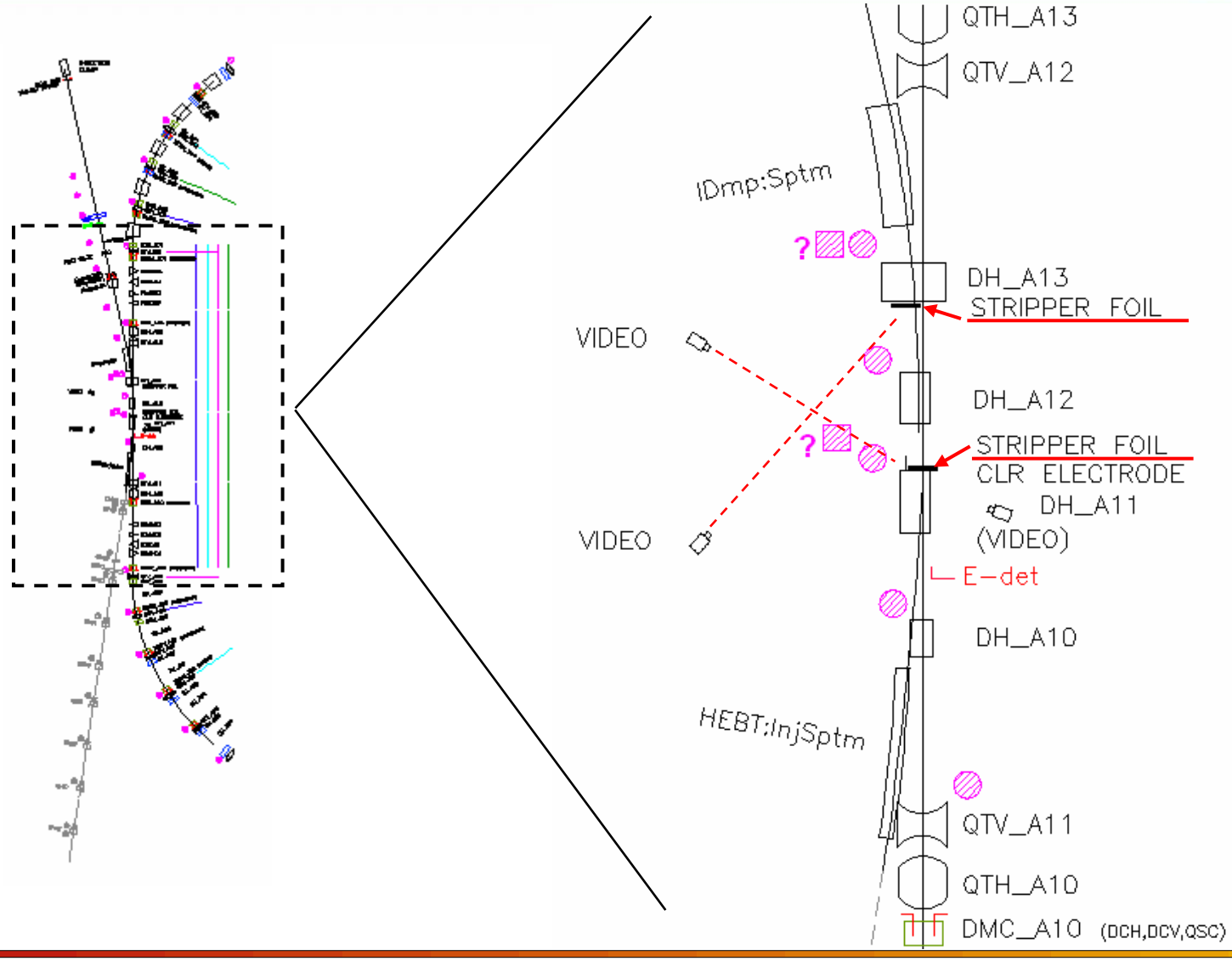
Why does SNS have stripper foils?

- Charge exchange injection is the most efficient way to inject a beam into a ring.
- Alternate method is to use a septum magnet, which causes about 10% beam loss. This could be OK for a low-power ring, but for the SNS this corresponds to 140 kW of beam loss!

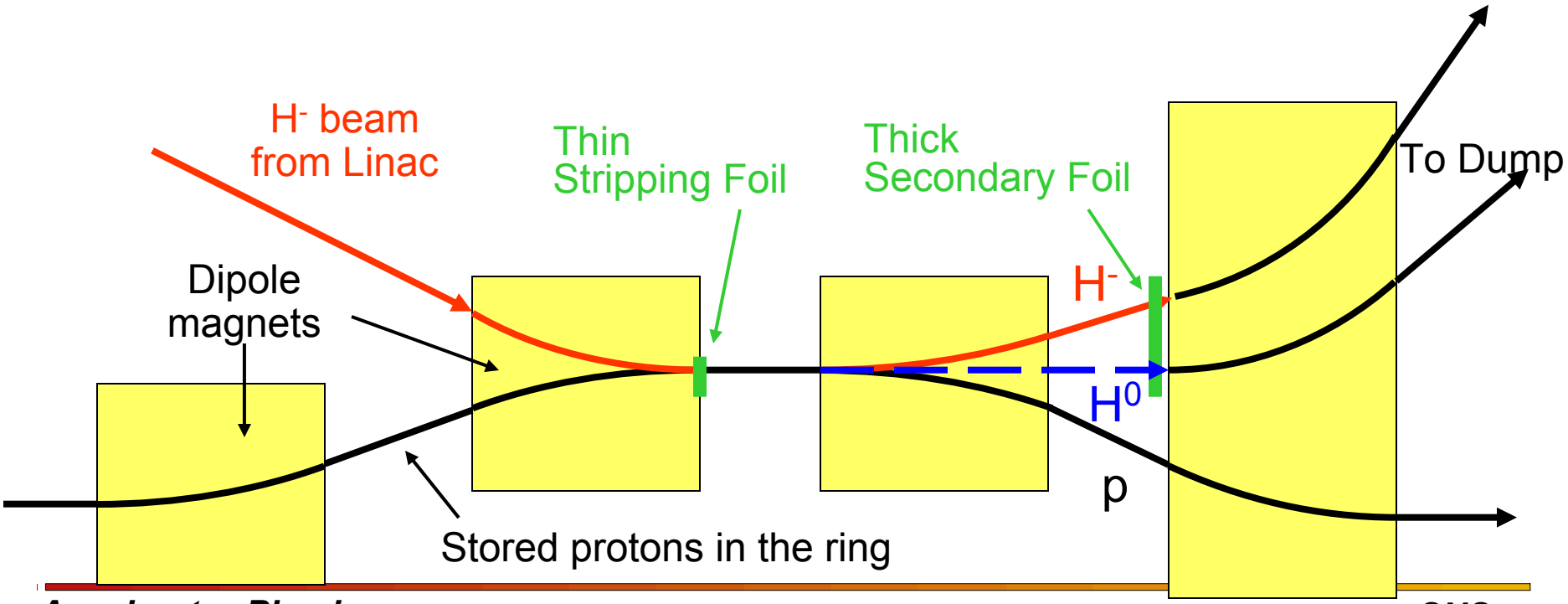


Where are the SNS stripper foils?



The SNS Injection Process

- The SNS relies on Multi-Turn Charge-Exchange Injection to create a short pulse of protons in the Ring (250 m) from a long beam pulse delivered by the Linac (250 km in length).
- Two electrons are removed by the stripping foil, injected protons are merged with previously accumulated beam.
- The Secondary foil strips the H^- and H^0 which survive the first foil.



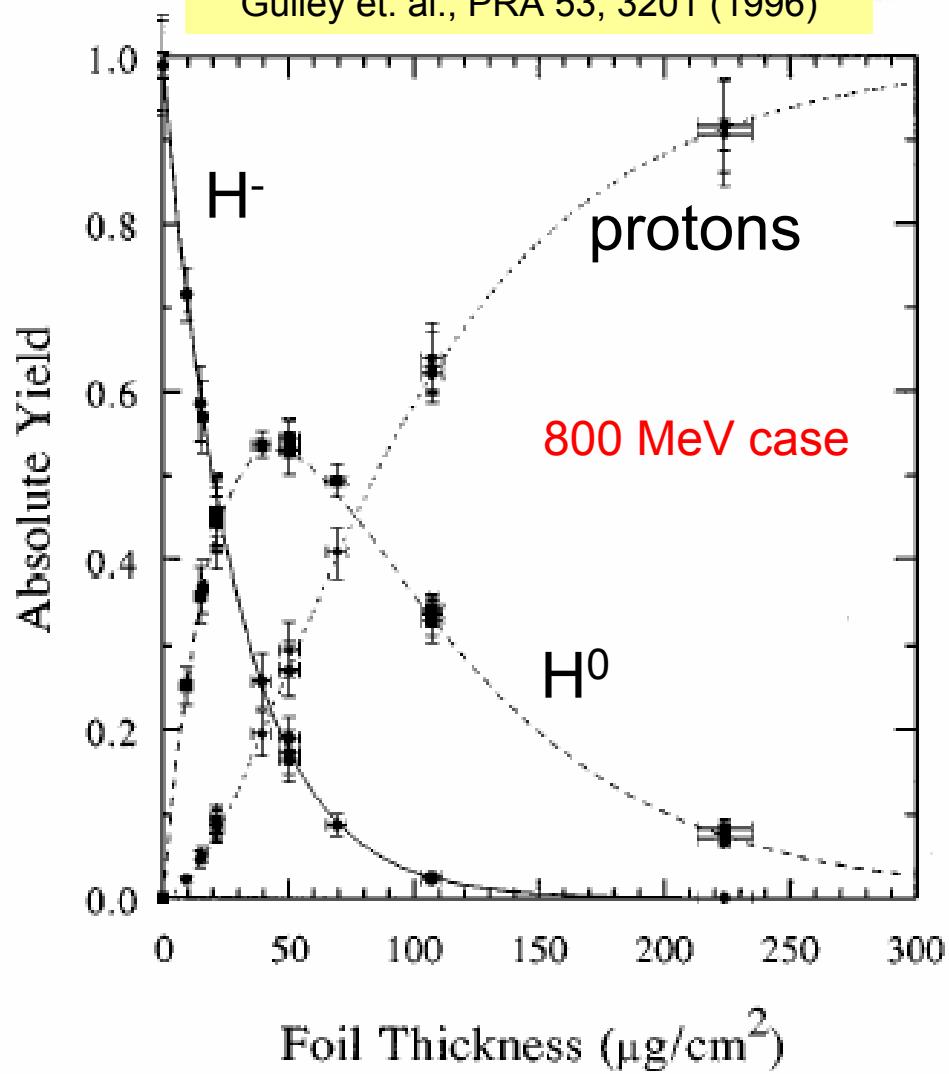
What makes a good stripper foil?

- **Thick enough** to strip off the electrons from the injected H^- beam.
- **Thin enough** to minimize the effect on the previously injected (circulating) beam.
- Our foil gets very hot, so it should also have a **high melting point**.
- Our foil is also ideally supported just from the top, and we don't want any extra material in the beam, so it should be **self supporting**.

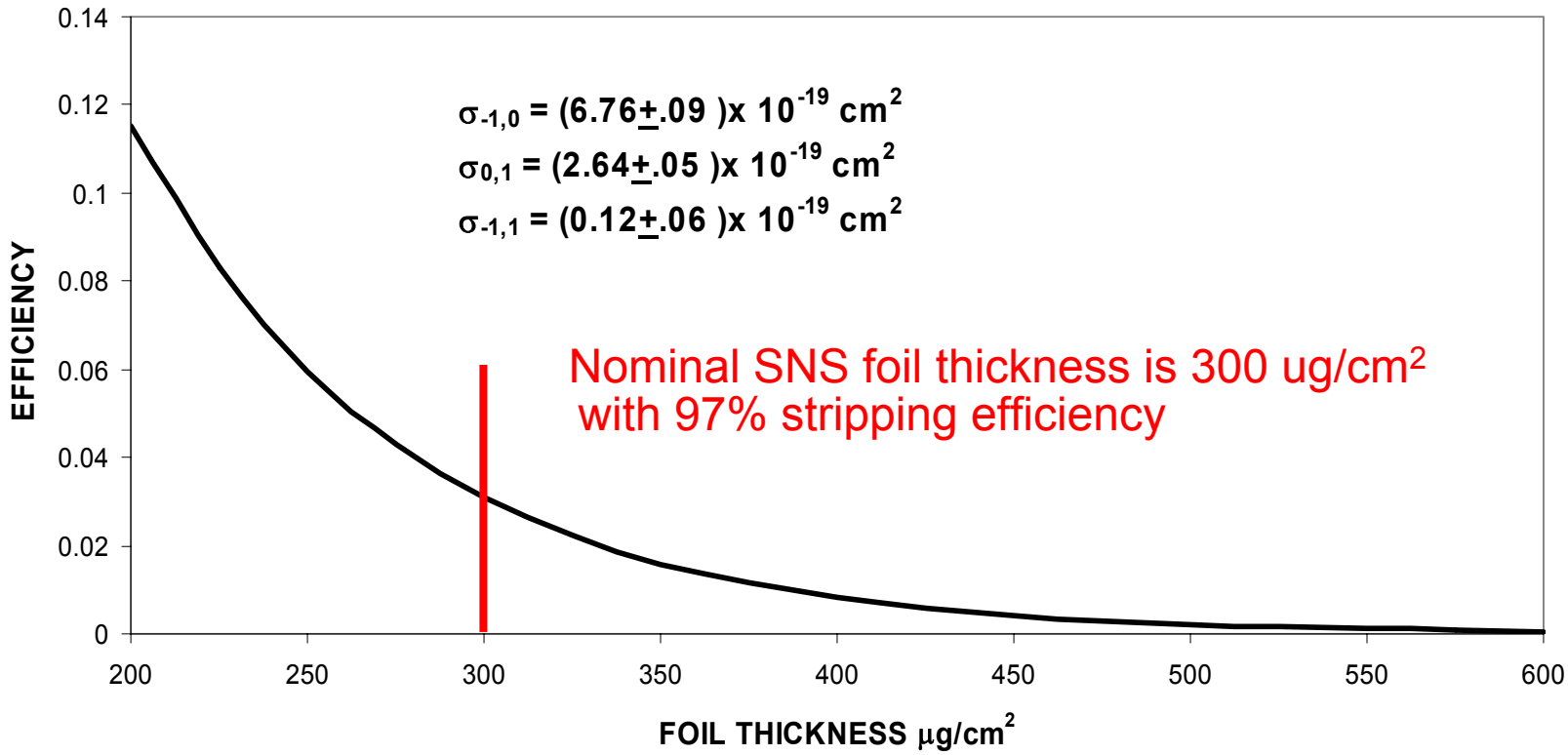
Thick enough to strip off the electrons…

- Not all incident H^- are fully stripped to protons in the foil.
- The fraction of partially stripped (H- to H^0) beam is a strong function of the foil thickness.

