Foil R&D and Temperature Measurements at the SNS

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On behalf of SNS Foil R&D Team

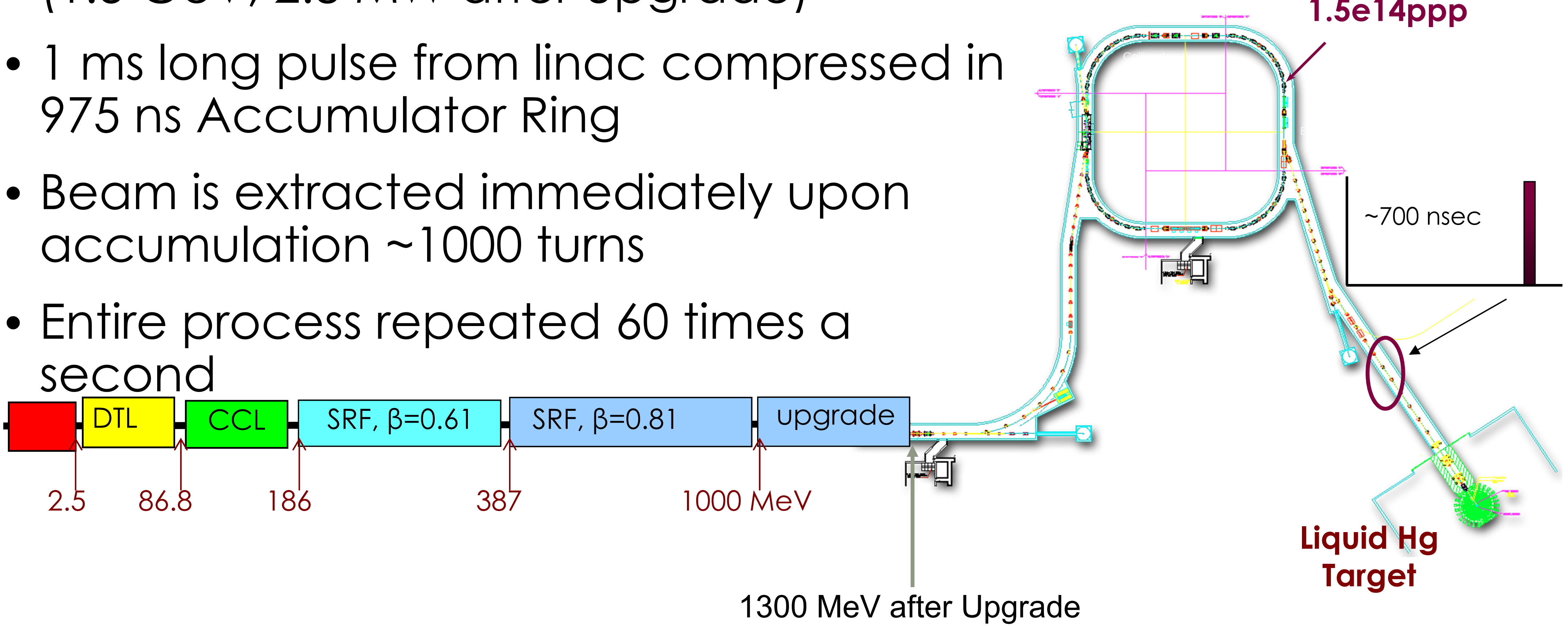
NAPAC'19 Lansing, MI

Outline

- Introduction to SNS
- Charge Exchange Injection at SNS
- R&D Effort
  - Center for Nanophase Materials Sciences (CNMS)
  - Foil Test Stand
  - **Operations and Foil Temperature**

