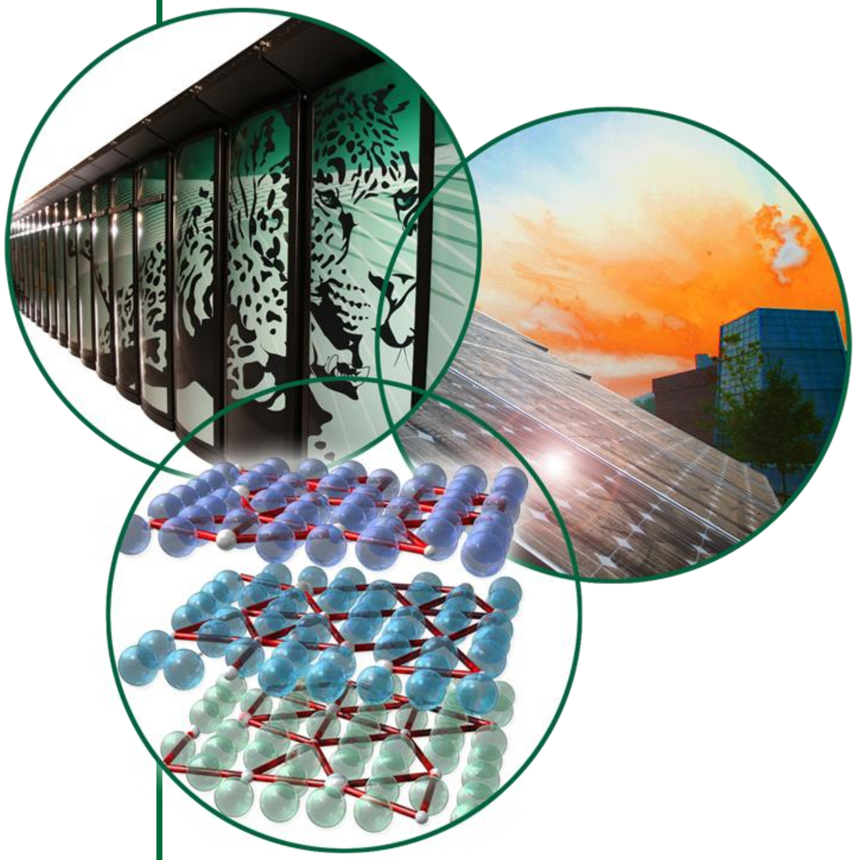
SNS Injection Foil Experience

HB2010
Morschach
Sep. 27 – Oct. 1, 2010

By Mike Plum, Ring Area Manager

On behalf of the Foil Task Force:
S. Cousineau, J. Galambos, S. Kim, P. Ladd, C. Luck, R. Macek (LANL), C. Peters, D. Raparia (BNL), R. Shaw



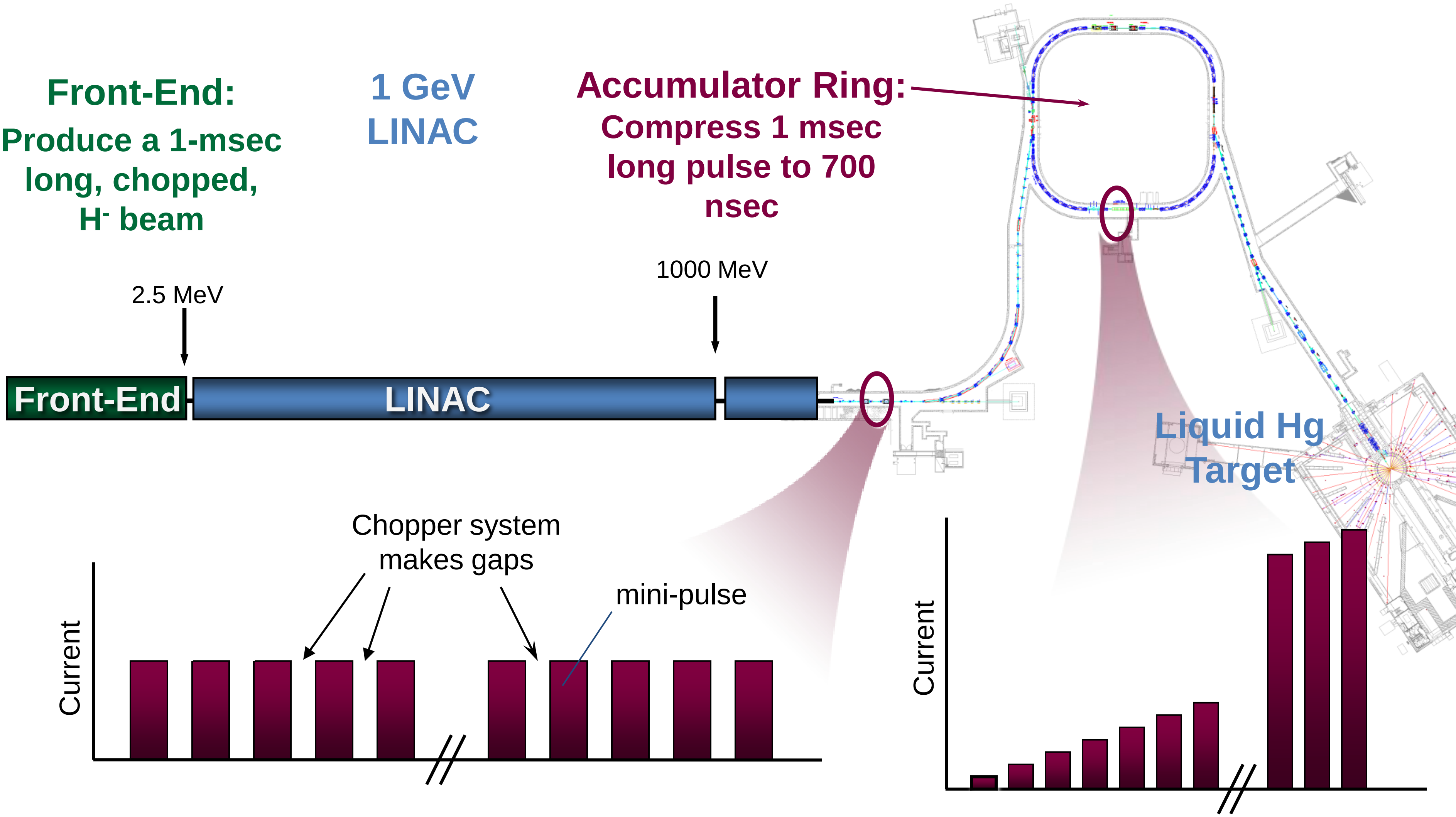
U.S. DEPARTMENT OF ENERGY

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

Outline

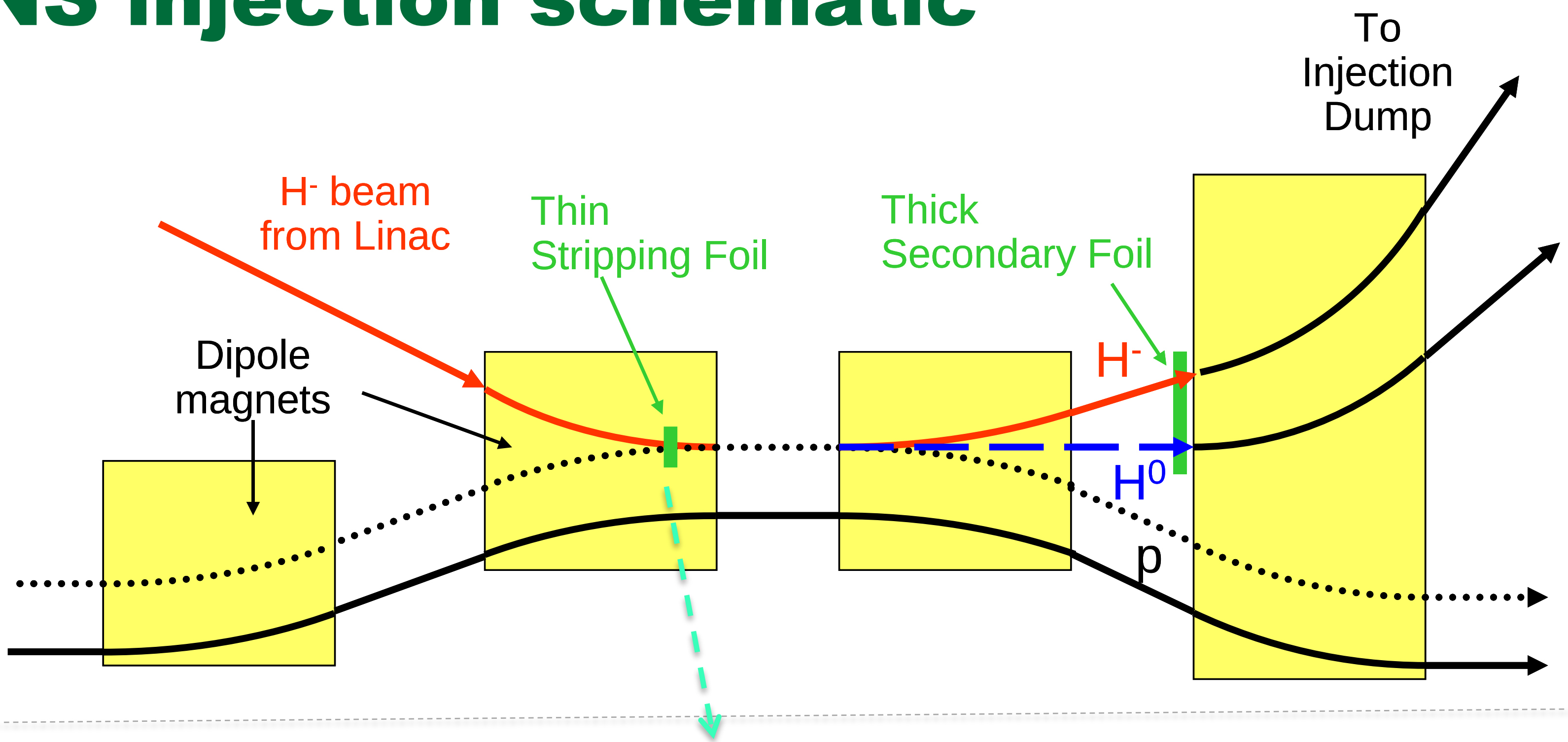
- SNS injection according to design
- Stripper foil failures and failure mechanisms
- What we did to mitigate the failure mechanisms
- Present status of SNS stripper foils