Gulley et. al., PRA 53, 3201 (1996)



Stripping efficiency @ 1 GeV



Thin enough to minimize impact on circulating beam…

- The average proton in the SNS ring passes through the stripper foil 6 to 7 times.
- A thicker foil will run at a higher temperature, will scatter the circulating beam, and increase the radio-activation levels.
- In thin foils a single scattering of ~100 times or more than rms scattering angle has a significant probability (much greater than from Gaussian approximation).
- Rutherford formula:

$$\frac{d\sigma}{d\Omega} \cong \left(\frac{2Ze^2}{pv}\right)^2 \frac{1}{\theta^4} = \frac{C_0}{\theta^4} \qquad \theta^2 = \theta_x^2 + \theta_y^2 \qquad C_0 = \left(\frac{2Ze^2}{pv}\right)^2 = \left(\frac{2Zm_e r_e}{\gamma\beta^2 M}\right)^2$$

- If scattering angle θ_x or θ_y is large enough particle will be lost on an acceptance-limiting aperture.

Foil scattering (cont.)

- The probability of scattering per foil traversal is

Want foils with low atomic number, low density and low thickness

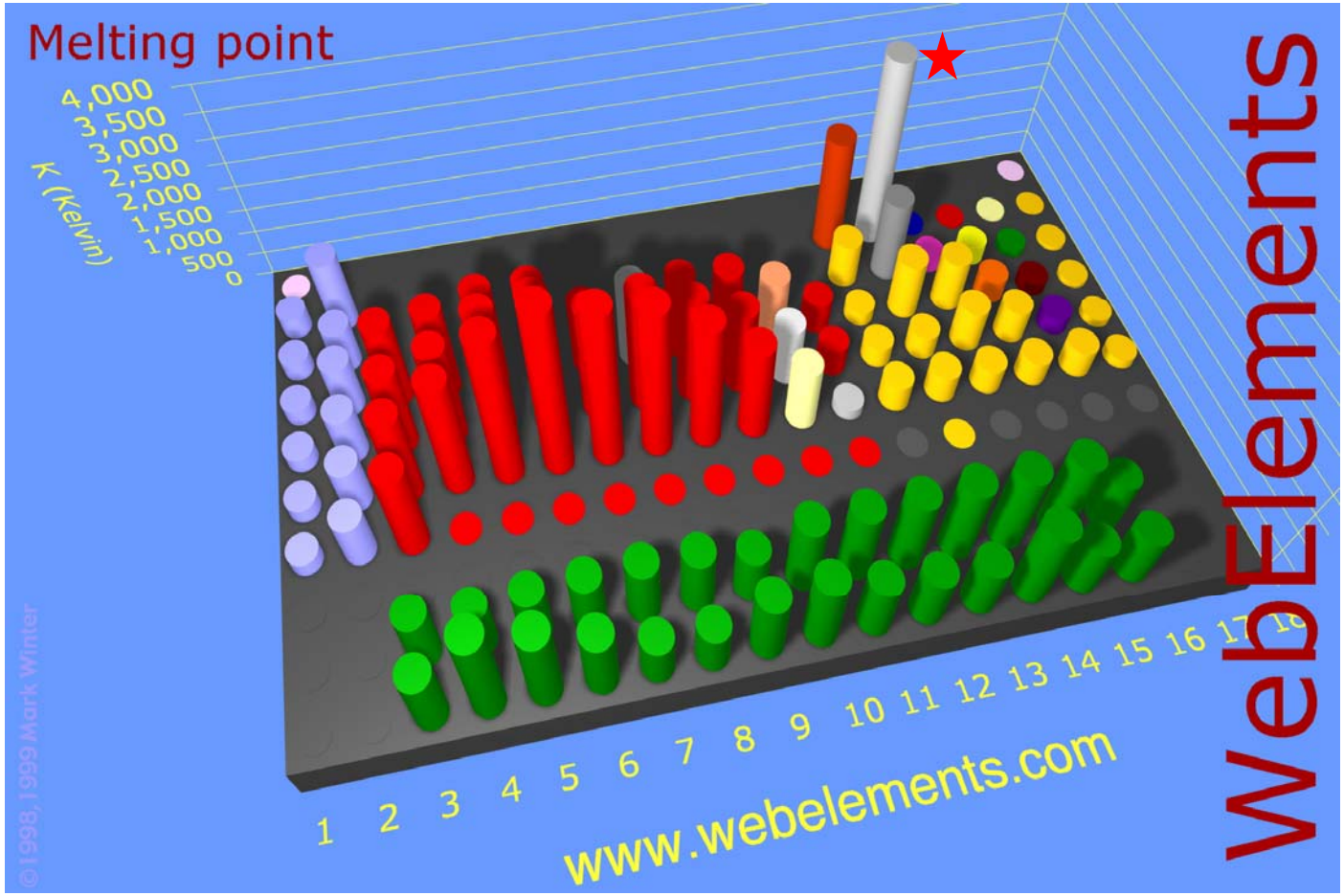
$$P = \left(\frac{2Zm_e r_e}{\gamma M \beta^2}\right)^2 N_0 \left(\frac{\rho t}{A}\right)\left[\frac{1}{\theta_{xl}\theta_{yl}} + \frac{1}{\theta_{xl}^2}\tan^{-1}\left(\frac{\theta_{yl}}{\theta_{xl}}\right) + \frac{1}{\theta_{yl}^2}\tan^{-1}\left(\frac{\theta_{xl}}{\theta_{yl}}\right)\right]$$

- Carbon is a good foil material because of its low density (<2 gm/cm^2), low atomic number, and can make them very thin.

Ref: Macek ICFA'04 @ FNAL

High melting point…

- Carbon has highest melting point (3800 ^{o}K) of any element.



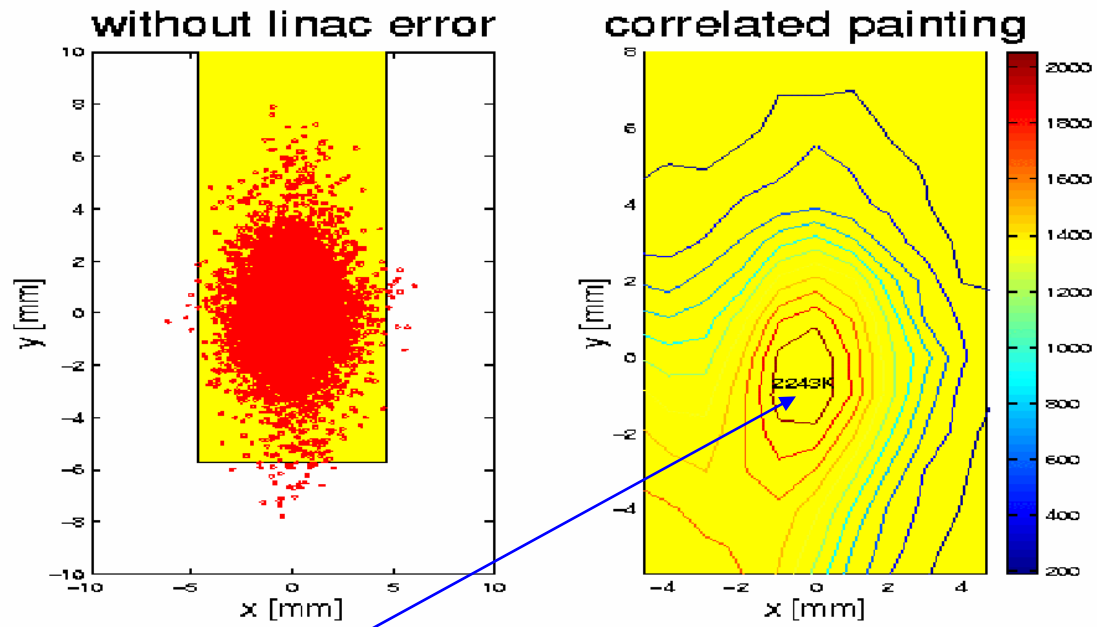
How hot does the foil get?

- Simulation includes: radiative cooling, heat conduction through foil to its base, 6 or 7 foil hits per proton.
- Does not include: secondary electron and thermionic electron cooling.
- Tests at BNL show that when temp exceeds 2500 ^{o}K lifetime decrease sharply.

Table 1 Design parameters used in the simulations.

Beam Kinetic Energy	1 GeV
Protons per Pulse	2.08×10^{14}
Stripping Foil Size	$6\sigma_{inj}$
Horizontal tune ν_x / Vertical tune ν_y	6.3 / 5.8
Injected beam Emittance	0.5 πmm-mr
Un-norm. Painted beam Emittance	120 πmm-mr

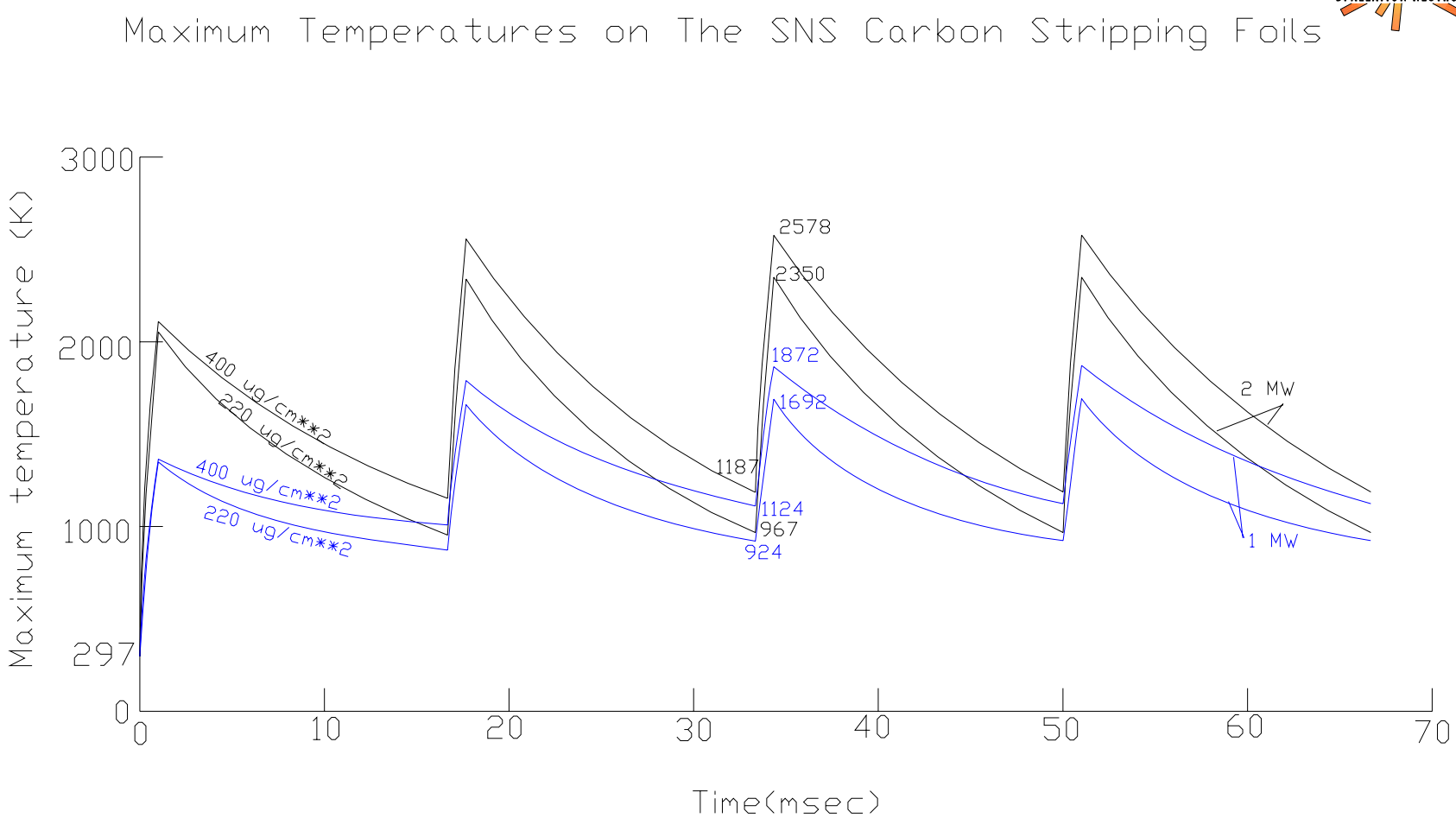
300 ug/cm^2



2243 ^{o}K

Ref: Injection Carbon Stripping Foil Issues for SNS, PAC01, J. Beebe-Wang et al.

Foil temperature vs. time



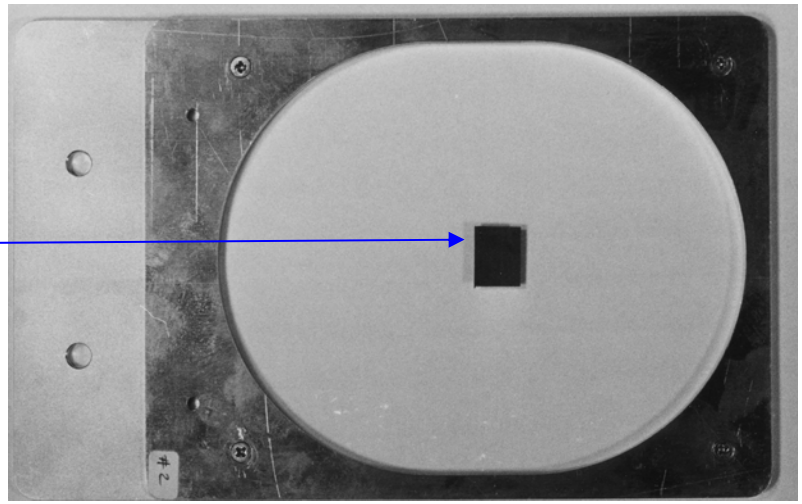
- Thick foils get hotter than thin foils
- More than 2500 ^{o}K is a problem!

Ref: YY Lee, ICFA'04 @ FNAL

Self supporting…

- Carbon foils can be made extremely thin – less than 1 micron thick, if they are supported from the edges.
- The SNS primary stripper foil nominal thickness is 300 $\mu g/cm^2$ (~1.5 microns), and it is best for our ring if it is supported only by its top edge.
- It's a tricky business to support carbon foils of this thickness by only one edge. Carbon fibers 5 to 6 micron diameter, have sometimes been used for support.

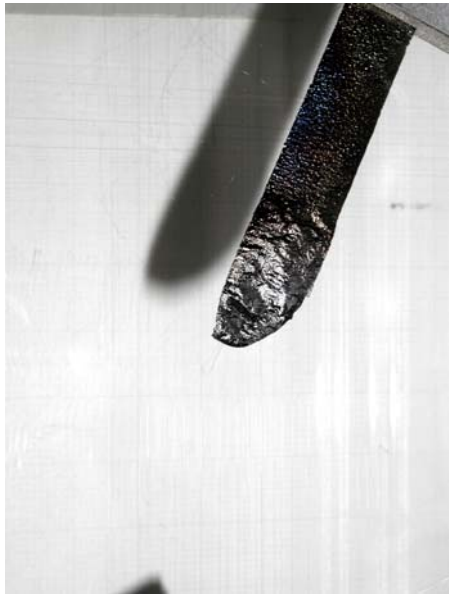
Old PSR foil completely supported by carbon fibers



Stripper Foil Damage

- The stripper foils really take a beating…
- A lot of time and money has been spent developing new types of carbon stripper foils.

