SNS Ring injection experience

Project X collaboration meeting,
FNAL, Sep 10-11, 2009

by

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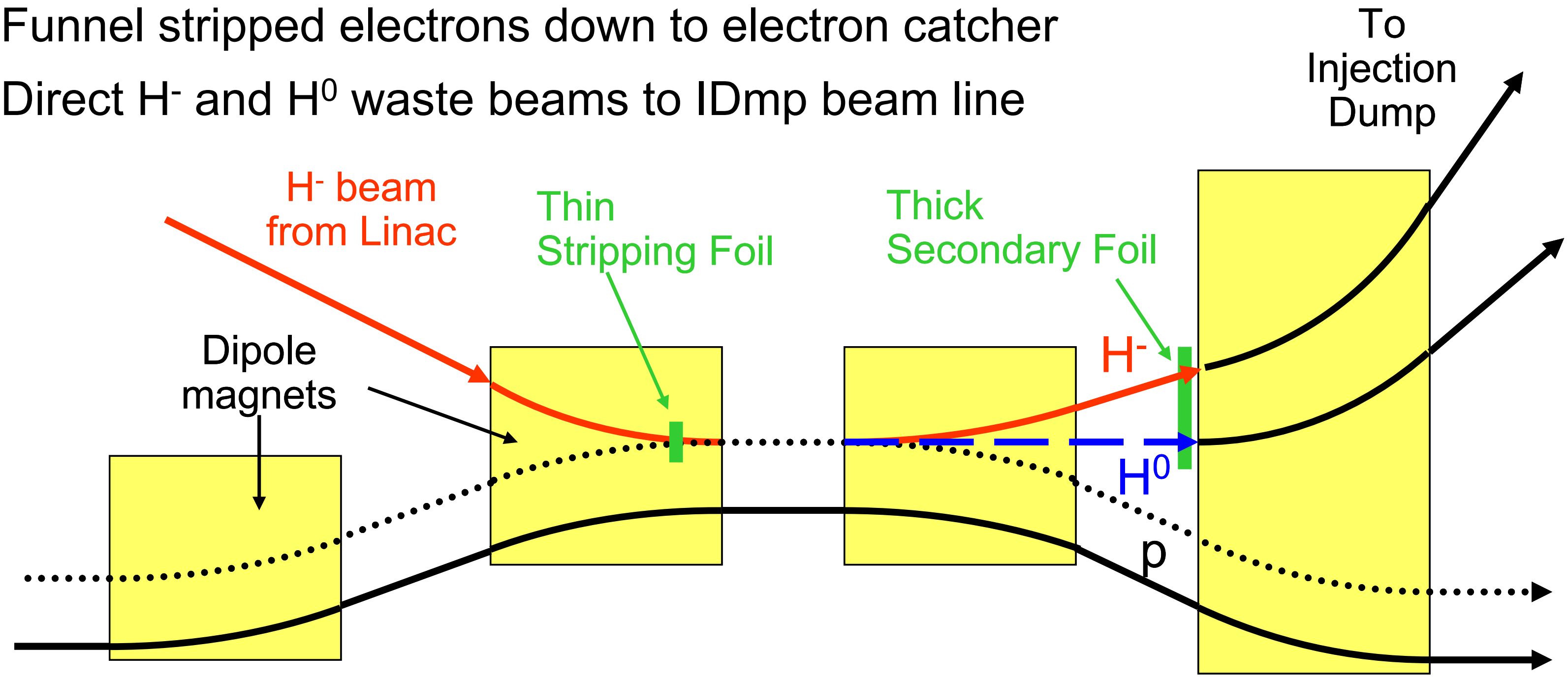
Outline

- SNS injection according to design
- Stripper foil failures and failure mechanisms
- Present status of SNS stripper foils
- Lessons learned

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

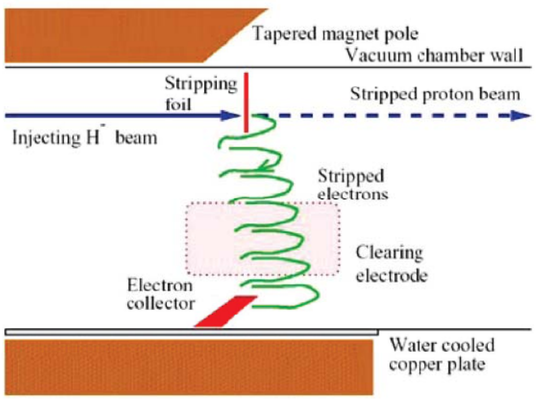


Electron trajectories

Stripped electron collection at the Spallation Neutron Source

L. Wang, Y. Y. Lee, G. Mahler, W. Meng, D. Raparia, and J. Wei
Brookhaven National Laboratory, Upton, New York 11973, USA

S. Henderson
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
(Received 6 May 2005; published 13 September 2005)



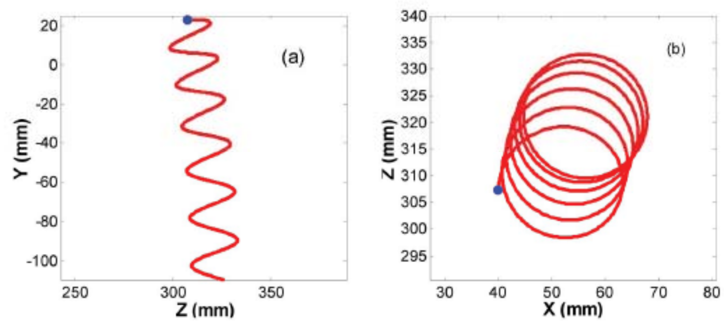
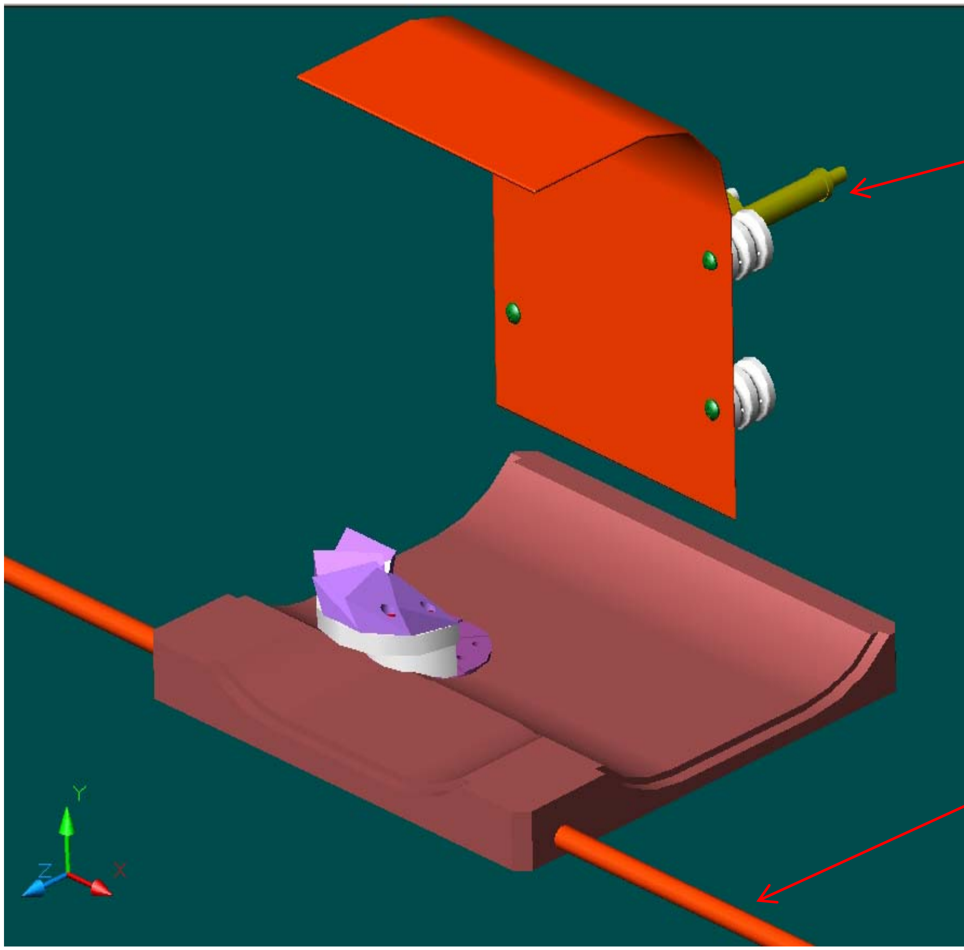


FIG. 2. (Color) Trajectory of a stripped electron from the foil's center. (a) Orbit in vertical and longitudinal plane and (b) in horizontal and longitudinal plane. The blue point is the position where the electron was emitted.

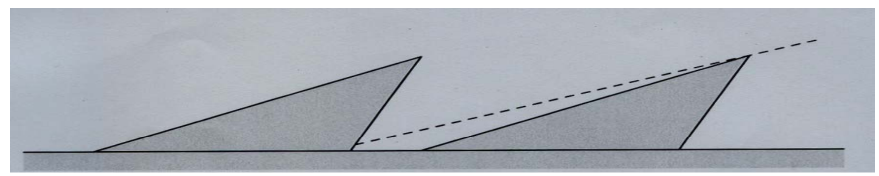
Convoy electrons from a 1 GeV H$^-$ beam have 545 keV energy, gyroradius 12 mm, period 0.29 ns, pitch 16-23 mm. Center of circular motion moves ~14 mm downstream and ~5 mm beam left. Electrons are collected in an "electron catcher". A 1 MW beam has ~1 kW power in the convoy electrons.

Electron catcher and clearing electrode

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



A +/-20 kV biasing system is being installed



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

Inj. dump beam line modifications to date

Oversize & thicker primary stripper foil, injected position moved ~8 mm beam left

Thinner, wider secondary stripper foil

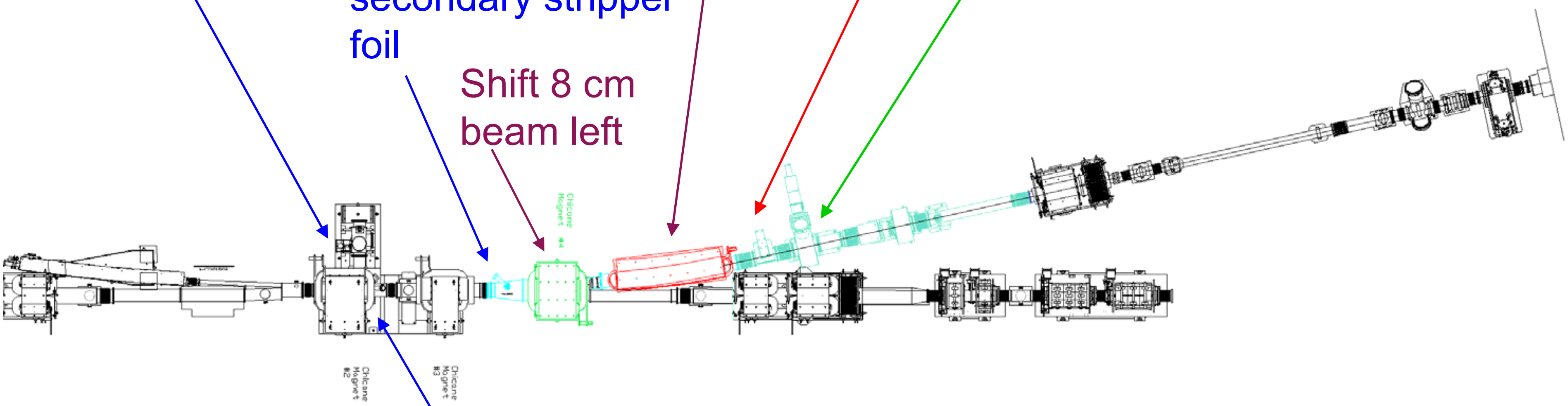
Shift 8 cm beam left

Increase septum magnet gap by 2 cm

New C-magnet

New WS, view screen, BPM, NCD (ridicules)