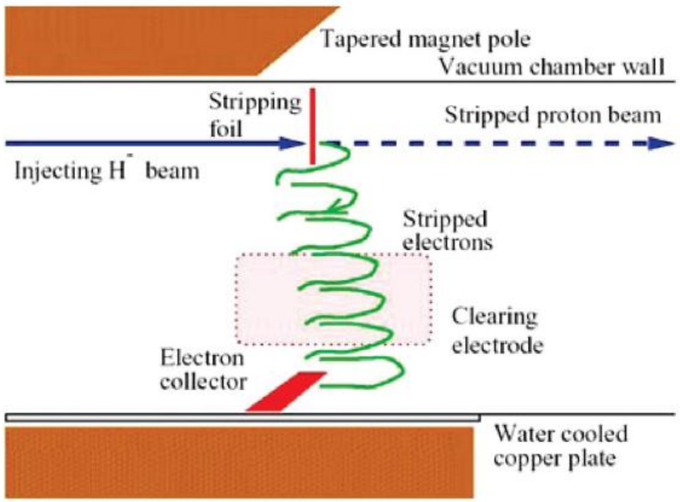
SNS Accelerator Complex



1.4 MW average power, 60 Hz

SNS injection schematic



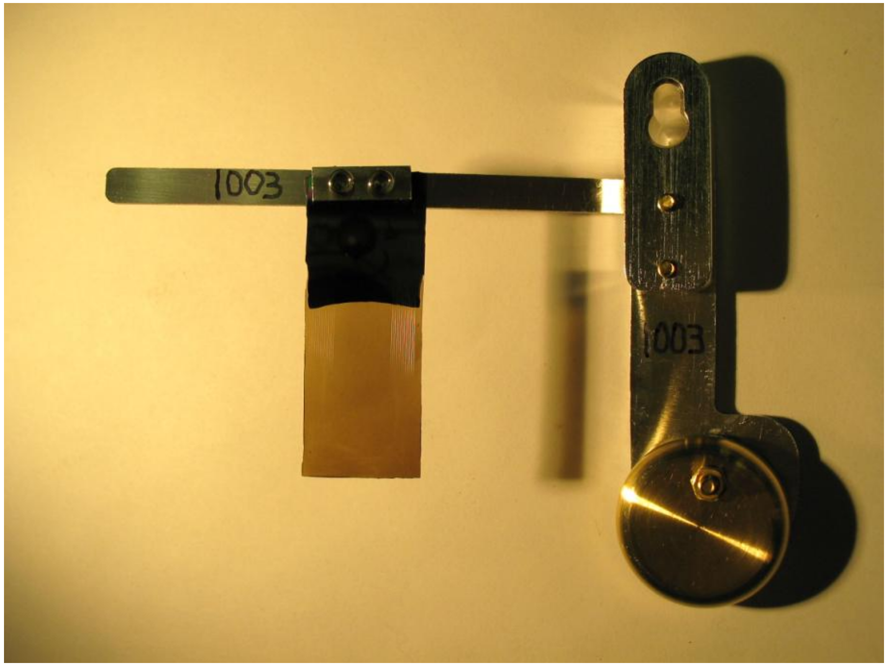


Brief history of SNS stripper foils

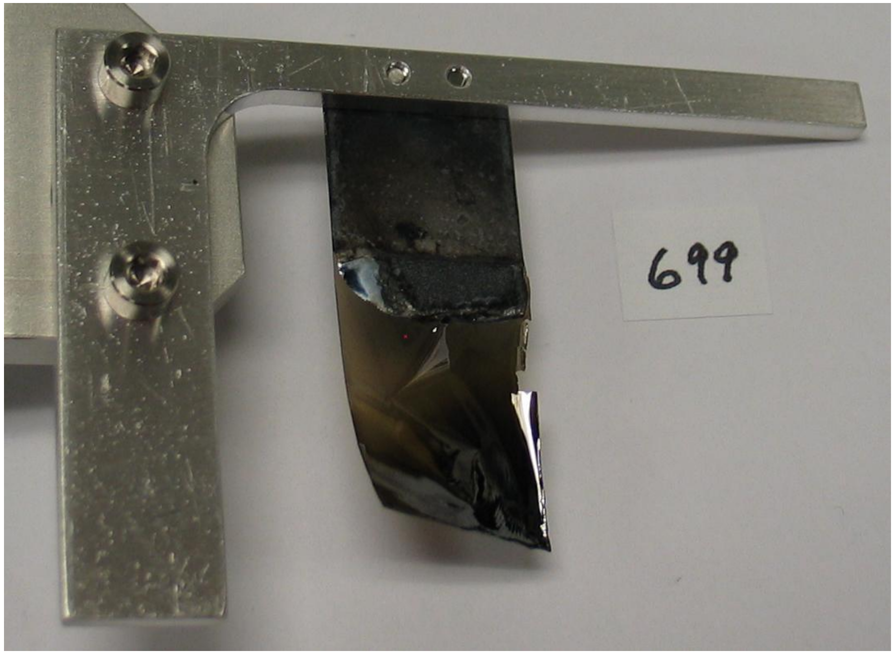
- Our home-grown diamond stripper foils worked successfully with no failures* until May 3, 2009, when we started experiencing a rash of foil failures shortly after increasing the beam power to ~840 kW. After a total of 3 failures on that day, the beam power was reduced to ~430 kW, and then to ~400 kW two days later after another failure.
- On May 19, 2009 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, 2009 using a new type of foil brackets, and a new mounting method, and slightly modified foils; and we have now completed two ~18 week run cycles using just one foil per run cycle, at beam powers up to ~1.08 MW. The foil lifetime issue seems to be solved (at least for now…)

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

Typical foil damage, prior to 3/May/09



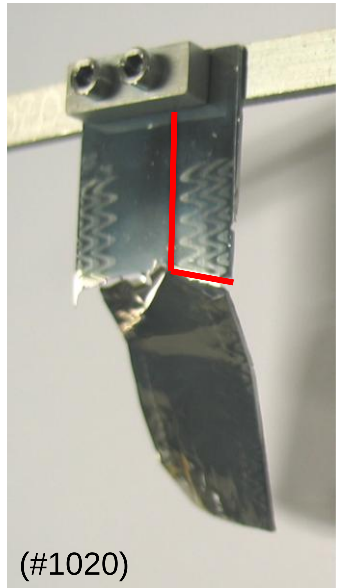
New foil

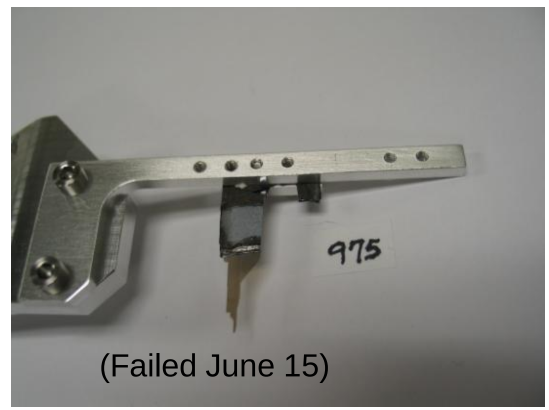


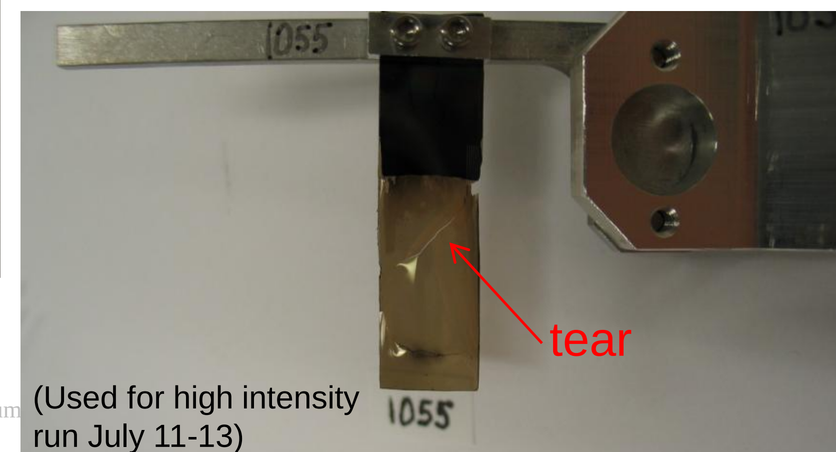
Typical foil damage before May 3, 2009

Typical foil:
- Nano crystalline diamond on Silicon substrate
- 0.350 mg/cm^2
- 17 mm wide, 45 mm tall
- (25-35 mm free standing height)

