AAC - HEBT/Ring/RTBT Overview

Feb. 2 - 4, 2010

by Mike Plum

Ring Area Manager

2009 Highlights

- Stripper foil failures caused the beam power to be reduced by ~2x for approx. the last 4 weeks of the March – July run cycle. Good foil availability for the following run cycle.
- We reached full design beam intensity (1.55e14 ppp) on July 11, 2009, at 1 Hz. Beam was stable using only Ring RF to control the e-p instability.
- Cross plane coupling in the RTBT cured by changing shims in extraction septum magnet
- Reliability and availability of the other ring systems is very good
- Activation per Coulomb has mostly leveled out, with a few small improvements (Galambos). Measured levels are in line with expectations.
- Beam optics in the HEBT, Ring, and RTBT are much closer to the design values

Key issues

- Stripper foil lifetime
- Activation hot spots
  - Unexpected hot spot ~10 m dnstrm of stripper foil, near ceramic vacuum chamber in inj. kicker V03 (Holmes)
- No profile / position measurement at injection dump vacuum window / face of dump
  - Risk of vacuum window and/or dump failure if beam density is too high and/or too far off center
- Possible radiolysis in water-cooled collimation systems
  - Risk of collimator system failure
  - We continue to closely monitor these systems
- Beam halo formation and control
  - Primary cause of beam loss in the injection dump beam line
  - More halo = more stripper foil hits = higher activation
- Should we continue to coat our vacuum chambers with TiN?

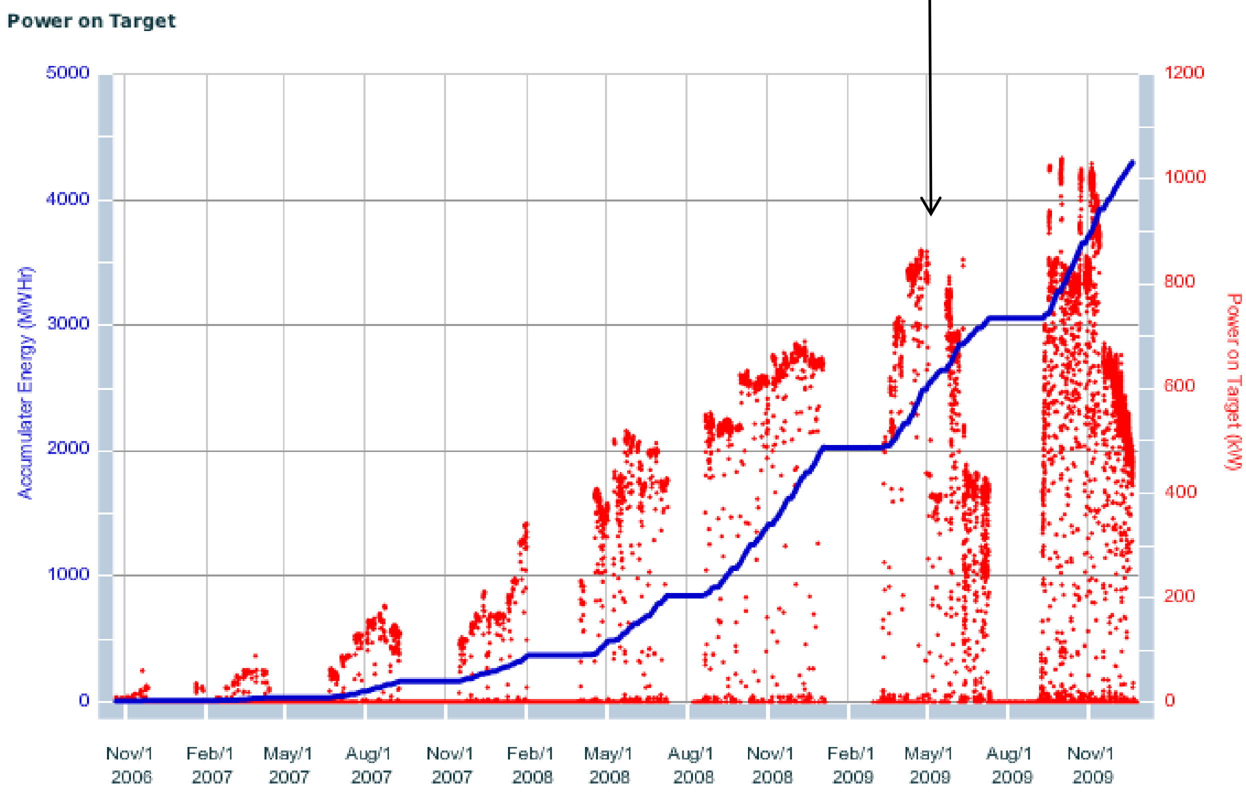
Brief history of SNS stripper foils

- Our home-grown diamond stripper foils worked successfully with no failures* until May 3, 2009, when we started experiencing a rash of foil failures shortly after increasing the beam power to ~840 kW. After a total of 3 failures on that day, the beam power was reduced to ~430 kW, and then to ~400 kW two days later after another failure.
- On May 19, we installed a new batch of foils (first time for a mid-cycle foil change out). Modified foil brackets were used. We returned to high power operations (~800 kW), but after two more foil failures in ~16 days, the beam power was again reduced to ~400 kW for the rest of the run cycle, and even then we had two more foil failures.
- A foil task force was formed June 16, 2009 to address the foil failures and to recommend a path forward.
- A new batch of foils was installed Sep. 2 using a new type of foil brackets, and a new mounting method. A single foil lasted for the entire run cycle, even after operating at beam powers up to ~1.03 MW.

* There was one failure during commissioning during a high intensity study, before we had good control over foil position.

SNS beam power history

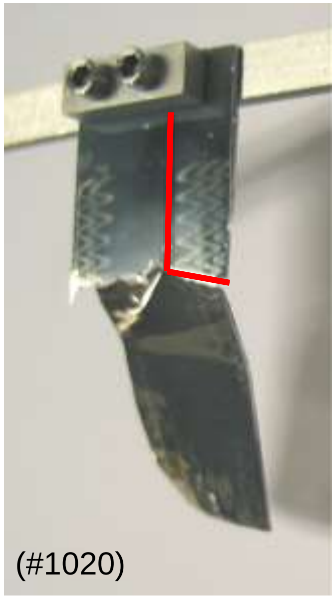
Until May 3, 2009, power ramp up was proceeding nicely and stripper foils were performing well. On May 3 we had our first foil failure.

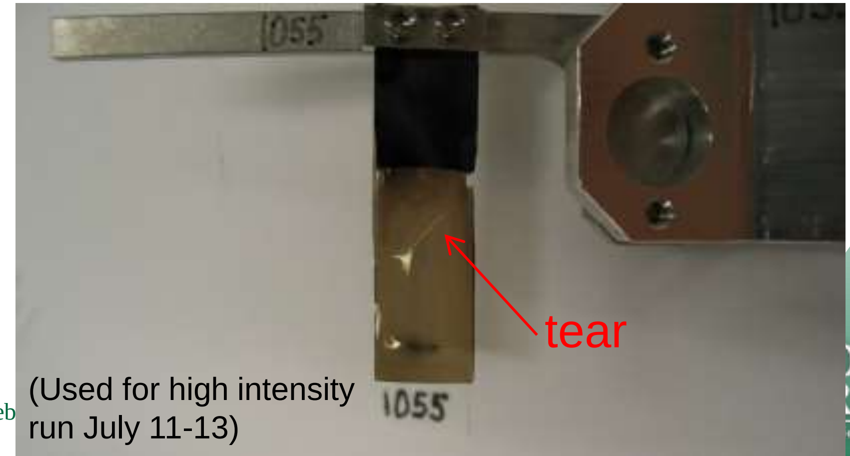


Oct '06 to Dec '09

Typical foil damage before May 3

Foil failures

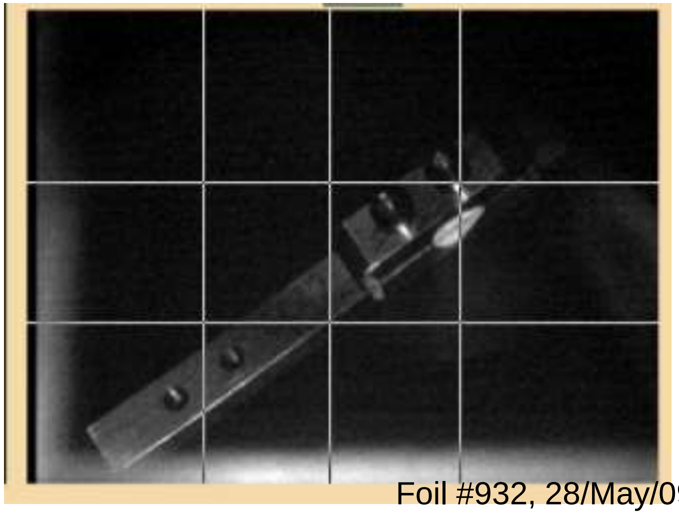




Photos by Chris Luck

Foil failures (cont.)