Radiation monitor on vacuum window water cooling return pipe

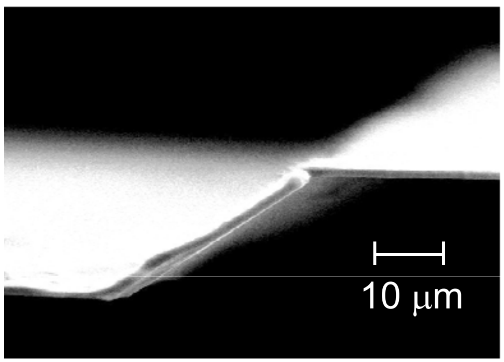


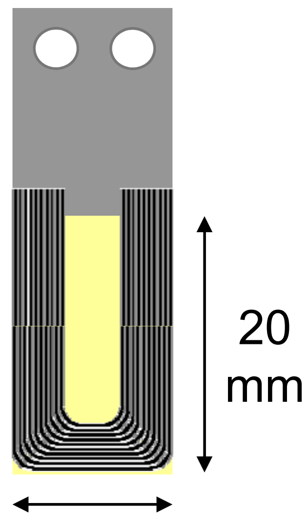
Electron catcher IR video

beam line drawing from J. Error

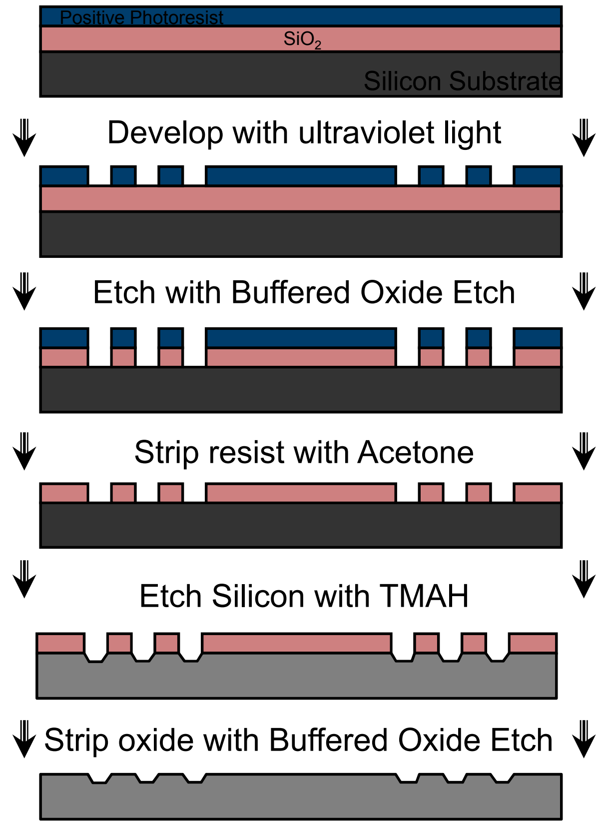
SNS diamond foils – original 12 mm size

- Thermal expansion mismatch
  diamond vs silicon
- Foils scroll upon release from Si wafer
- Foil corrugation method developed

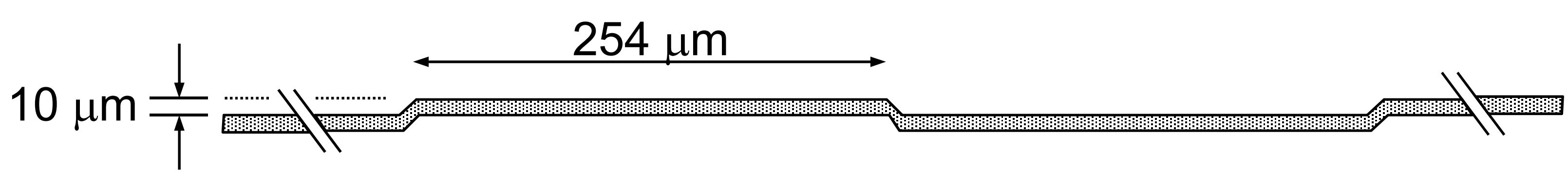




Patterning Process



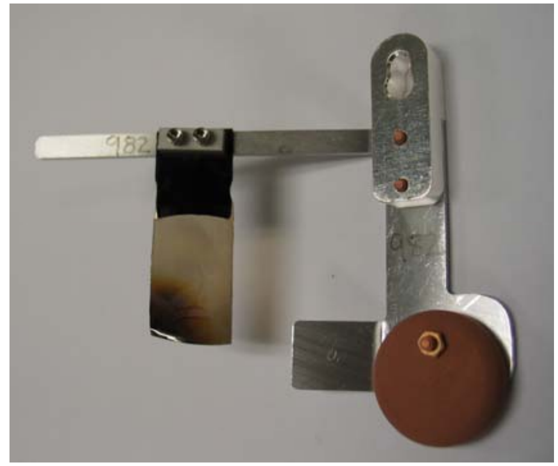
50 Line/inch Foil:



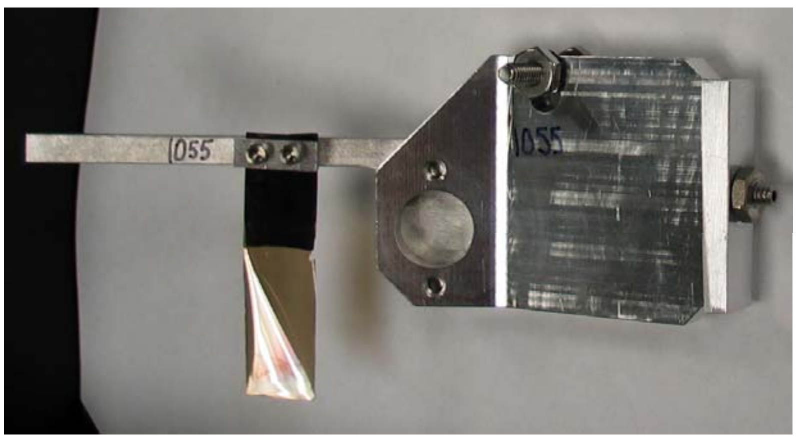
Courtesy R. Shaw

Foil brackets – 4 generations

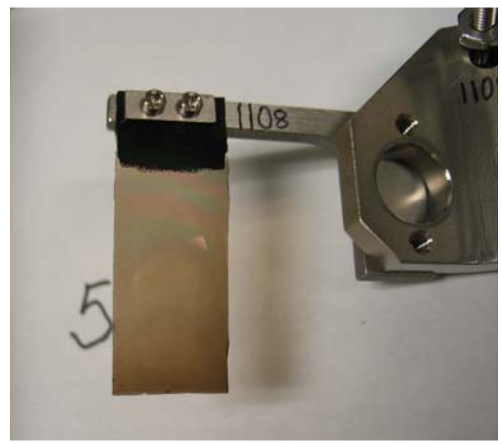
1st gen., used thru Jan/09
Aluminum snap ring washer, 1/8 inch thick



2nd gen., used Mar/09 – 17/May/09
Silver plated “tombstone” hanger, ~0.080” thick



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

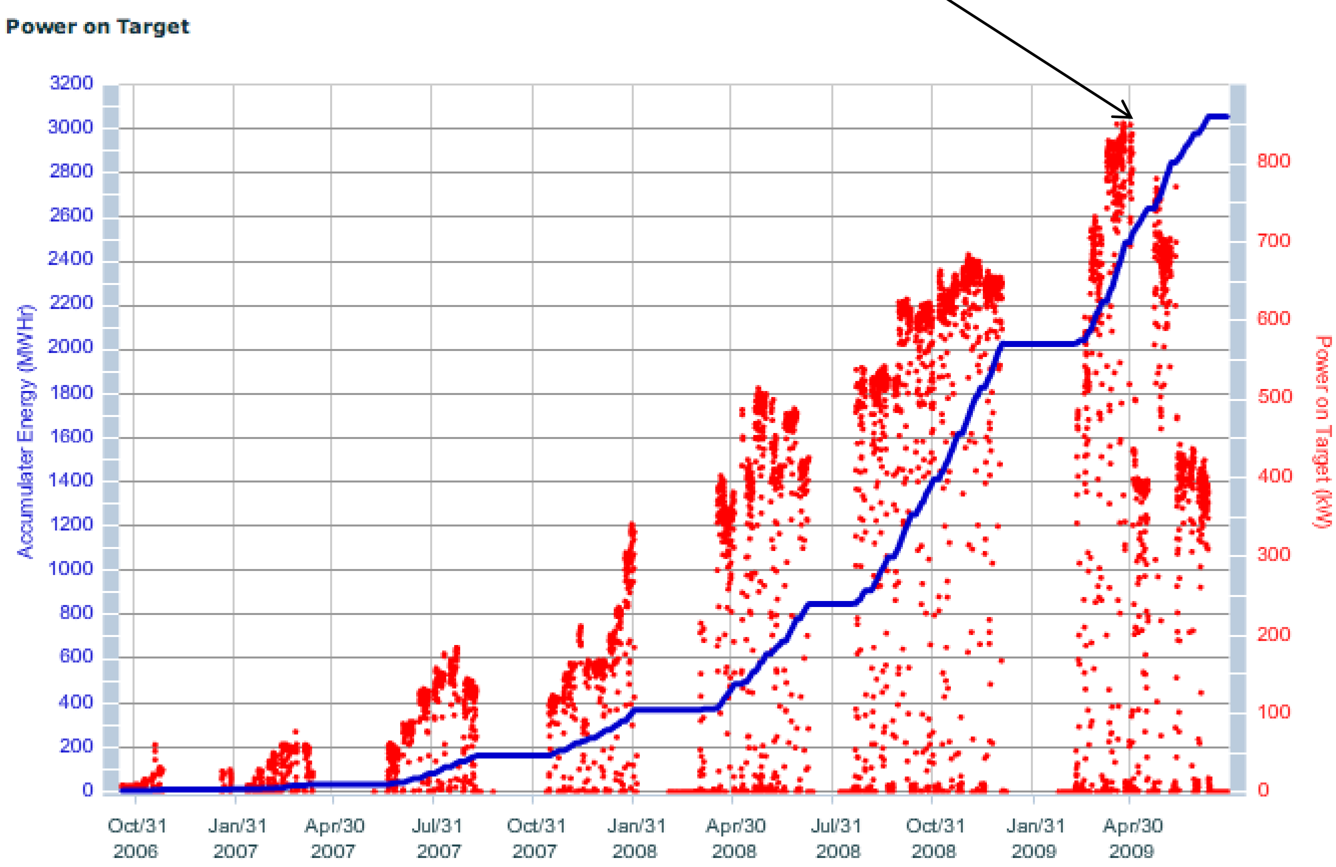


4th gen., used Sep/09 to present
Ti bracket, SS washer, +1 cm position

Photos by Chris Luck

SNS beam power history

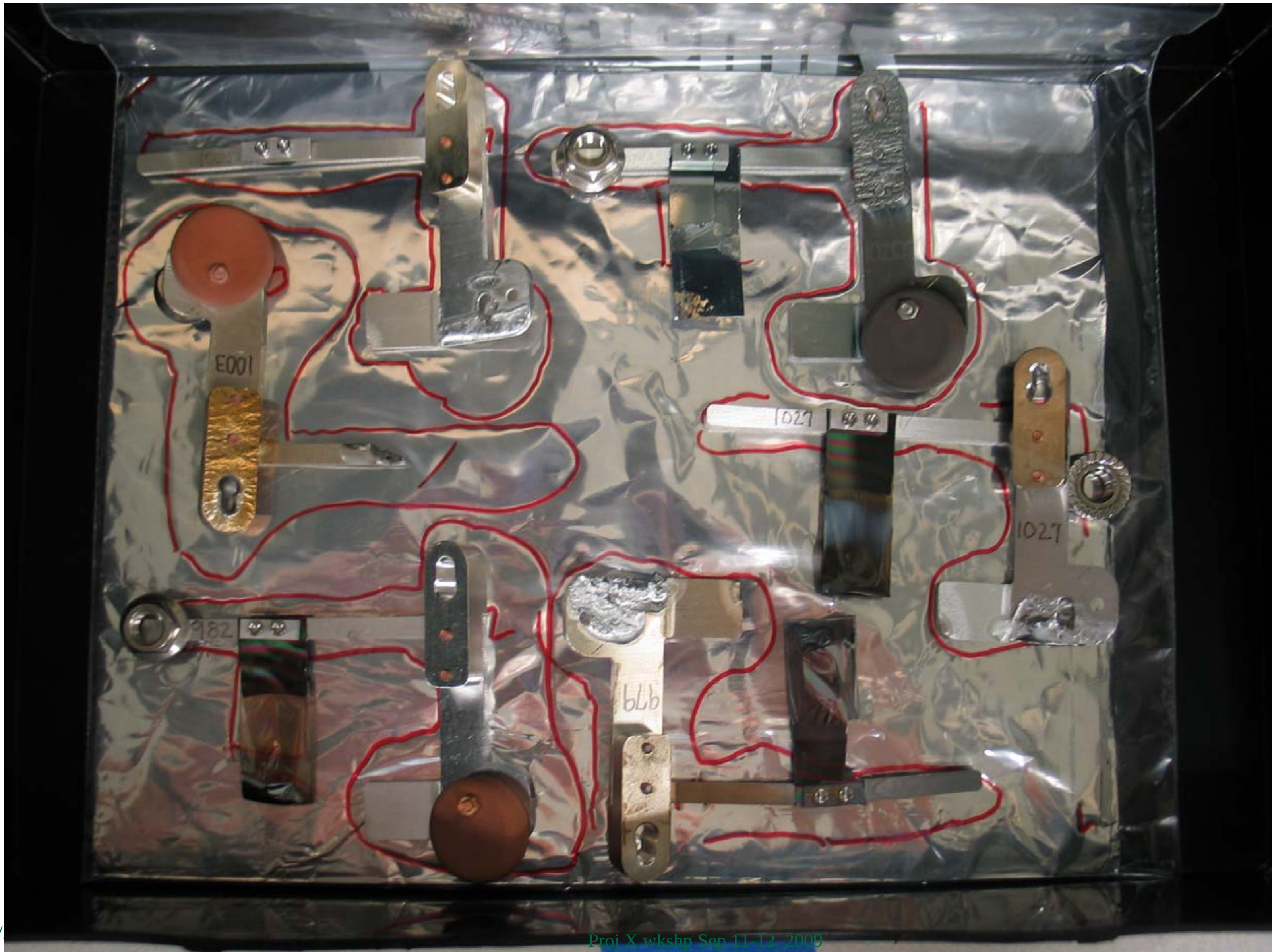
Until May 3, 2009, power ramp up was proceeding nicely and stripper foils were performing well. On May 3 we had our first foil failure.