Some PSR stripper foils

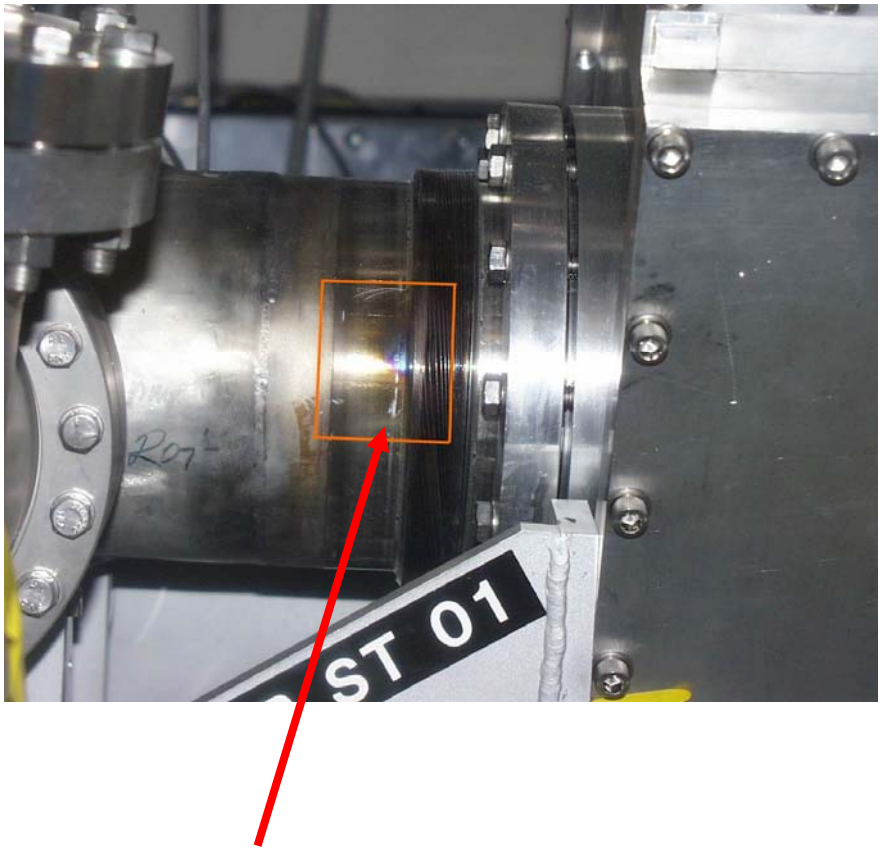


Brief history of carbon foil development

- The first carbon foils were made by just evaporating carbon on a glass slide (e.g. foils from Arizona Carbon Foil Co.).
- Around 1985 Isao Sugai invented a new method to make carbon foils.
  - AC/DC discharge method, where carbon rods are alternately heated with DC and AC currents.
  - Creates a mixture of large and small carbon particles.
  - These foils are now used in the PSR.
- Around 2001 R. Shaw et al. at ORNL began developing diamond foils for the SNS.
  - Longer lifetimes based on test results at the BNL 750 keV H^- linac.

Stripped electrons

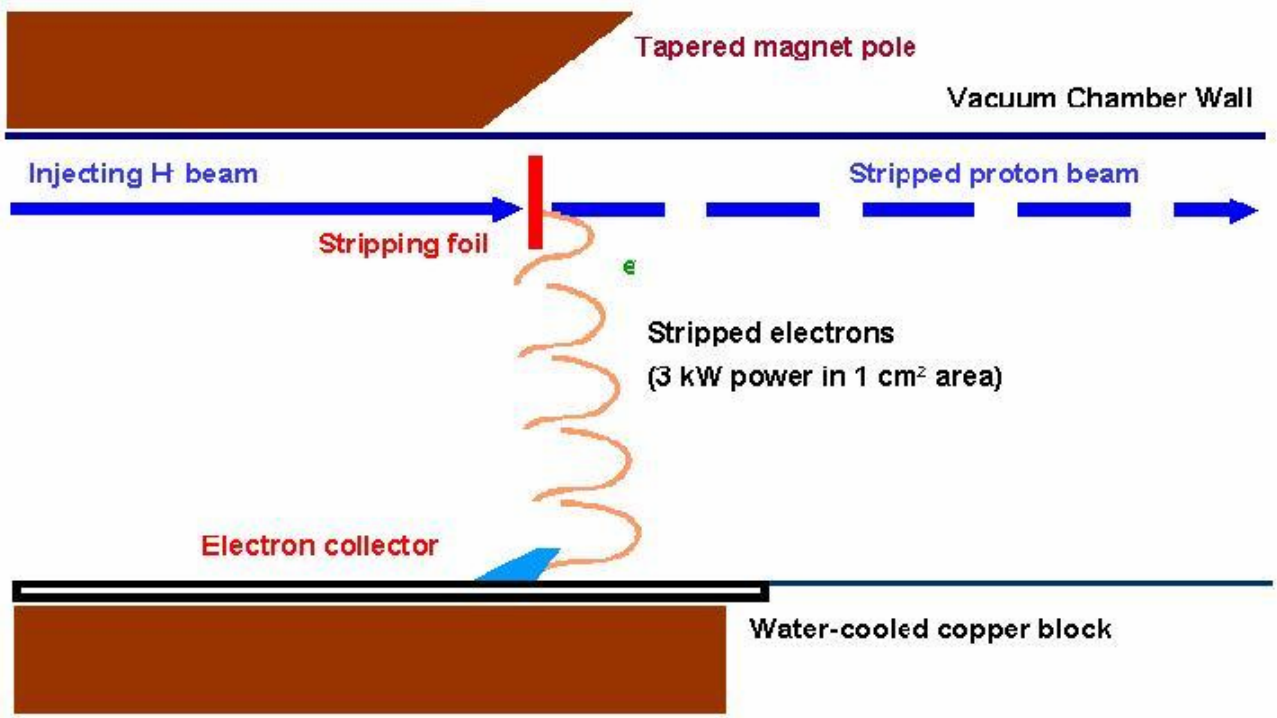
- There's a lot of power in the stripped electrons. Each proton comes in with 2 electrons, and each electron has 545 keV of kinetic energy.
- (1.5×10^{14} ppp) x (60 Hz) x (2 electrons) x (545 keV) = 1.6 kW.



Burn mark from stripped electrons in PSR

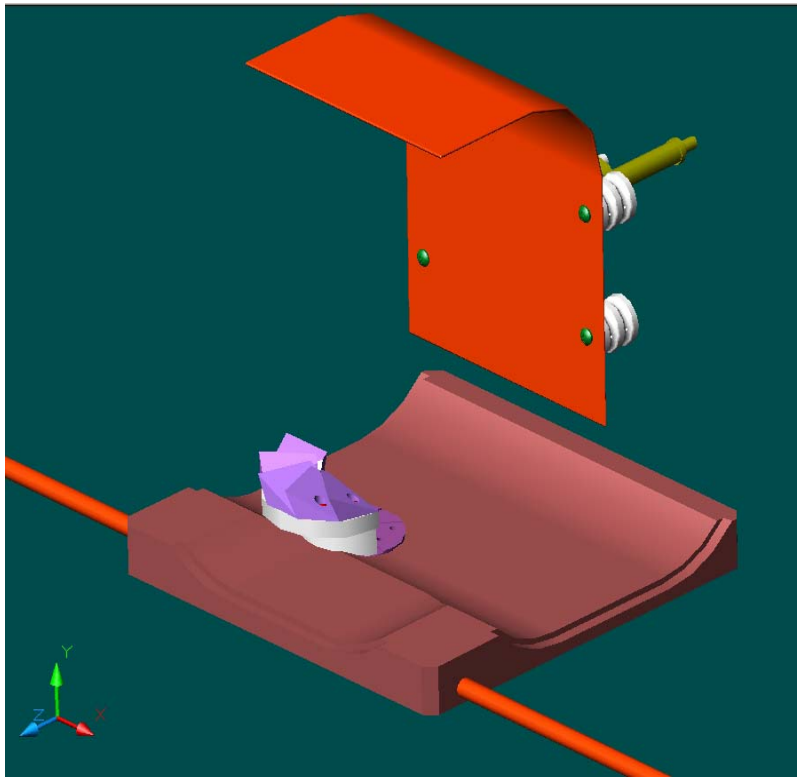
Control of stripped electrons in SNS

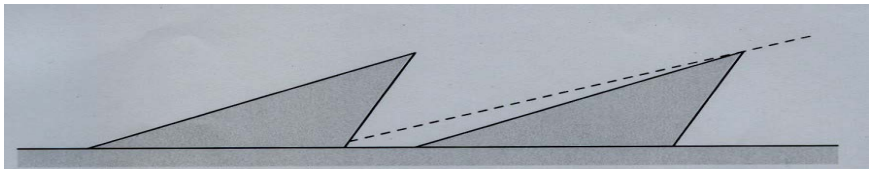
- The SNS primary stripper foil is in a tapered magnetic field, which directs the electrons down to a water-cooled electron catcher.

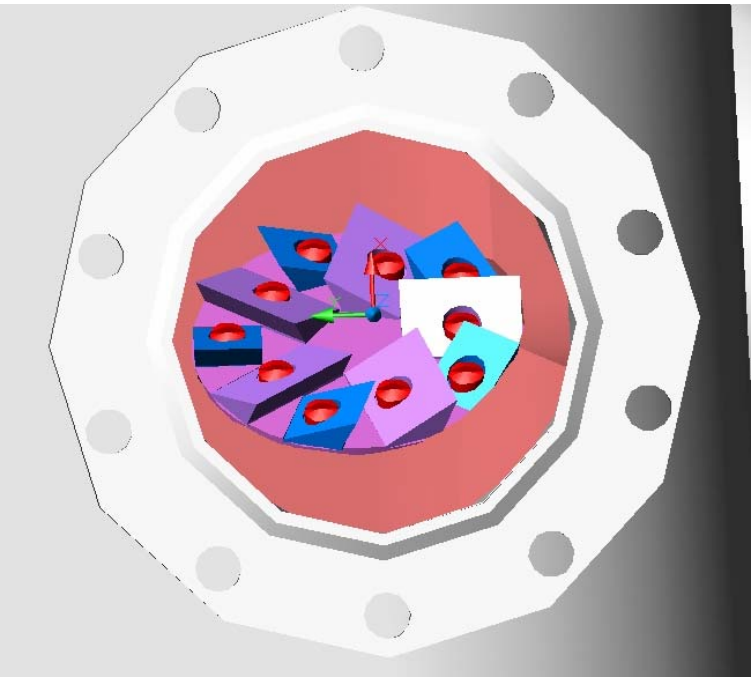


The SNS electron catcher

- Water cooled carbon-carbon wedges.
- Undercut prevents secondary electrons from escaping.







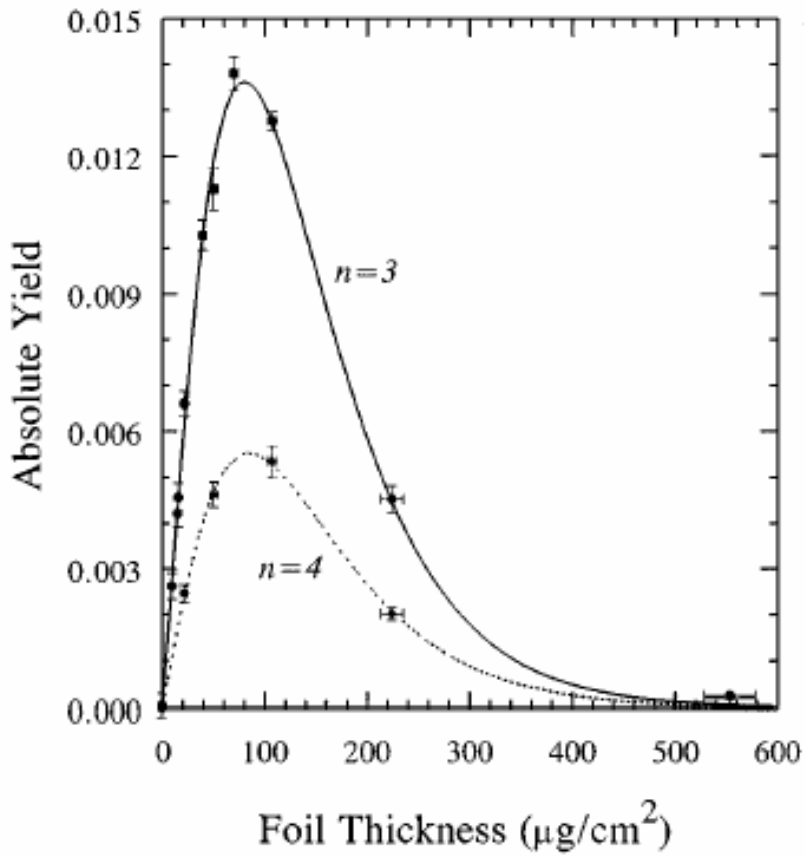
Excited H^0 states

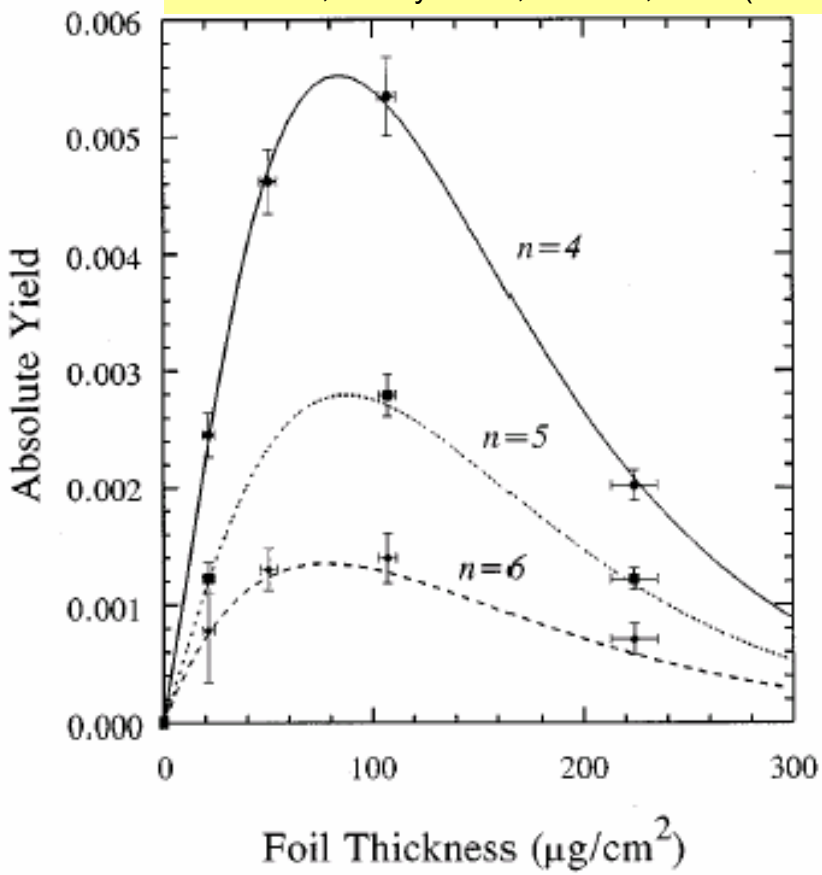
- Excited H^0 states can be a major source of beam loss, as first realized at the LANSCE PSR.
- Some of the H^0 particles exiting the foil are in excited states (i.e. orbiting electron is not in the lowest-energy orbit).
- In the rest frame of the H^0 particle magnetic fields appear to have an electric field component (relativistic Lorentz transformation), which can be strong enough to pull the electron the rest of the way off the proton.
- Depending on the excitation state and the magnetic field, the electron may or may not be stripped off. Sometimes it is stripped off outside the dynamic aperture of the ring.
- To manage excited H^0 states, the SNS primary stripper foil is placed in the fringe field of chicane mag. #2, and the chicane mag. #3 field is kept low.