(Failed June 12)



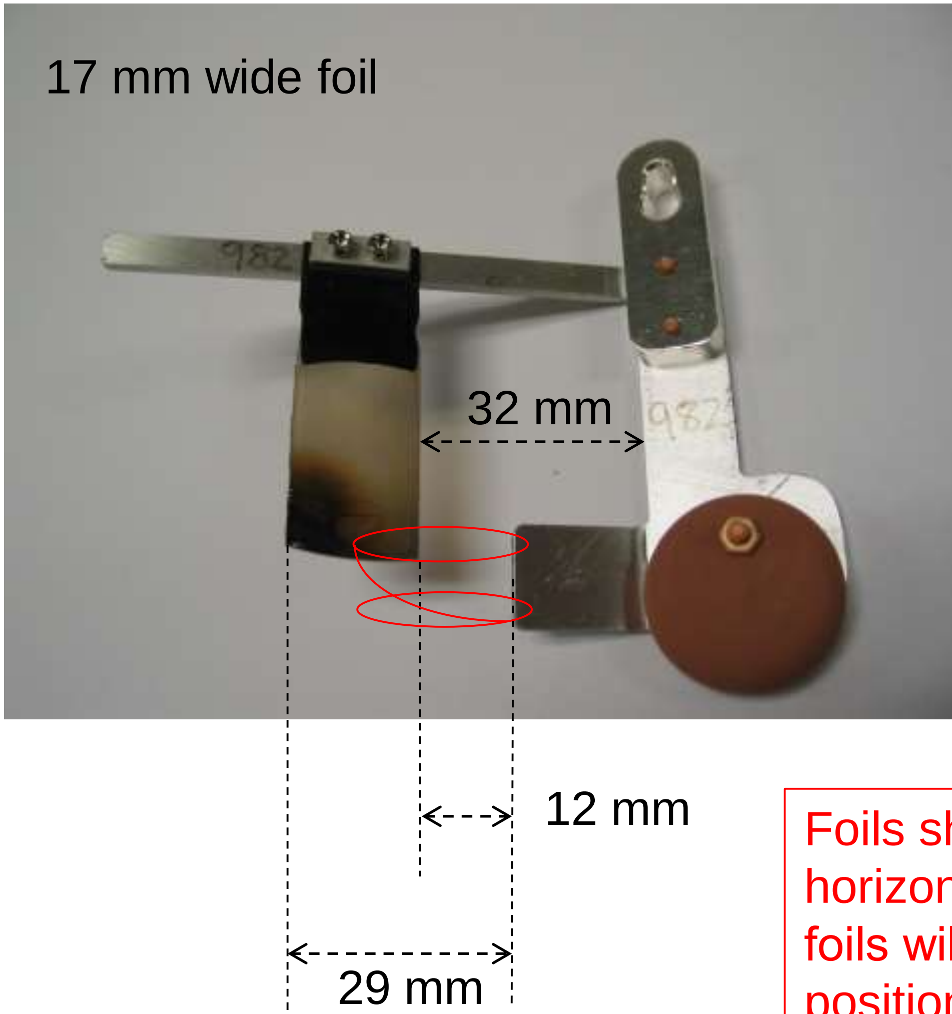
Foil #932, 28/May/09

Photos by Chris Luck

Inventory of foil issues

- Counterweights falling off
- Bracket melts where foil is attached
- Foils break where foil is attached to silicon, and where the silicon meets the bracket
- Foil flutter
- Glow from bottom edge and occasional spots on foil
- Foils sometimes have bright beam spots
- Material deposited / evaporated on foils, brackets, and other nearby components
- Foil brackets stick to the foil-changer pin that they hang from
- Some foils have much higher A13b losses
- Foil corner curls up after a while

Bracket failures and convoy electrons



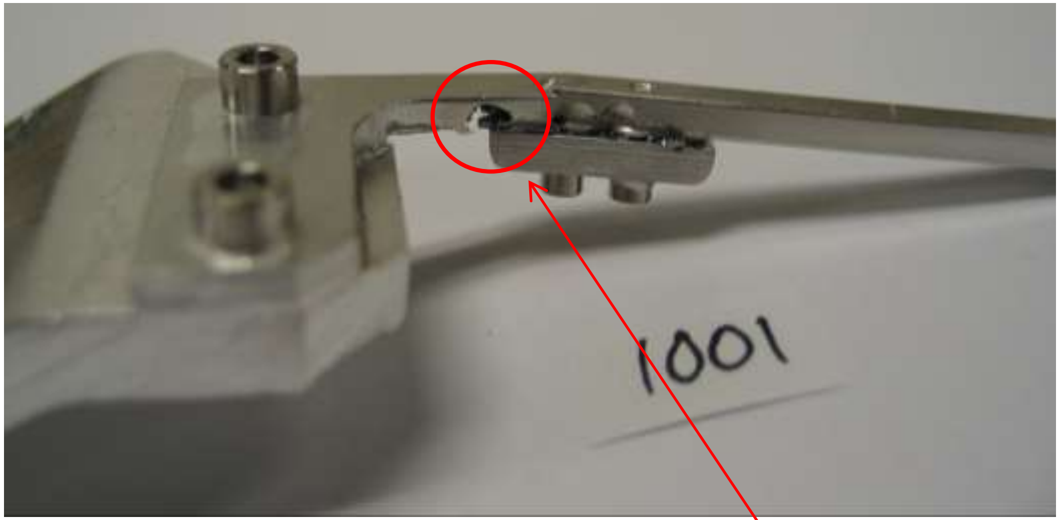
All this melted aluminum evaporated and was deposited on the vacuum chamber walls, other foil brackets, and everything else in sight

Foils should be mounted >24 mm horizontally from the bracket. All new foils will be mounted at the “+1 cm” position. Also helps to use high temperature material for brackets.

Causes of foil failures

- Best foil failure theory to date is that one of the primary causes is vacuum breakdown (arcing) caused by charge build up on the stripper foils, caused by secondary electron emission (SEM) and maybe also thermionic electron emission
- Another primary cause is reflected convoy electrons and possibly also electrons from trailing edge multipacting
- Some of our foil failures also involved convoy electrons hitting the foil bracket
- Other contributing factors may be:
  - Aluminum coating on vacuum chamber which may increase the trailing edge multipacting electrons
  - Beam halo hitting Si substrate and/or bracket
  - Sudden beam excursions (e.g. RF station 2.1 failures), causing beam to hit Si substrate and/or bracket
  - Eddy current heating
  - Electron collector in wrong position
  - Normal operation – foil just gets too hot

Arcs and sparks (vacuum breakdown)



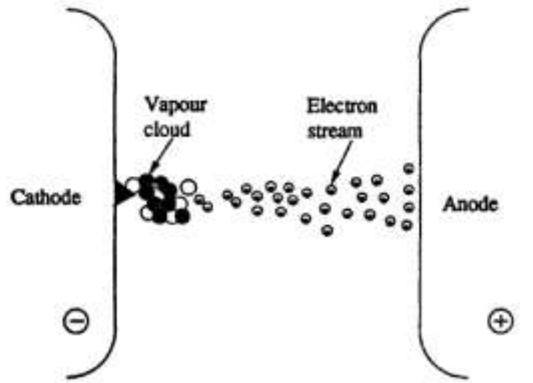
(no tab on this bracket)

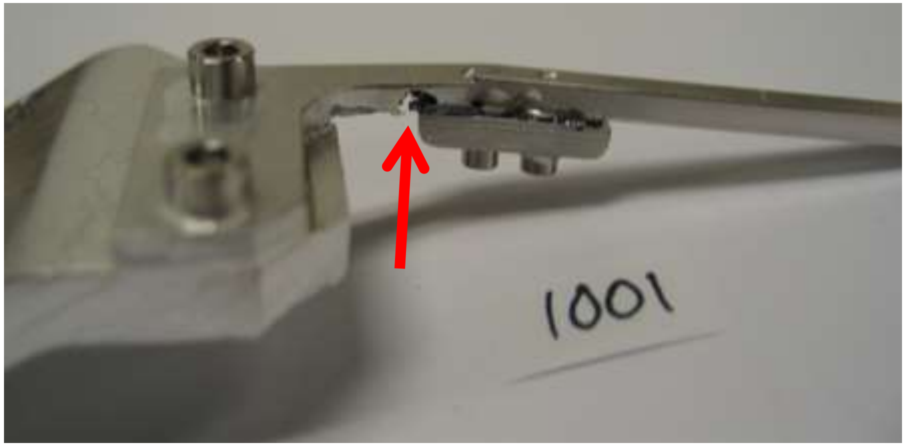
Clearest evidence to date of vacuum breakdown

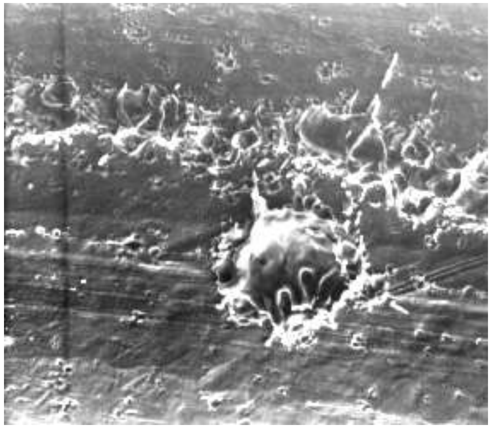
Cathode spot in-vacuum breakdown

"Vacuum arcs, also referred to as cathodic arcs, are high current discharges between cold electrodes. Typical currents are 100 Amperes or more while the voltage between anode and cathode is only about 20 Volts… <u>This leads to "micro-explosions," and one can observe microscopic craters left on the cathode surface</u>."