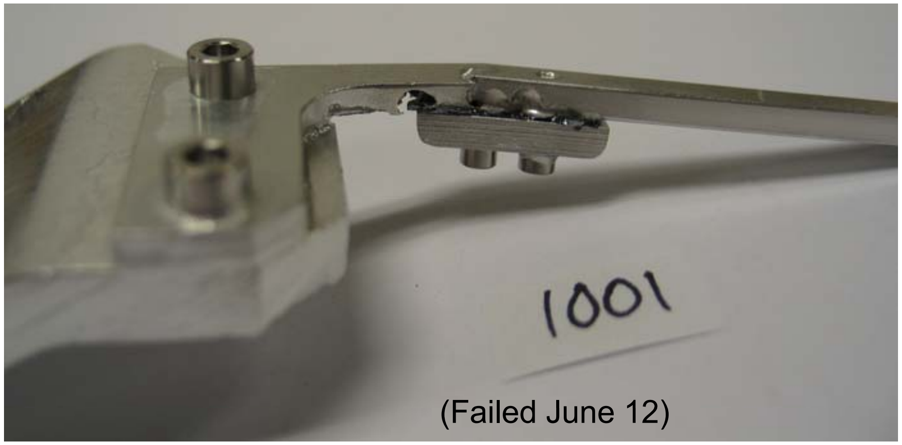
Oct '06 to July '09

Typical foil damage before May 3

All six foils used for production beam from March to the May 19, 2009 change out



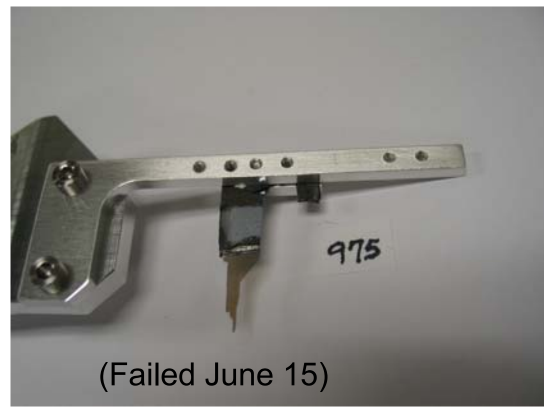
Foil failures (cont.)



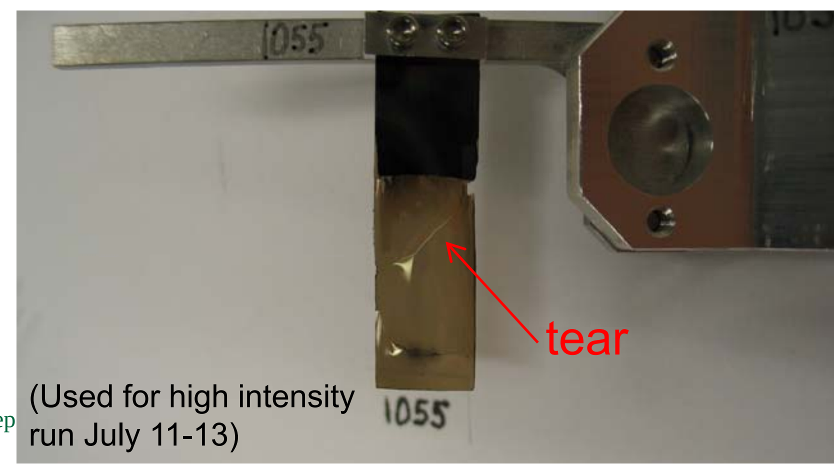
(Failed June 12)

(Failed May 3)

(Failed May 3)



(Failed June 15)



(Used for high intensity run July 11-13)

Photos by Chris Luck

Boroscope snapshots on 19/May/09

Inventory of foil issues

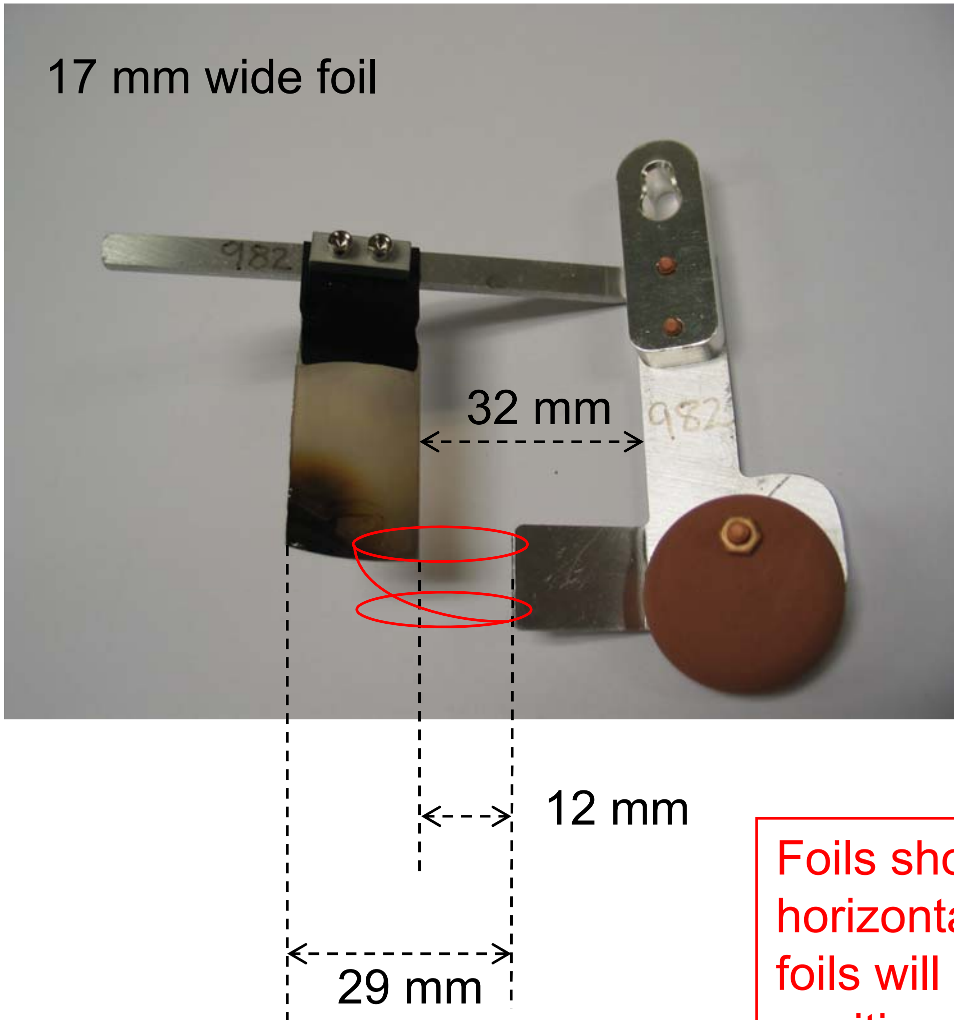
- Counterweights falling off
- Bracket melts where foil is attached
- Foils break where foil is attached to silicon, and where the silicon meets the bracket
- Foils have bright beam spots (and very high heating?) for a few weeks following May 3.
- Material deposited / evaporated on foils, brackets, and other nearby components
- Foil brackets stick to the pin they hang from
- Some foils have much higher A13b losses
- Foil corner curls up after a while

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 SEM and maybe 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:
  - Trailing edge multipacting electrons complicated by Al coating on vacuum chamber
  - 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

Convoy electrons hitting bracket

12 mm gyroradius electron



<u>Melting points</u>
Aluminum = 660 ^{o}C

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.

Vacuum Breakdown

Estimate of voltage on an isolated foil in the SNS Ring:

Assume:
- 1 MW ops (1e14 ppp)
- 10 pf foil capacitance to ground (just a rough estimate for now)
- 0.02 SEM coeff (good to factor of 2 or so)

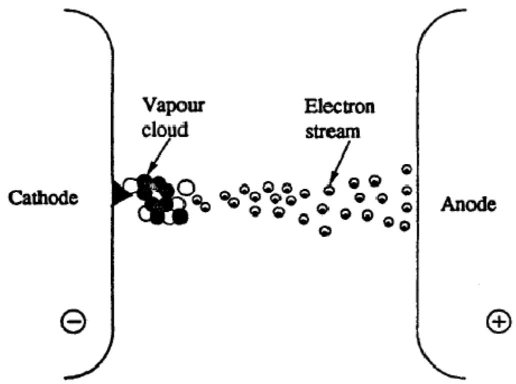
V = Q/C = (1e14 ppp) (10 hits/prot) (0.02 SEM) (1.6e-19 Coul/prot) / (10 pF)
= (3.2e-6 Coul) / (10 pF)

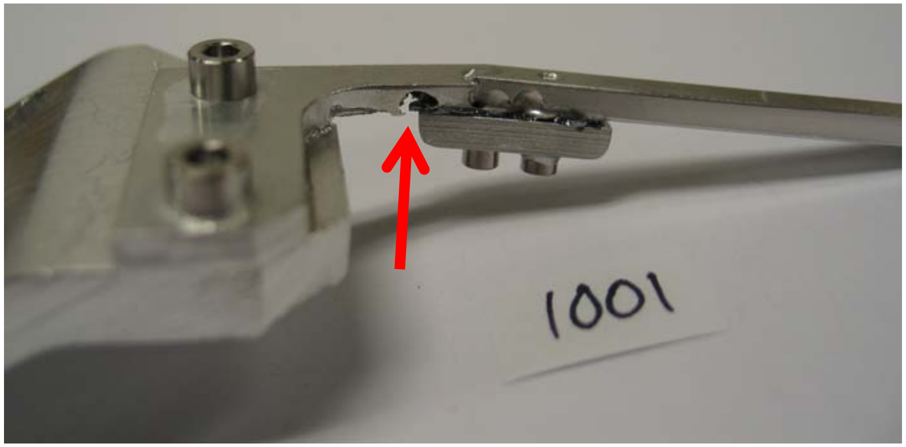
= 320,000 V **per pulse** !!!

