SNS Foil Development Program

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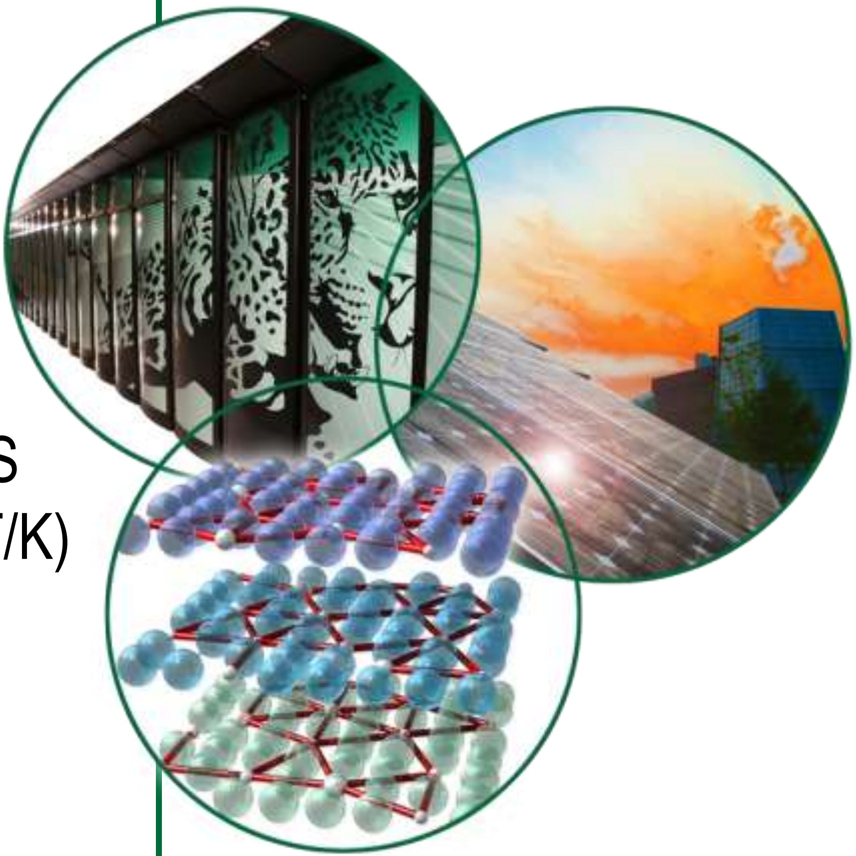

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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Outline

- Corrugated, nanocrystalline diamond SNS foils
- 30 keV electron beam test stand
- Diamond *vs* carbon stripping efficiency
- Foil charging - How can we make our diamond foils more electrically conducting?
- Hybrid Boron Carbon (HBC) foils
- Summary / Future directions

Nanodiamond foils at SNS

Requirements:

- Withstand peak temperatures up to 2500 K ???
- Stripping efficiency of 97% (of intercepted beam)
- Foil set of 10 foils must last 90 day cycle --> 200 hr each
- 20 mm x 12 mm freestanding foil, single edge support
- Uniform thickness of 280 μg/cm^2 (~0.8 μm for diamond)

- Nanodiamond foils were in use on the 1st day neutrons were created and when the 1 MW threshold was crossed.

- 130 foils delivered; 54 foils mounted in 10 loadings.

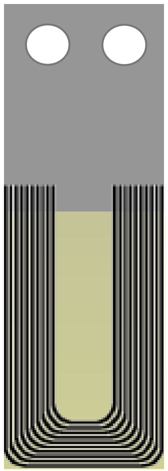
- No foil failures until the May 2009 problems (details in M. Plum presentation)

- Recent Good News:
  During the last cycle, a *single foil* served for the entire campaign (4820 Coulomb*).

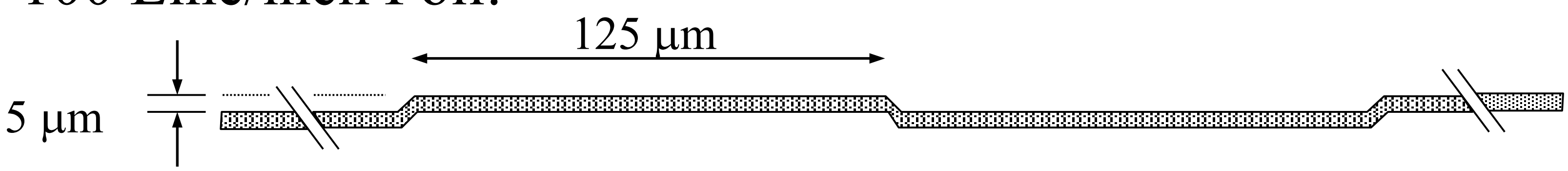
(* 1 month at 1.4 MW ~ 3500 C)