Foil failures

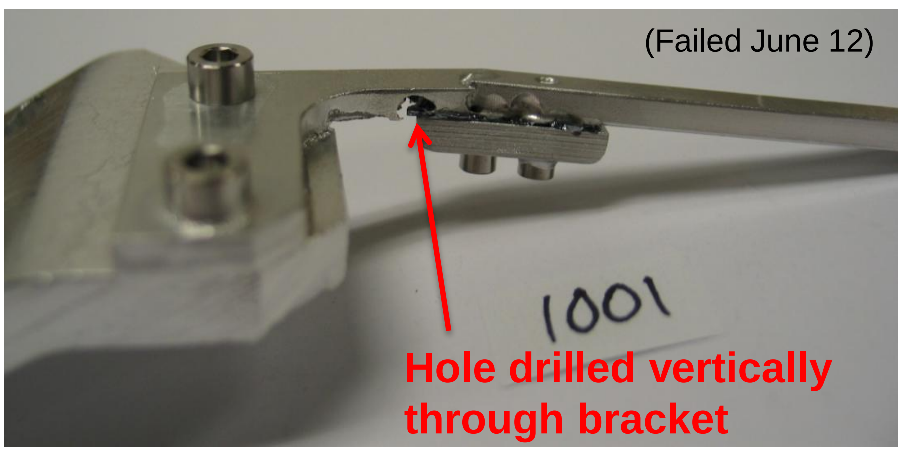


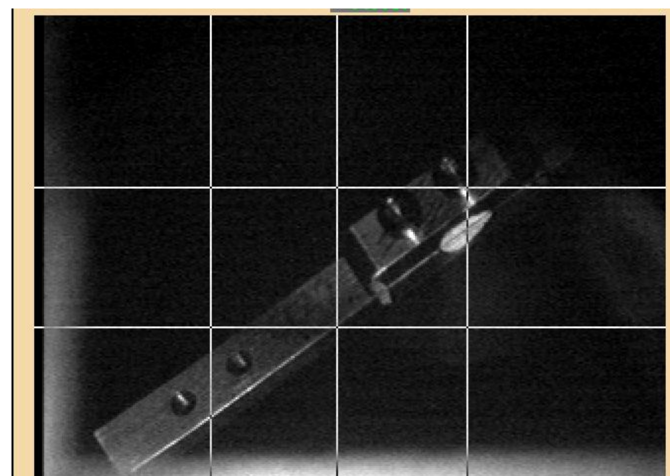




Photos by Chris Luck

Foil failures (cont.)





Foil #932, 28/May/09

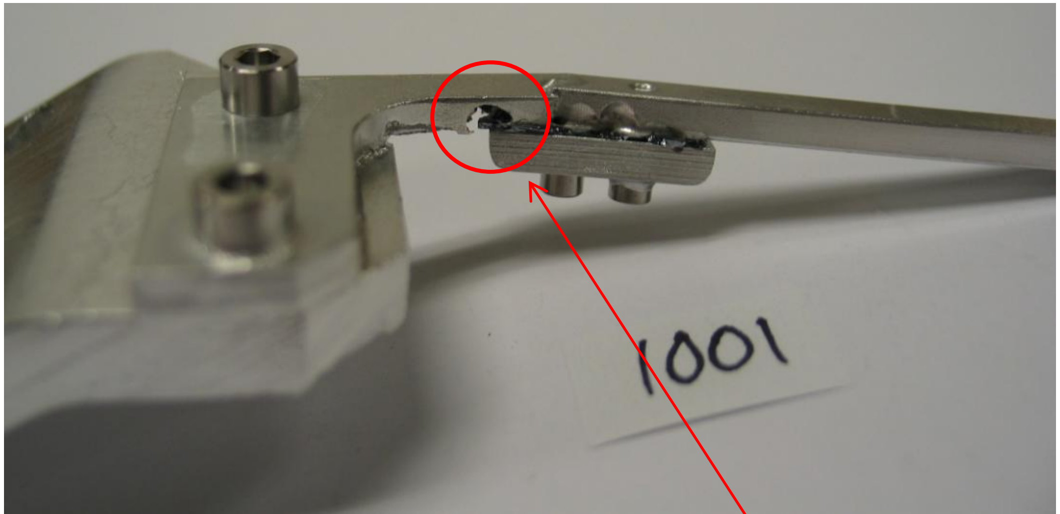
Photos by Chris Luck

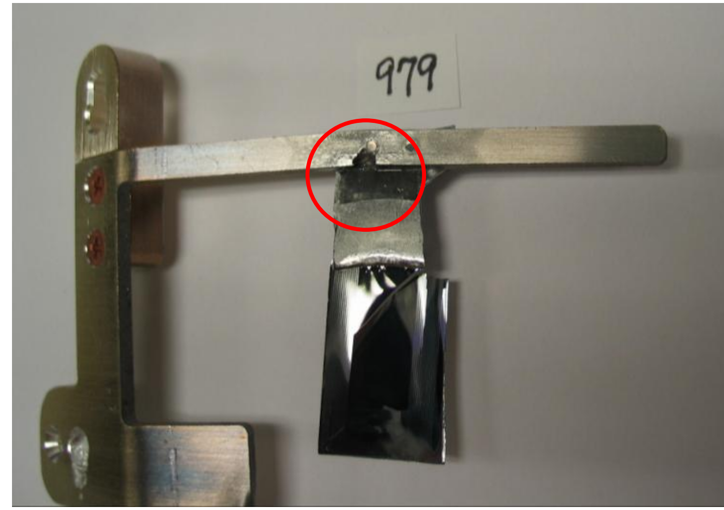
Causes of foil failures

- A primary cause is believed to be vacuum breakdown (arcing) caused by charge build up on the stripper foils, due to secondary electron emission (SEM) and maybe also thermionic electron emission
- Another primary cause is reflected convoy electrons striking the foil and bracket
- Some of our foil failures also involved convoy electrons hitting the foil bracket as they travel downward to the electron catcher
- Other contributing factors may be:
  - Aluminum coating (from previous foil bracket melting) on vacuum chamber which may increase the trailing edge multipacting electrons
  - Trailing edge multipacting
  - 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)

Photos by Chris Luck





Clearest evidence to date of vacuum breakdown

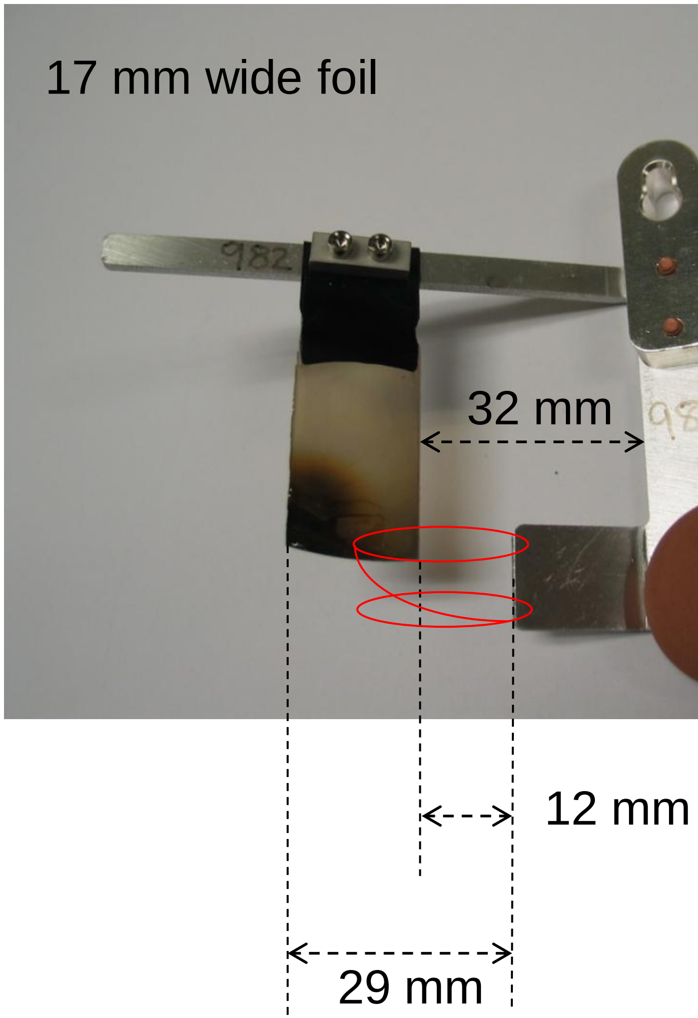
Estimate of voltage on an <u>isolated</u> foil in the SNS Ring:

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

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

Bracket failures and convoy electrons

Photos by Chris Luck

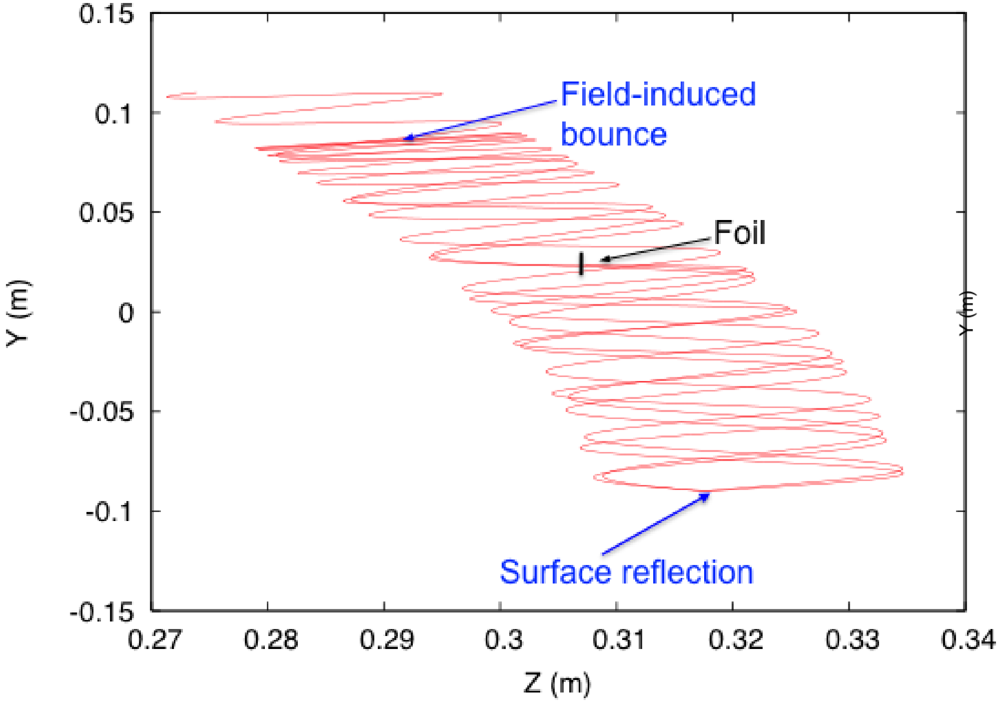


All this melted aluminum evaporated and was deposited on the vacuum chamber walls, other foil brackets, and everything else in sight