(From http://pag.lbl.gov/Proj_VacArcRes.htm)







Crater traces left by cathode spots
(Picture taken with an electron microscope).
From http://pag.lbl.gov/Proj_VacArcRes.htm

Anode spot in-vacuum breakdown

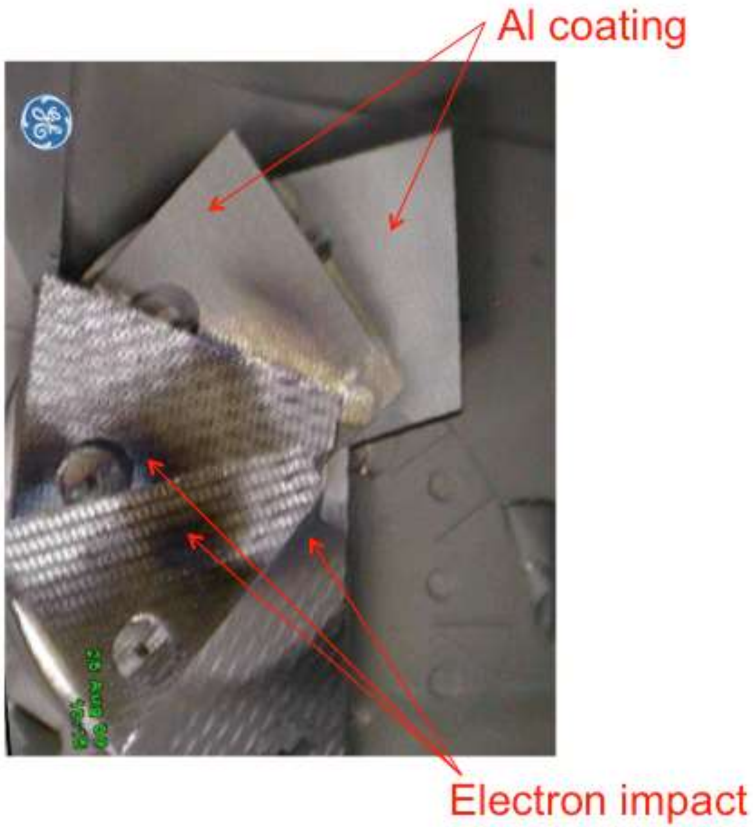
Beam on (1.02 MW, 18/Sep9)

1 – 2 sec after beam shuts off

- “Hot spots” on the bottom edge of the foil were observed for the first time in September 2009. They are visible at 600 kW, maybe less… Not always just on the bottom edge.
- Most likely explanation is anode-spot in-vacuum breakdown. If so, this could actually be helping us.
- Next most likely explanation is something nearby, with some thermal mass, glowing visibly hot. This light is then reflected off the foil.

Reflected convoy electrons

- If the electrons do not hit the catcher just right, they can be reflected, travel back up, hit the foil and/or foil bracket, and cause foil failure
- The electron catcher is made of carbon to minimize the probability of reflection
- Interior surfaces of the vacuum chamber were coated with aluminum due to the bracket melting problems
- The foil is probably not optimally aligned w.r.t the catcher
- All of the above contributes to convoy electrons reflecting off the electron catcher, rather than being absorbed by the catcher



Bracket damage by refl. convoy e's

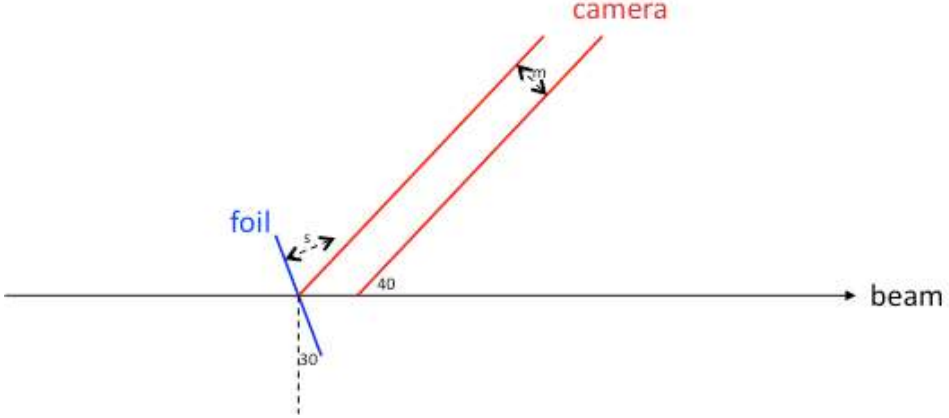
Photo by Chris Luck

Reflected convoy electron damage?

Graphitization at top of vacuum chamber

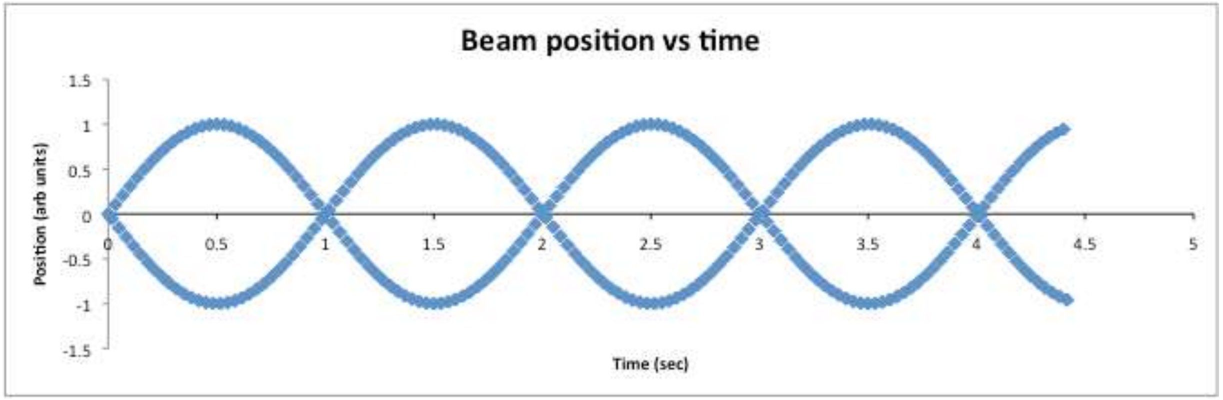
Could be reflected convoy electrons or trailing-edge multipactoring

Foil flutter



movie

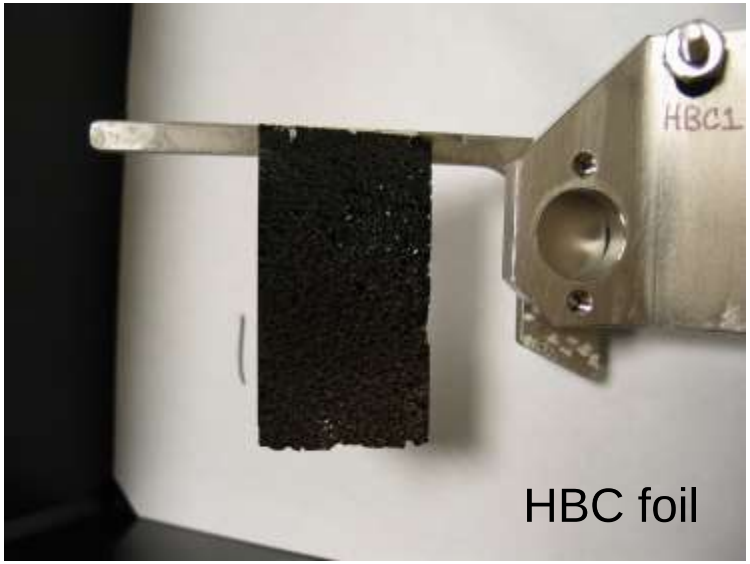
29.5 Hz sine wave sampled at 60 Hz (30.5, 89.5, 90.5 Hz … also work)

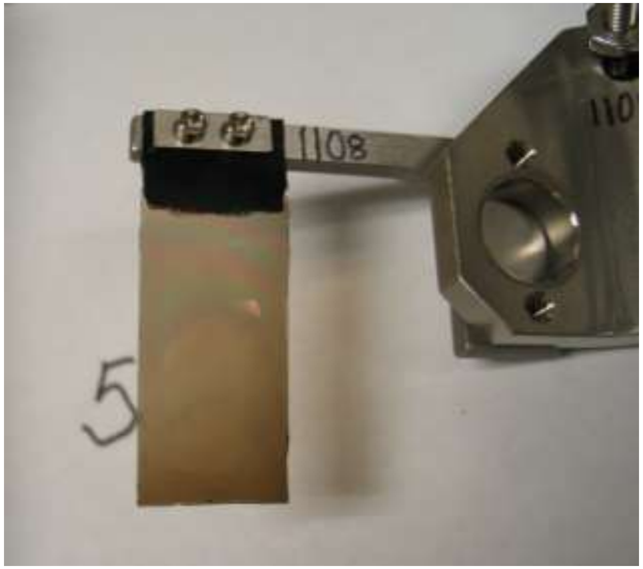


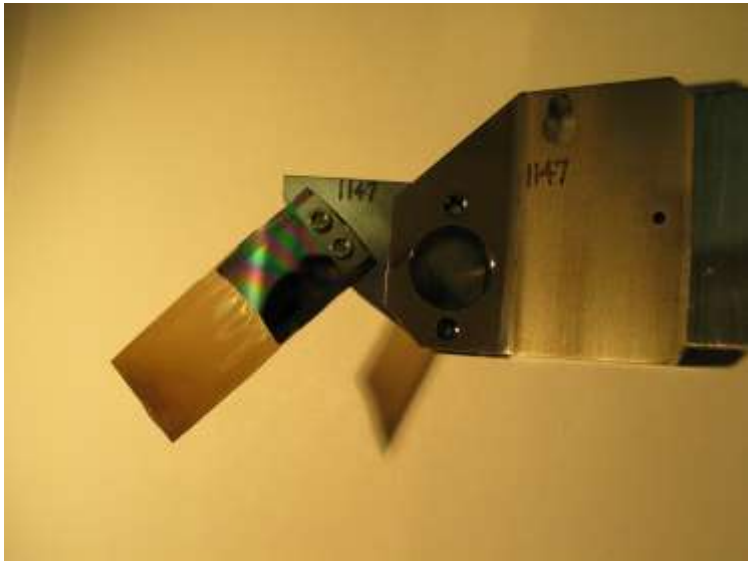
Foil and bracket modifications for Sep – Dec run