SNS Nanocrystalline diamond foils

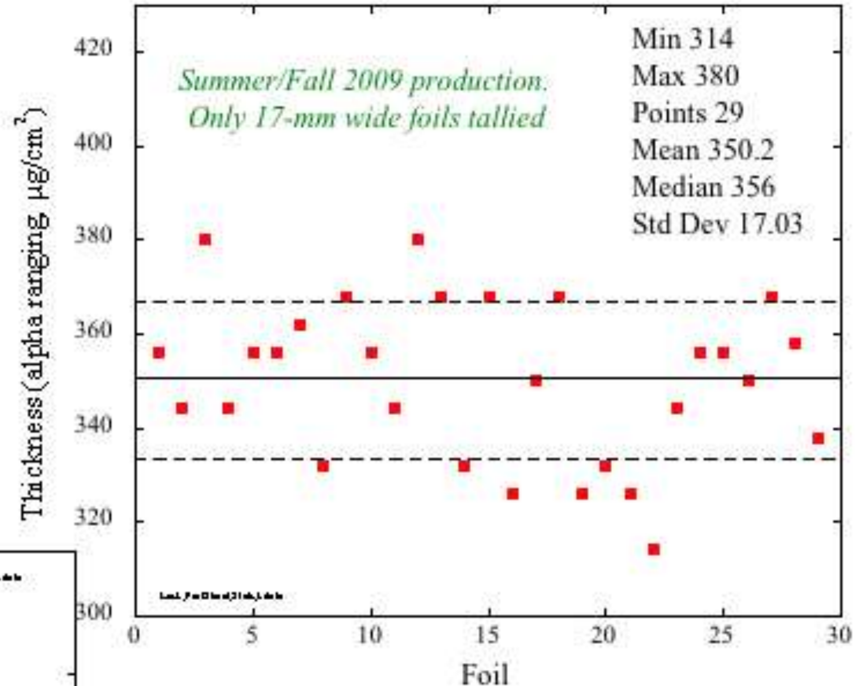
- Freestanding foils up to 35x17 mm^2 have been loaded.
- U-shaped corrugations keep the foil flat.
- Carbon support fibers are not necessary.
- At thickness below about 300 $\mu g/cm^2$ (α-ranging value), we have greater problems with tears and pinholes.