Further complications from H^0 excited states

- Low n states (n ≤ 3) are long-lived and survive to the second foil
- High n states (n ≥ 6) are short-lived and are Lorentz-stripped immediately
- n = 4 and n = 5 states are controlled by magnetic fields in chicane magnets. About 0.5 to 1% of excited H^0 states result in beam loss.

800 MeV, Gulley et. al., PRA 53, 3201 (1996)

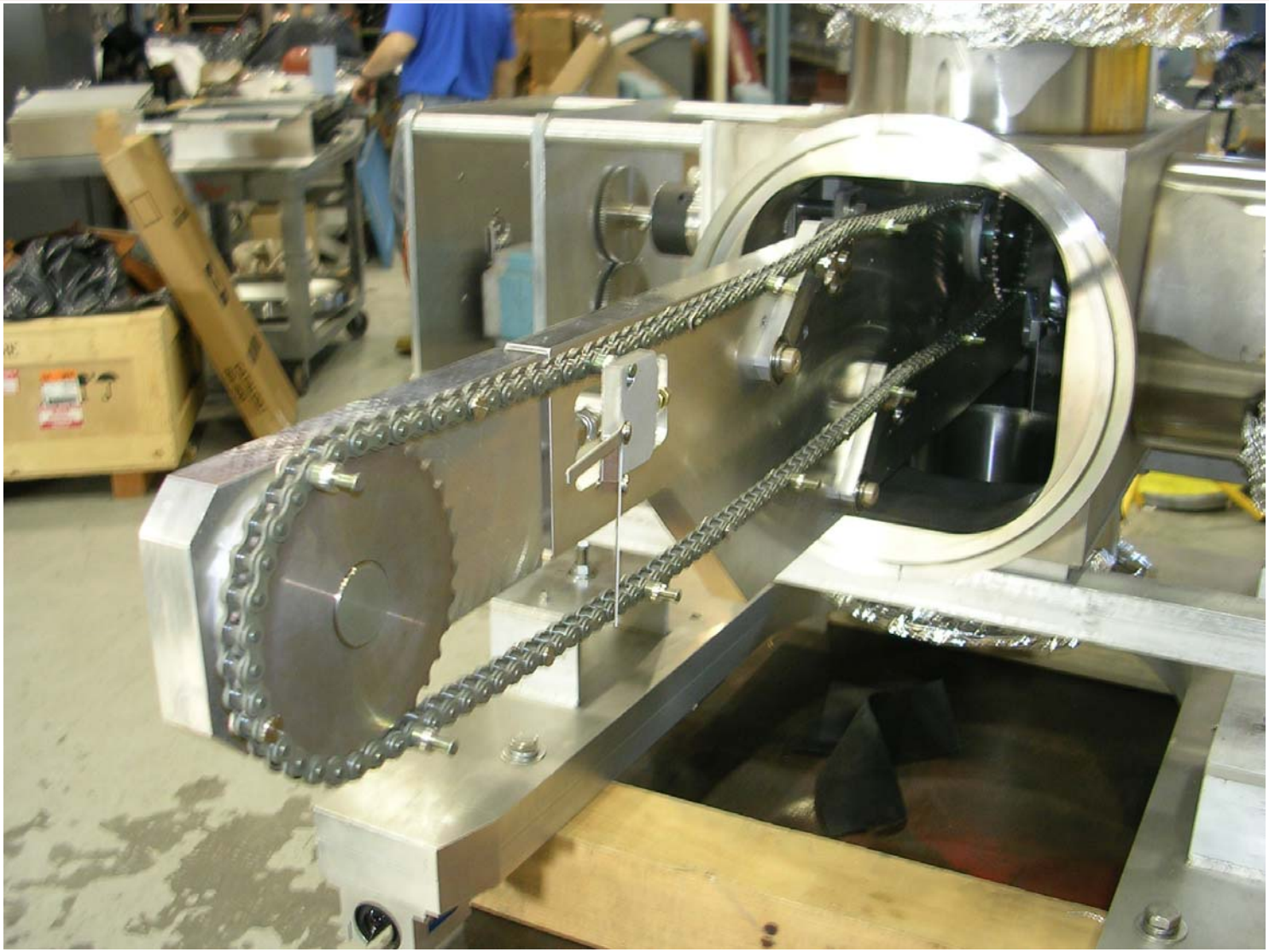




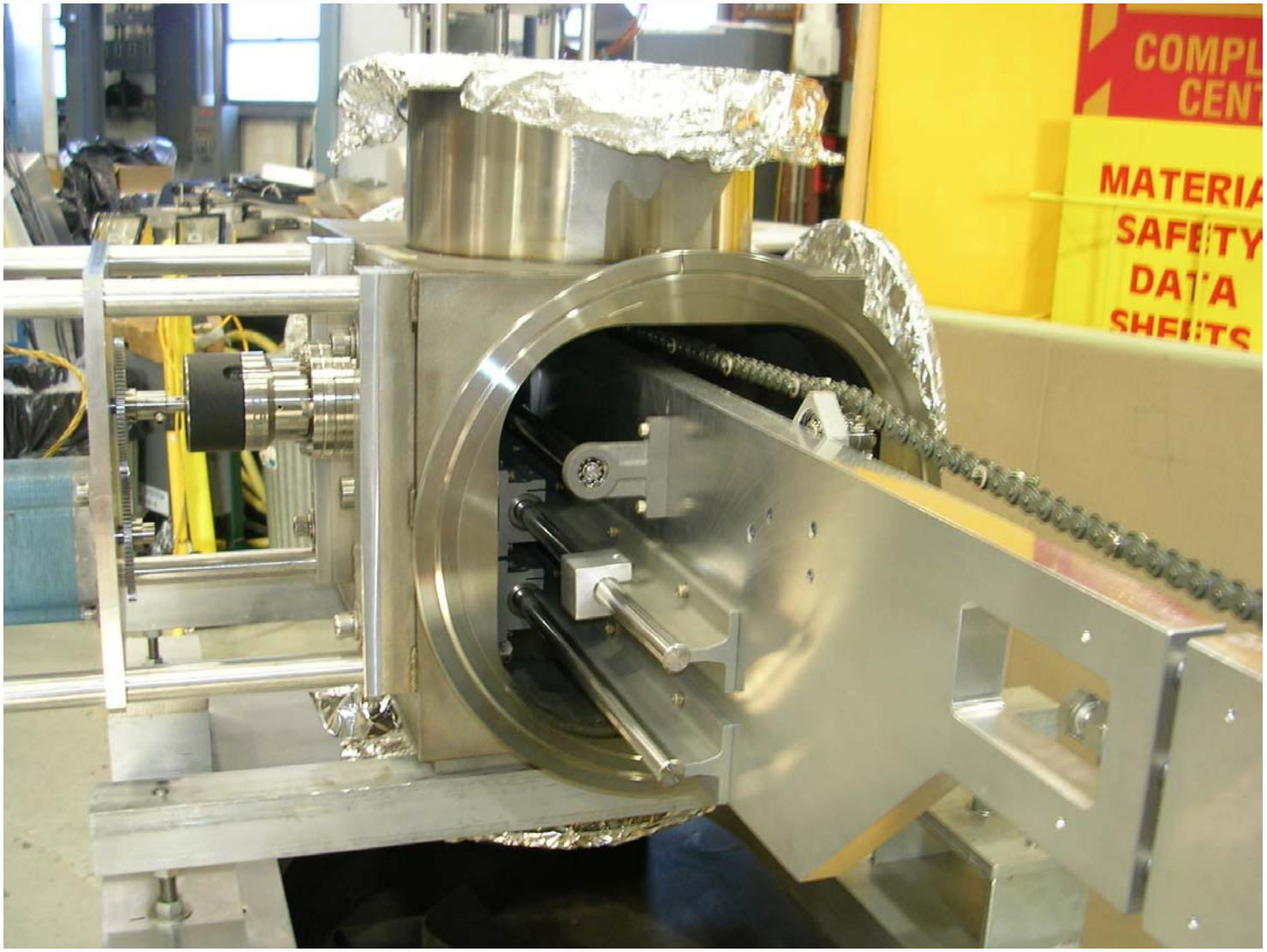
The SNS primary stripper foil mechanism

- The primary stripper foil mechanism has 12 positions.
  - 10 for stripper foils.
  - 1 for a blank (to tune up the HEBT beam to the inj. dump).
  - 1 for a view screen (to measure the incoming H^- beam profile).
- The foil is monitored by a video camera.
- Foil will start to emit light once we have approx. a few x 10^{13} protons circulating around the ring.
- Each circulating proton makes an average of ~7 passes through the foil, but each injected H^- counts as 3, and injected beam is more focused, so the light emitted from the foil is due to a combination of injected and circulating beam – can't be used to measure incoming H^- beam profile.

Primary stripper foil mech. photo tour (1)



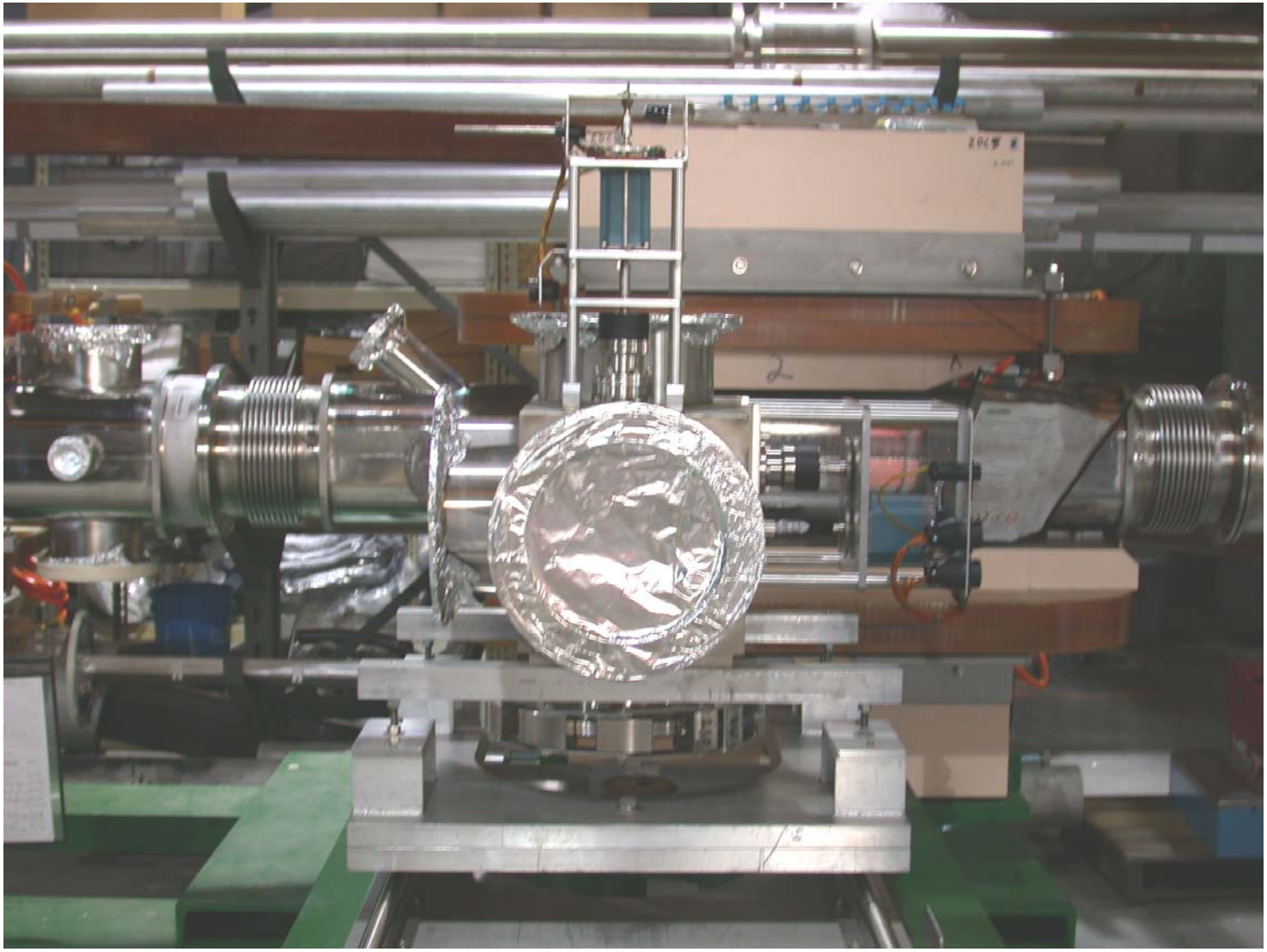
Primary stripper foil mech. photo tour (2)