- The brackets have been modified:
  - High-temperature material with low coeff. of thermal expansion (Ti)
  - Bracket material removed from path of convoy electrons (both arm and leg cut off)
  - All foils mounted at the “+1 cm” position
  - Improved mounting method to make better electrical contact
- Foils have been modified:
  - Longer free-standing length (was 25 mm, now 30 – 35 mm)
  - Some have longer corrugations with finer pitch (back to same 100 LPI pitch that was used for original 12 mm wide foils)
- Washer on chain saw pin is now stainless steel (was aluminum or silver coated aluminum)
- There is also one HBC foil, and one diamond foil mounted at an angle

Foils installed Aug. 31, 2009







Photos by Chris Luck

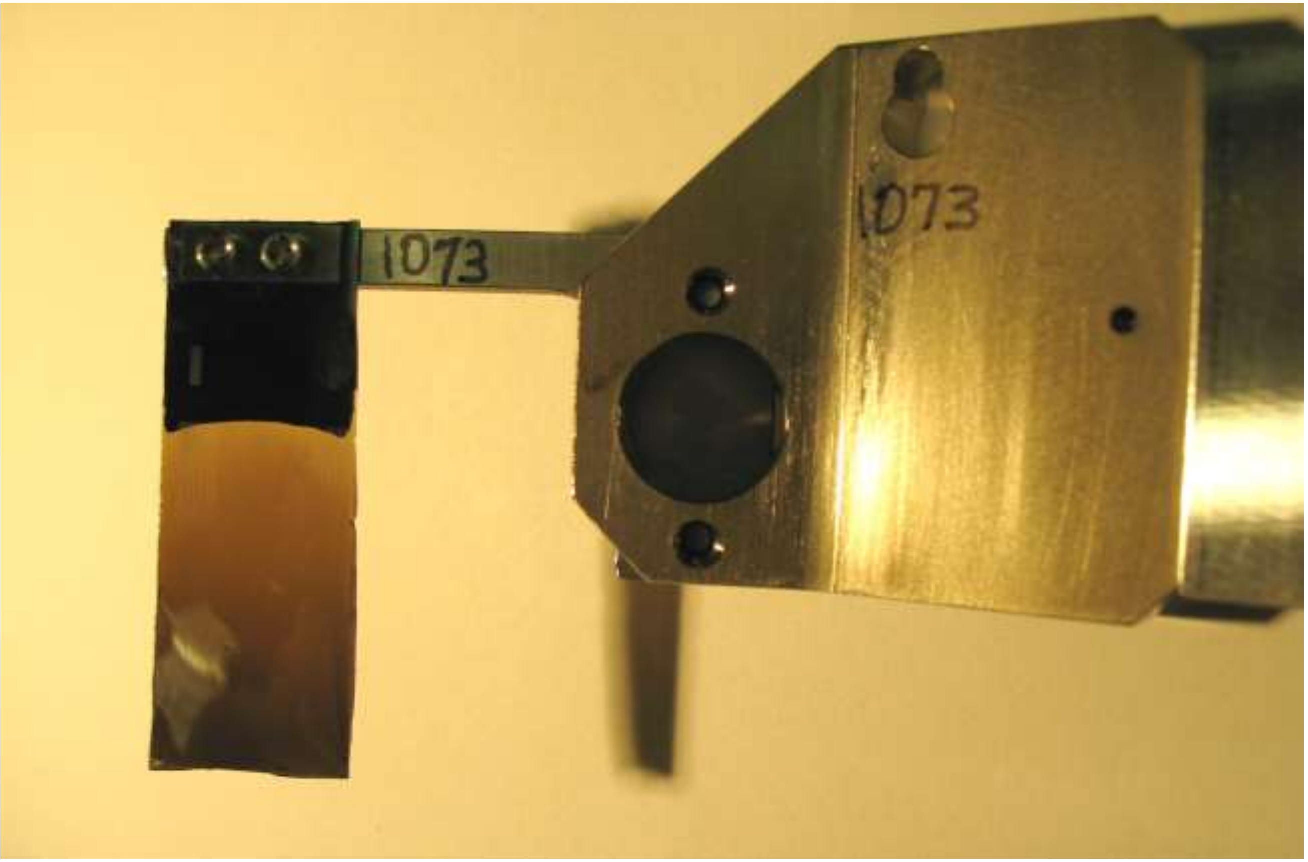


Photo by Chris Luck

Champion foil used for entire Sep-Dec/09 run cycle.
Mounted with gold foil, 17x30 mm free area, 344 μg/cm^2, peak beam power ~1.03 MW. Charge to target = 4820 Coul.
Pivots freely on chain-saw pin.
Previous record for >680 kW operation was ~14 days, 978 Coul.

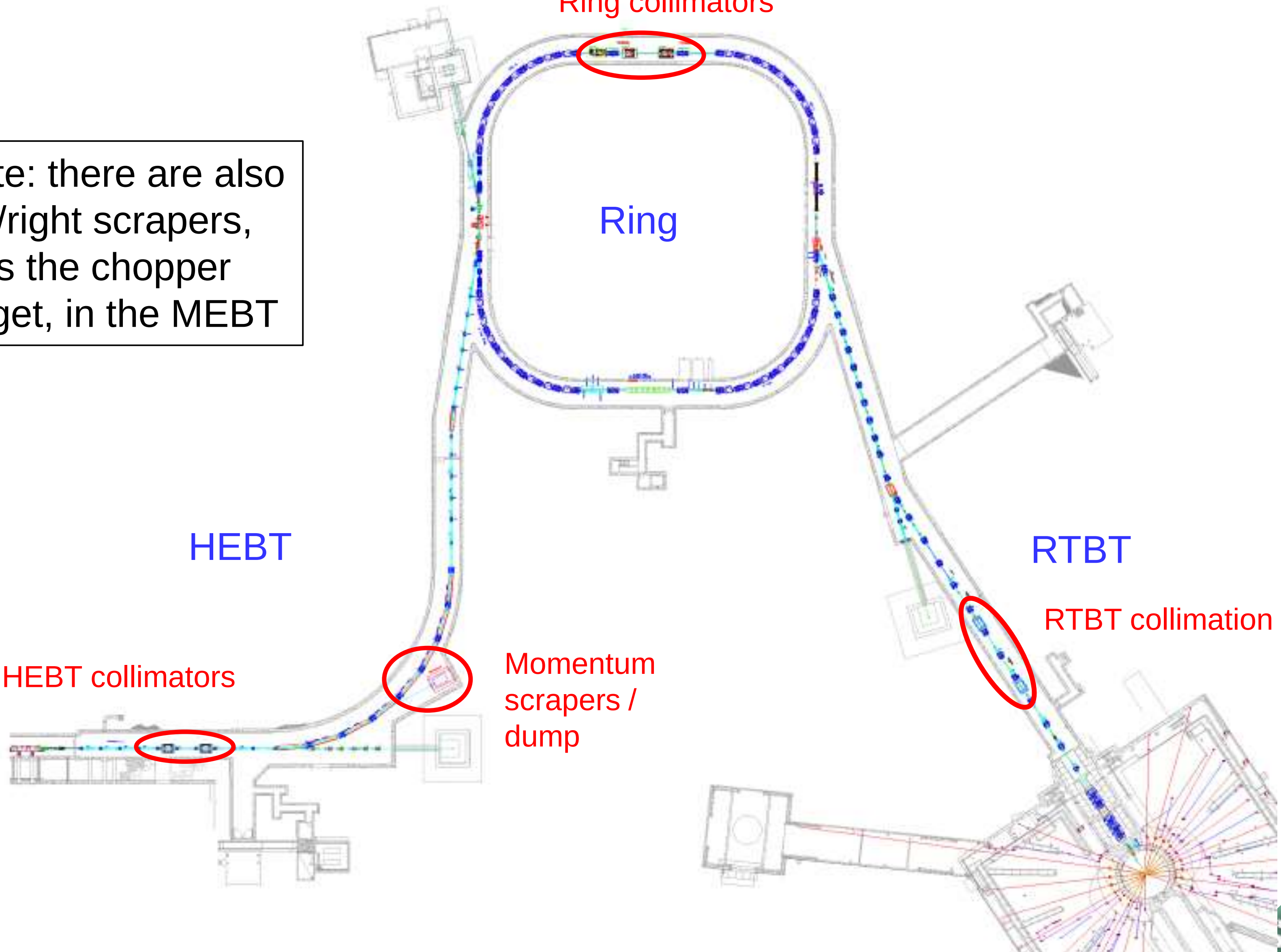
Stripper foil plans

- Develop more conductive foils
  - Boron doping, collaboration with MSU / Fraunhofer
- Measure foil resistivity
- Develop new lithography (corrugation) patterns
- New stripper foil mechanism (Murdoch)
  - Will allow measurement of electrical signal from foil, better motion control, full view of foil
  - New electron catcher design will also be installed
- Continue effort to measure foil temperature
- Use new e-beam test stand to test foils
- Develop other HBC growth methods (EPSCoR proposal for B_4C foils)