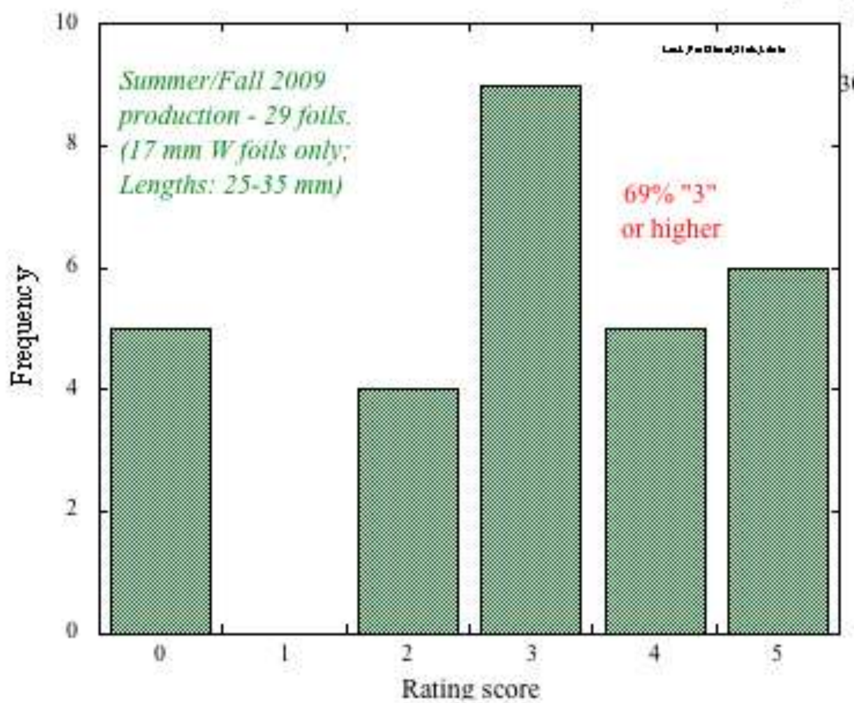


100 Line/inch Foil:



Summer / Fall 2009 Production - - Foil Statistics

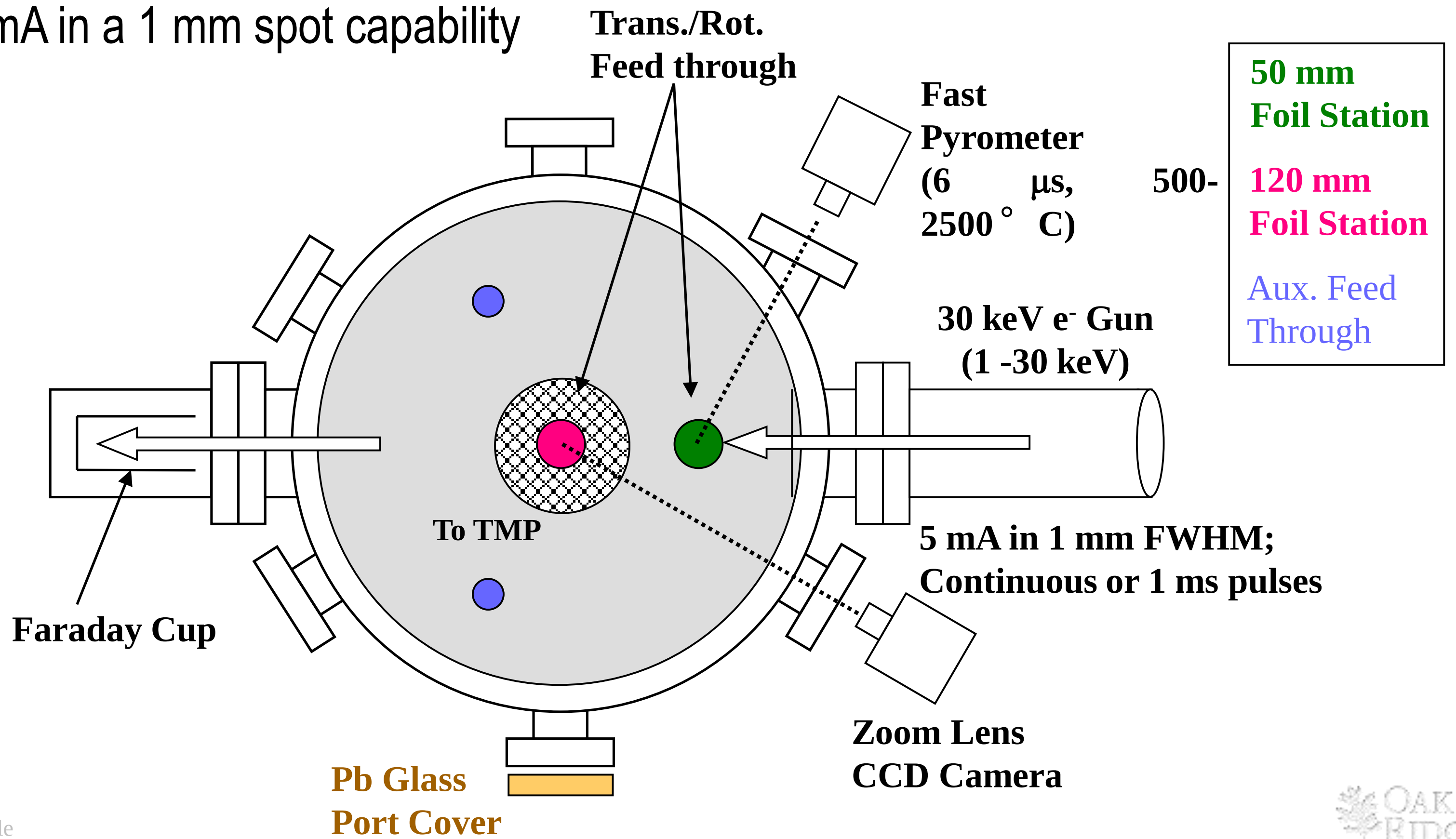




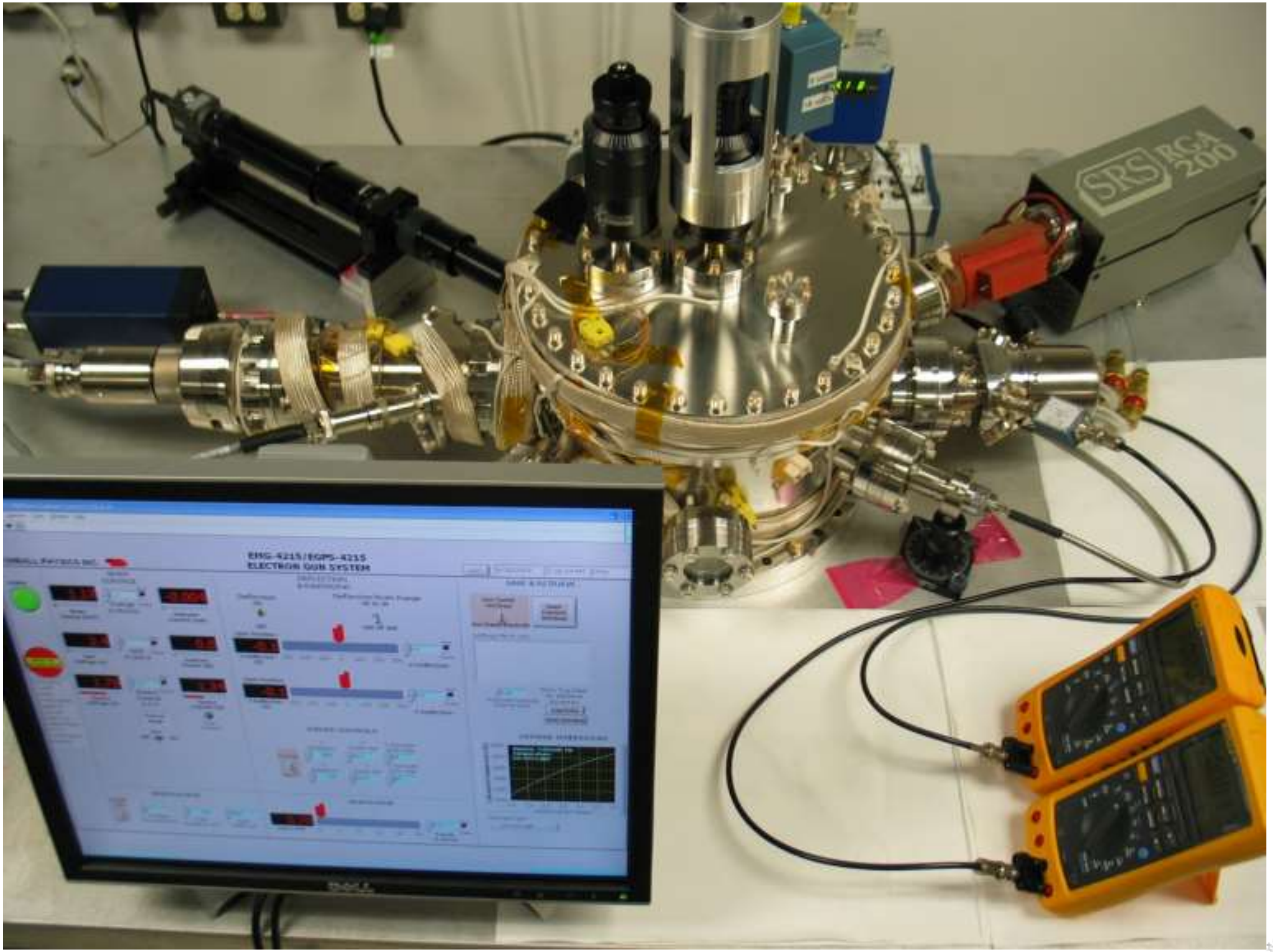
- Foil thickness deviation is ±5%
- 70% of foils scored ≥ "3"
- Lack of foils <300 $\mu g/cm^2$ due to high production failure rate