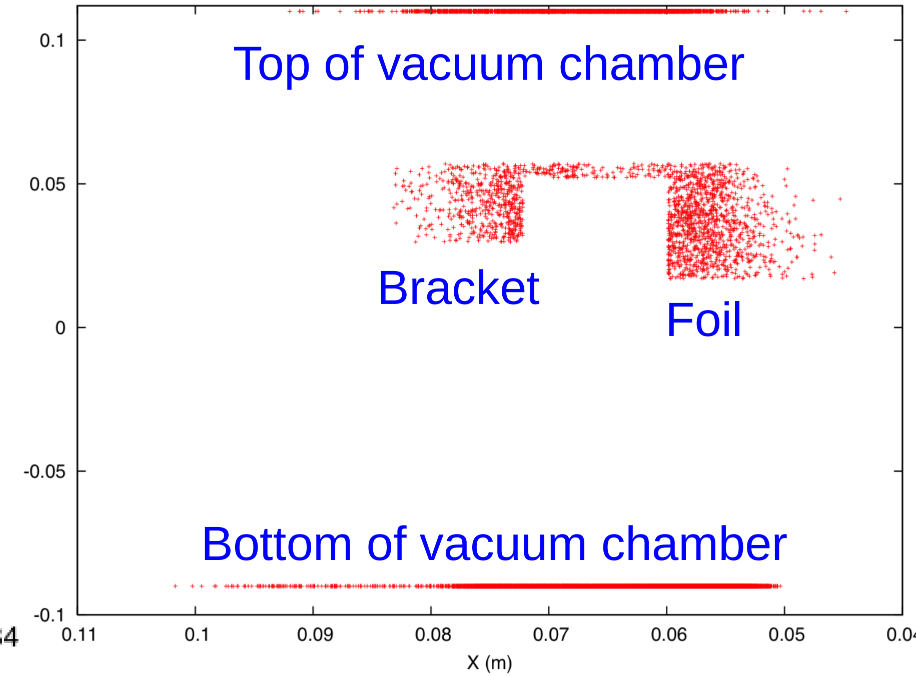
Foils should be mounted >24 mm horizontally from the bracket. All new foils will be mounted at the “+1 cm” position. Also helps to use high temperature material for brackets.

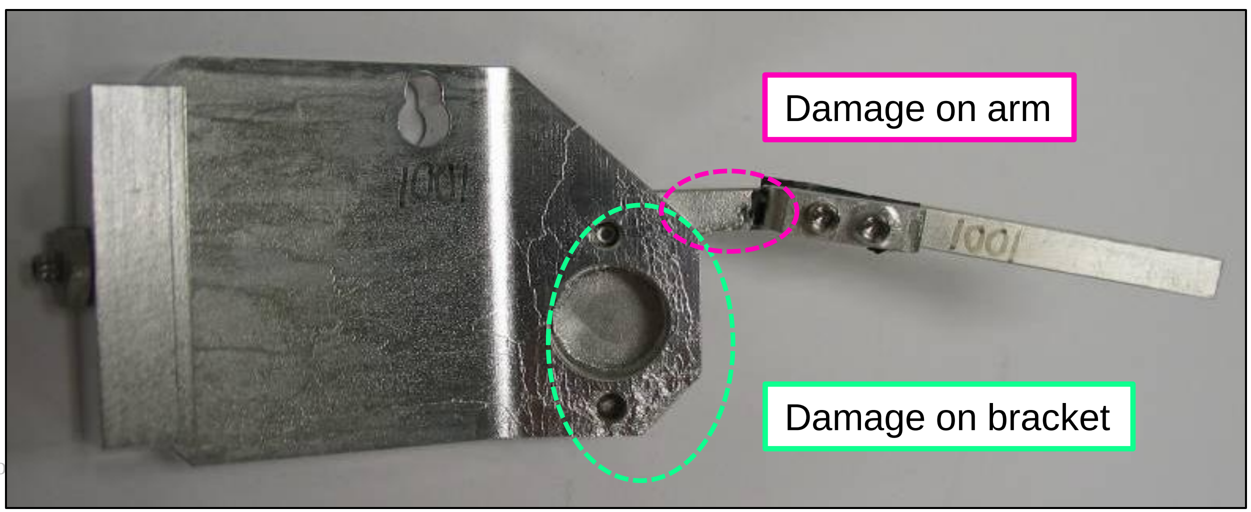
Reflected convoy electrons (S. Cousineau)

Simulation - Side view



Impact locations

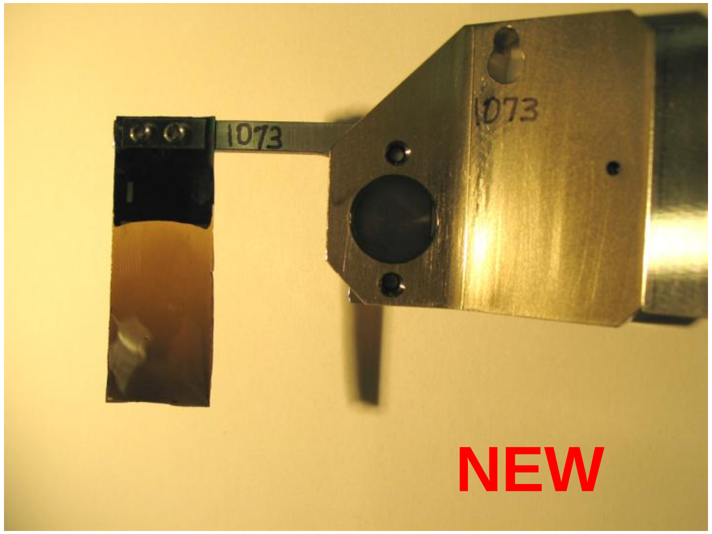




Photos by Chris Luck

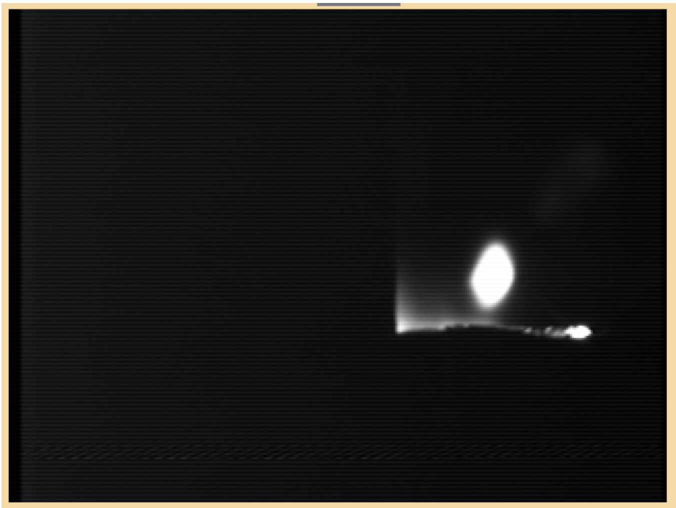
Foil and bracket modifications

- **Brackets modifications:**
  - 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
  - Bracket arm and clamp are machined flat and then polished for good electrical contact
- **Foils modifications:**
  - Longer free-standing length (was 25 mm, now 30 – 35 mm)
- **Results:**
  - A single foil was used for each of the next two run cycles.

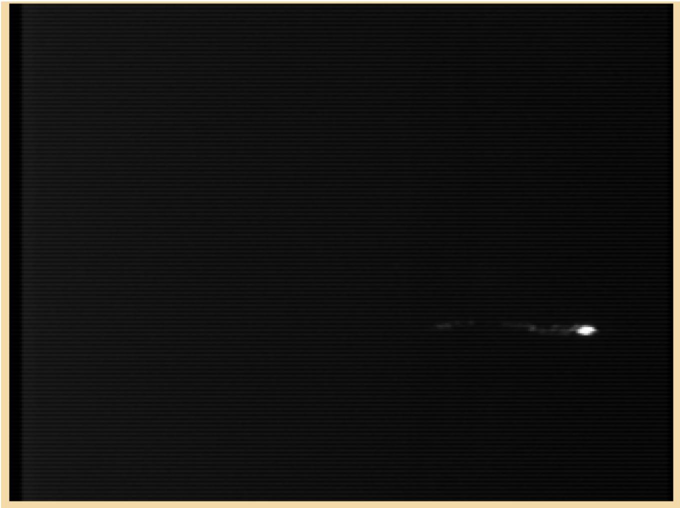


Photos by Chris Luck

A remaining puzzle: Anode spot in-vacuum breakdown?



Beam on (1.02 MW, 18/Sep/09)



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.

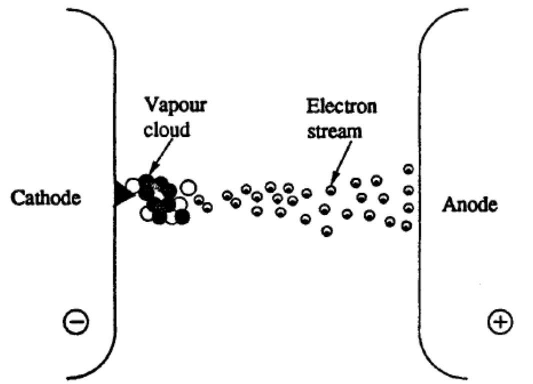
Thank you for your attention!