Details in Bob Shaw's presentation tomorrow

HEBT/Ring/RTBT collimators

Note: there are also left/right scrapers, plus the chopper target, in the MEBT



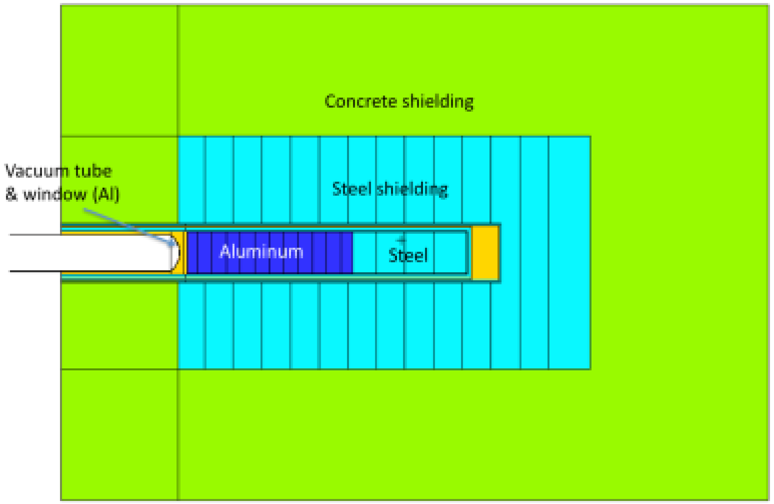
Collimation

- Collimation / scraping is now a routine part of our production tune
- It is best to scrape at low beam energies, with the newly installed (summer 2009) MEBT scrapers
- We typically also scrape in the HEBT, but this is not always necessary, esp. when scrape in MEBT
- The HEBT momentum scrapers were very useful (sometimes at least 8x better losses in IDmp) until the momentum dump failed in April 2008
- We do not routinely use the ring scrapers, since there has not been a clear improvement when we have tried them

Momentum dump

- In April 2008 the dump failed due to excessive pressure in the cooling loop, caused by a combination of excessive beam power (~9 kW for ~36 hours vs. 2.5 kW design power), and unanticipated gas creation from the beam passing through the cooling water
- Once the gas creation problem was discovered the dump was removed from service since this is an issue at any beam power
- A new dump was designed and installation is now in progress
  - Capable of 5 kW vs. old design of 2.5 kW
  - Air cooled to avoid radiolysis issues
  - Beam diagnostics added to allow measurement of beam power, profile, position, and loss
  - Redundant blowers for high availability
  - Not quite ready for start of next run cycle

Momentum dump (cont.)



TiN coating

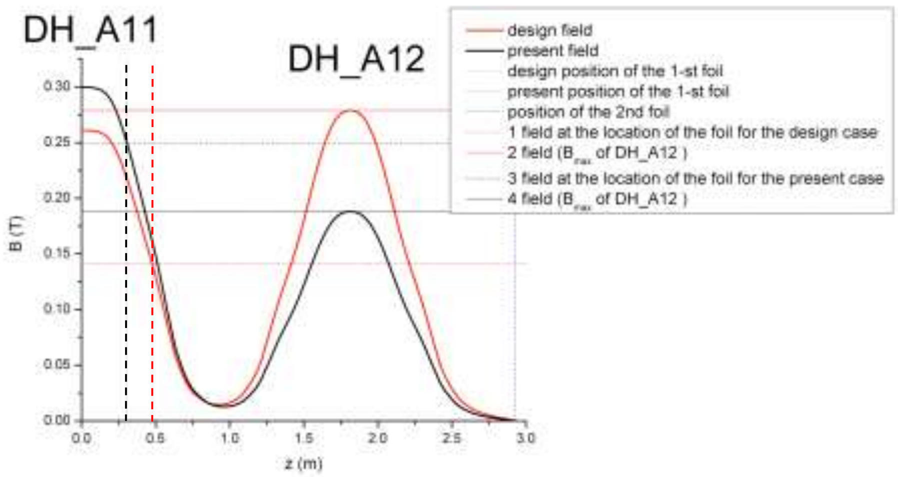
- Original design specifications called for 100% of the ring vacuum chambers to be coated with TiN to mitigate the e-p beam instability
- Today about 95% is coated, and we see the e-p instability at levels as low as 1/5 design intensity
  - So far we have always been able to suppress the instability using the ring RF – but just barely on the one occasion we had the full design intensity of 1.5×10^{14} ppp
- The latest information available on TiN coatings calls into question the desirability of TiN coatings for proton machines
  - Secondary emission yield improvements are similar for stainless steel and TiN
- The cost, in dollars and time, has been high to coat our new vacuum chambers
- Our plan is to continue to coat everything, and to use our electron detector system to determine if we should continue down this path, while at the same time continue to develop the active damping system

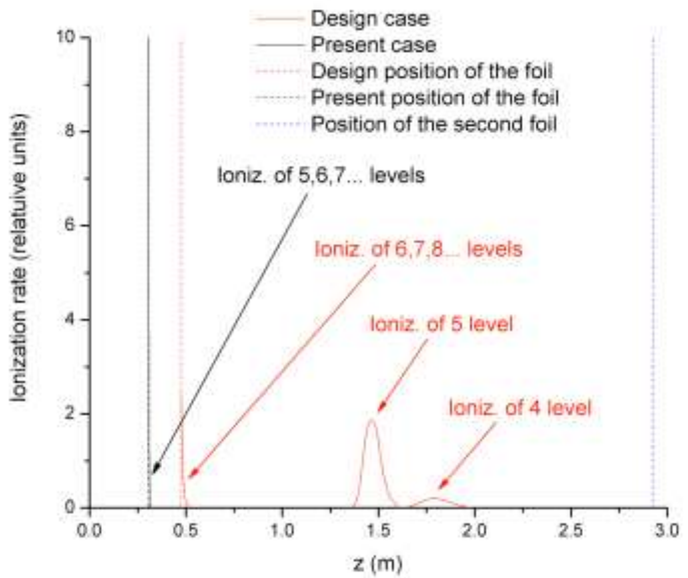
Ring injection update

- The beam trajectories in the ring injection chicane were significantly changed during commissioning, when the consequences of a design oversight were finally realized:
  - Injection point was moved about 8 mm beam left
  - H^0 and H^- waste beams could not be properly transported to the injection dump, which lead to many modifications to the injection dump beam line
- We are now in the process of fabricating a new primary stripper foil mechanism and a new beam line vacuum chamber. Should we use this opportunity to change the foil position and recover the original design bend angles and trajectories?

Ring injection update (cont.)

- H^{0*} tracking shows that if we move the foil to recover the original design bend angles, the H^{0*} losses would be 200 – 300 W during 1 MW operation





Plots by T. Gorlov,

T. Gorlov and M. Plum, SNS-NOTE-AP-185, 2009-12-17

Upgrades and improvements

- Now in progress
  - New momentum dump
  - New primary stripper foil actuator / beam vacuum chamber
  - New secondary stripper foil actuator / beam vacuum chamber
  - Injection dump beam line aperture increase and add two BPMs
  - View screen for ring injection dump vacuum window
  - Ring diagnostics (electron beam profile monitor, damping system)
  - RTBT harp actuator
  - Target imaging system (McManamy)
- Future
  - Add 3 BPMs and a steering magnet in ring extraction region
  - Additional extraction kicker supplies for improved availability
  - Ring LLRF

Summary and conclusions

- Except for the stripper foil problems we experienced last year, the Ring has kept up with the power ramp up, with activation in line with expectations, and good availability and reliability
- The path to full design power of 1.4 MW is reasonably clear now that we've demonstrated this intensity at 1 Hz
- The equipment situation continues to improve (new momentum dump, inj dump aperture increase, new primary and secondary stripper foil mechanisms, …)

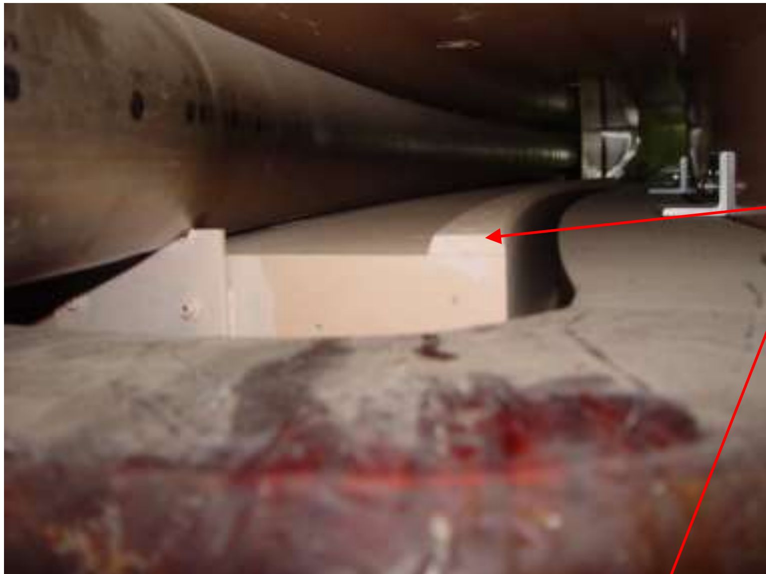
Thank you for your attention!