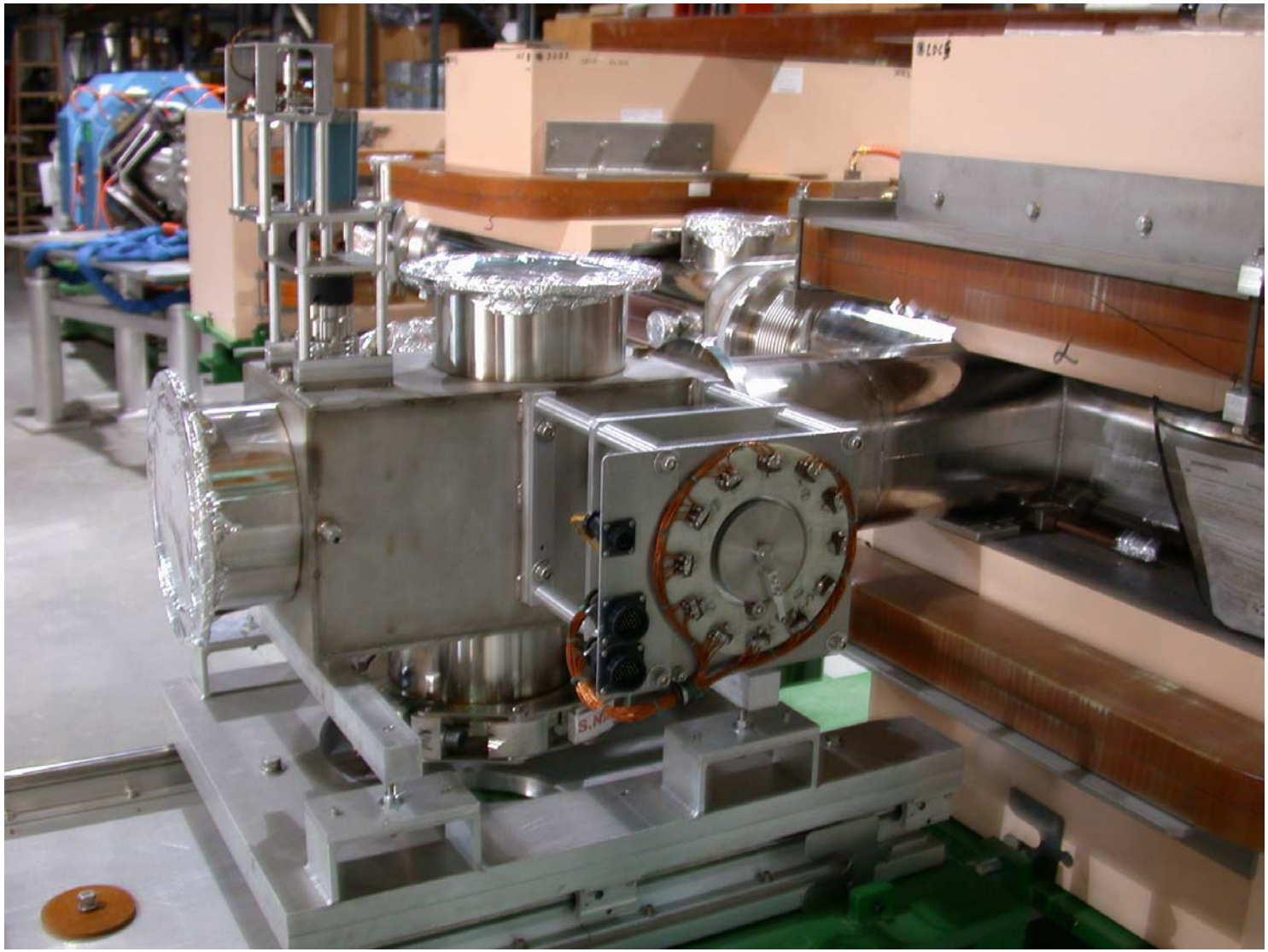
Primary stripper foil mech. photo tour (3)

Primary stripper foil mech. photo tour (4)

Primary stripper foil mech. photo tour (5)

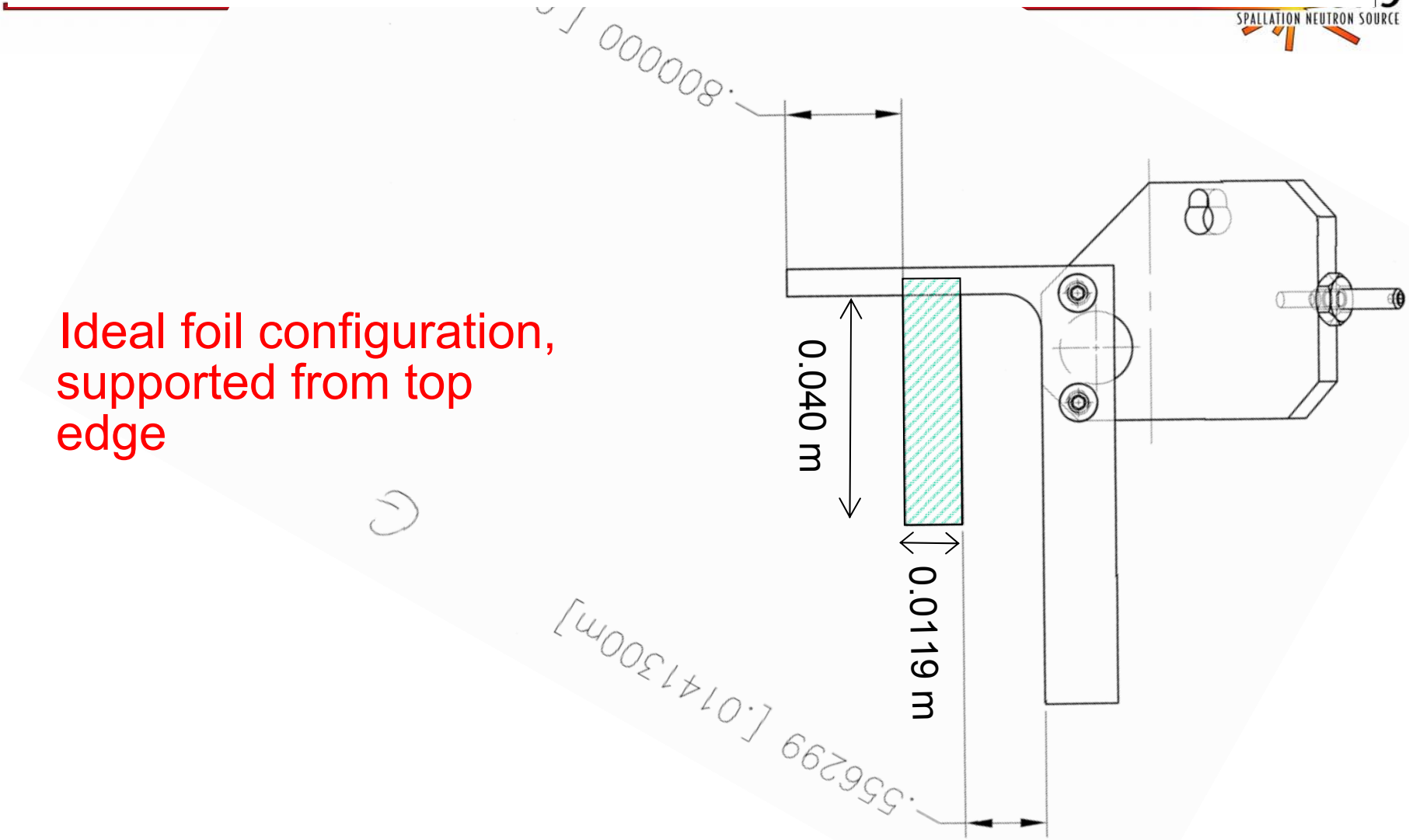


Primary stripper foil mech. photo tour (6)



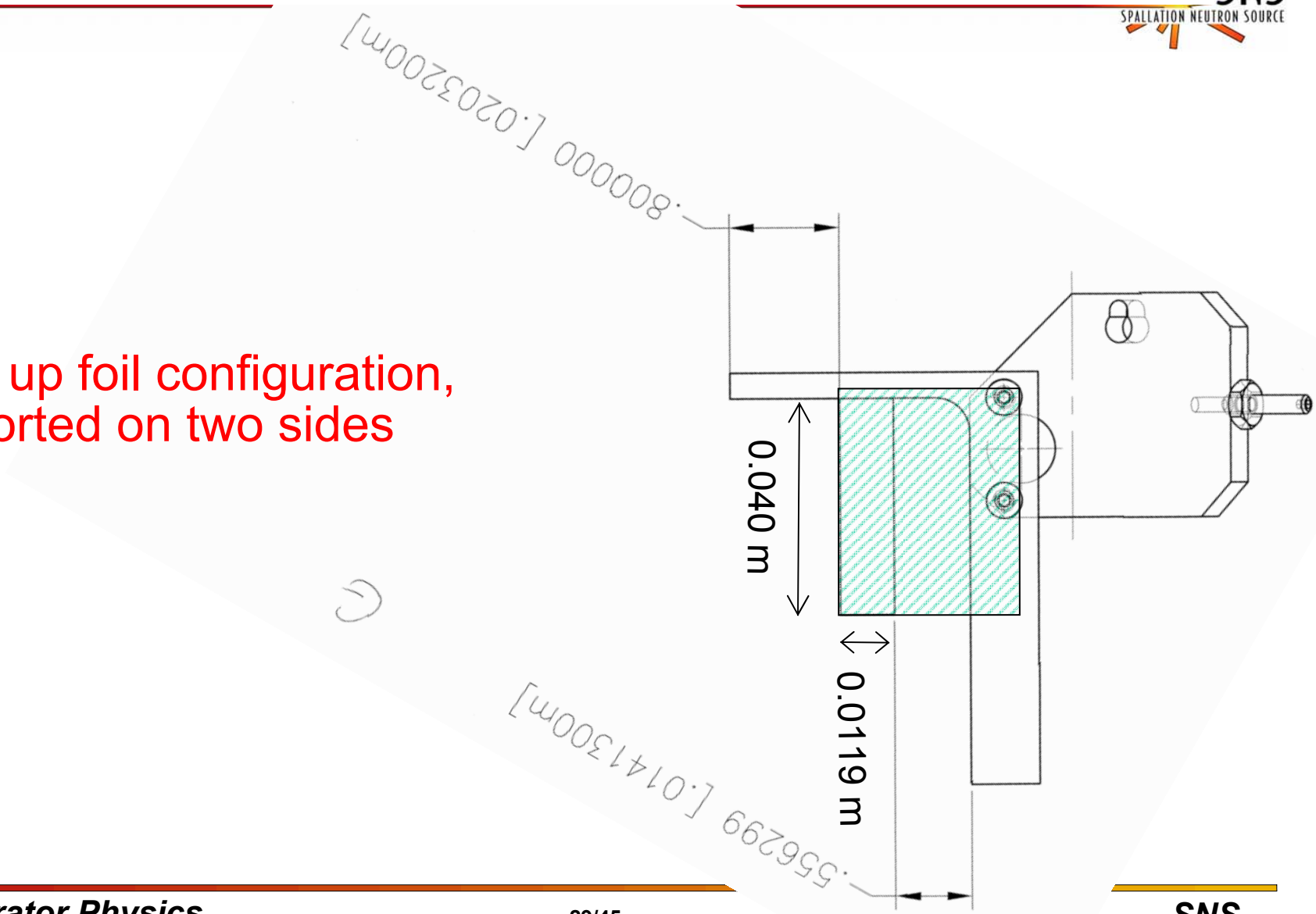
SNS ring primary stripper foil. Single-sided, 30-deg. foil mount.

Ideal foil configuration, supported from top edge



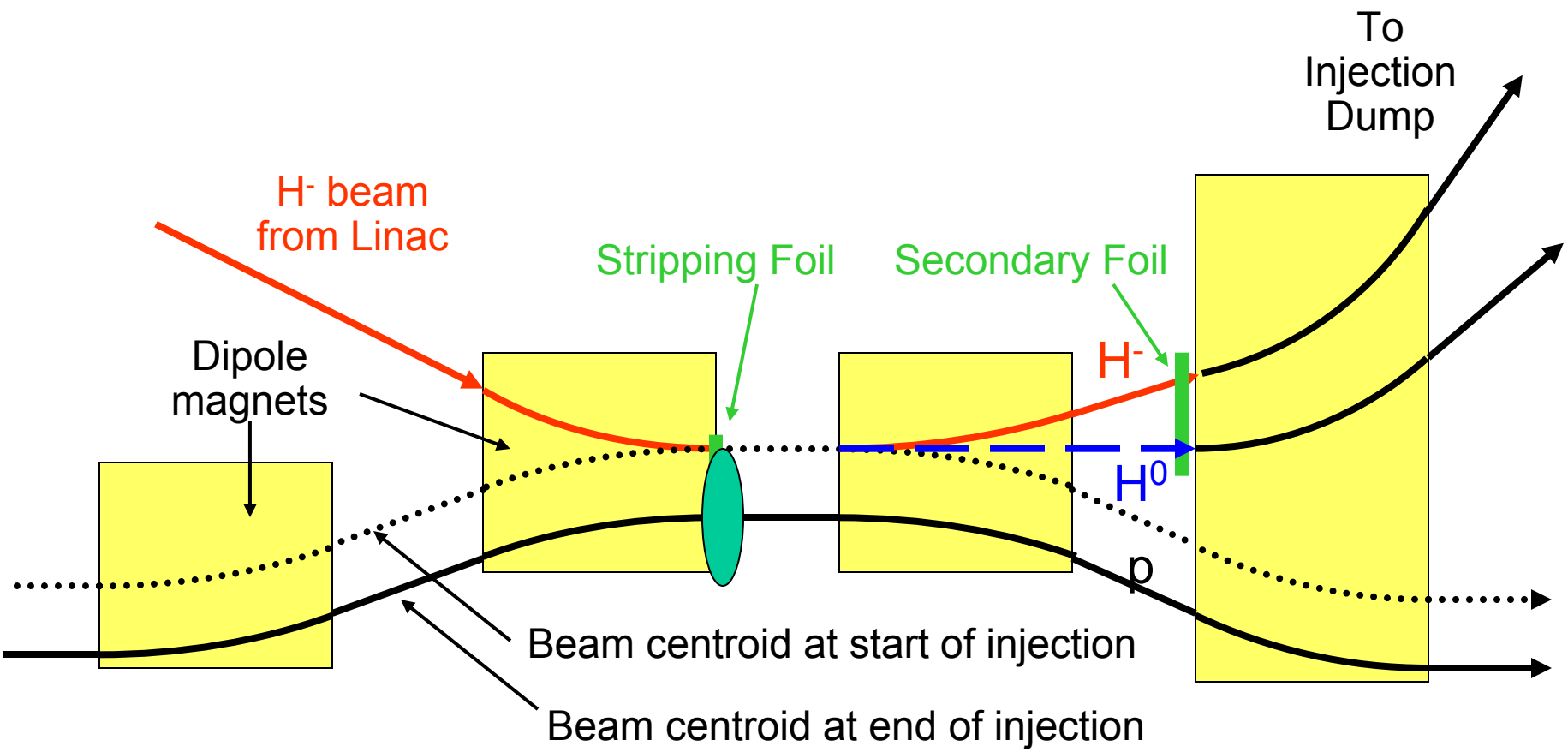
SNS ring primary stripper foil. Double-sided, 30-deg. foil mount.