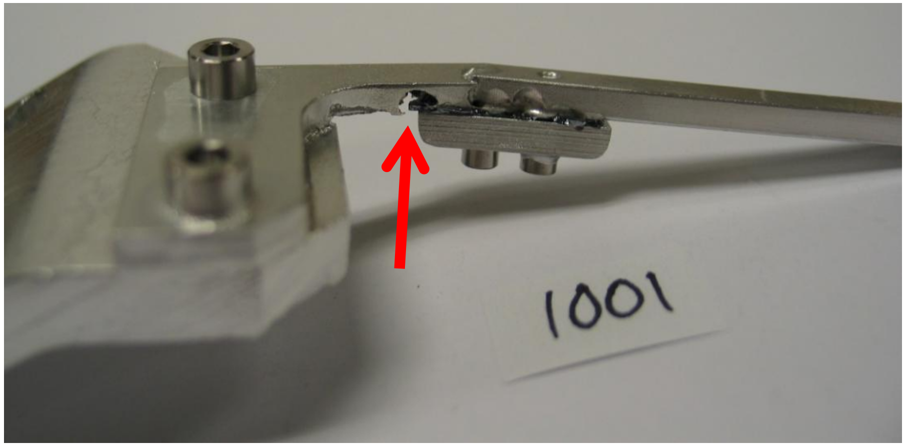
Back up slides

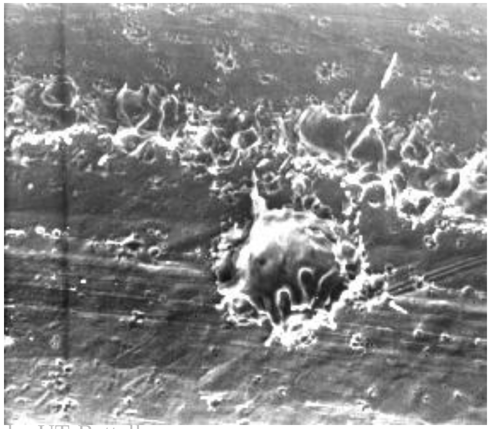
Cathode spot in-vacuum breakdown

"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)

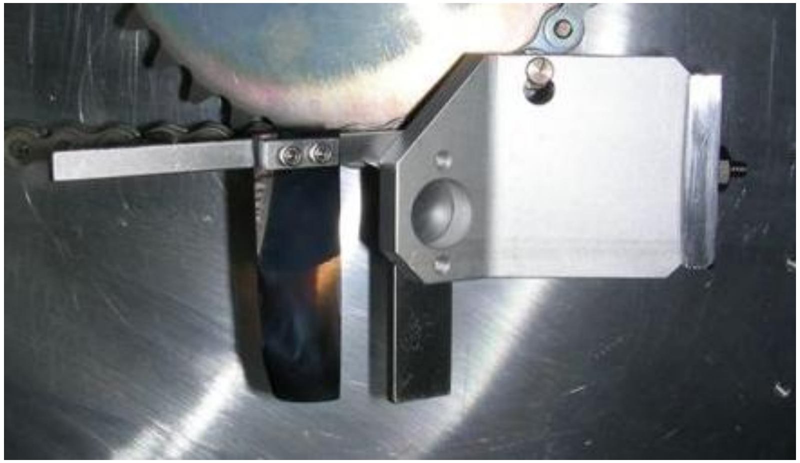






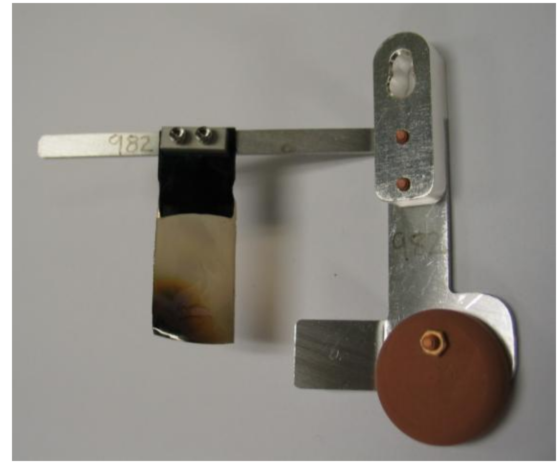
Crater traces left by cathode spots
(Picture taken with an electron microscope).
From http://pag.lbl.gov/Proj_VacArcRes.htm

Foil brackets – 4 generations



1st gen., used thru Jan/09

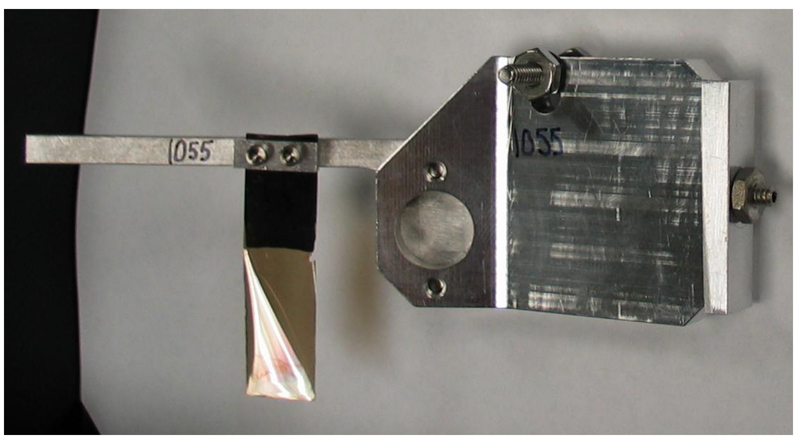
Al bracket 0.25 in, Al snap ring washer 0.090 in



2nd gen., used Mar/09 – 17/May/09

Silver plated Al "tombstone" hanger, 0.340 inch thick

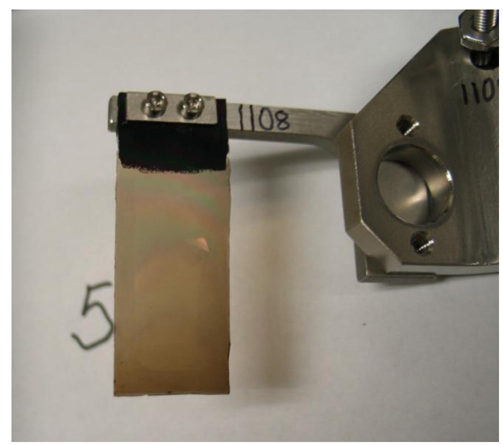
Photos by Chris Luck



3rd gen., used 19/May/09 – 13/Jul/09

Same original but has bottom cut off.