30 keV Electron Beam Test Stand Schematic

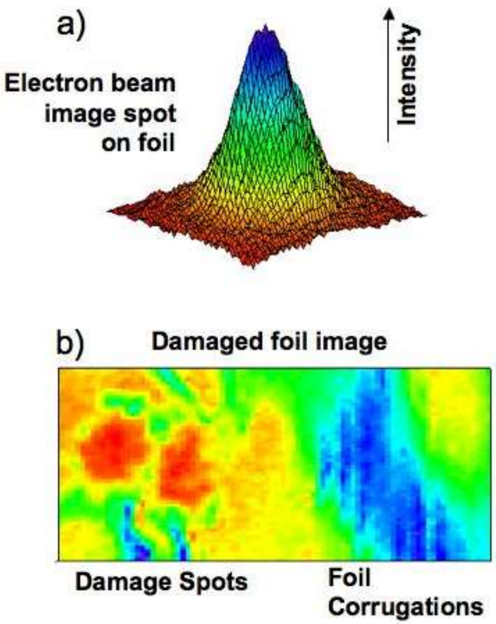
- Foil testing has always been a bottle neck.
- Test stand designed to match the SNS foil heating.
  - 1.6 mA/mm^2 (peak) current required
  - 5 mA in a 1 mm spot capability



Electron beam foil test stand



Electron beam test stand results

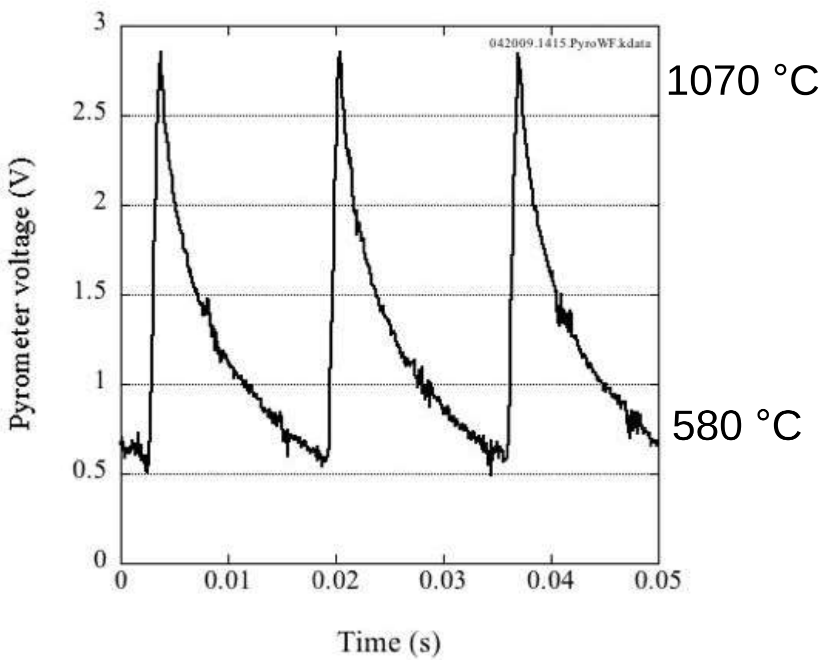


Electron beam profile:
Comparing the damage spots to the foil corrugation pattern -

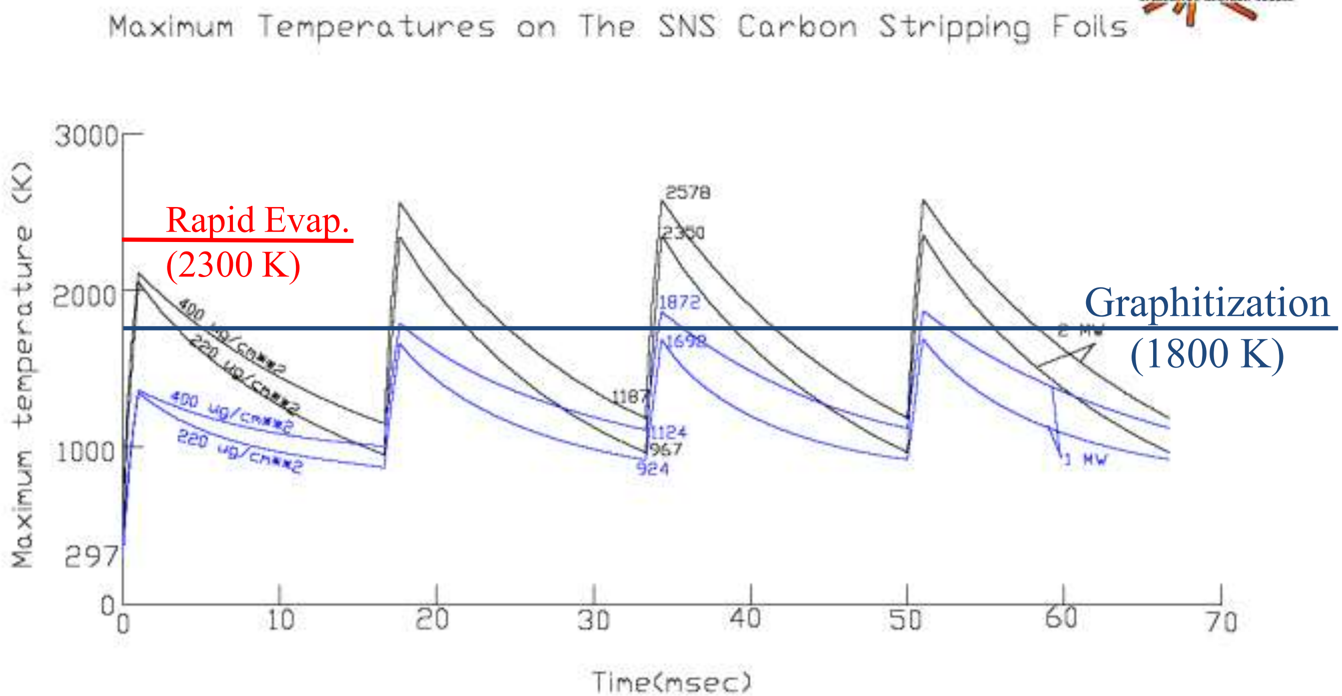
Diameter < 0.5 mm

Foil temperature excursions for ~ 0.8X the simulated SNS power loading

0.24 mA current: 385 $\mu g/cm^2$



CALCULATED FOIL TEMPERATURE



Foil temperatures measured using the test stand for different materials and power loadings will give us an indication how foils will fare at 1.4 and 3 MW.