Back up foil configuration, supported on two sides

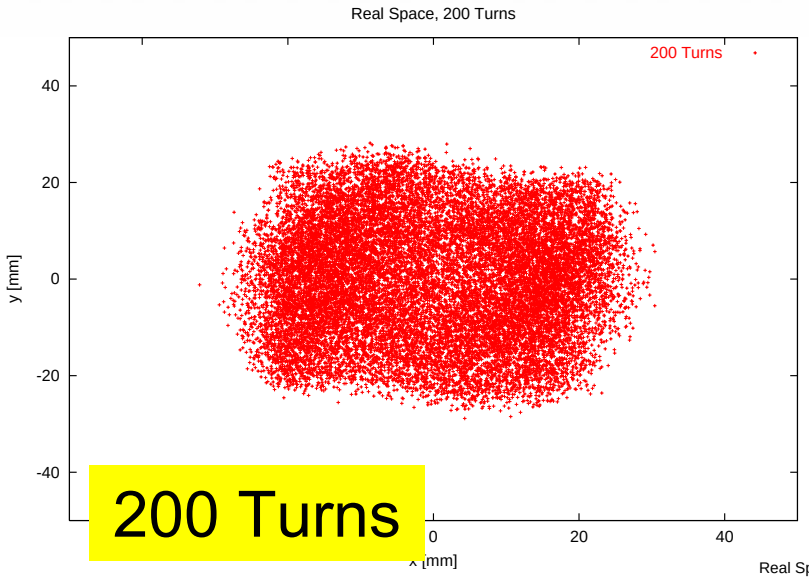


The SNS Injection Process: Painting

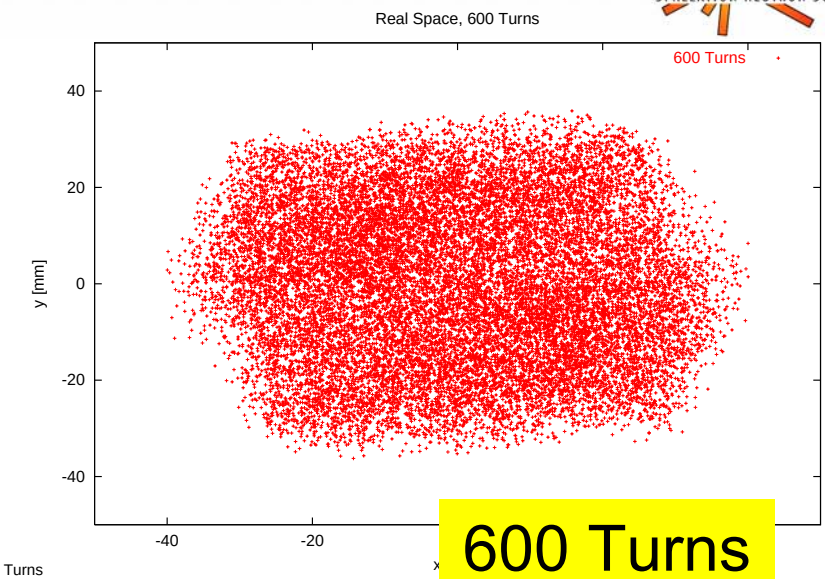
- To control the space charge forces and the foil hits due to circulating protons, we paint the beam in the ring using the injection kickers.



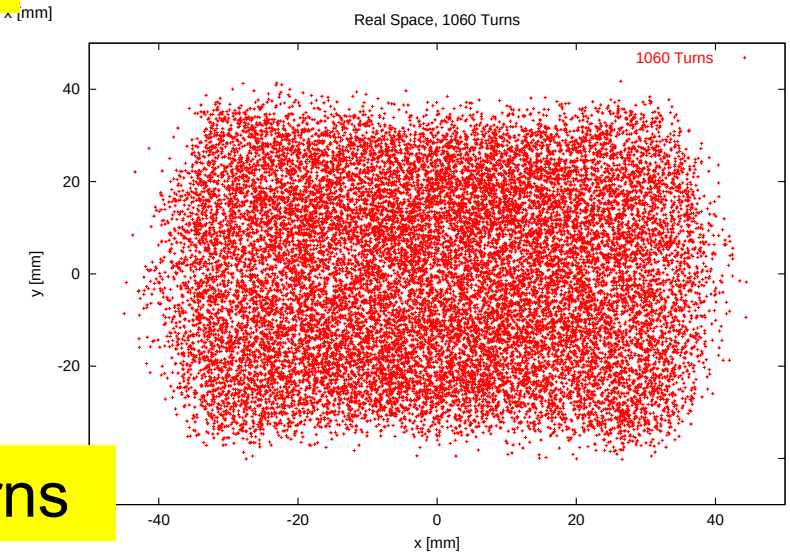
Phase-Space Painting with Space-Charge -- Real Space: Y vs. X



200 Turns



600 Turns

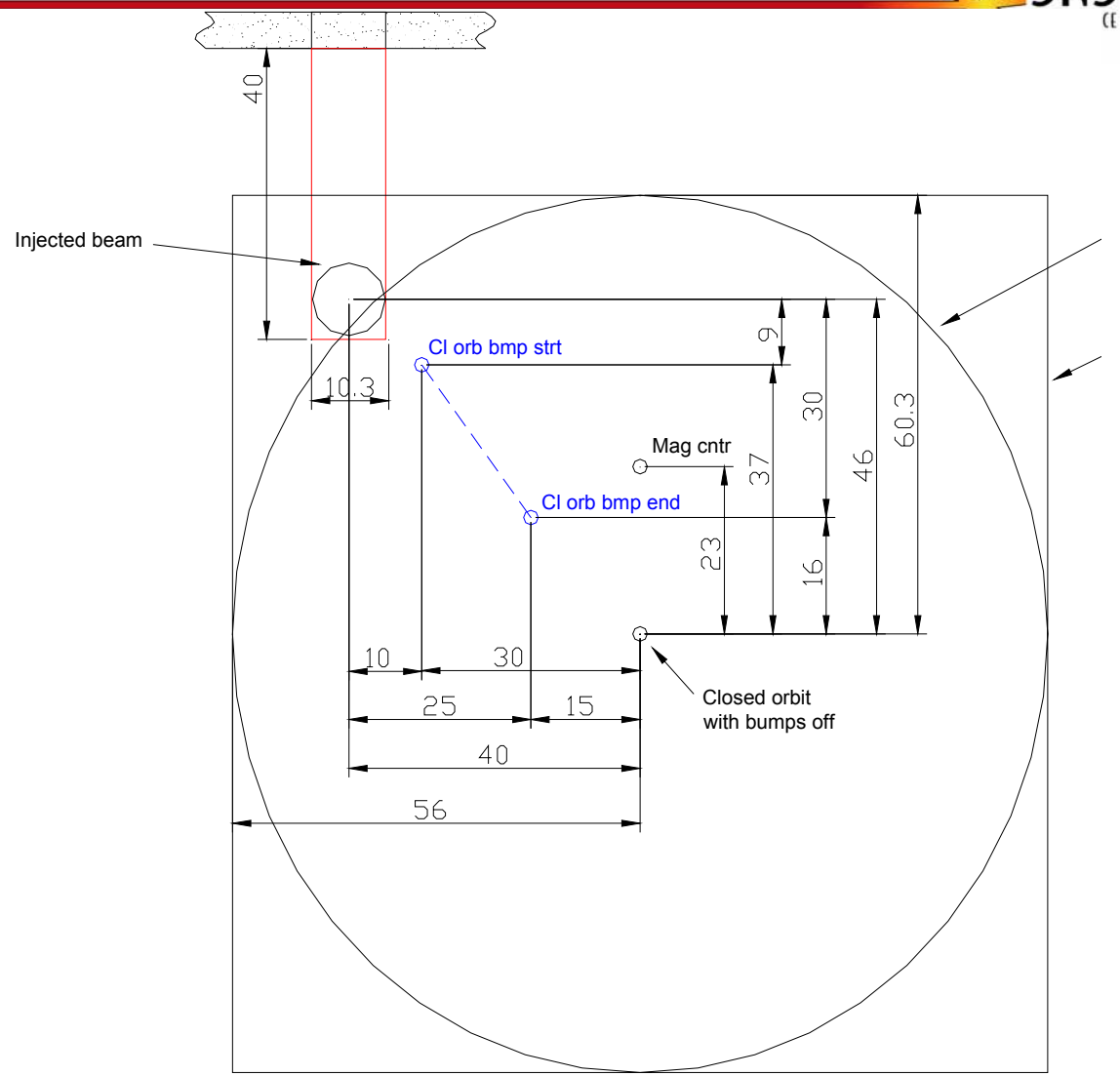


1060 Turns

Courtesy J. Holmes

Painting coords. & time structure

- Nominal closed orbit starts 10 mm horiz. & 9 mm vert. from foil.
- Ends 25 mm horiz. & 30 mm vert. from foil.
- Bump profile is proportional to sqrt(t).

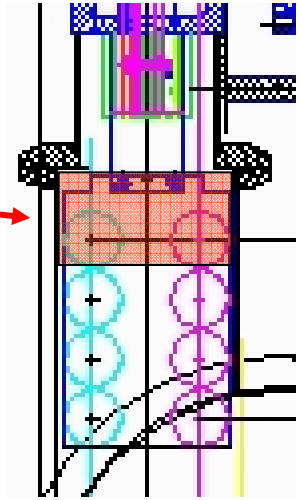


Secondary stripper foil

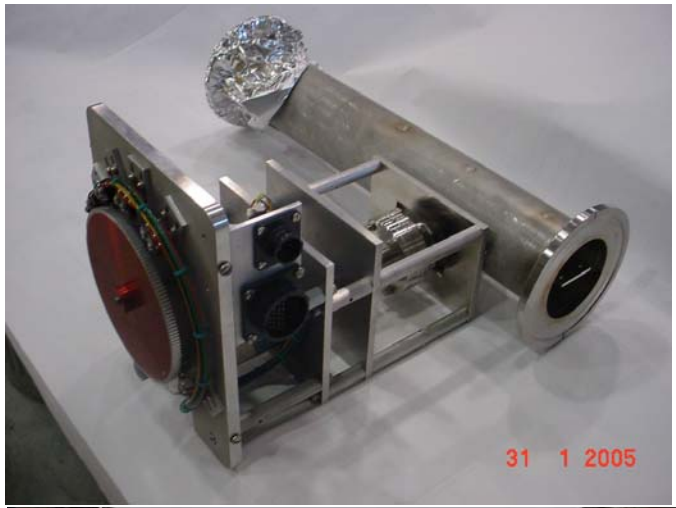
- Purpose is to catch beam that either misses the primary stripper foil or is only partially stripped by the primary stripper foil.
- 2% is nominal value of beam missing foil. Can be higher or lower, depending on condition of the foil and size of beam spot on the foil.
- 3% is nominal value of partially stripped H^0 beam. This value can also be higher or lower, depending on the thickness of the primary foil.
- Since number of particles passing through the secondary foil is much lower (~150 times), foil heating is not as big an issue and foil can be thicker. Also want 100% stripping efficiency from this foil.
- Foil is thick enough to be self supporting and robust.
- 10 mg/cm^2 carbon-carbon foil.

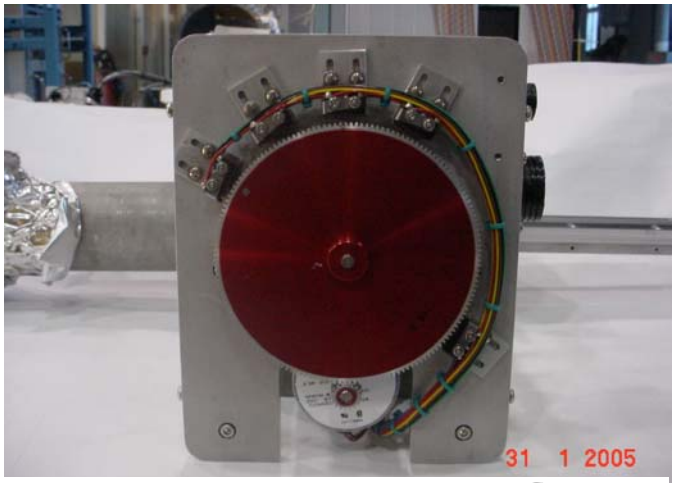
Secondary Stripping Foil Assembly

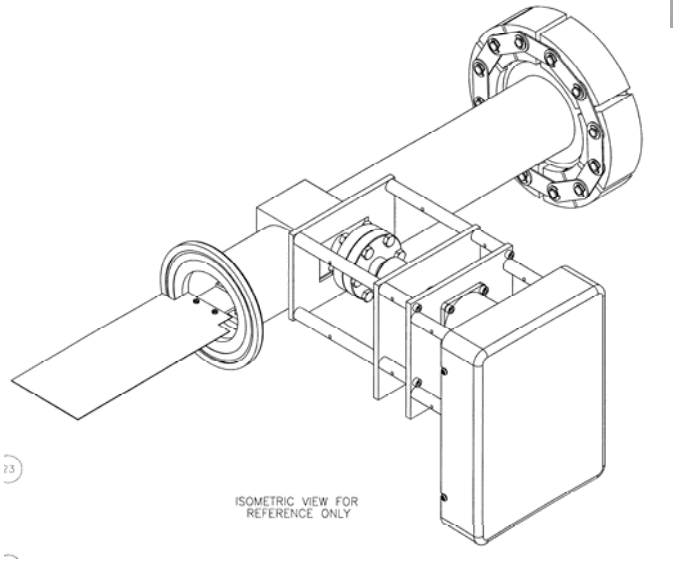
- **C-C foil will not get hot enough to see visible light during operations**
- Top foil position to have a view screen



Images of the secondary stripper foil assembly





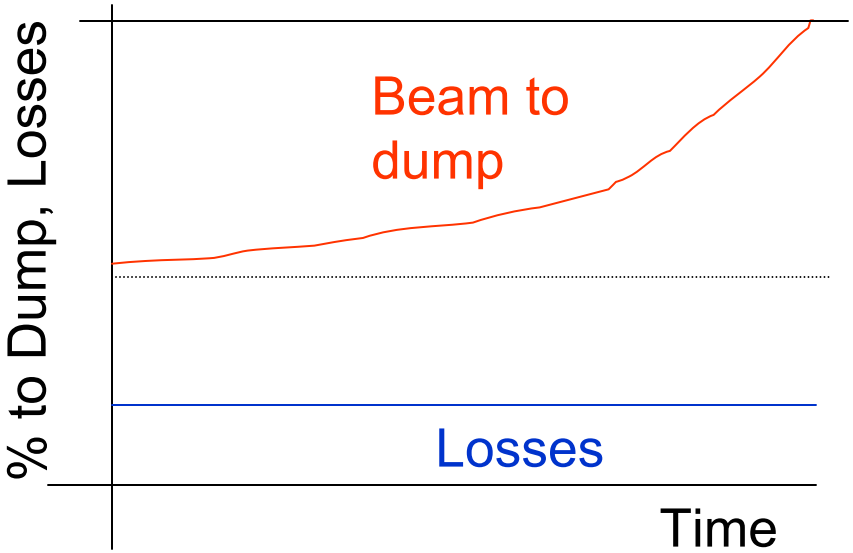


SNS Injection Beam Dump

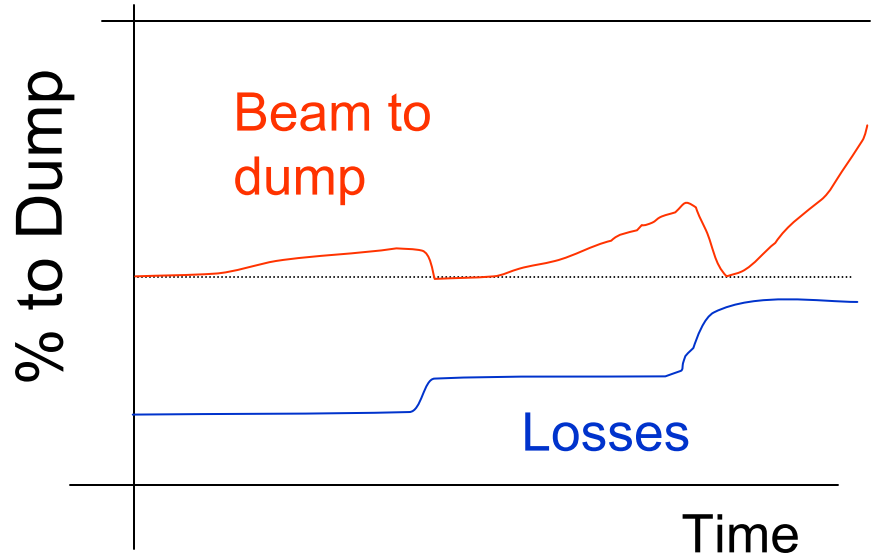
- The injection beam dump capacity is 150 kW beam power.
- When the ring is operating perfectly and the foil is in perfect shape, we expect about 5% of the beam to go to the dump (3% from stripping efficiency, 2% H^- missing foil), or 72 kW for 1.4 MW operations.
- The extra beam dump capacity is important for operating margin and beam availability.
- At the PSR the beam dump capacity is 10% (8 kW) and that has proved very useful.
- Minimum power to dump is 3% if no beam misses the foil, but if change quads in HEBT to focus beam to smaller spot size on foil, H^- and H^0 beams will no longer arrive at the same place at the injection dump.
- For the 3 MW power upgrade, 5% to the dump will exhaust the capacity of the dump and leave no operating margin.