Silver-plated aluminum washers, 0.085 inch thick

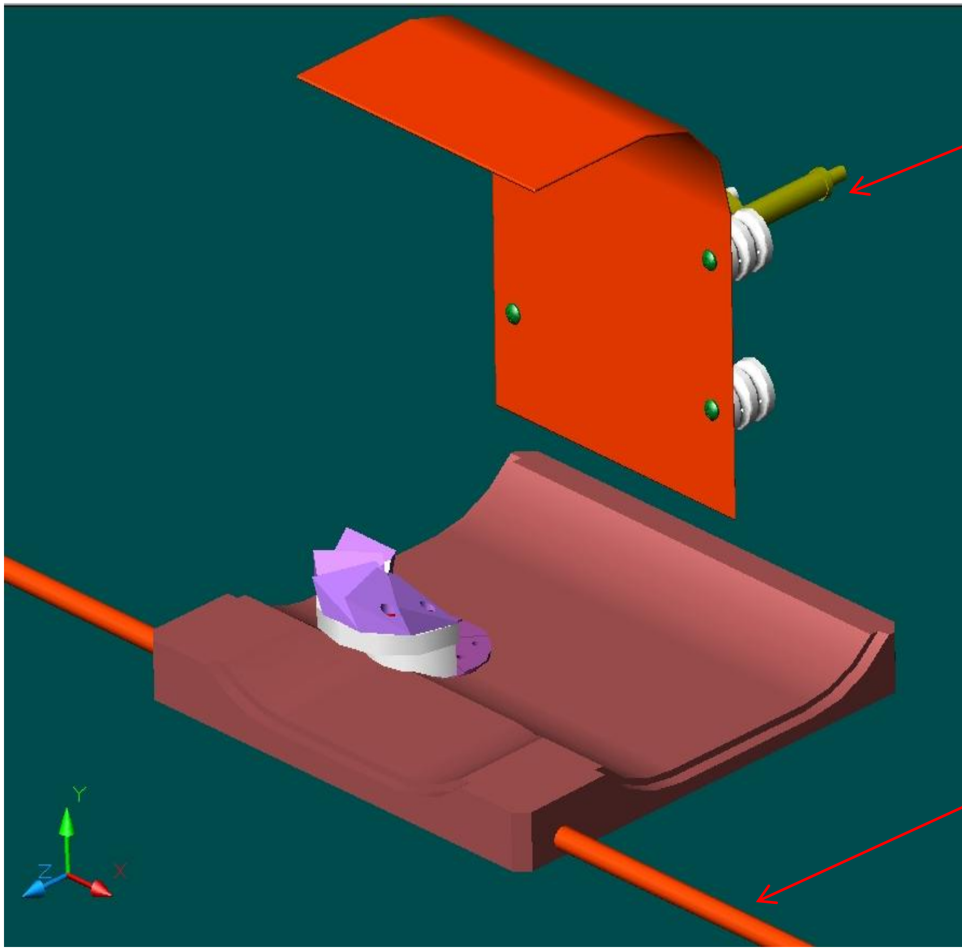


4th gen., used Sep/09 to present

Ti bracket, SS washer 0.093 inch, +1 cm position

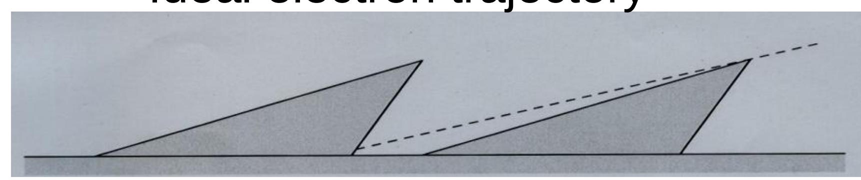
Electron catcher and clearing electrode

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



+/-20 kV biasing system

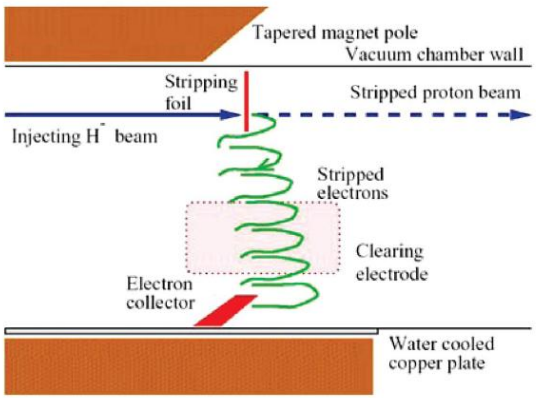
Ideal electron trajectory



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

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



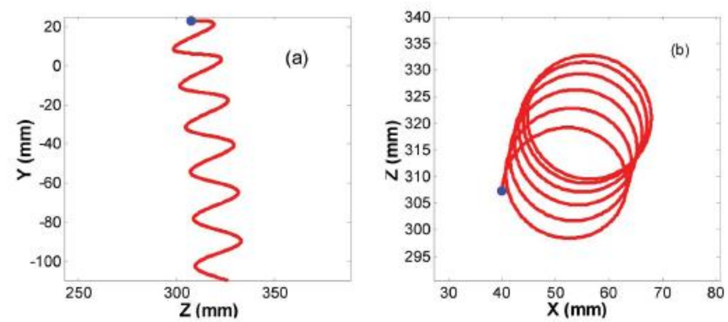


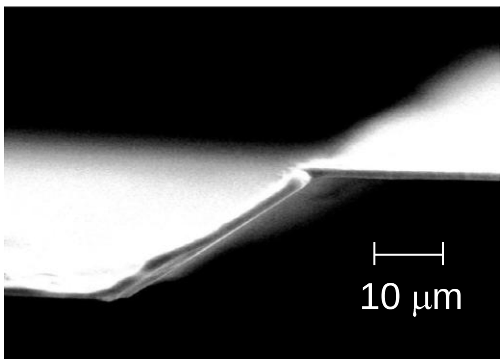
FIG. 2. (Color) Trajectory of a stripped electron from the foil's center. (a) Orbit in vertical and longitudinal plane and (b) in horizontal and longitudinal plane. The blue point is the position where the electron was emitted.

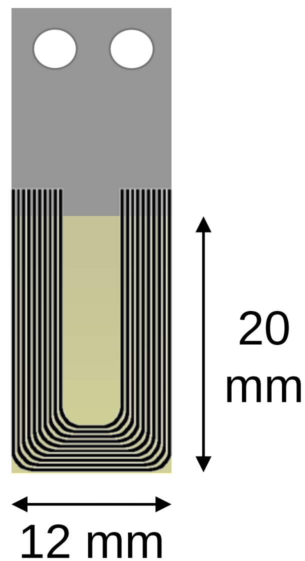
(From L. Wang et al.)

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.

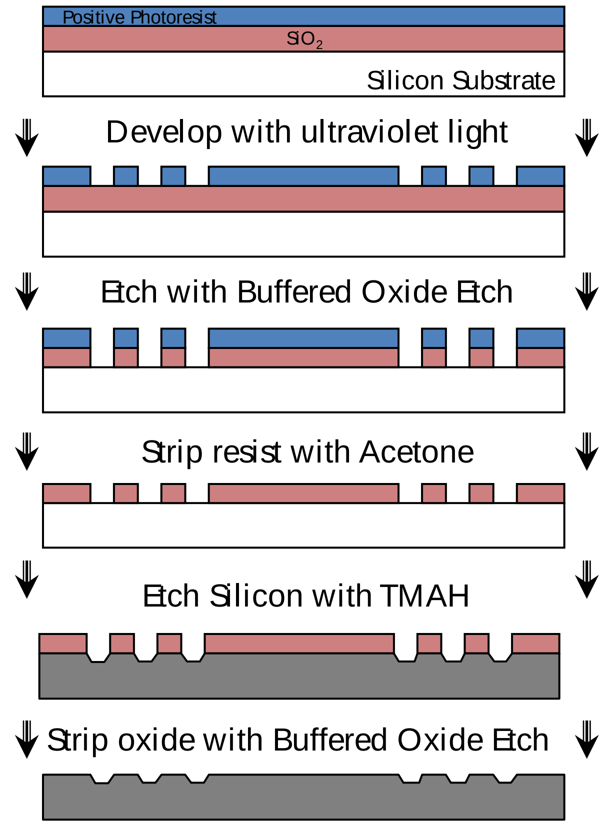
SNS diamond foils – original 12 mm size

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

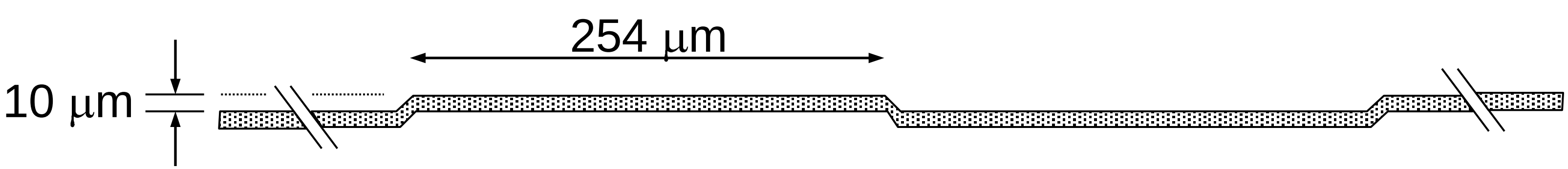




Patterning Process



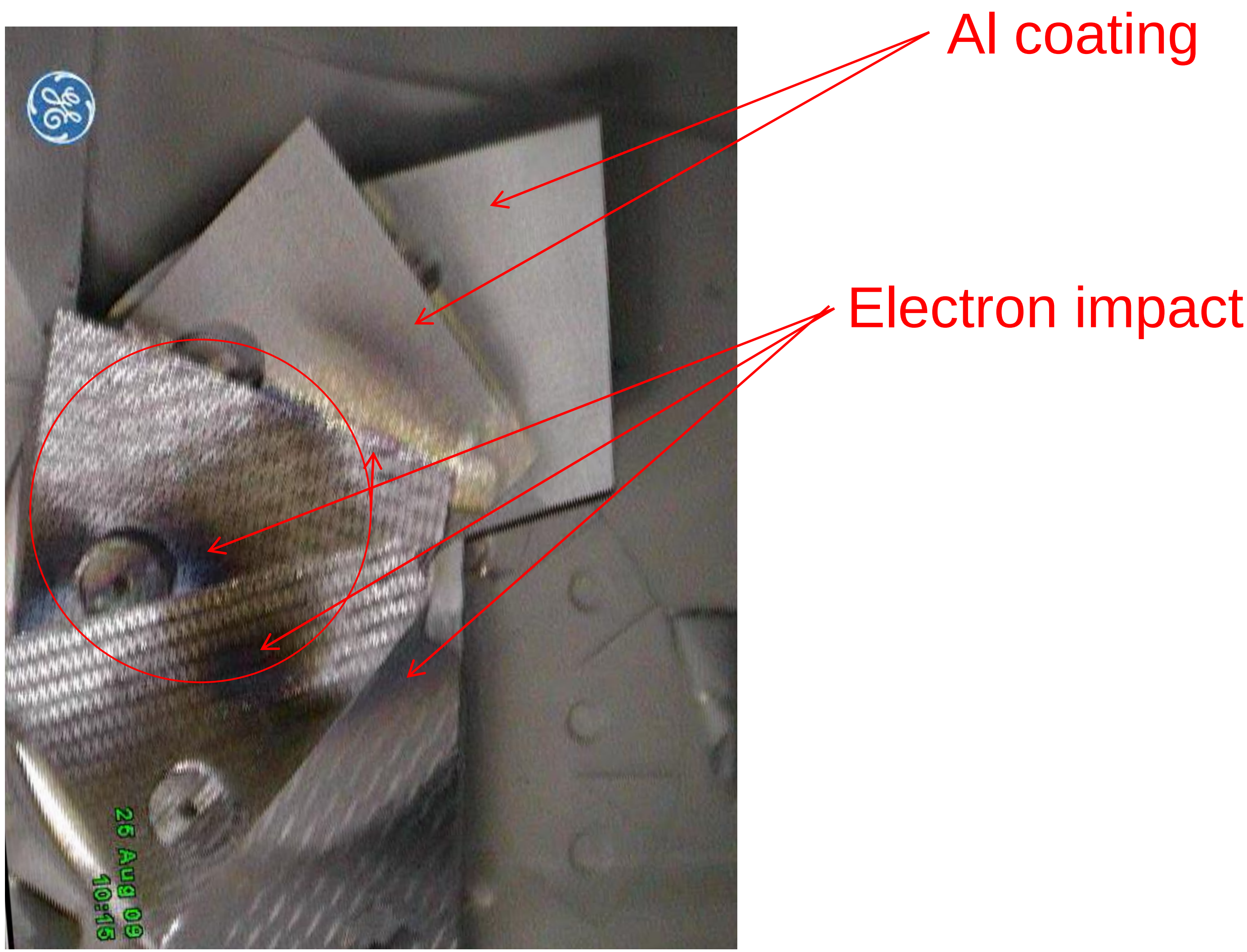
50 Line/inch Foil:



Courtesy R. Shaw

Convoy electron footprint

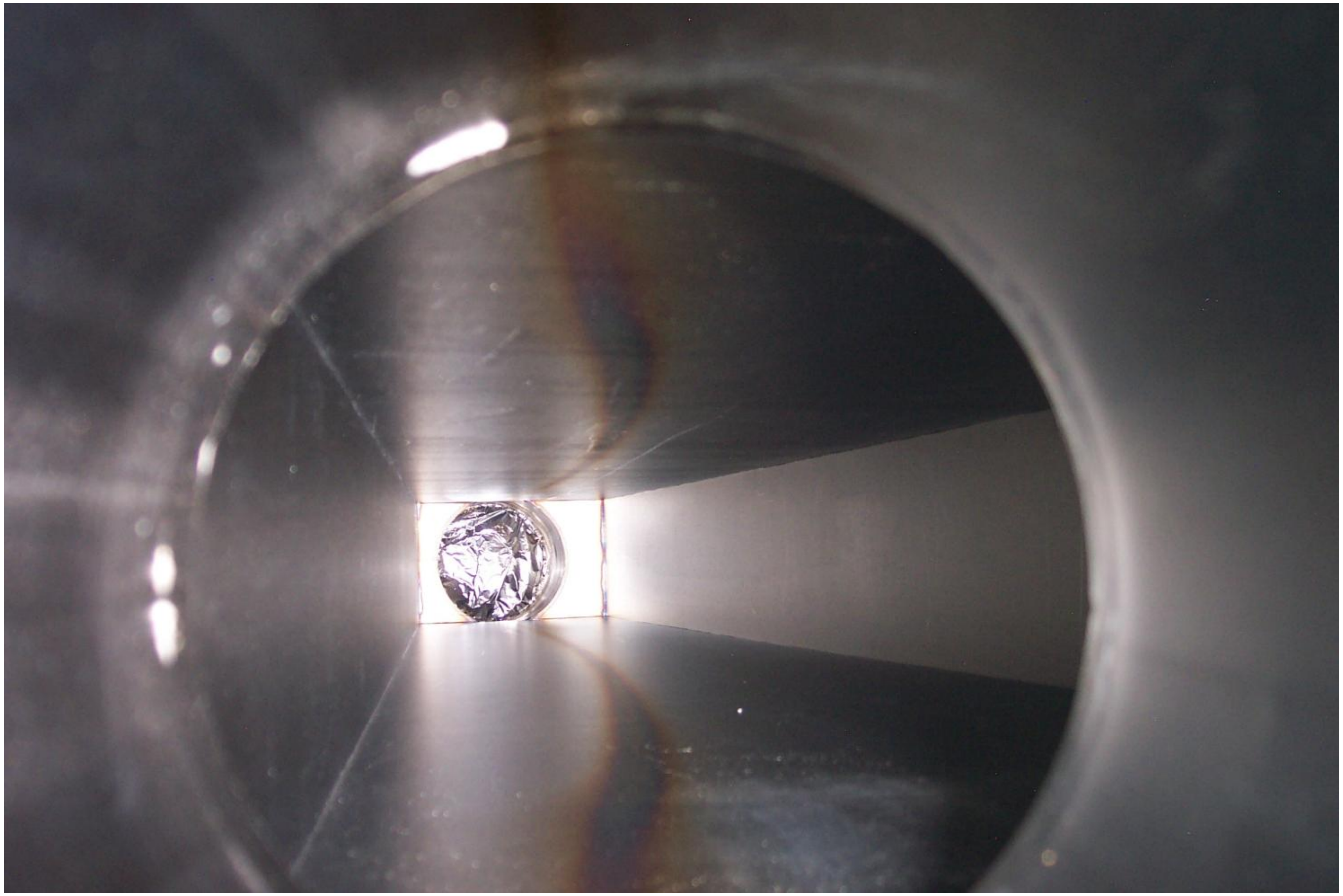
Electrons that hit the top of the catcher can be easily reflected back up into the vacuum chamber



Graphitization at top of vacuum chamber

Could be reflected convoy electrons or trailing-edge multipactoring

Graphitization

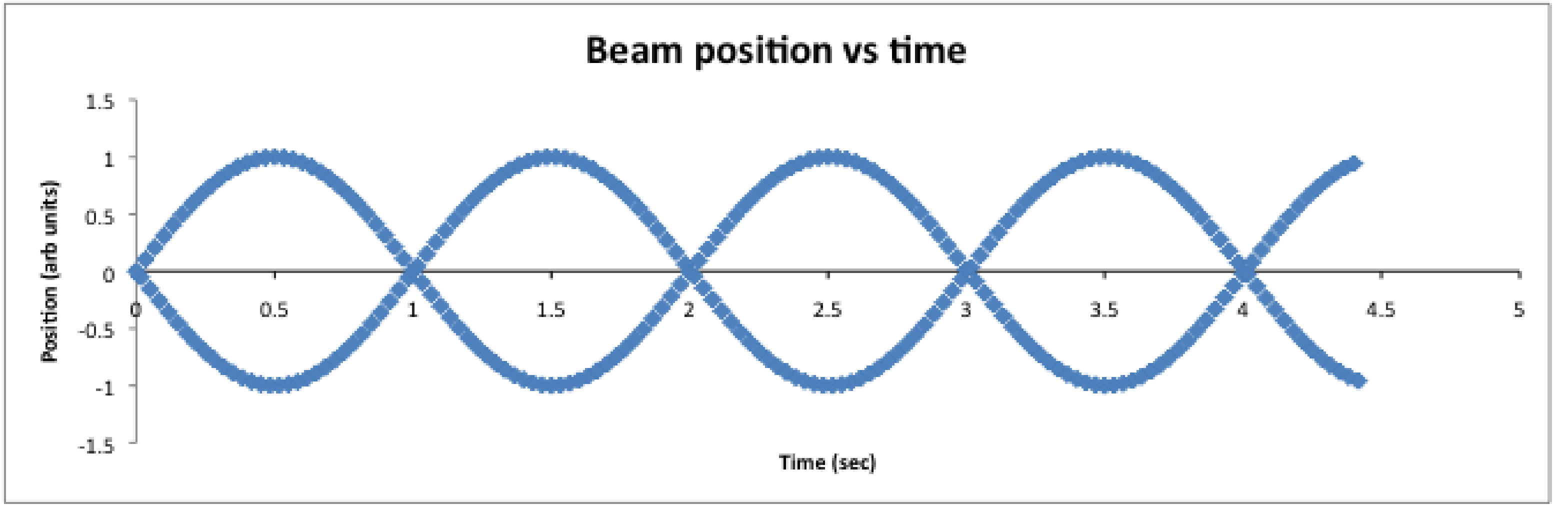


Example of graphitization by multipacting electrons in SRBM11 at PSR. This is not a thermal effect!

(R. Macek, HB2008 & private comm.)

Foil flutter and 2 beam spots

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

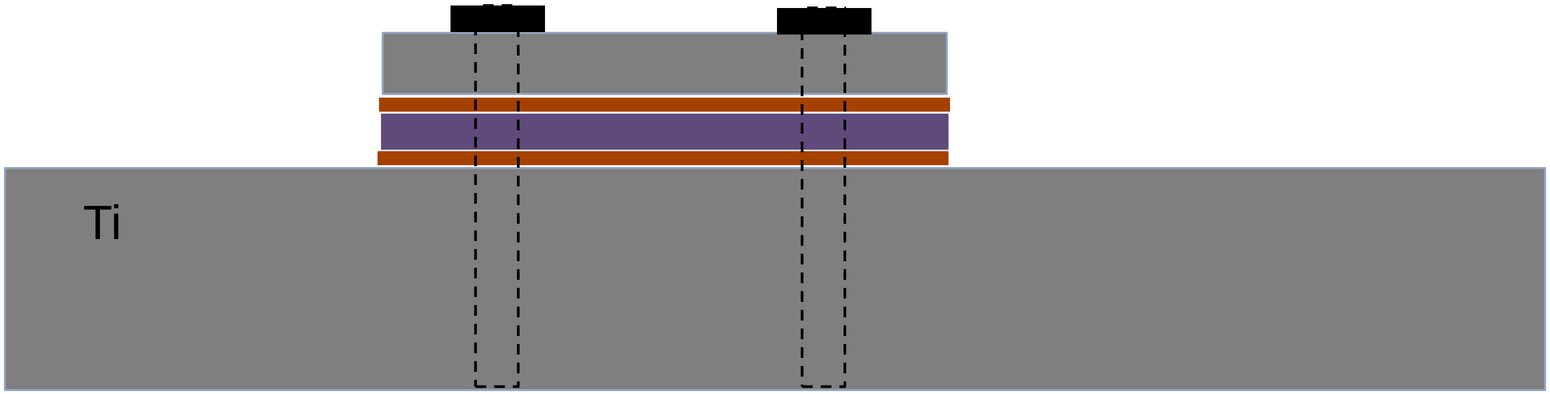


New foil mount method

Foil mount for good electrical contact:

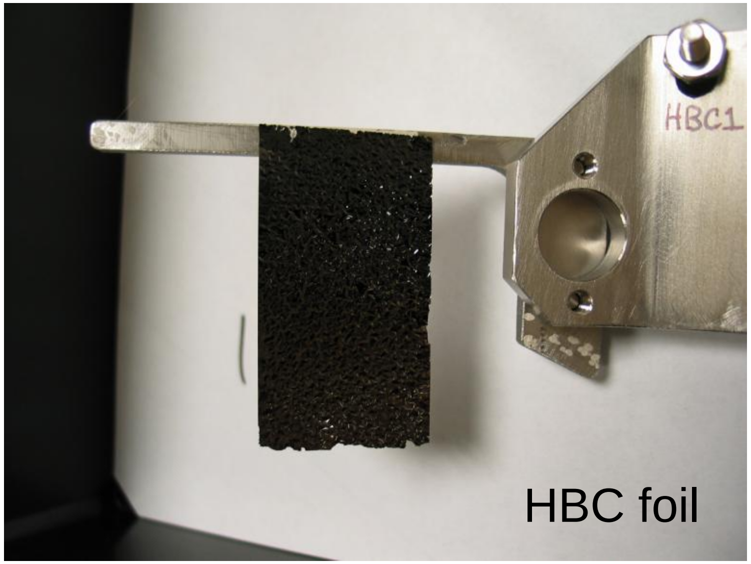
- machine flat then polish bracket and clamp
- sandwich Si substrate between thin sheets of Cu or Au (~0.001" thick)
- OR use conductive adhesive in place of Cu or Au sheets
- OR use all the above