Carlos Reinhold stripping efficiency calculations

Dominant processes for H^- stripping in carbon:

- inelastic e-e collisions (one e of H^-; one e in foil)
- elastic collisions (one e of H^-; screened C nucleus)

$F(H^-) \sim e(-x/L)$ where x= foil thickness; L_t = total MFP

$1/L_t \sim 1/L_i + 1/L_e$

Elastic MFP ~ 1/Density

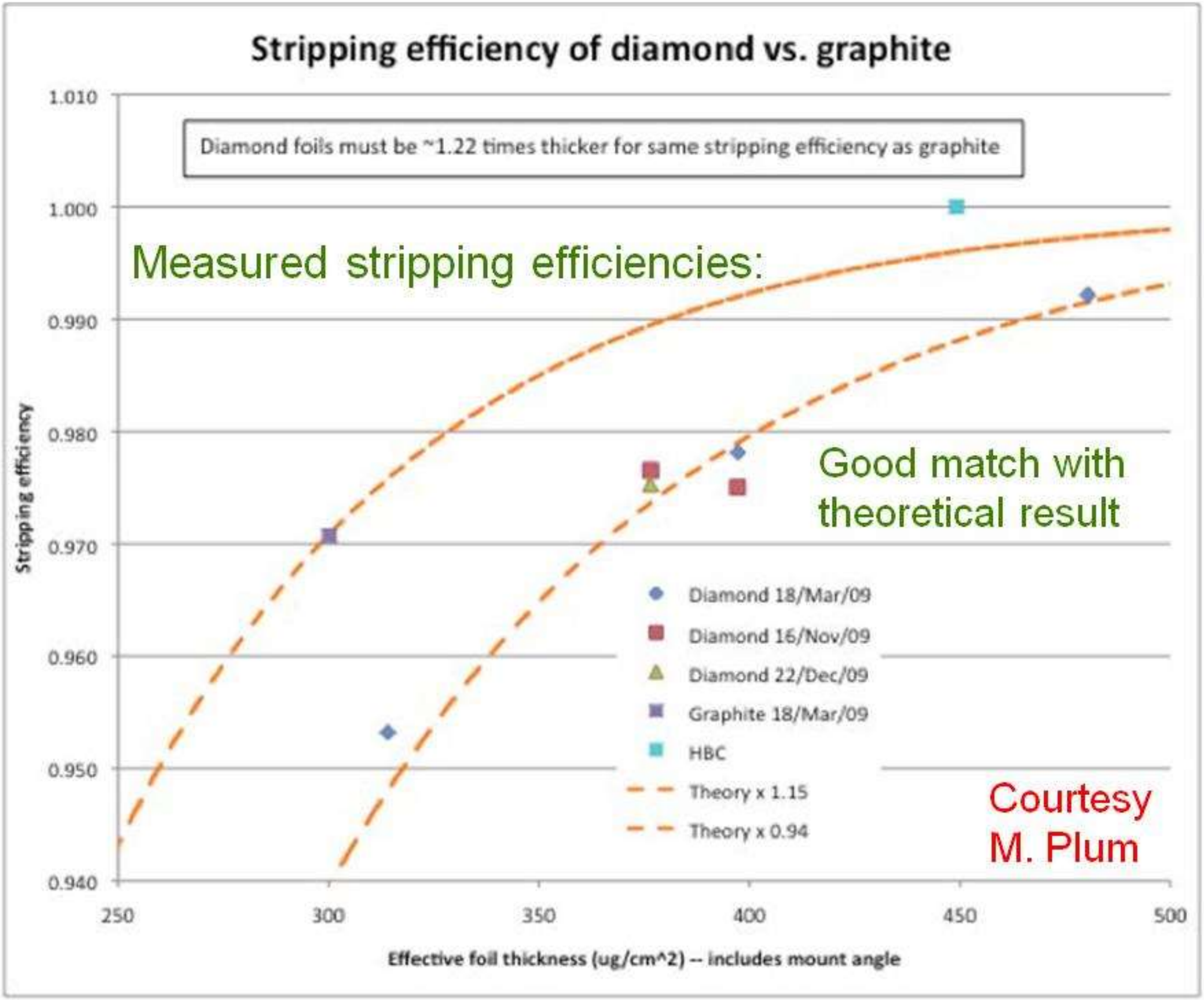
Inelastic MFP ~ Same for diamond and carbon
(even though diamond is more dense;
harder to excite the e's in diamond)

Total MFP: Carbon > Diamond

➡ To get the same stripping efficiency,
must use 20% thicker diamond foil ($\mu g/cm^2$)

Problem:
20% thicker SNS foils will create substantially greater foil scattering.

Stripping efficiency of diamond vs. graphite



SNS foil charging

- Secondary electron emission from both foil faces due to proton passage.
- Thermionic emission, if foil is hot enough
- If the foil is an insulator, it will charge up and distort, break apart, or arc
- Applied bias on the SNS clearing electrode deflects foils, even before they are exposed to the proton beam
- The PSR experience with SNS nanodiamond foils is that the foil current dissipates in < 1 ms between the pulses

Is SNS foil flutter caused by foil charging ?