Foil Failure

- When foils begin to degrade, they become less efficient
- Overhead in the injection dump is useful to handle the increased inefficiency of the foil to prolong foil life



No operator intervention



With operator intervention

Linac Beam Missing Foil

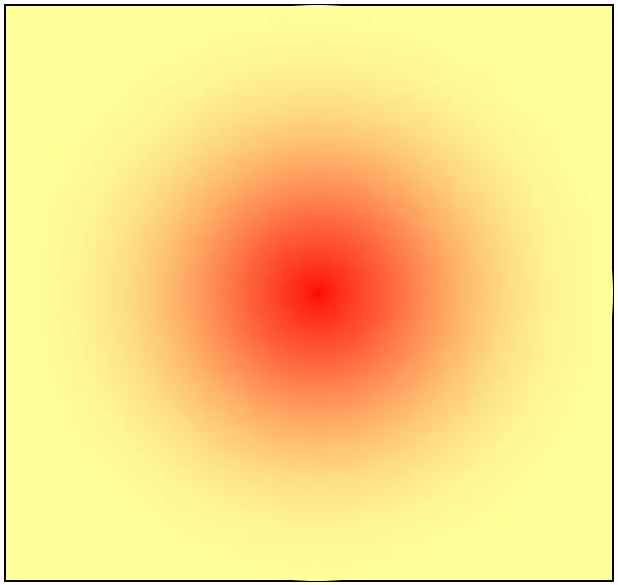
It is not so easy to get 100% of the injected beam to hit the foil. Many pathologies can cause some beam to miss the foil

Beam Centroid Errors

- Static (time-independent)
  - Trajectory error from misalignments
  - Energy centroid error coupled with residual dispersion
- Dynamic (time-varying)
  - Drift tube vibration, quad vibration
  - Dipole power supply ripple
  - Dispersion errors coupled with momentum painting

Beam Size Errors

- Static
  - Quadrupole strength errors
- Dynamic
  - Quad power supply ripple
  - Ion source pulse current variation

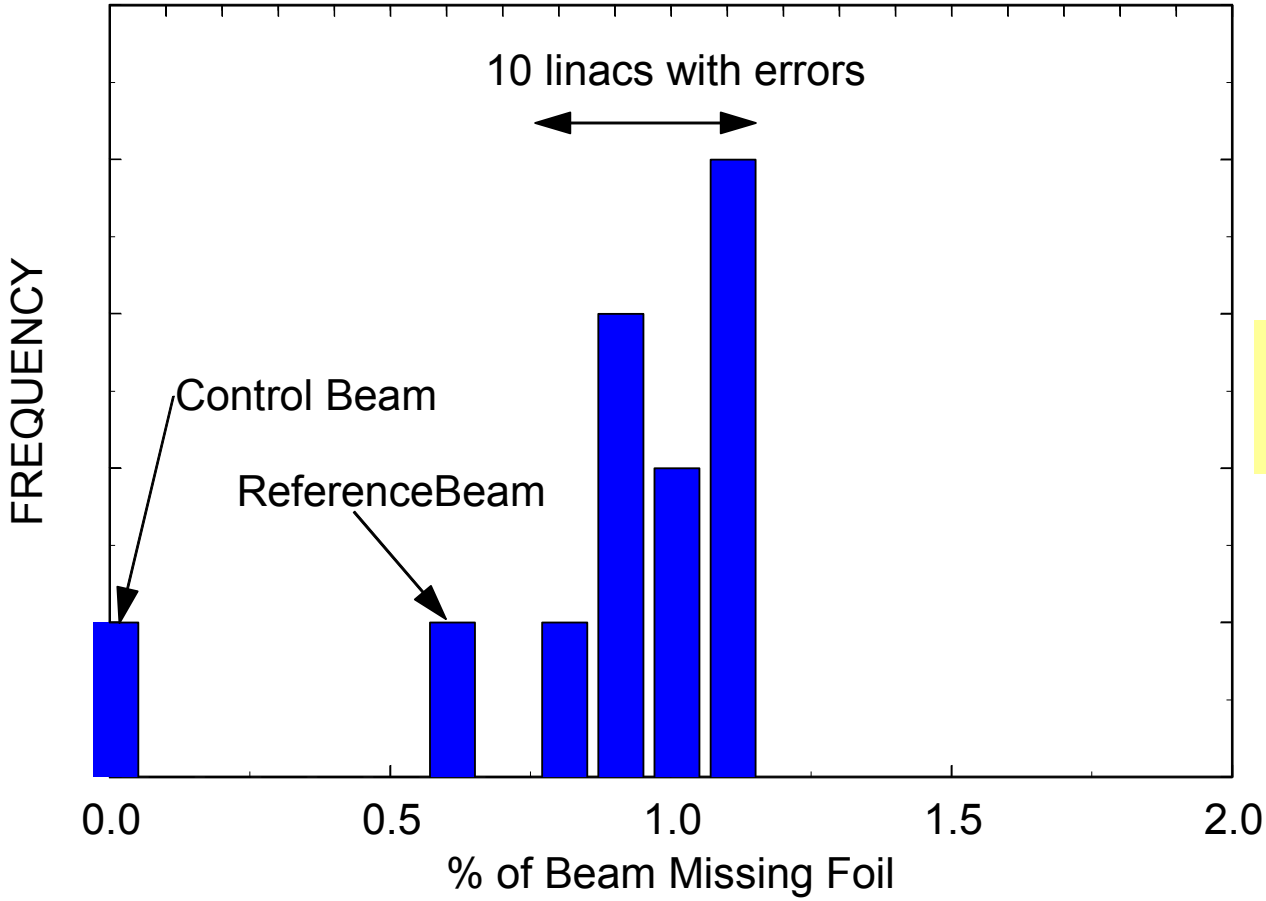


Beam Halo

- Diffuse, non-gaussian beam tails
- Driven by space-charge force in a variety of mechanisms

Beam Missing Foil: End-to-end simulations show 1-2% of beam misses

Such simulations should only be considered good to a factor of 2! Real life is usually more complicated!



Courtesy J. Stovall, S. Nath and Co.

So what's the problem? Just use a big, thick foil and get rid of the Injection Dump

Thin — Foil Thickness — Thick

- Less efficient:
  - more power sent to the dump
- Less loss and activation:
  - Reduced chance of large angle or nuclear scattering
- Longer foil lifetime:
  - Lower peak temperatures
  - SNS availability is greater

- More efficient:
  - less power sent to the dump
- More losses and activation:
  - Each proton passes through foil 6-10 times: increased chance of large angle scattering or nuclear interaction in the foil
- Lower foil lifetime:
  - Higher beam power deposition
  - Reaches higher temperature, and therefore doesn't last as long
  - SNS availability is reduced

So what's the problem? Just use a big, thick foil and get rid of the Injection Dump

Small — Foil Size — Big

- Less efficient:
  - More power sent to the dump
- Less loss and activation:
  - Reduced number of foil hits

- More efficient:
  - less power sent to the dump
- More losses and activation:
  - Large amplitude beam particles are injected into ring
  - Number of foil hits by stored beam is increased

Choice of foil size and thickness is a complicated optimization problem, and the injection dump capabilities are one constraint

Injection Dump Requirements in the SNS Beam Power Upgrade

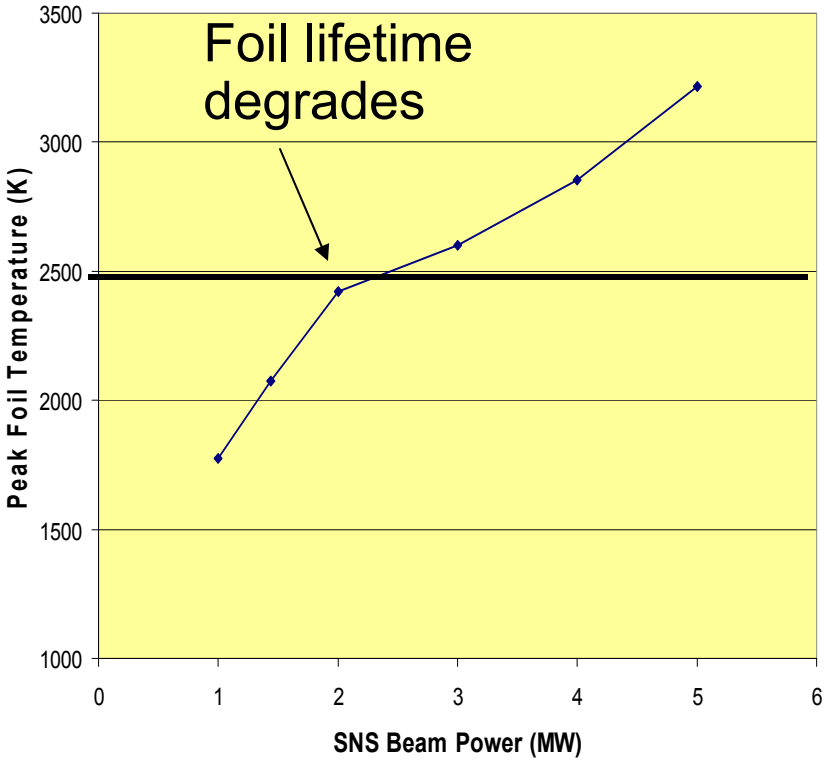
- **Bottom Line: We need operational experience with balancing power to the dump, ring losses and foil lifetime to predict needs for the Upgrade**
- We know some things now…
- At 1.3 GeV, 3 MW
  - We expect foil misses to be about the same (same halo)
  - Foil efficiency will get worse (more H^0 produced)
  - Expect about 7% H^0 at same foil thickness. Thicker foil can reduce to about 4%.
  - Foil hits by stored protons will increase (more losses)
- With an upgrade path for the dump to 200 kW, we will have a 6.7% beam power dump at 3 MW operation.
- Once we understand the “foil-failure routine” maybe there will be more overhead.

Foil Lifetime issues

- We need foil lifetimes in excess of 100 hours to maximize the availability of the Accelerator Complex
- Experience from PSR:
  - A single foils lasts for 1-2 months.
  - When a new foil is inserted, a conditioning procedure lasting about two hours is required.
- SNS foil mechanism holds 10 foils.
  - At 100 hrs/foil, take an immediate ~2% hit in availability.
  - Change holder every 40 days.
  - Requires vacuum system intervention and substantial radiation dose to personnel.

Foil lifetime for 3 MW SNS

- This is a big issue!
- Carbon foils will not survive at 3 MW.
- Need some further development of foil technology or use of foil-less stripping.
- Only three (?) possibilities:
  - Use lasers.
  - Use multiple foils.
  - Develop a Super-Foil.