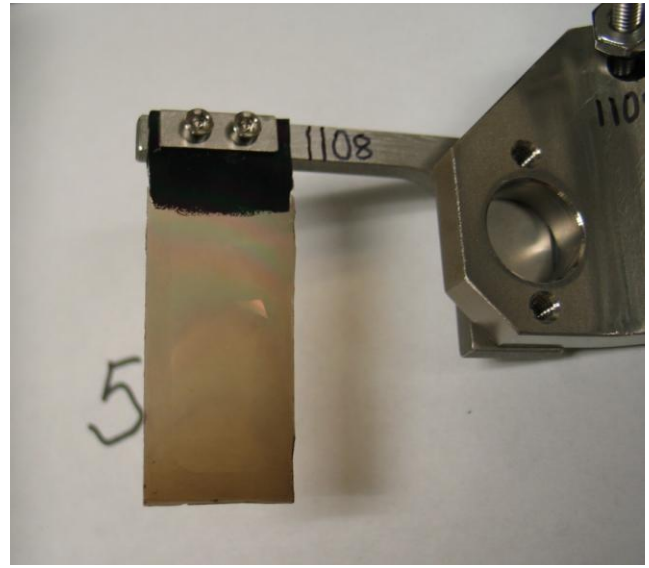
Could also use Bellville washers to maintain positive pressure

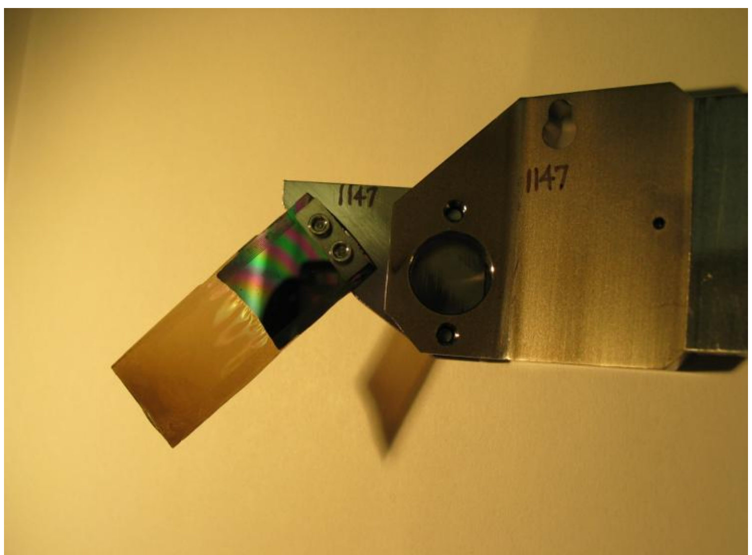


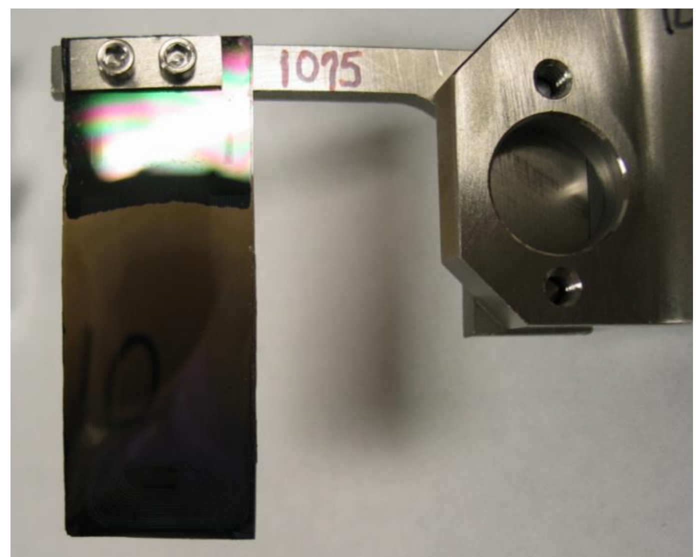
Sep – Dec run: about half the foils were mounted using ~1.1 mil thick gold. No Bellville washers, no conductive adhesive. Brackets machined to a flatness spec then polished.

Foils installed Aug. 31, 2009









Photos by Chris Luck

Inj. dump beam line modifications to date

Radiation monitor on vacuum window water cooling return pipe

New C-magnet

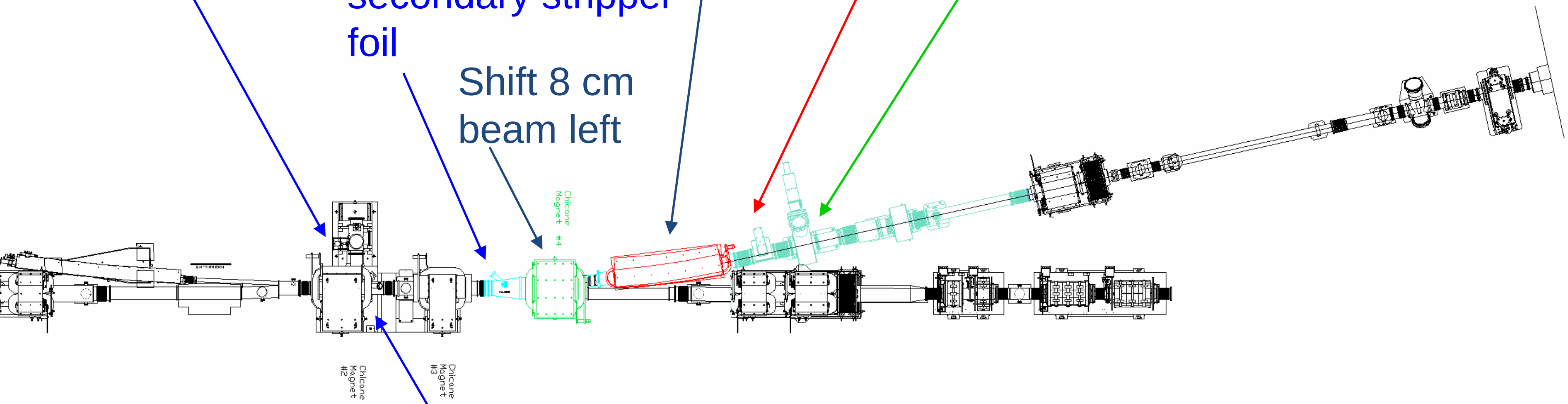
Oversize & thicker primary stripper foil, injected position moved ~8 mm beam left

Increase septum magnet gap by 2 cm

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

Thinner, wider secondary stripper foil

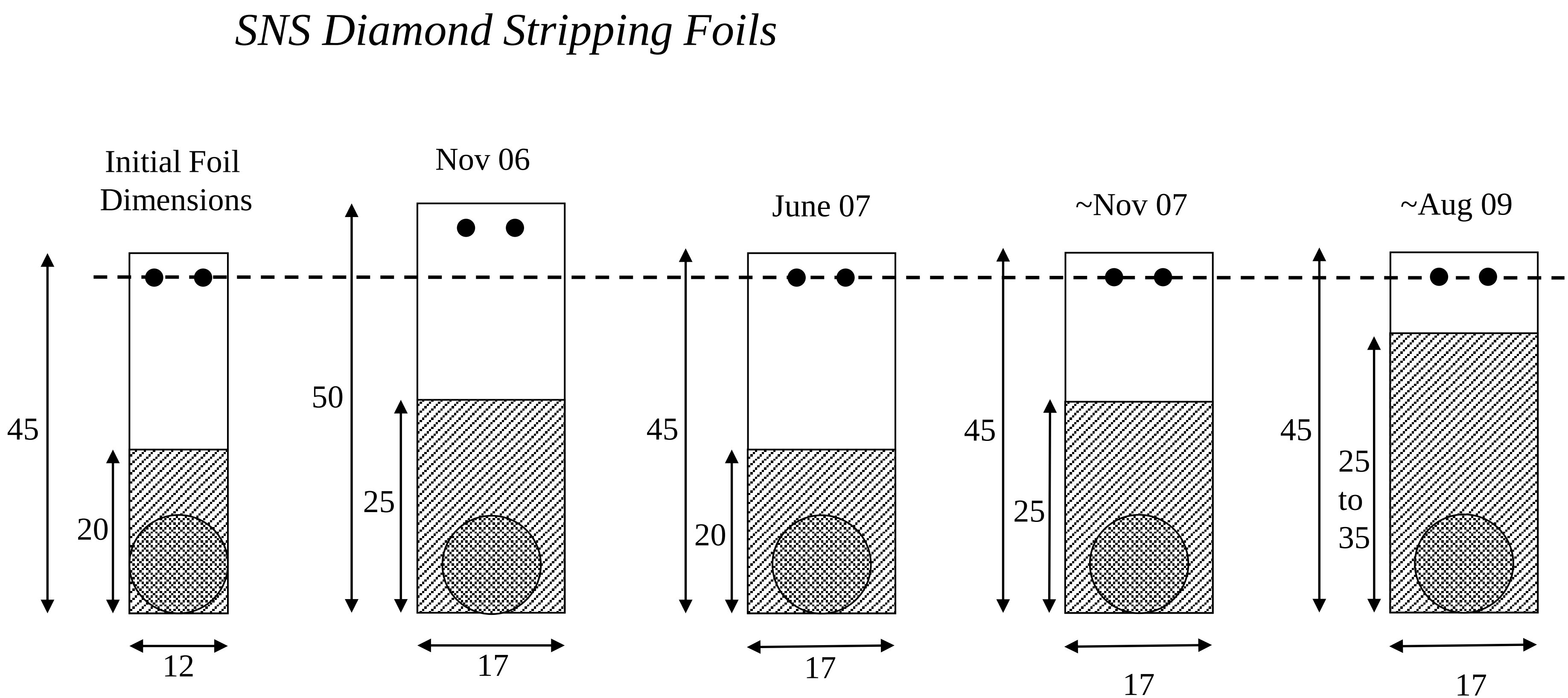
Shift 8 cm beam left



Electron catcher IR video

beam line drawing from J. Error

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.