- Diamond resistivity can be altered by doping:
  - We are beginning to dope our foils with boron using B metal
  - Collaborating with Fraunhofer/MSU for boron doped nanodiamond
  - Collaborating with Argonne for nitrogen doped nanodiamond

Doped Diamond

- As grown CVD diamond (μxstal): $\rho = 1 \times 10^{7}\ \Omega$-cm
- Annealed CVD diamond: $\rho = 1 \times 10^{13}\ \Omega$-cm
- For 1 x 1 cm x 1 μm ⇨ $10^{17}\ \Omega$
- ρ decreases slightly with temperature

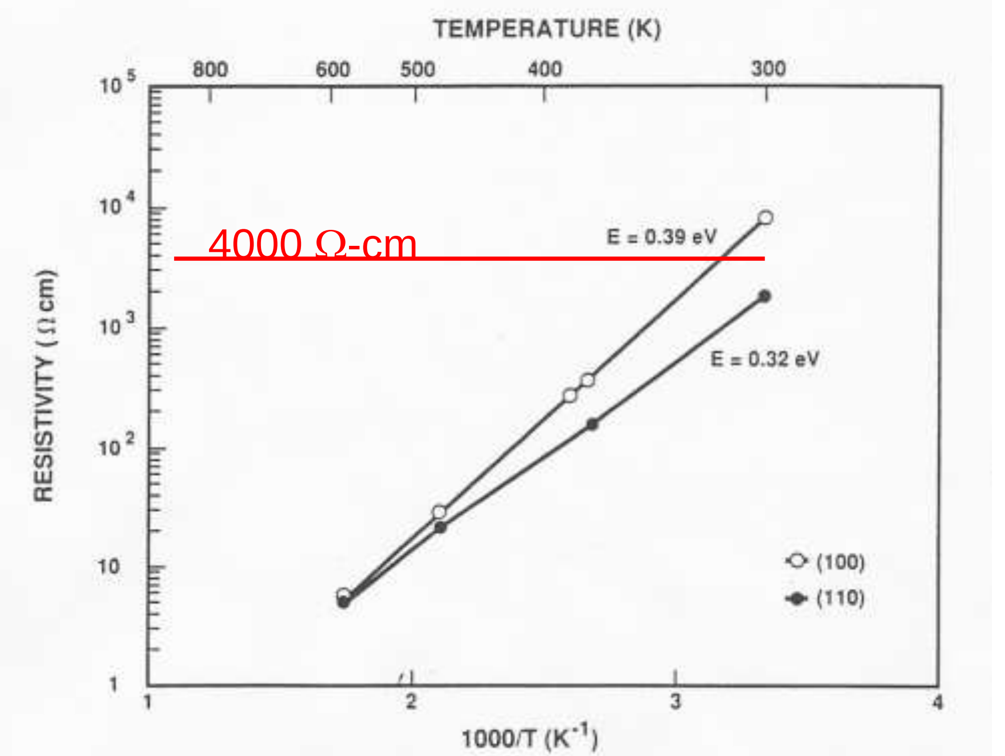
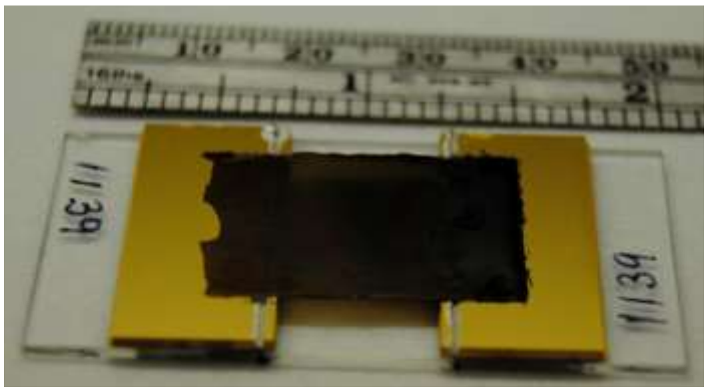


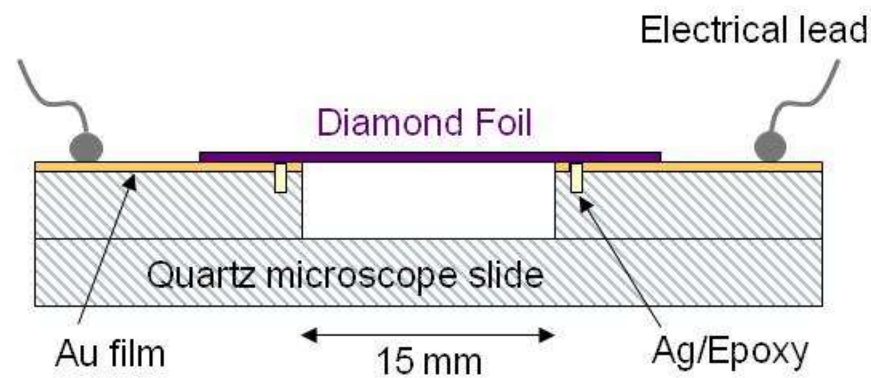
Figure 10.2. Resistivity as a function of temperature for (100) and (110) oriented lightly boron-doped diamond films. *E* is the thermal activation energy of the resistivity. (From Geis (1991).)

- B_2H_6 or BF_3 in CVD gas mixture yields B doped diamond
- Hazardous, toxic gases
- At the foil operating T, will boron stay put?