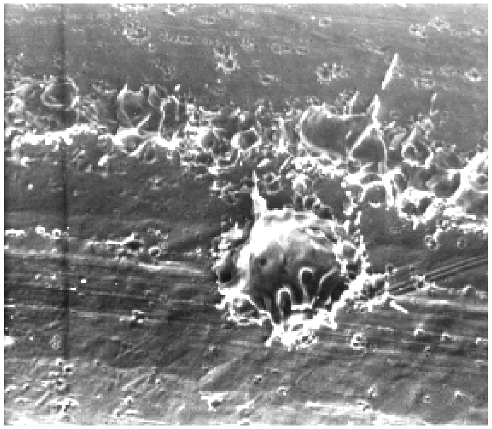
Could be even higher if foil is also charged by thermionic emission

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… This leads to "micro-explosions," and one can observe microscopic craters left on the cathode surface."
(From http://pag.lbl.gov/Proj_VacArcRes.htm)





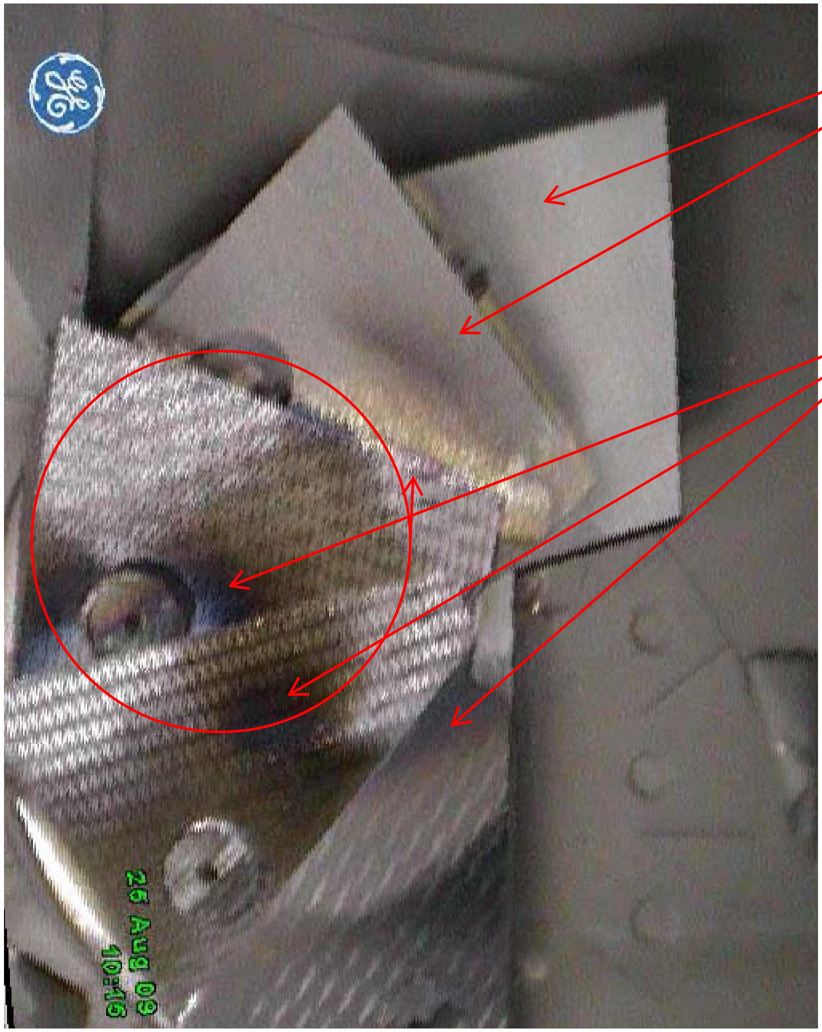


Crater traces left by cathode spots
(Picture taken with an electron microscope).
From http://pag.lbl.gov/Proj_VacArcRes.htm

Reflected convoy electrons

- The position of the electron catcher in the installation drawings may not be correct, and the as-built vacuum chamber cannot be positioned according to the installation drawings (prelim. #'s: Δx = 7 mm, Δz = 11 mm)
- The position of the injected H^- beam was shifted ~8 mm beam left to accommodate problems in the injection dump transport
- This causes the convoy electrons to hit the top surfaces of the carbon-carbon electron catcher blocks
- Interior surfaces of the vacuum chamber were coated with Al due to the bracket melting problems
- All of the above contributes to convoy electrons reflecting off the electron catcher, rather than being absorbed by the catcher
- The electrons continue their counter-clockwise motion and spiral back upward

Convoy electron footprint (cont.)



Al coating

Electron impact

Bracket damage by refl. convoy e's

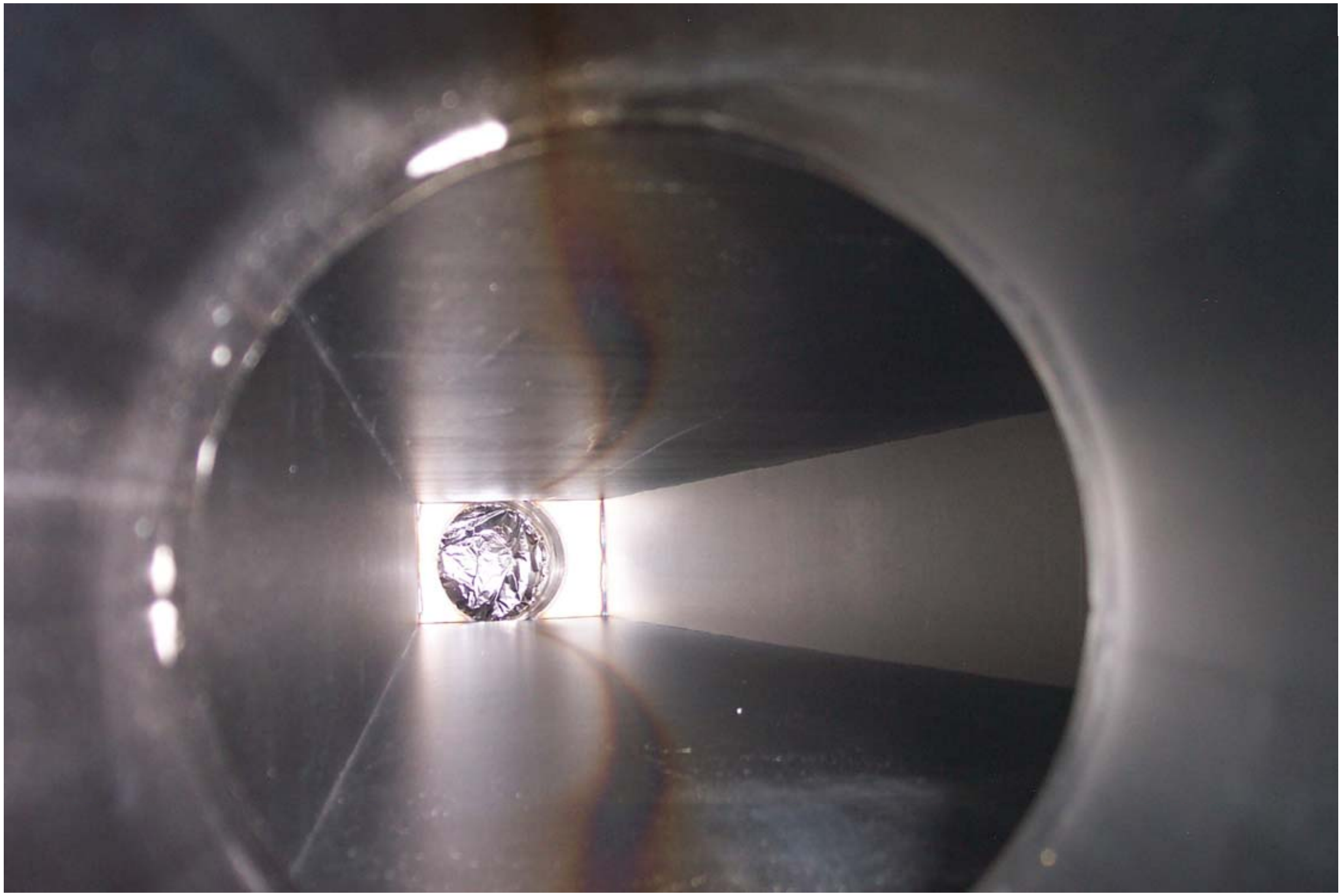
Photo by Chris Luck

Reflected convoy electron damage?

Graphitization at top of vacuum chamber

Could be reflected convoy electrons or trailing-edge multipactoring

Graphitization



Example of graphitization by multipacting electrons in SRBM11 at PSR. This is not a thermal effect!

(R. Macek, HB2008 & private comm.)

Foil and bracket modifications for Sep – Dec run

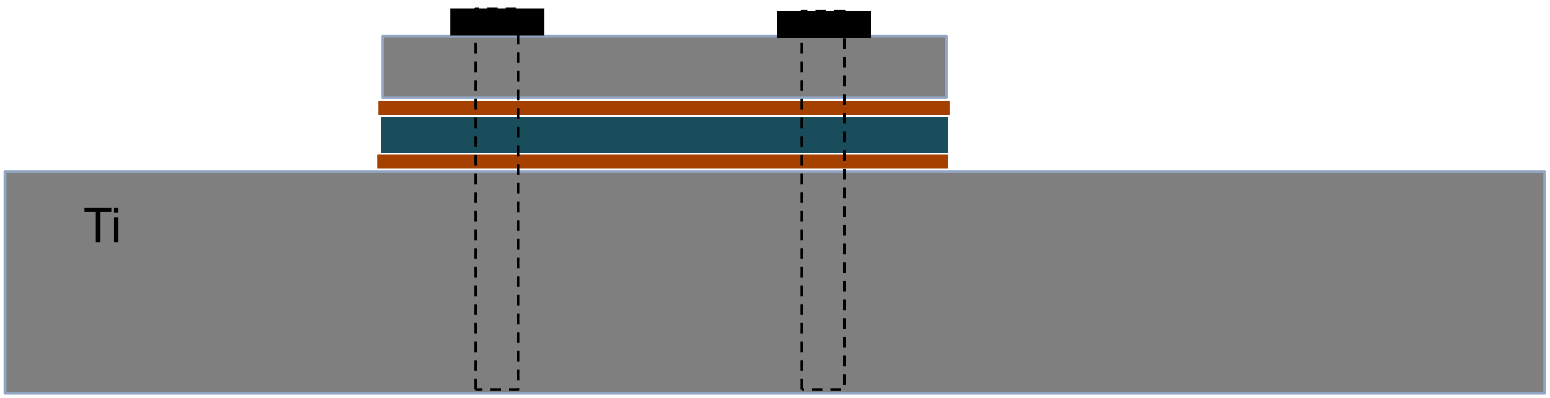
- The brackets have been modified:
  - High-temperature material with low coeff. of thermal expansion (Ti)
  - Bracket material removed from path of convoy electrons (both arm and leg cut off)
  - All foils mounted at the "+1 cm" position
  - Improved mounting method to make better electrical contact
- 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 will be stainless steel (no silver coated aluminum)
- There will also be one HBC foil, and one diamond foil mounted at an angle

New foil mount method

Foil mount for good electrical contact:

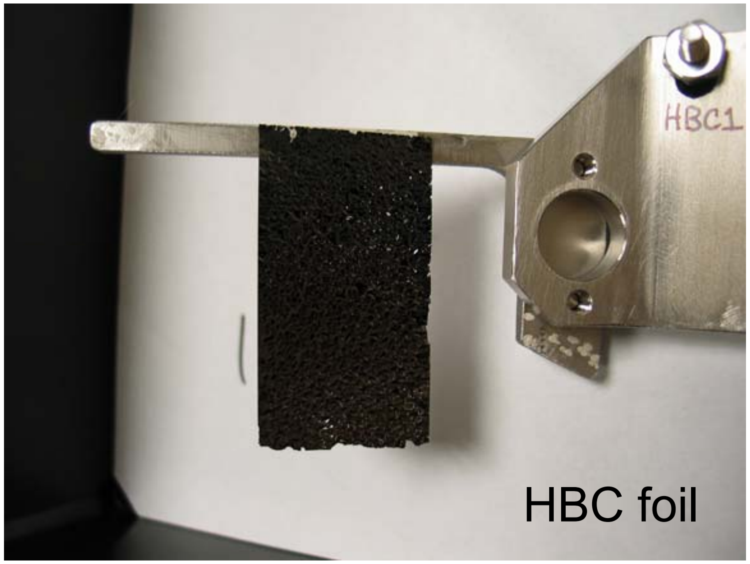
- machine flat then polish bracket and clamp
- sandwich Si substrate between thin sheets of Cu or Au (~0.001" thick)
- OR use conductive adhesive in place of Cu or Au sheets
- OR use all the above