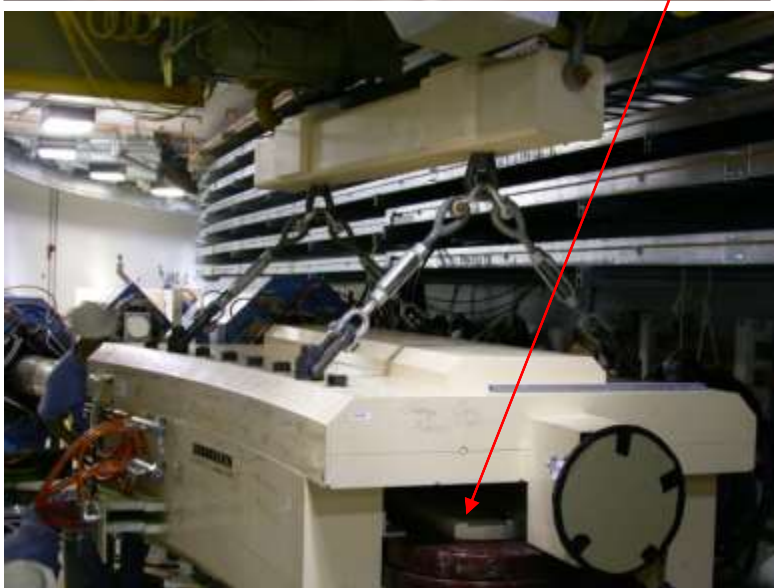
- Backup slides

Action items from last review

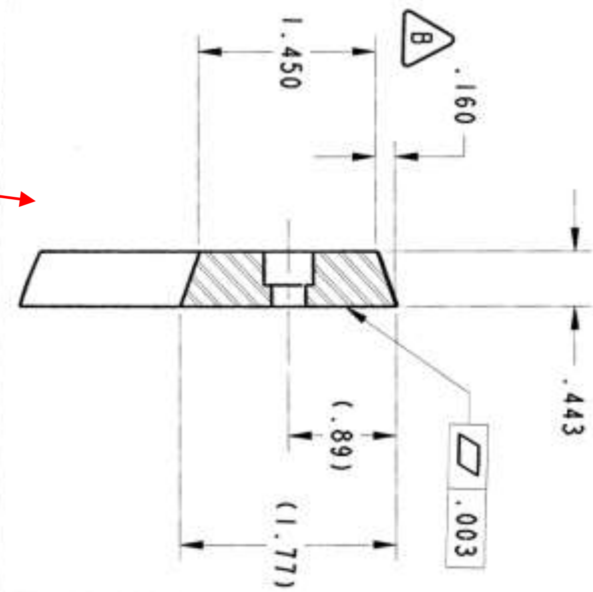
2299	Significant beam loss in the ring down stream of the stripper foil is not fully understood. Improvements to simulation of injection painting are needed to help understand this issue.
2316	More work is needed to increase the transmission of the injection dump line, simplify its tuning and enable recovery of the design optics and closed orbit in the ring. In addition, improved diagnostics for determining the beam position at the injection line beam dump are needed to speed up steering of the beam onto the dump. The committee concurs that it is important to finish fixing the Idump line as soon as possible, so that the ring and HEBT may operate with the design optics instead of the compromise tune.
2317	Improvements to the simulation of injection painting are needed to better reproduce measured ring beam transverse profiles and might also help to better understand ring losses.
2318	A view screen system is being developed for the target window to improve the determination of the beam profile on target. The committee recommends high priority for its development, along with control system augmentations to ensure that the beam spot on target does not get too small and damage the target.
2319	It should be possible to measure foil temperatures with commercial optical pyrometers looking at the light emitted from the foil. We would recommend consideration of such a capability.
2320	Foil temperatures can be calculated if the foil emissivity is known along with the spatial and temporal distributions of power deposition. We would recommend additional calculations/simulations of foil temperatures at higher beam power, especially at 3 MW, as well as calculations of thermionic emission thresholds at the higher beam power.
2321	More applicable short-term tests of the most promising foils can be tried at PSR or SNS with special beam conditions (highest accumulated charge, smaller stored beam size, foil moved further into the stored beam, etc.) that give high foil hits/proton, hence high instantaneous power-deposition rates. These would be done at low rep rate for durations commensurate with beam study time. One goal would be to determine the peak power-deposition rate (and temperature) that causes foil failure in a short period of time, of order 1-2 hours. The committee recommends consideration of such tests for the power upgrade activities
2322	The Hybrid Boron mixed Carbon (HBC) foil developed at KEK shows promise of higher operating temperatures and longer life and its development along with development of other promising materials should be vigorously pursued for the power upgrade
1912 (2008)	The discrepancy of the beta-y measurements compared with calculation at some ring locations does not appear to be a serious problem; however, its origin should be identified. It might be due to the overlap of magnetic fields from large aperture quadrupoles, which are close together. Inclusion of this effect in the modeling is encouraged.

Extraction septum shim replacement

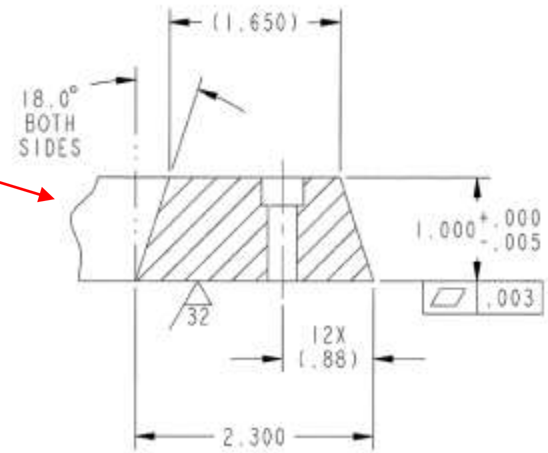




OLD

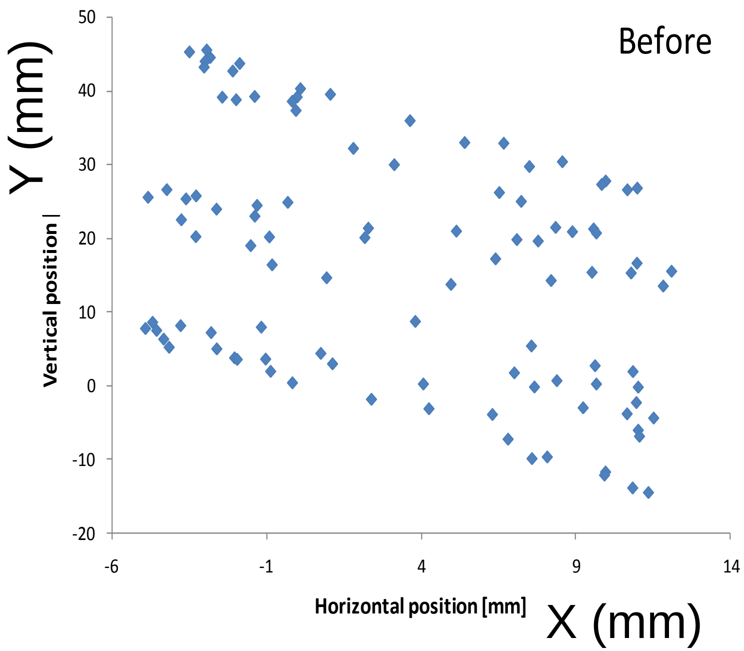


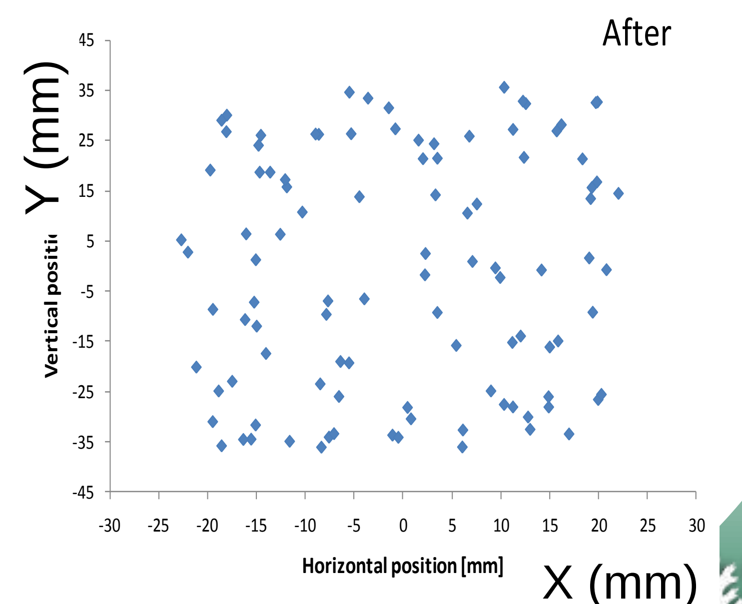
NEW



Cross plane coupling

- After replacing shims in February 2009, the single minipulse reconstruction measurements were repeated
- Cross plane coupling is now below measureable limit!