Measuring diamond foil resistivity

- Nanocrystalline material has increased grain boundary content that contains defective “graphitic” material.
- Resistivity = ????
- For reference: the Si we use is ρ = 10 Ω-cm



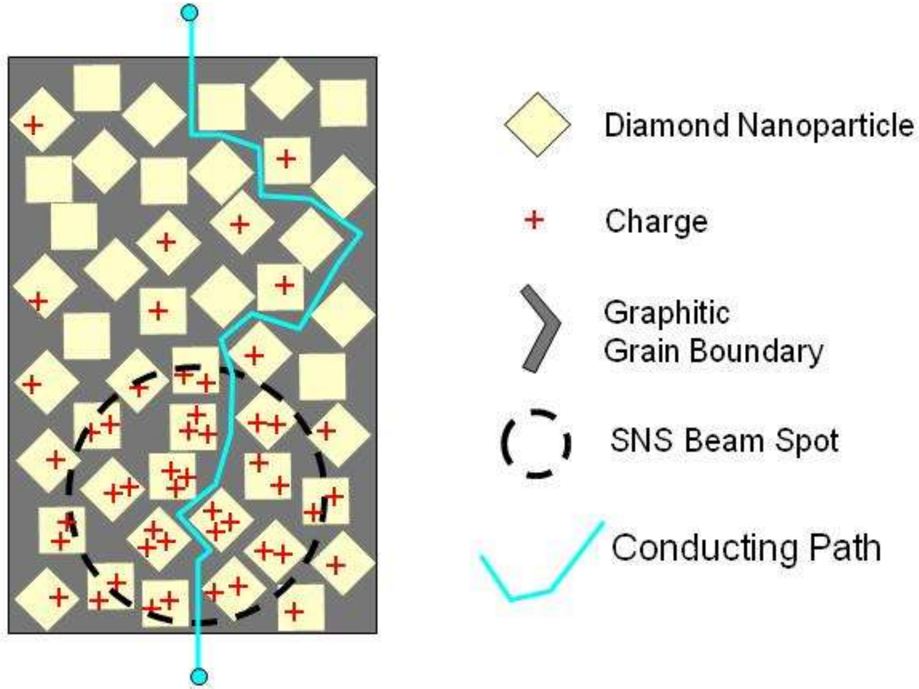


Measured resistance: (3 samples)

- ~ 200 kΩ (17 x 15 mm x 1 μm)
- Corresponds to ~ 25 Ω-cm

So why are the foils so sensitive to static charge ?

Low resistance nanodiamond foil that can charge up in the SNS beam



N-doping thought to affect the grain boundaries
B-doping substitutes into the grains
➡ Boron doping will be the most beneficial

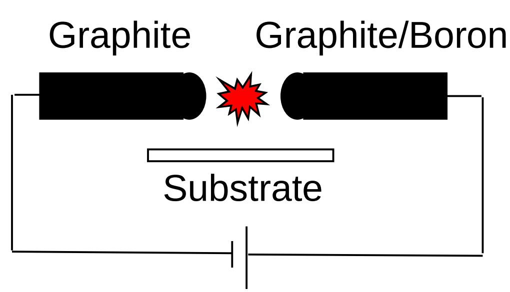
<Cont.Insul.foil.ppt>

Hybrid Boron Carbon (HBC) Foils

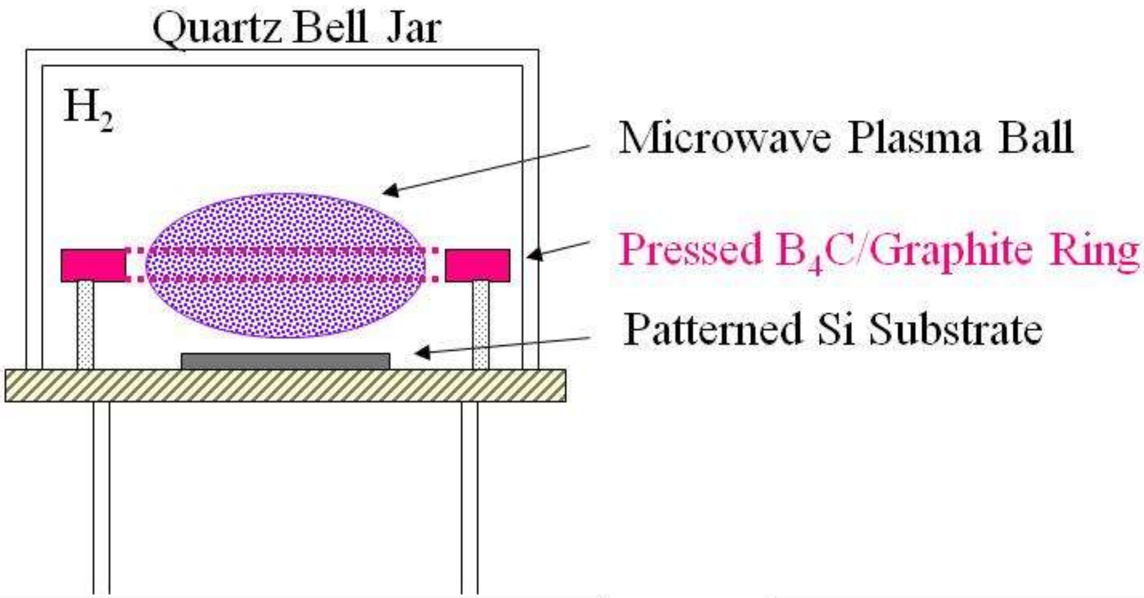
- Isao Sugai at KEK has reported HBC foils with excellent life times for proton beams.
  - 20-25% Boron
  - 256 hr lifetimes *vs* 62 hr for SNS nano-diamond
  - Single foil survived full PSR campaign at LANL

- Limitations: Thickness < 200 μg/cm^2
  Pinholes
  Carbon fiber mounting

- We have begun to prepare similar foils using our CVD growth reactor.



Concept for Growth of HBC-like foils



- Same reactor as for diamond foils
- Substrate retains patterning and foil “handle”
- Plasma should create vapor phase B and C
- Foil composition varied by make-up CH_4
- Properties may differ from Japanese foils

- B_4C ring fabricated
- Problems with ring epoxy
- No film production yet for reasonable run times
- More parameters to vary

CVD B_4C collaboration with C.S. Feigerle (UT/Chem) - pending EPSCoR proposal

SNS Foil Development Program

Summary

• Corrugated, nanodiamond stripper foils have performed well at SNS.
• Diamond vs carbon stripping efficiency has been compared.
• Nanodiamond foil resistivites have been measured.
• Preparation of more conductive foils is underway.
  - Boron doping
  - Thin metallic coating ?