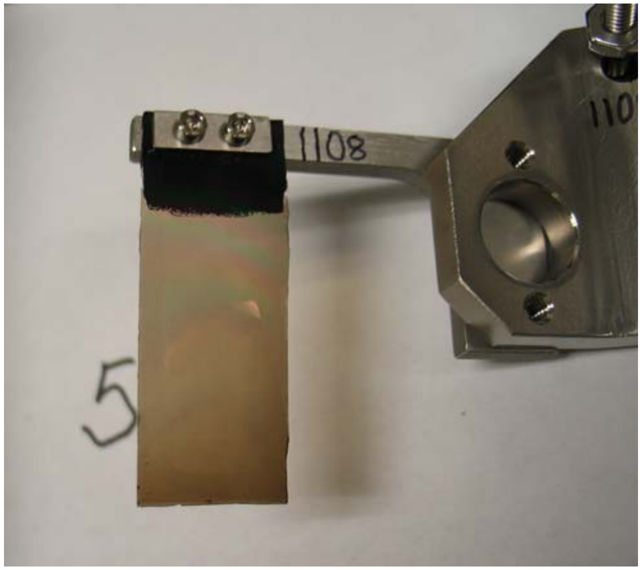
Still would like to use Bellville washers if we can find some non-magnetic ones

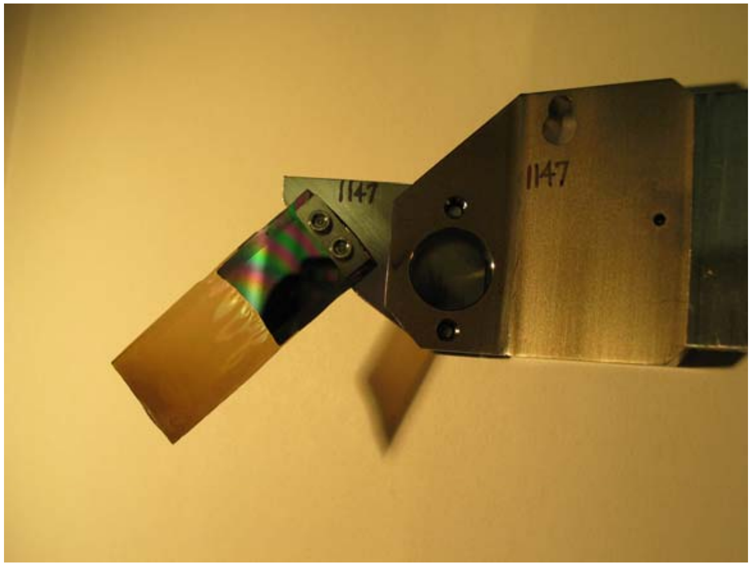


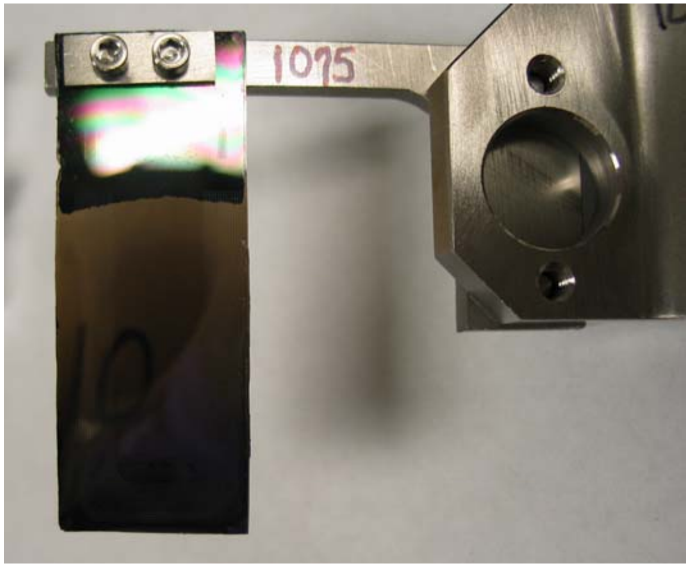
Sep – Dec run: about half the foils will be mounted using ~1.1 mil thick gold. No Bellville washers, no conductive adhesive. Brackets machined to a flatness spec then polished.

Foils installed Aug. 31, 2009









Photos by Chris Luck

Lessons learned

- Stripper foils in magnetic fields are a tricky business
- Electrical signals from the foil are valuable. PSR has made very good use of them, and this would have been a big help with our stripper foil problems. (Our next-generation mechanism will have this capability.)
- Be careful with stripper foils that are not good conductors
- Particle tracking studies through 3-D magnetic fields are valuable – they could have prevented some of the injection regions problems we've experienced at SNS

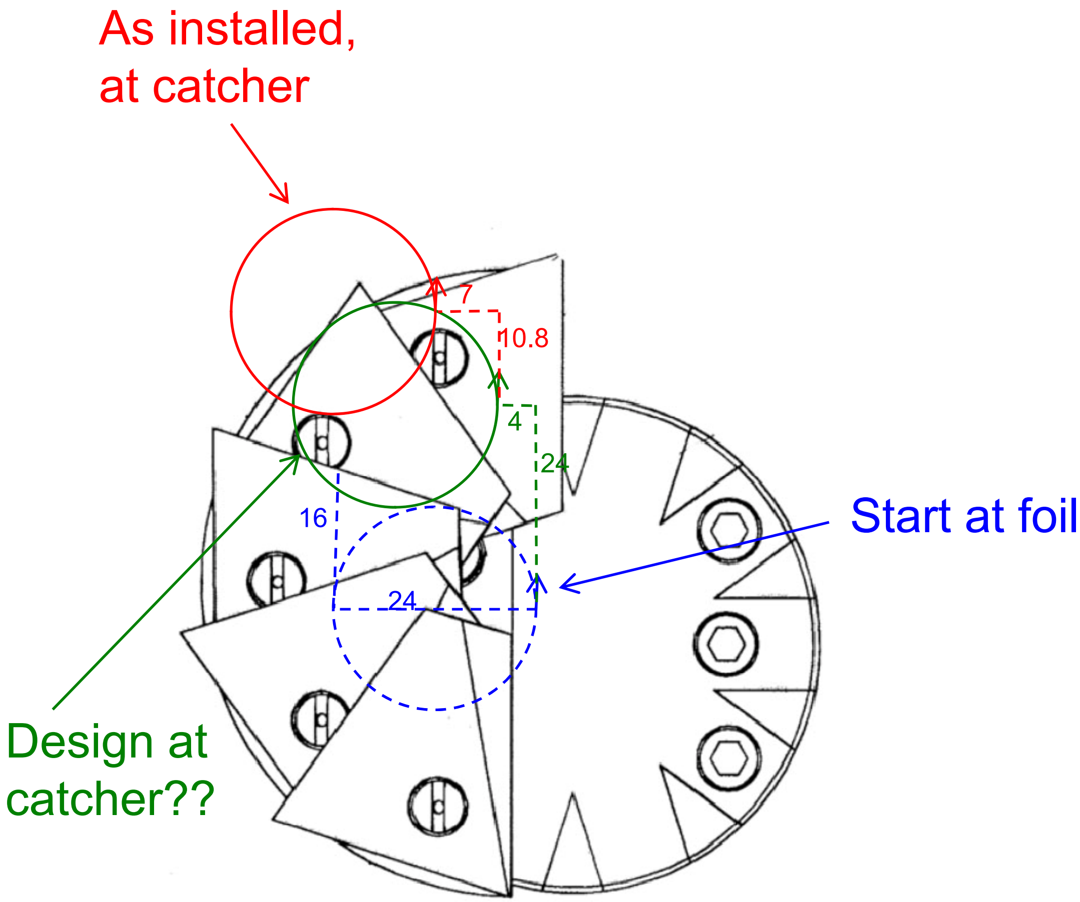
Summary

- Our best guess to date is that we have multiple foil failure mechanisms, and the biggest ones are vacuum breakdown, reflected convoy electrons, and trailing edge multipacting
- The Sep – Dec run has new Ti brackets, new foil mounting method, and diamond foils with a longer free length
- Also an HBC foil, and a diamond foil mounted at an angle
- The new instrumentation (foil camera, temperature measurement, clearing electrode, faster vacuum update rates) should help us to understand what is going on

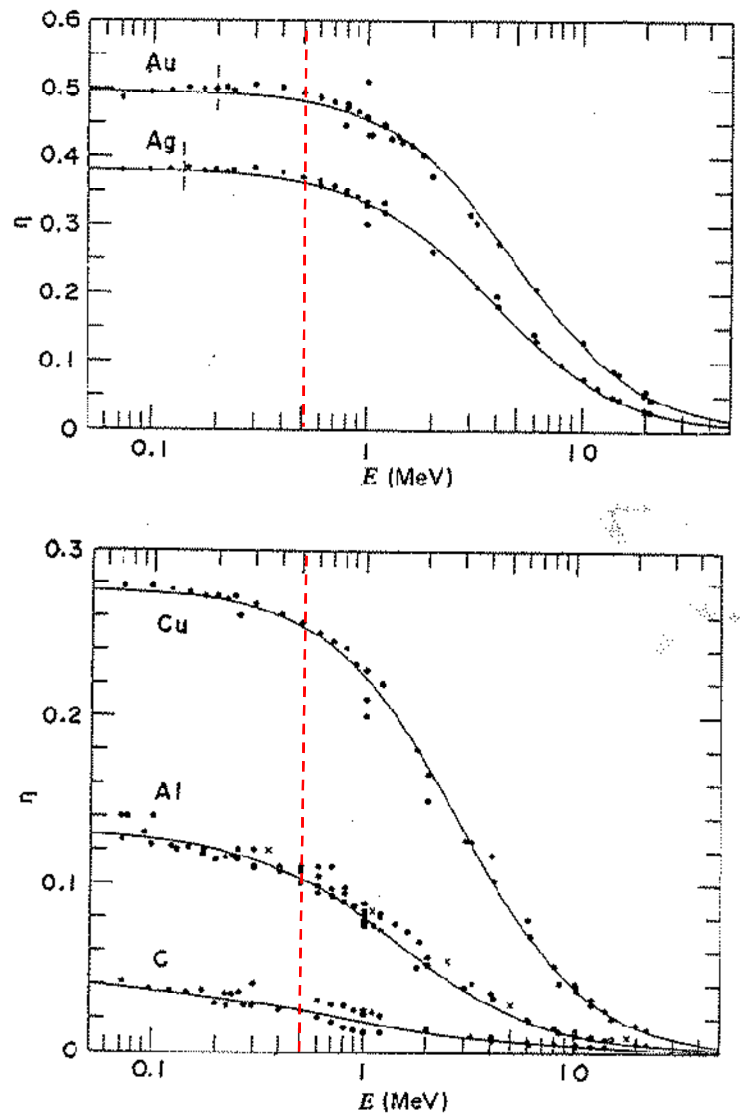
Thank you for your attention!

Back up slides

Convoy electron footprint on catcher

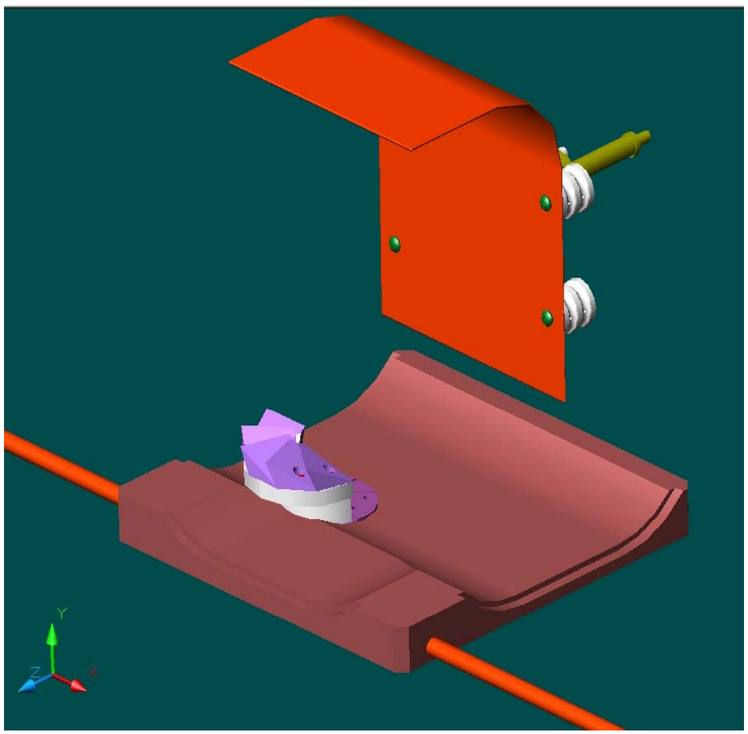


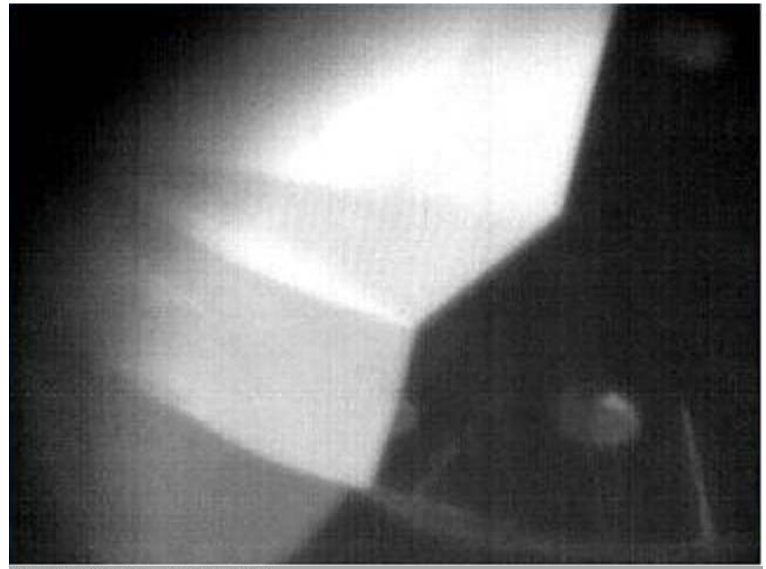
Fraction of electrons backscattered. (Knoll, "Radiation Detection and Measurement")