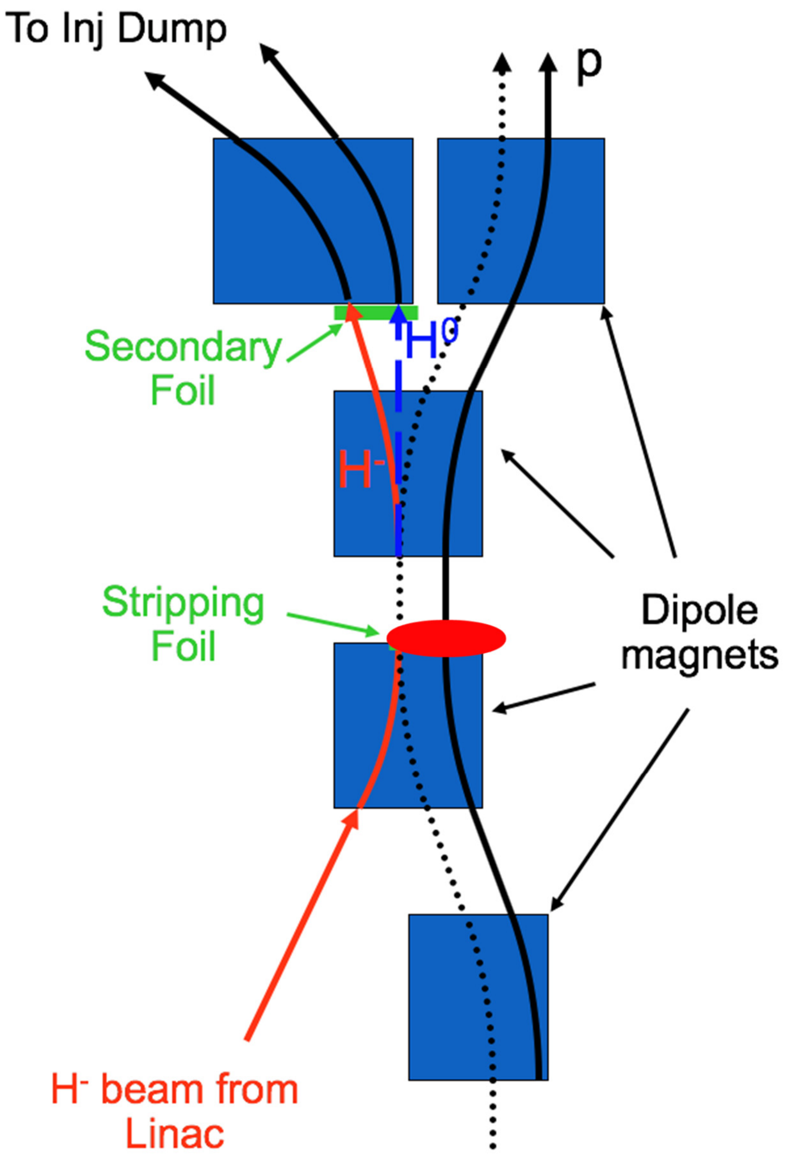
The SNS Accelerator

- 1 GeV, 1.4 MW H- Linac
  (1.3 GeV, 2.8 MW after upgrade)
- 1 ms long pulse from linac compressed in 975 ns Accumulator Ring
- Beam is extracted immediately upon accumulation ~1000 turns
- Entire process repeated 60 times a second



Charge Exchange Injection at SNS

- 1 GeV H- ions stripped of 2 545 keV electrons by nanocrystalline diamond foil
- Thickness chosen to balance stripping efficiency with heating, scattering, mechanical stability
- Each stored proton traverses the foil 5.5 times on average during painting
- Interactions causes foil heating, beam loss
- A thicker secondary foil strips waste beams to protons for transport down the dump line (~70 kW standard, 150 kW limit)
- Waste beams comprise unstripped H- which misses foil, partially stripped H0 that passes through the foil, and some late stripped H0 in an excited state