Future directions

• New corrugation patterns for increased foil flatness.

• Different materials may be necessary for the SNS upgrade to 3 MW.

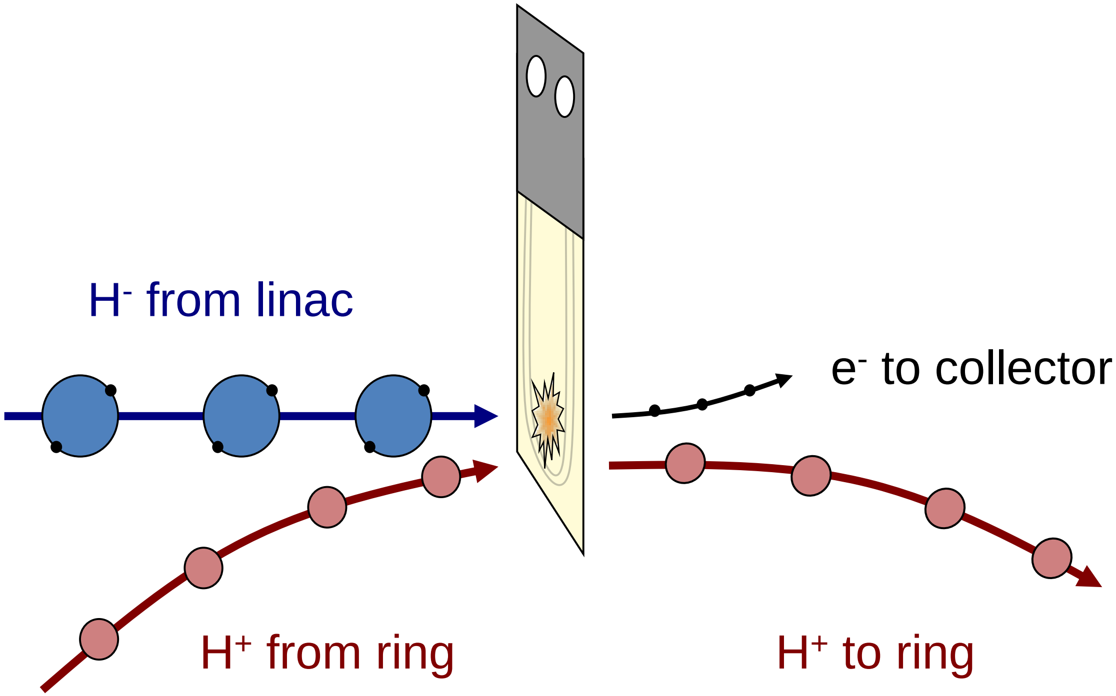
  - Growth of other materials emphasized (doped diamond, HBC, B_4C)

  - The e-beam test stand will be used for foil lifetime and T_{max} testing for several materials - doped diamond, DLC, HBC, carbon nanotube foils

Thank You !

Back-up Slides

SNS Foil Requirements



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- Stripping efficiency of 97% (of intercepted beam)
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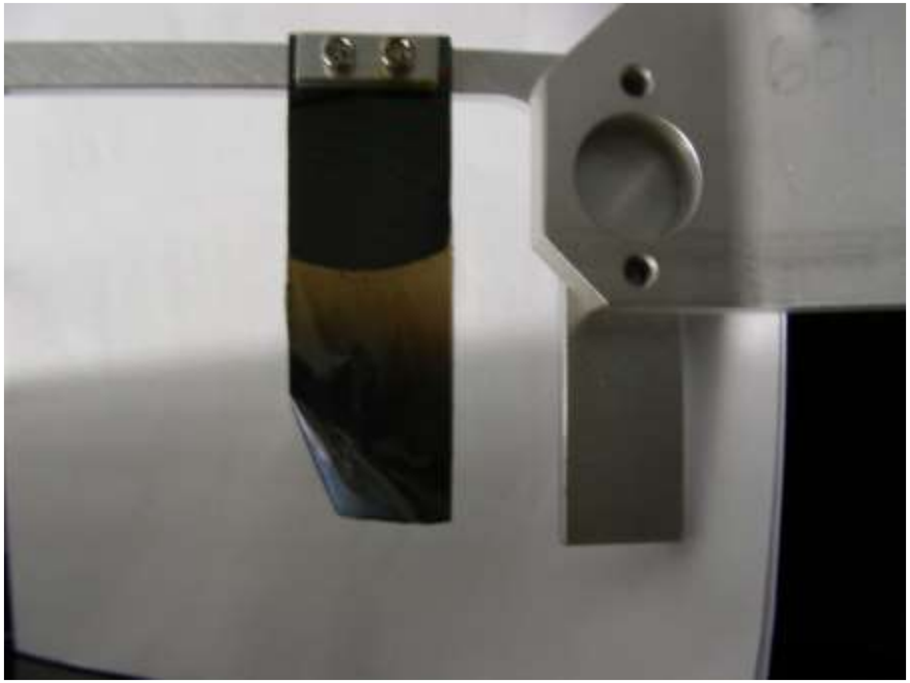
- Uniform thickness of 280 $\mu g/cm^2$ (~0.8 μm for diamond)

“Normal” foil failure mode

Photograph of a nanocrystalline SNS foil (#601; 463 ug/cm2 avg) after experiencing 300 C of injected charge. The lower left corner is curled away from the camera from interaction with the injected and circulating ion beam.



<601 looking upstream.jpg>

Carlos Reinhold Results