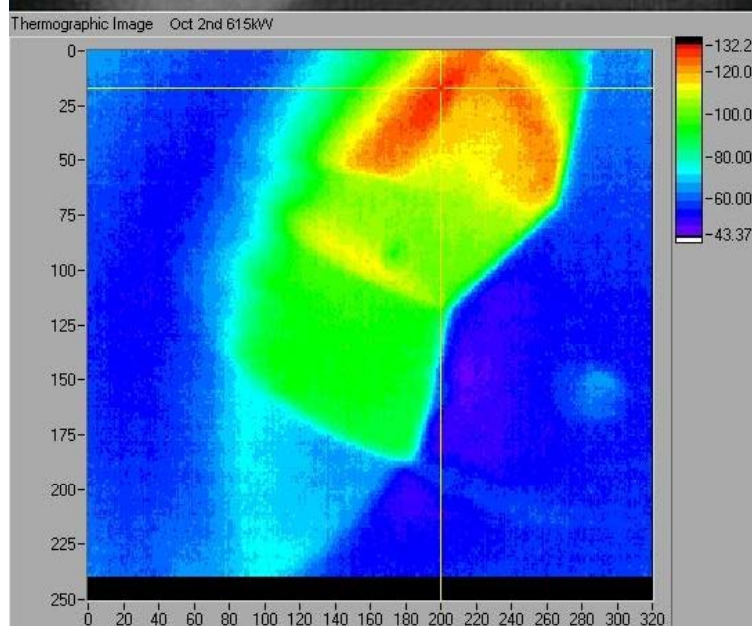


Electron collector temperature measurement (G. Link, S. Murray III)

Measured the temperature of the carbon-carbon electron collector is 130 ^{o}C for 625 kW beam, (~12 ^{o}C lower than expected)





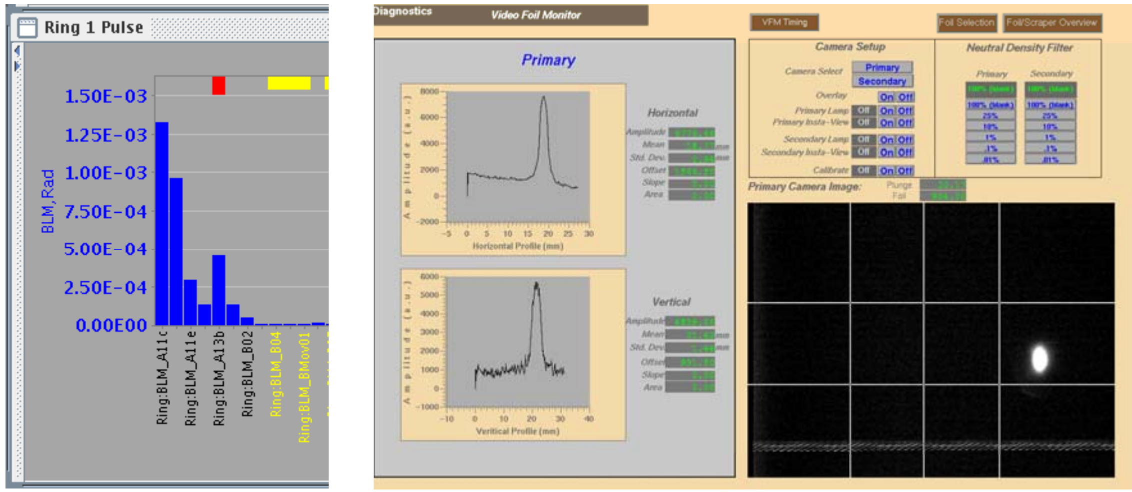


Bright beam spots

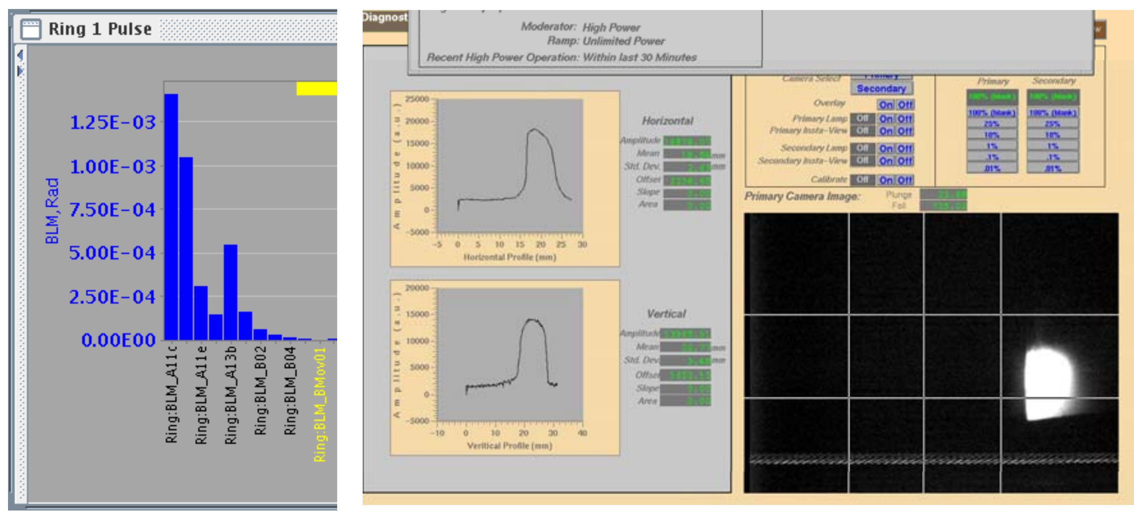
Typical spot up until ~May 3, 2009

Brighter spots are not accompanied by higher beam loss, so it can't be due to more protons hits

We believe that the brighter spot means higher foil temperature



May 1, 2009, 820 kW, 344 ug/cm^2



May 3, 60 Hz, 9:38, ~840 kW, 386 ug/cm^2

Foil failed shortly after

Bright beam spot (cont.)

- We don't have a good explanation for the bright beam spots. Our best guess is that it is related to the aluminum deposited on the vacuum chamber walls. This could affect the reflected convoy electrons, the secondary emission electrons, and the trailing edge multipacting (all electron-related)
- The good news is that they seem to have returned to normal in the weeks following their first occurrence on May 3

Foil brackets stick to pin

- This problem first showed up in fall 2008
  - Aluminum snap ring on same pin as bracket adhered to bracket by galling or melting
- Brackets redesigned and installed February 2009
  - But these had the counterweight and tab problem. Sticking would have been good in this case!
- 3rd generation brackets installed May 19, using silver plated aluminum washers
  - But this design also causes sticking / pinching
  - Best guess is that the silver plating on the washers de-laminates, and the washer effectively expands to pinch the bracket against the shoulder of the pin
- 4th gen, installed Aug. 31, 2009, has Ti brackets, stainless steel washers, no plating

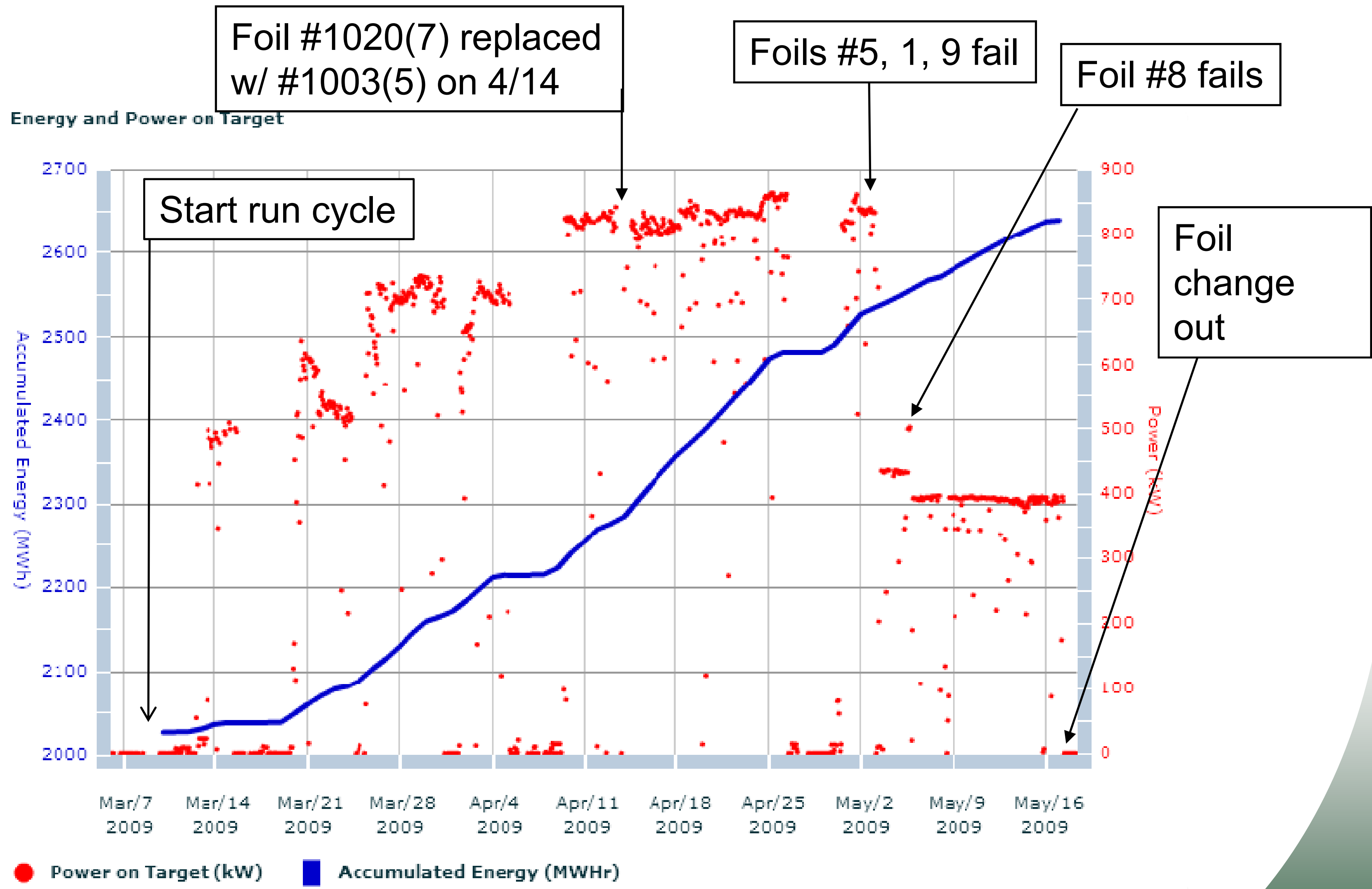
Brief history of SNS stripper foils

- Started diamond foil development program at ORNL in 2001. These foils worked successfully with no failures* until May 3, 2009, when we started experiencing a rash of foil failures after increasing the beam power to ~840 kW. After a few more failures, the beam power was reduced to ~400 kW.
- Until the next foil load on May 19, all but one** failure (the first) can be attributed to convoy electrons hitting the foil bracket, causing the counterweights to fall off. Vacuum chamber becomes coated with aluminum.
- On May 19, we installed a new batch of foils (first time for a mid-cycle foil change out). New foil brackets were used to fix the convoy electron issue. We returned to high power operations (~800 kW), but we saw two more foil failures. The beam power was reduced to ~400 kW for the rest of the run cycle.
  - At ~400 kW we used three foils due to fluttering and problems with beam delivery to the IDmp
- A new run cycle is about to start, with new brackets and a new mounting scheme…