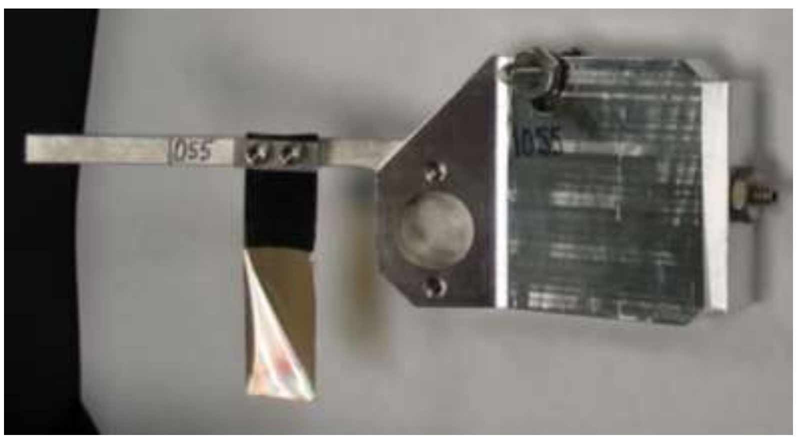




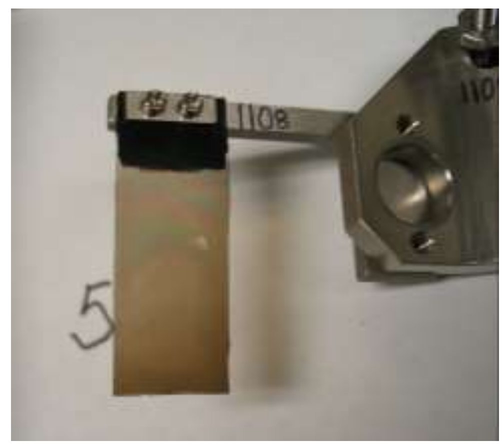
Foil brackets – 4 generations

1st gen., used thru Jan/09
Al bracket 0.25 in, Al snap ring washer 0.090 in

2nd gen., used Mar/09 – 17/May/09
Silver plated Al "tombstone" hanger, 0.340 inch thick



3rd gen., used 19/May/09 – 13/Jul/09
Same original but has bottom cut off.
Silver-plated aluminum washers, 0.085 inch thick



4th gen., used Sep/09 to present
Ti bracket, SS washer 0.093 inch, +1 cm position

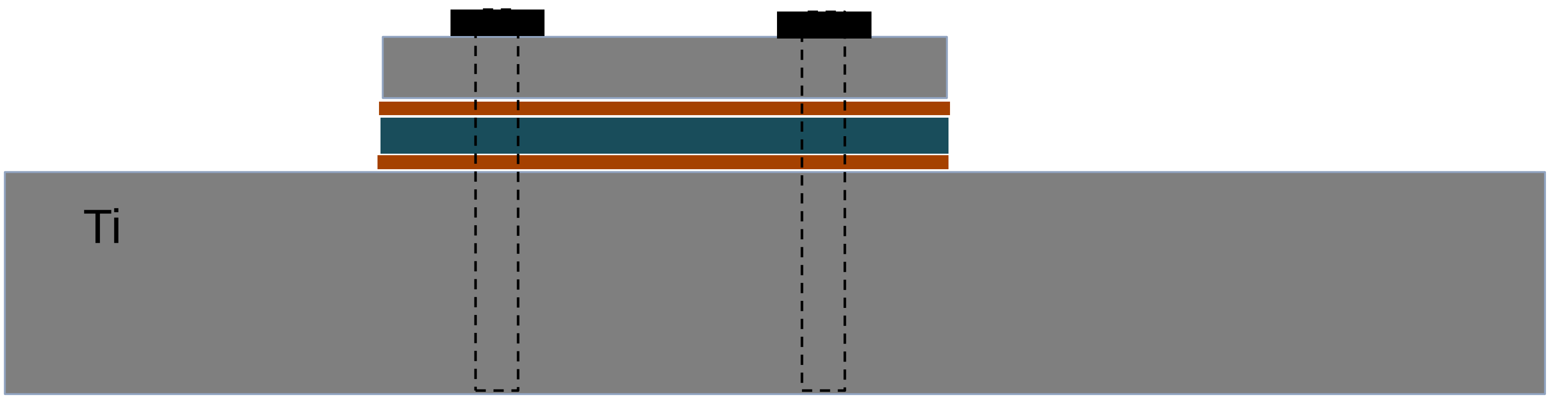
Photos by Chris Luck

New foil mount method

Foil mount for good electrical contact:

- machine flat then polish bracket and clamp
- sandwich Si substrate between thin sheets of Cu or Au (~0.001” thick)
- OR use conductive adhesive in place of Cu or Au sheets
- OR use all the above

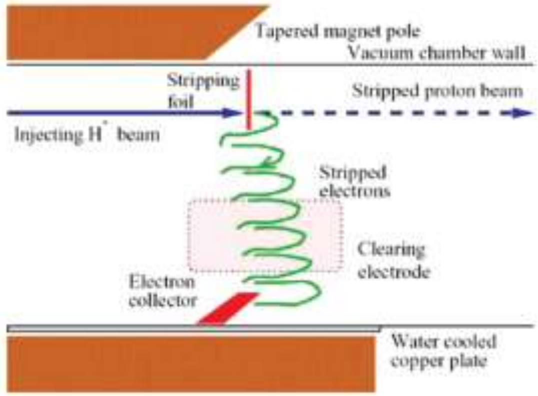
Could also use Bellville washers to maintain positive pressure



Sep – Dec run: about half the foils were mounted using ~1.1 mil thick gold. No Bellville washers, no conductive adhesive. Brackets machined to a flatness spec then polished.

Convoy electron trajectories

- Prior to May 18, when we installed a new type of foil bracket, the main cause of foil failures was due to convoy electrons hitting the foil brackets



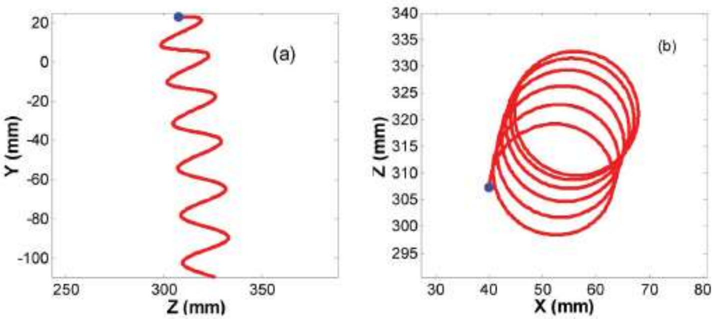


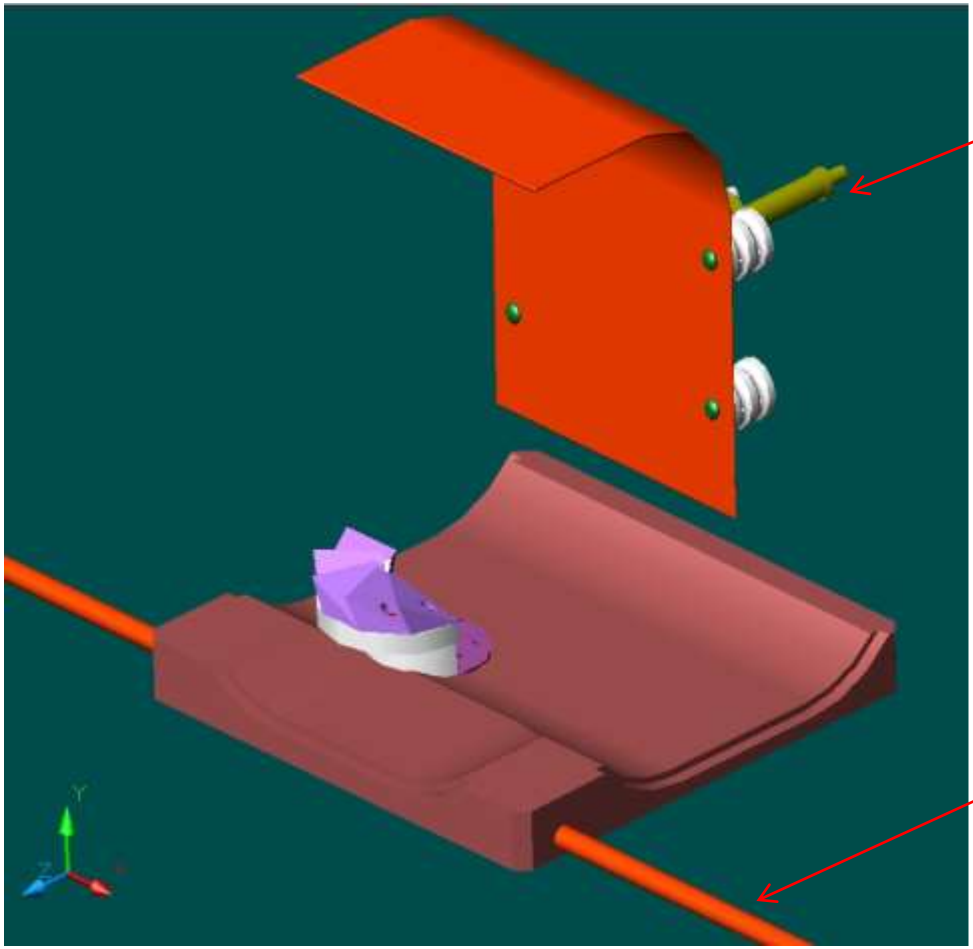
FIG. 2. (Color) Trajectory of a stripped electron from the foil's center. (a) Orbit in vertical and longitudinal plane and (b) in horizontal and longitudinal plane. The blue point is the position where the electron was emitted.