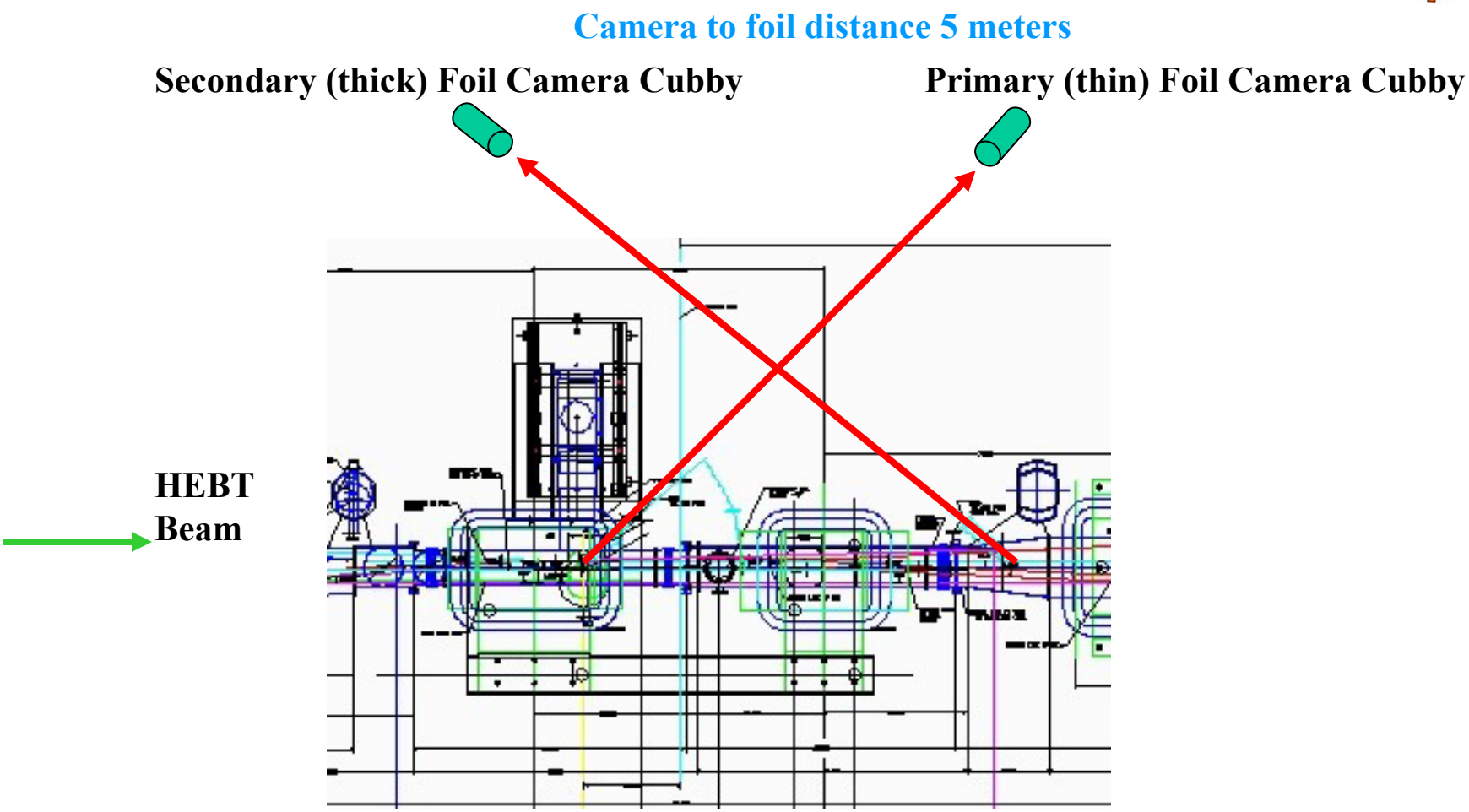


Diamond stripper foils, by Bob Shaw…

The end

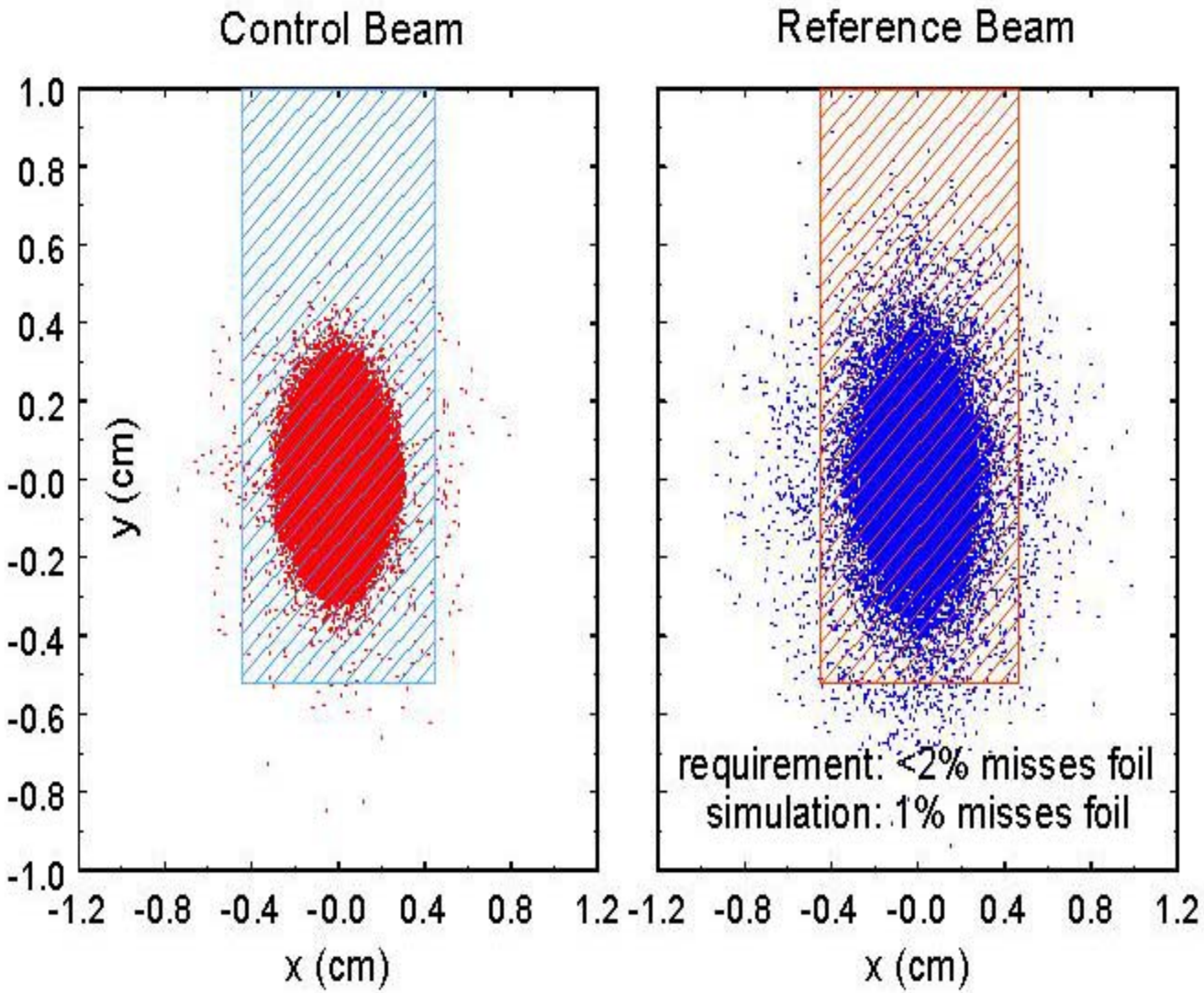
Back up slides

SNS Video Foil Layout



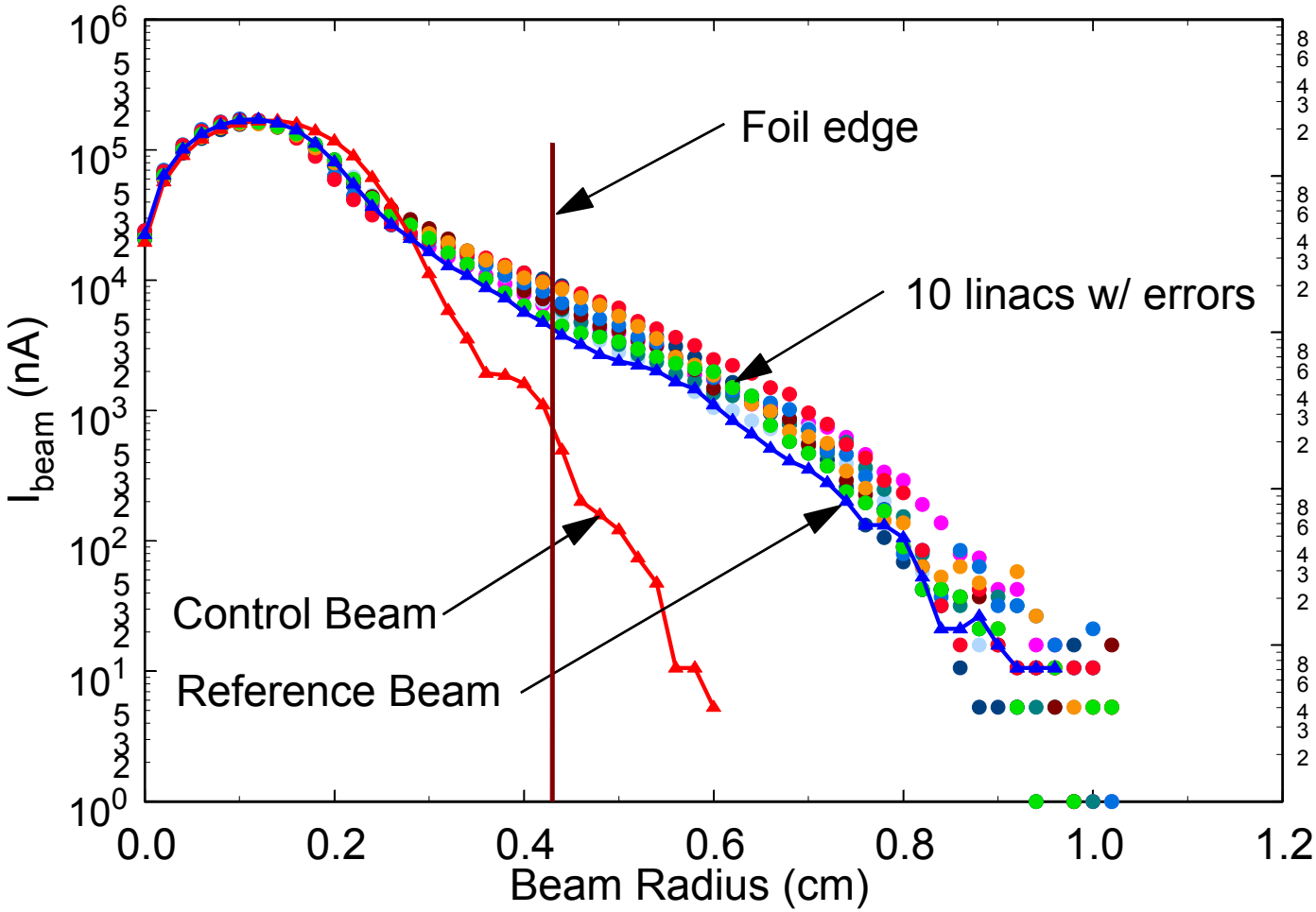
Paraffin or boron type neutron shield in cubbies.

Linac Beam on Foil: Simulations using a realistic beam including dynamic errors



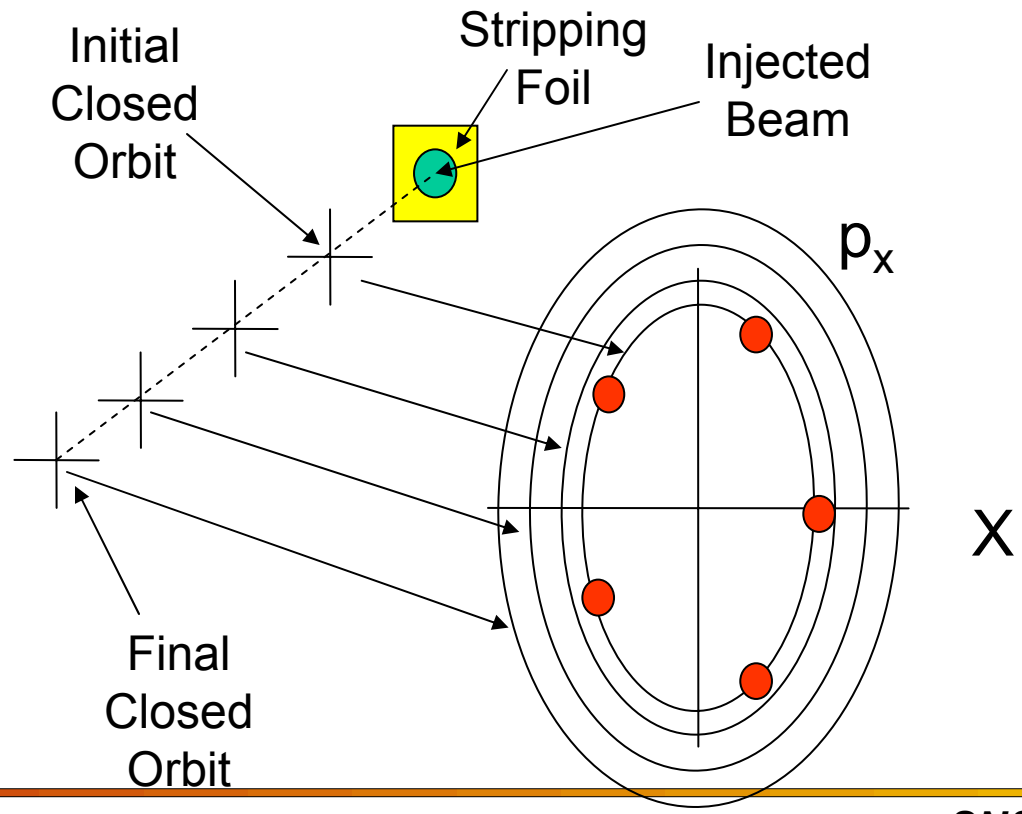
Courtesy J. Stovall, S. Nath and Co.

Beam Distributions at the Injection Foil



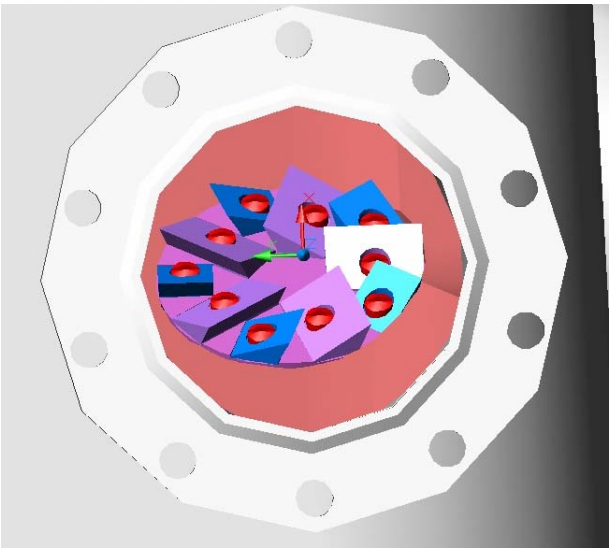
Multi-Turn Injection in the Ring: Phase Space Painting

- The primary challenge for the ring is handling the high-space charge forces that exist in such an intense beam
- To control the space-charge forces, the beam is accumulated in the ring using Multi-Turn Charge-Exchange Injection



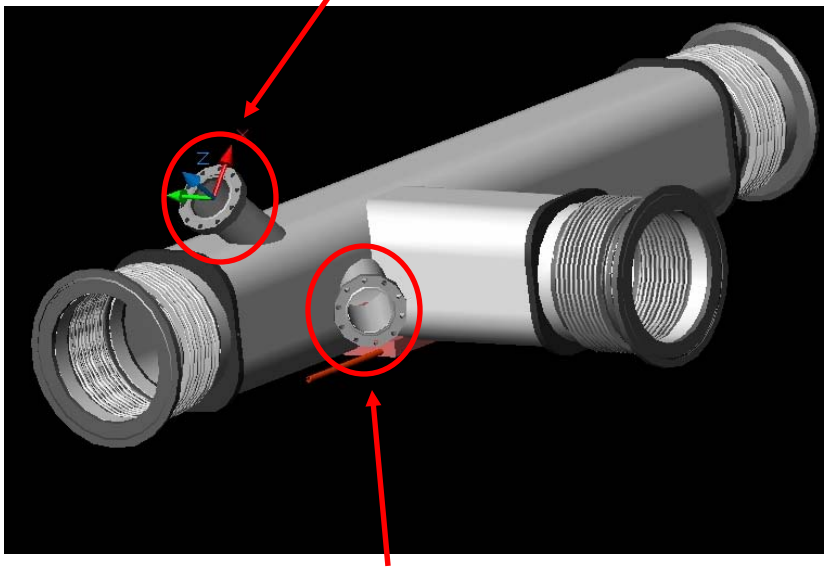
Foil Changer Mechanism

Electron Catcher Assembly



View looking into Electron Catcher viewing port

Electron Catcher viewing port facing downstream & up at 40º.



Primary Stripping Foil viewing port

The carbon electron catcher must carry off the 4mA of stripped electrons, & is expected to get hot 2kW, water cooled.

- Infrastructure for future installation.

The electron catcher video monitor is to make sure we do not melt the vacuum chamber by missing the catcher, so visible light spectra is fine.