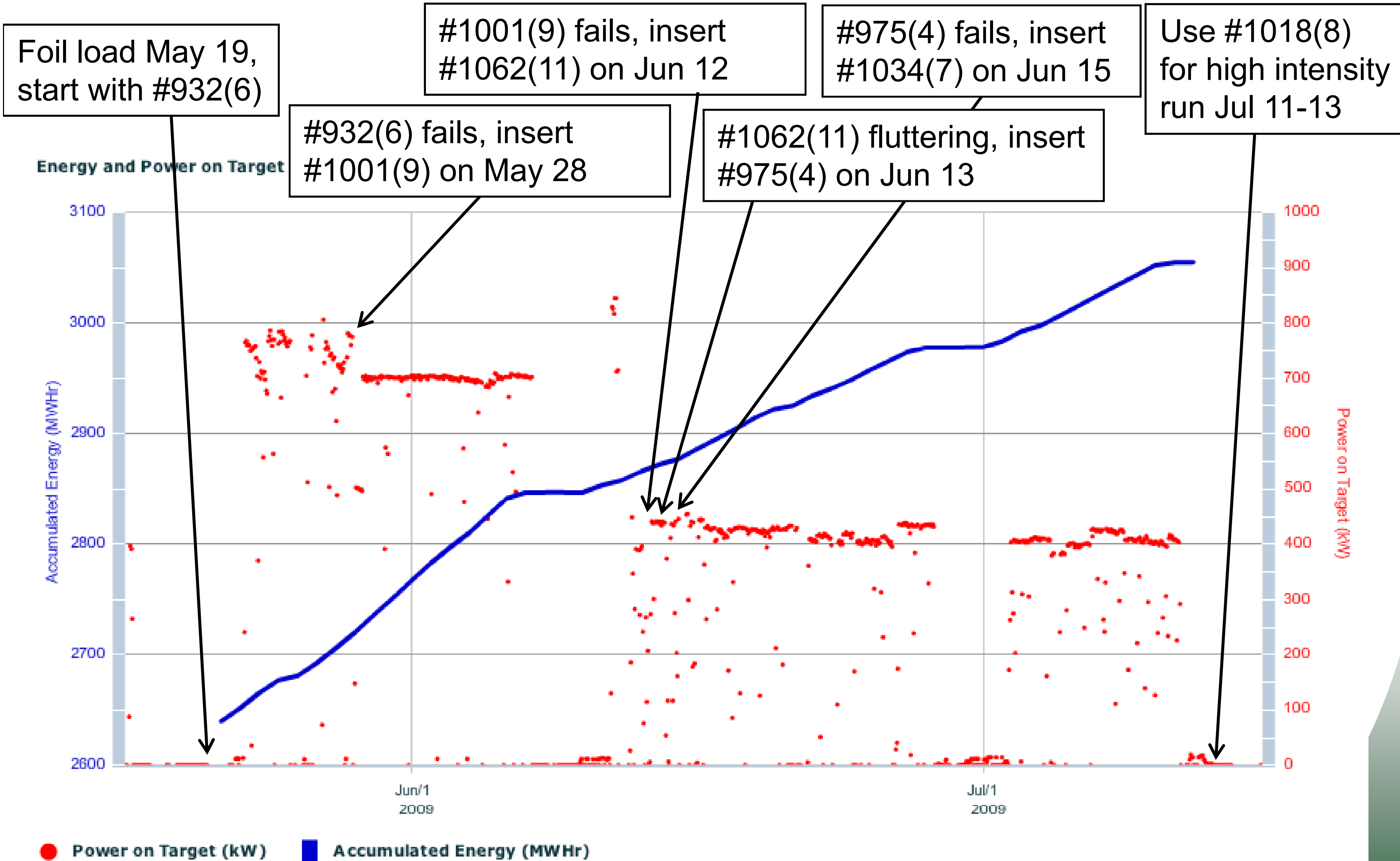
* There was one failure during commissioning during a high intensity study, before we had good control over foil position.

** Also had “fluttering” issue with the first foil used in this production run. First time that “fluttering” became an issue.

Foil failure time line for first load

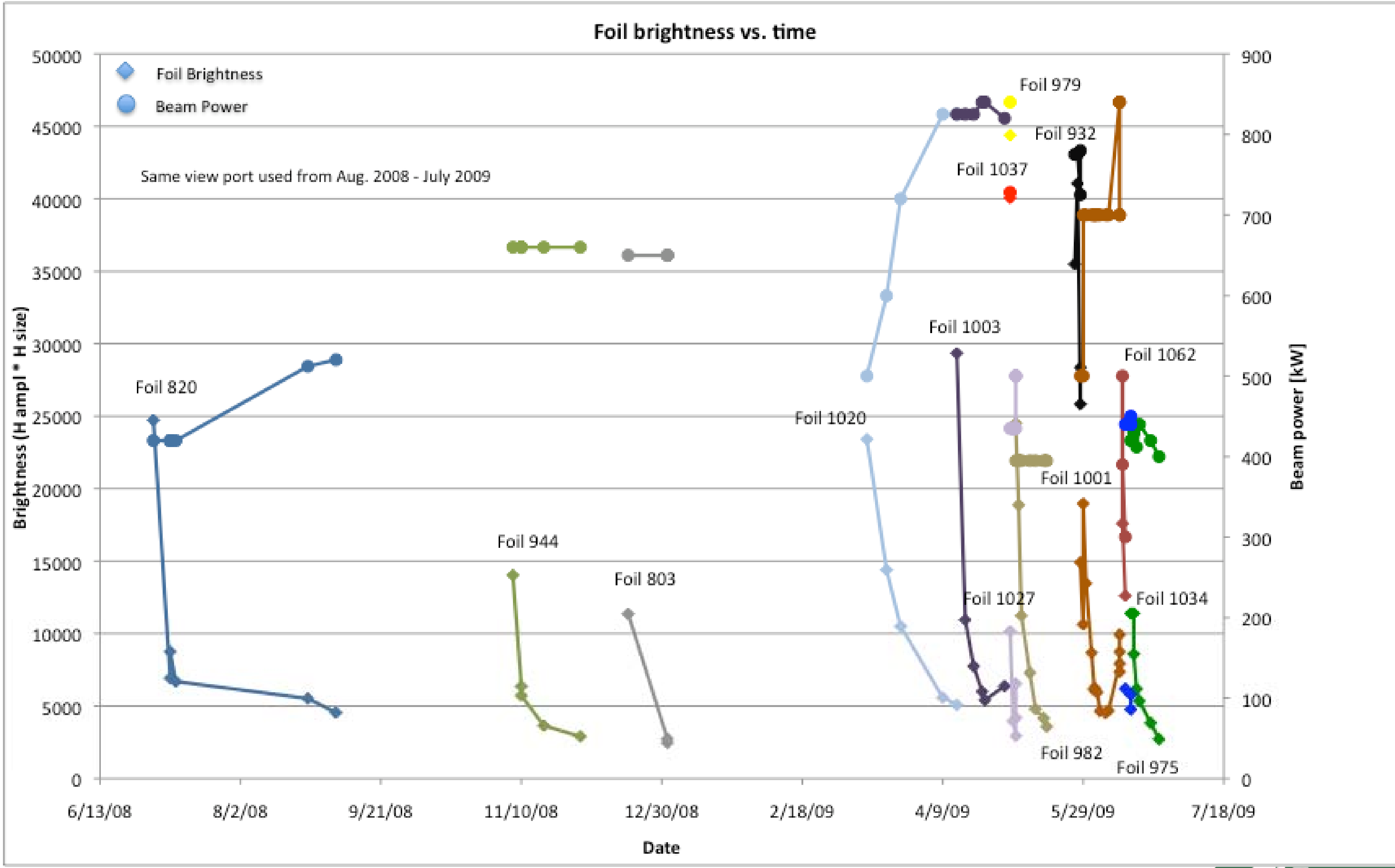


Foil failures from second foil load

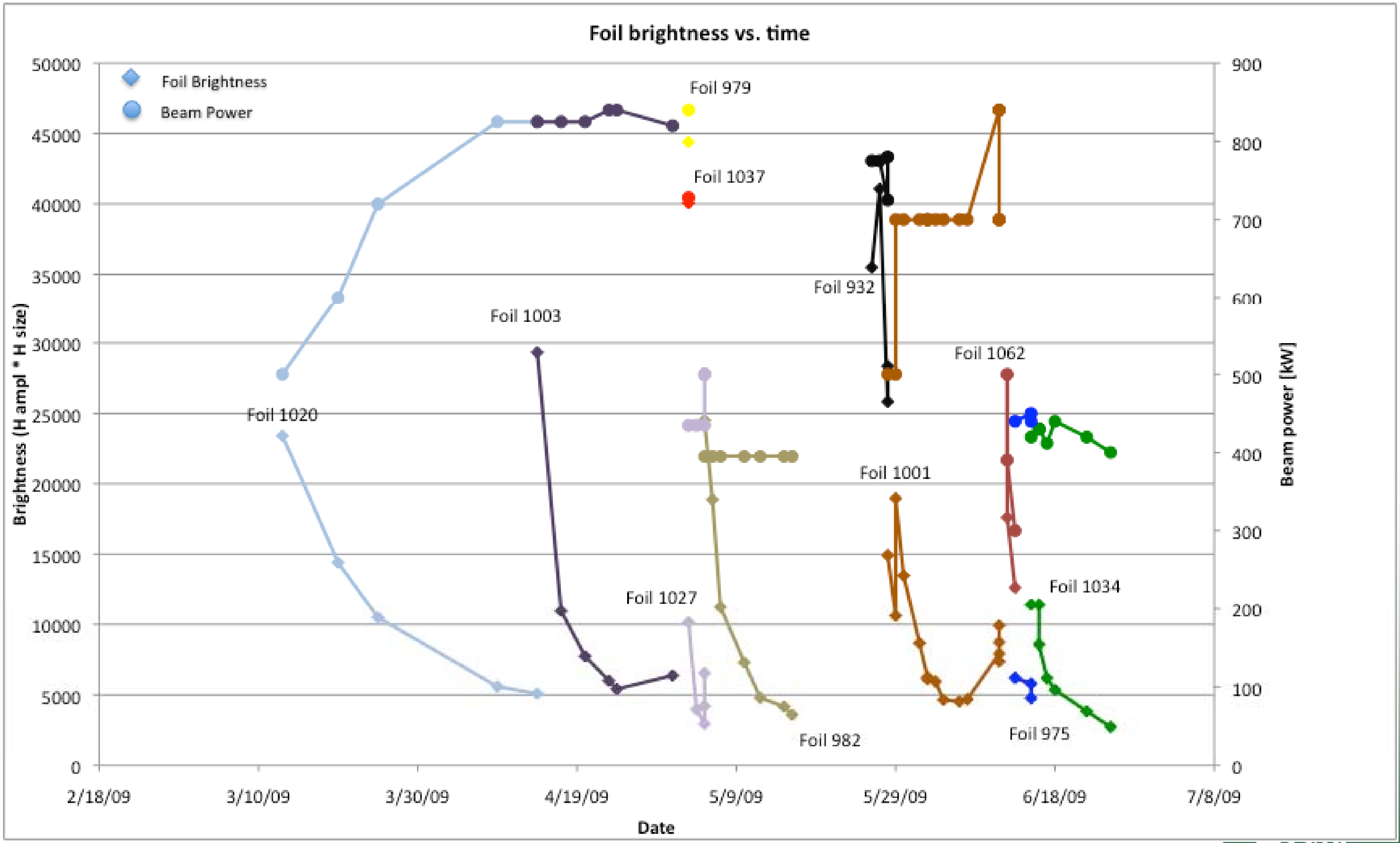


Boroscope images from 25/Aug/09

Bright beam spot (cont.) (C. Peters)