(From L. Wang et al.)

Convoy electrons from a 1 GeV H^- beam have 545 keV energy, gyroradius 12 mm, pitch ~16 – 23 mm. A 1 MW beam has ~1 kW power in the convoy electrons.

Electron catcher and clearing electrode

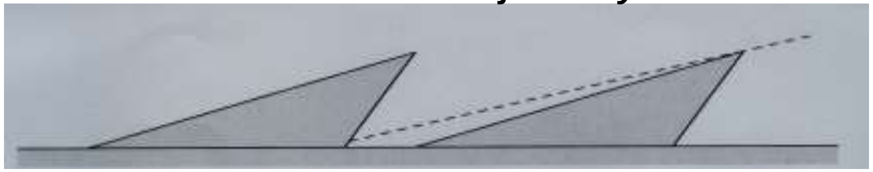
Water cooled carbon-carbon wedges
Undercut prevents secondary electrons from escaping



+/-20 kV biasing system

Inlet and outlet water cooling lines have thermocouples, read out by EPICS and archived

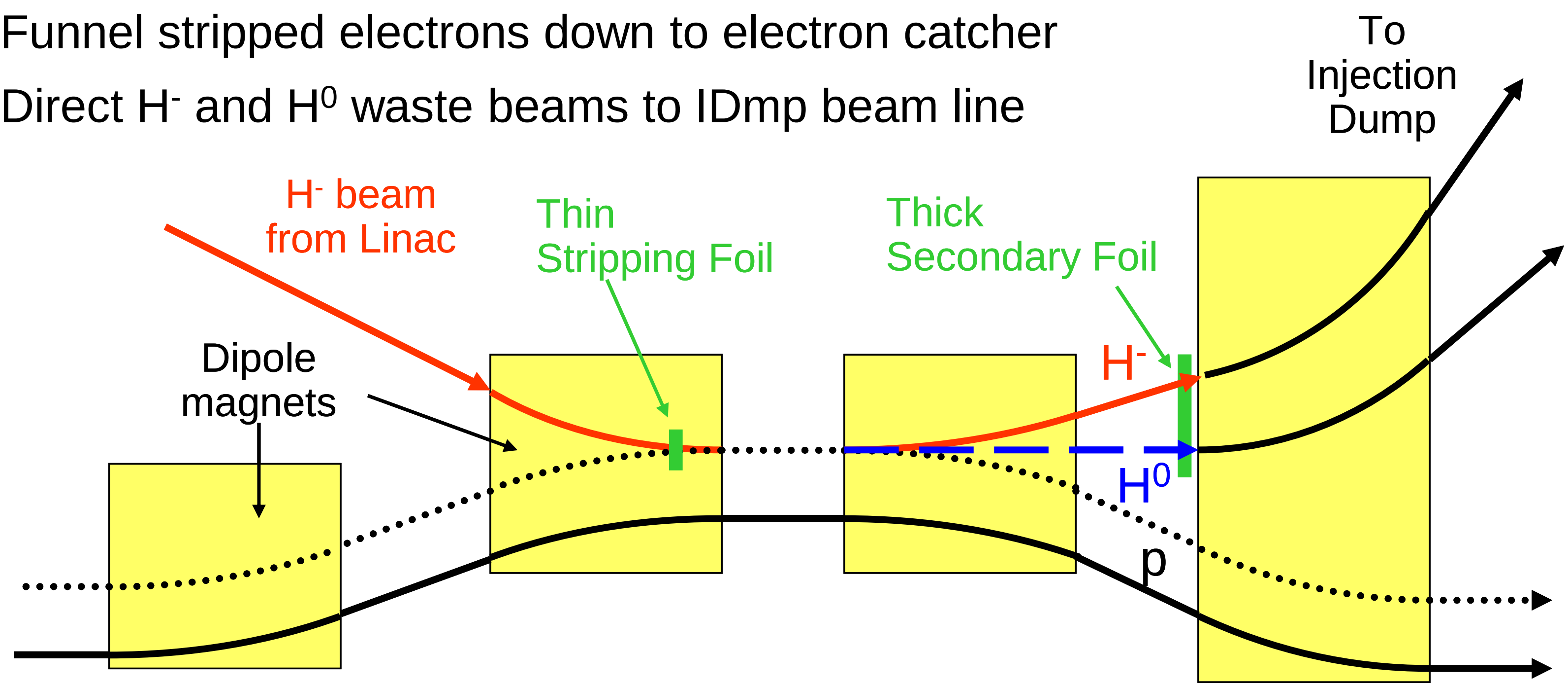
Ideal electron trajectory



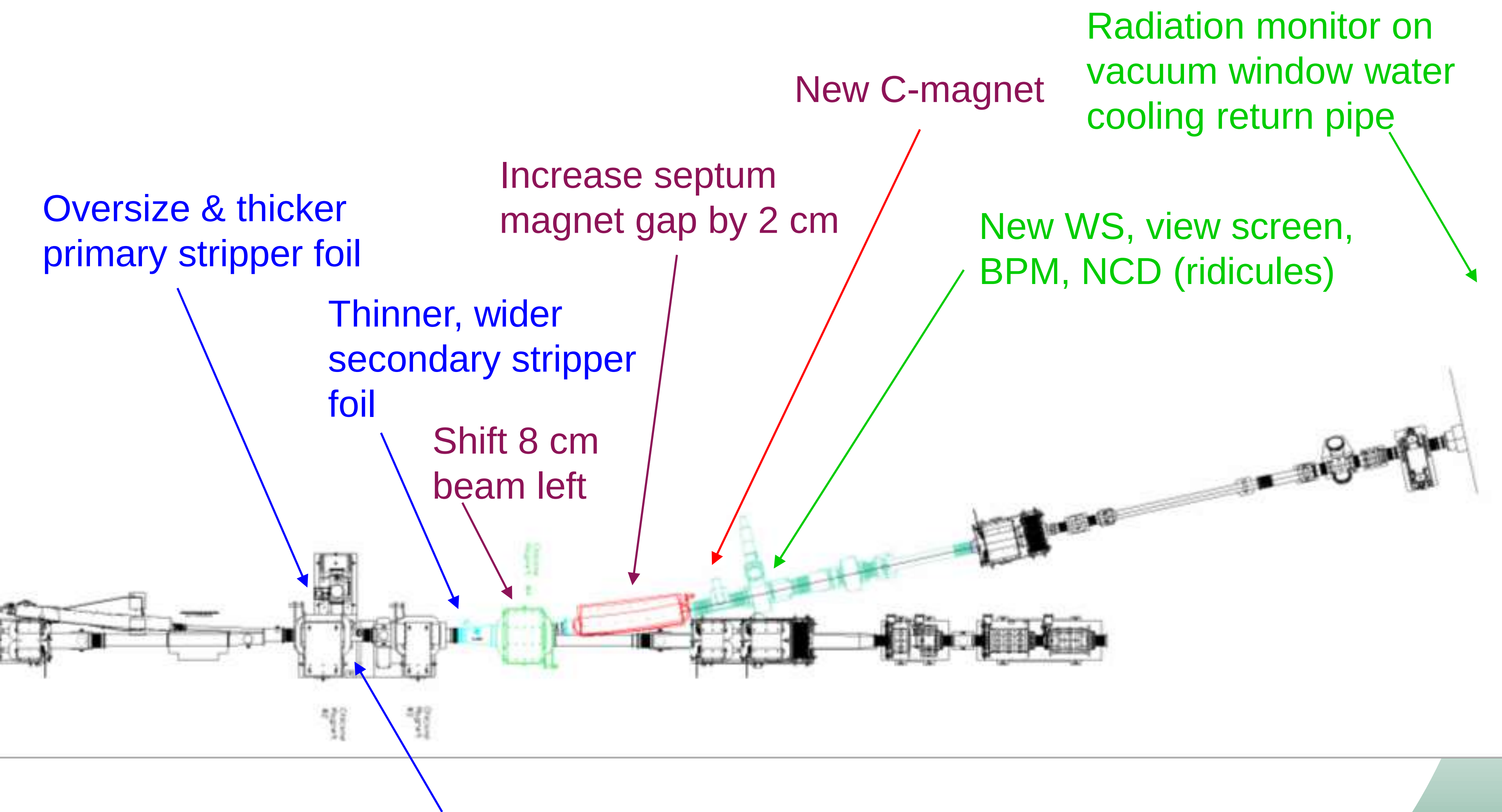
Boroscope snapshots on 19/May/09

SNS injection schematic

- Closed orbit bump of about 100 mm
- Merge H^- and circulating beams with zero relative angle
- Place foil in 2.5 kG field and keep chicane #3 peak field <2.4 kG for H^0 excited states
- Field tilt [arctan(By/Bz)] >65 mrad to keep electrons off foil
- Funnel stripped electrons down to electron catcher
- Direct H^- and H^0 waste beams to IDmp beam line



Inj. dump beam line modifications to date



beam line drawing from J. Error