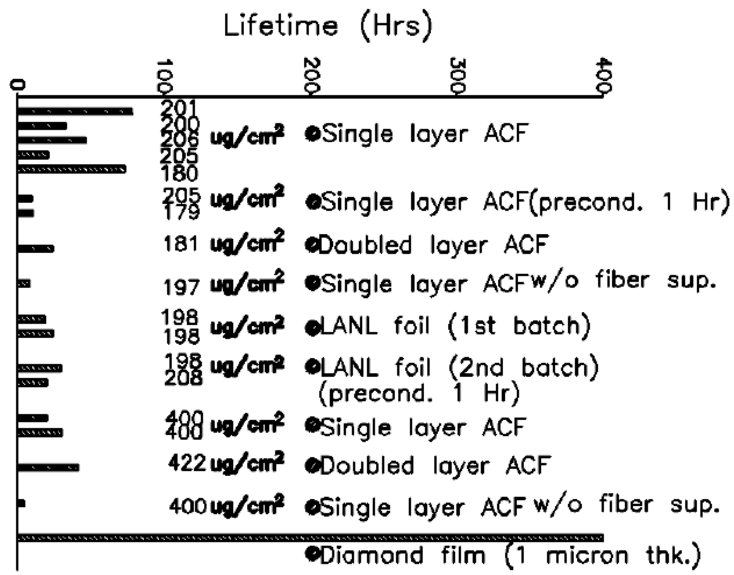


Bright beam spot (cont.) (C. Peters)



Alternative foil technologies

- We started with diamond foils at SNS because tests at BNL showed that diamond was better than ACF carbon and LANSCE AC-DC carbon. Until May 3, they were working great.
- New HBC foils developed for J-PARC, also look promising. We are installing one of these for this next run.
- A UT-ORNL collaboration has a proposal in the works to develop B_4C foils for SNS



(C.J. Liaw, PAC01)

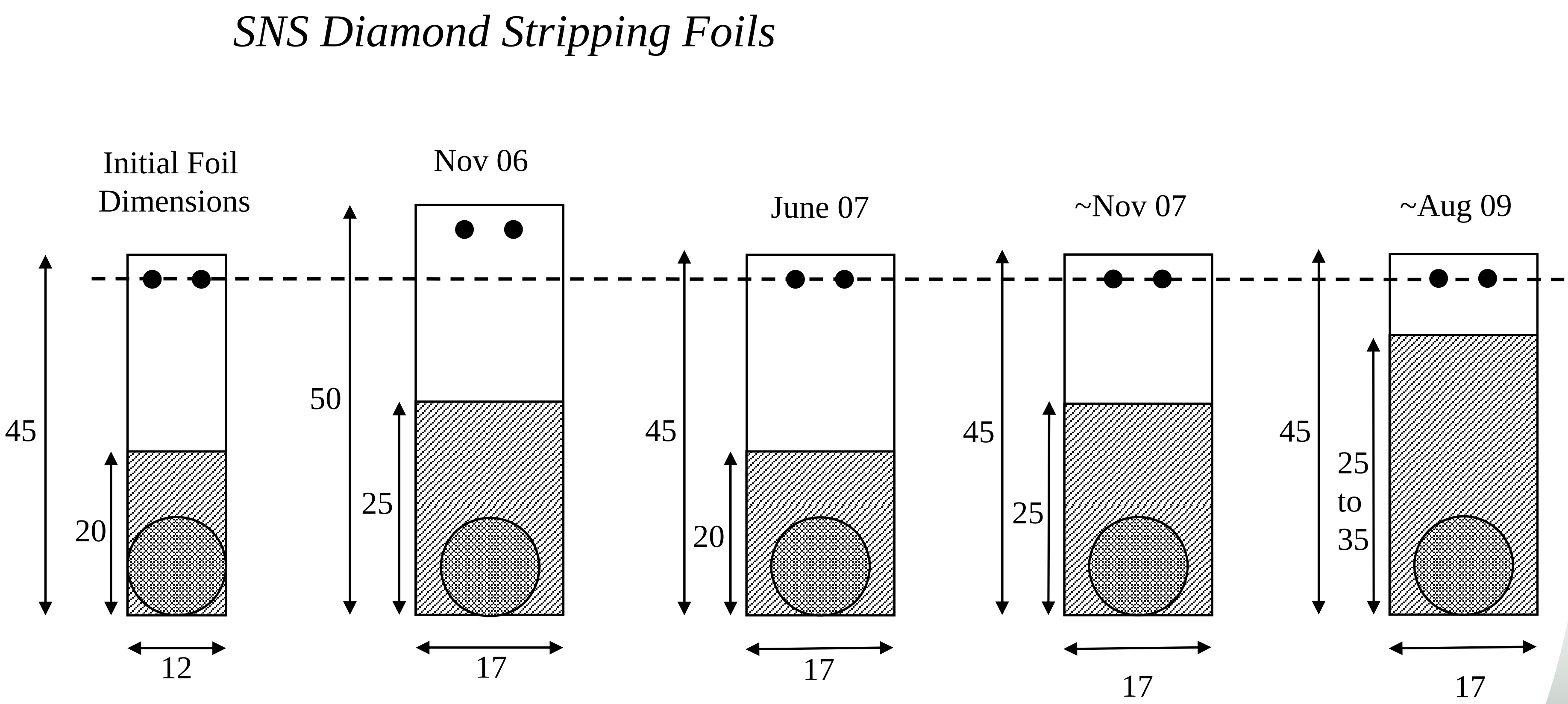
New instrumentation for this run cycle

- Temperature measurement, based on two cameras with narrow bandwidth filters, installed this outage by BI Group
- New video foil monitor camera
- Clearing electrode new cable and new +/-20 kV power supply. This power supply will be able to be controlled from CCR
- Faster update rates on the vacuum gauges and ion pump currents

Foil thickness

- Foil thickness is a trade off between stripping efficiency and beam loss in the ring caused by H^0 excited states and foil scattering
- The SNS design foil thickness is 260 ug/cm^2, based on model simulations and optimizations.
  - Stripping efficiency is 97% when a foil of this thickness is mounted at a 30 deg angle.
- It is a challenge to make diamond foils of this thickness. Hence most of the foils that we install will be 300 to 350 ug/cm^2.

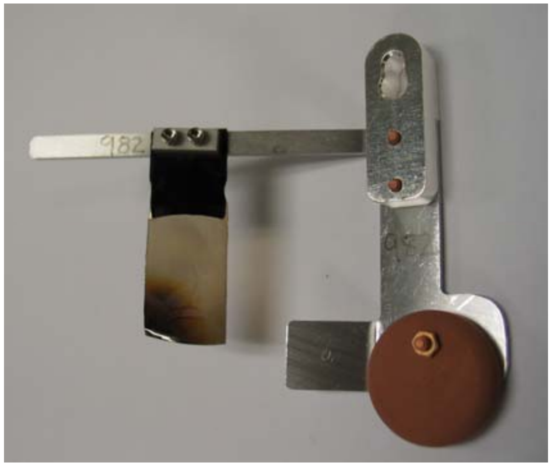
SNS foil size evolution



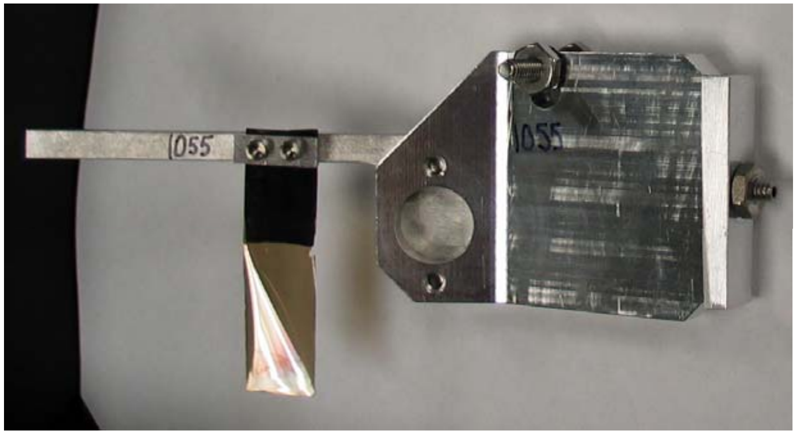
Sep – Dec run: All foils will be 17 mm wide (except the HBC foil). Free lengths will vary between 25 and 35 mm.

Foil brackets – 3 generations

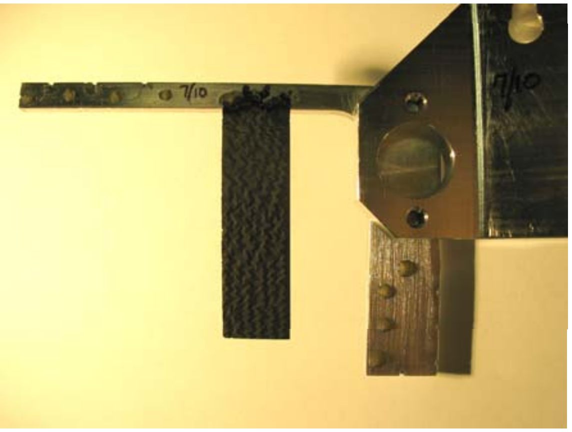
1st gen., used thru Jan/09
Aluminum snap ring washer, 1/8 inch thick



2nd gen., used Mar/09 – 17/May/09
Silver plated “tombstone” hanger, ~0.080” thick



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

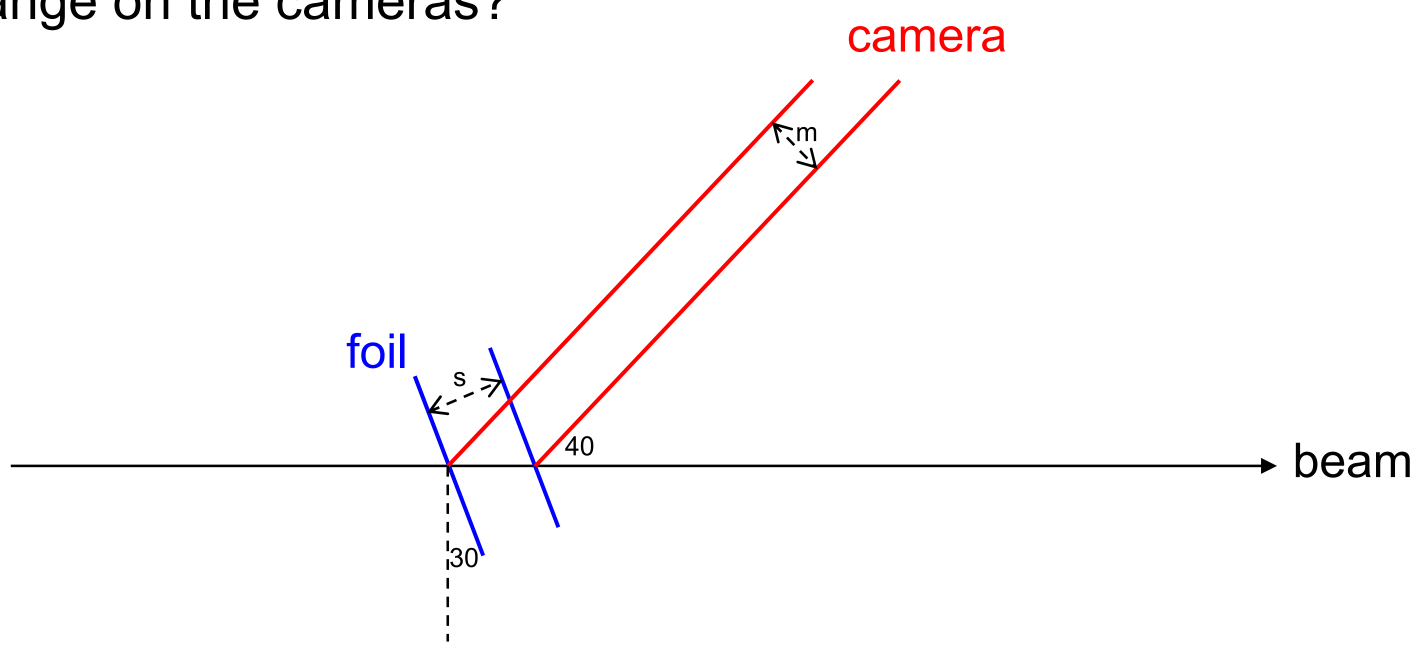


Special fiber supported foils
Thin carbon fibers support the foil

Foil flutter

First time that more than tiny beam spot movements were observed was with foil #1020, used from March – April 14, 2009

How much does the foil have to move by to see an apparent position change on the cameras?



If foil moves distance *s*, how much does the image on the camera move?

$$m = s \cos(30) \sin(40) = 0.557\ s$$

Foil flutter (cont.)

- Foil2.avi – spot moves 3 mm on camera
  - Corresponds to 3/0.557 = 5.4 mm foil movement
- Foil3.avi – spot moves 4 mm on camera
  - Corresponds to 4/0.557 = 7.2 mm foil movement
- This stripper foil, #1020, with “U sine” corrugations, was relatively floppy to start with. When removed, found that substrate was cracked and foil was partially separated from substrate. +/-3 mm is certainly possible.