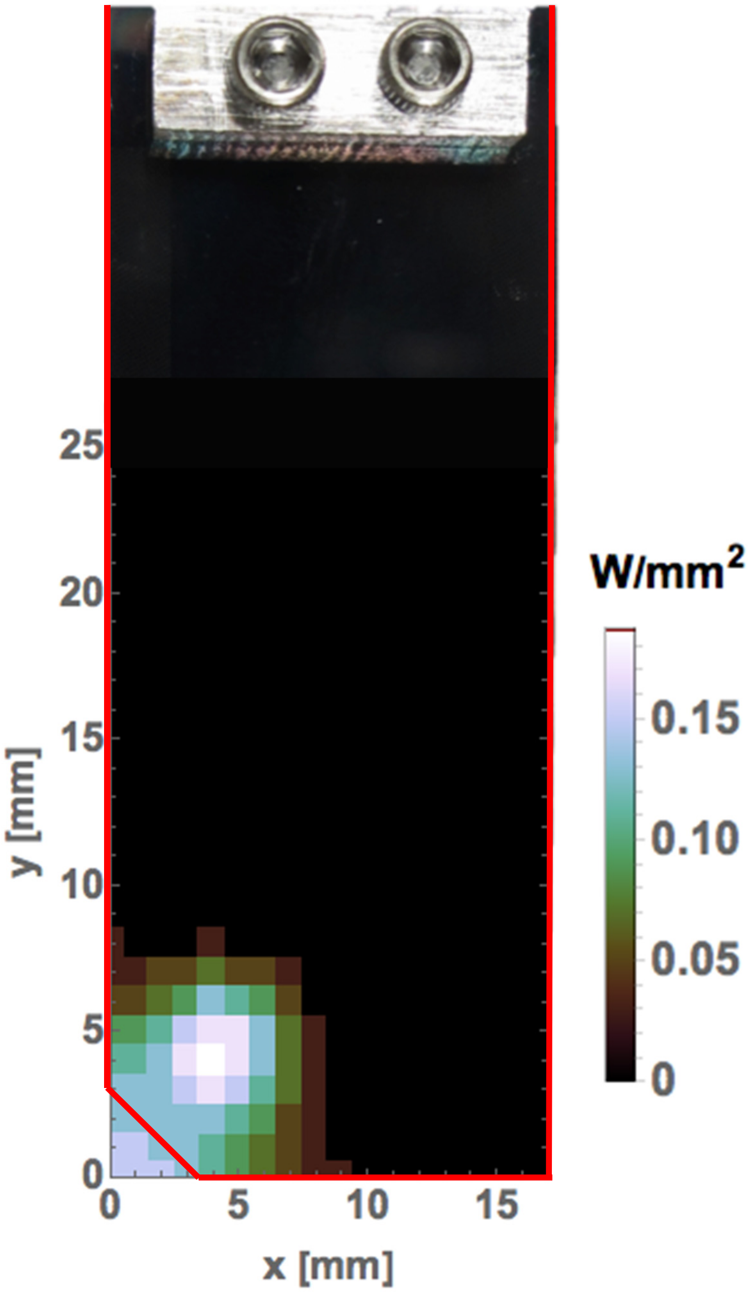
Charge Exchange Injection at SNS

- 1ms injection, 6% duty cycle, 38 mA peak current
- Protons and stripped electrons contribute to heating

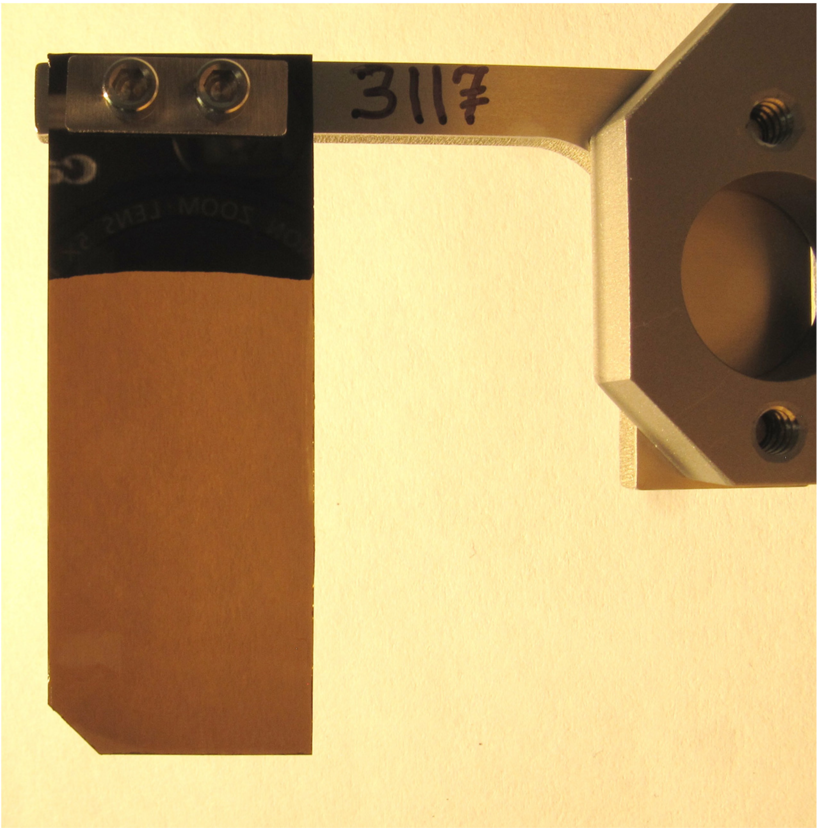
Parameter	Design	Present Op.
Linac Beta at foil(m) x/y	10.44/12.12	2.8-3.8/3.0-4.0
Linac emit at foil (mm ·mrad) x/y	0.3/0.3	0.3/0.3
Pk Avg Power (W/mm^2)	0.2	0.6 - 0.8

*Linac and ring not necessarily matched because of painting

- Plot shows average power on 400 $\mu g/cm^2$ foil



Foils for Charge Exchange Injection



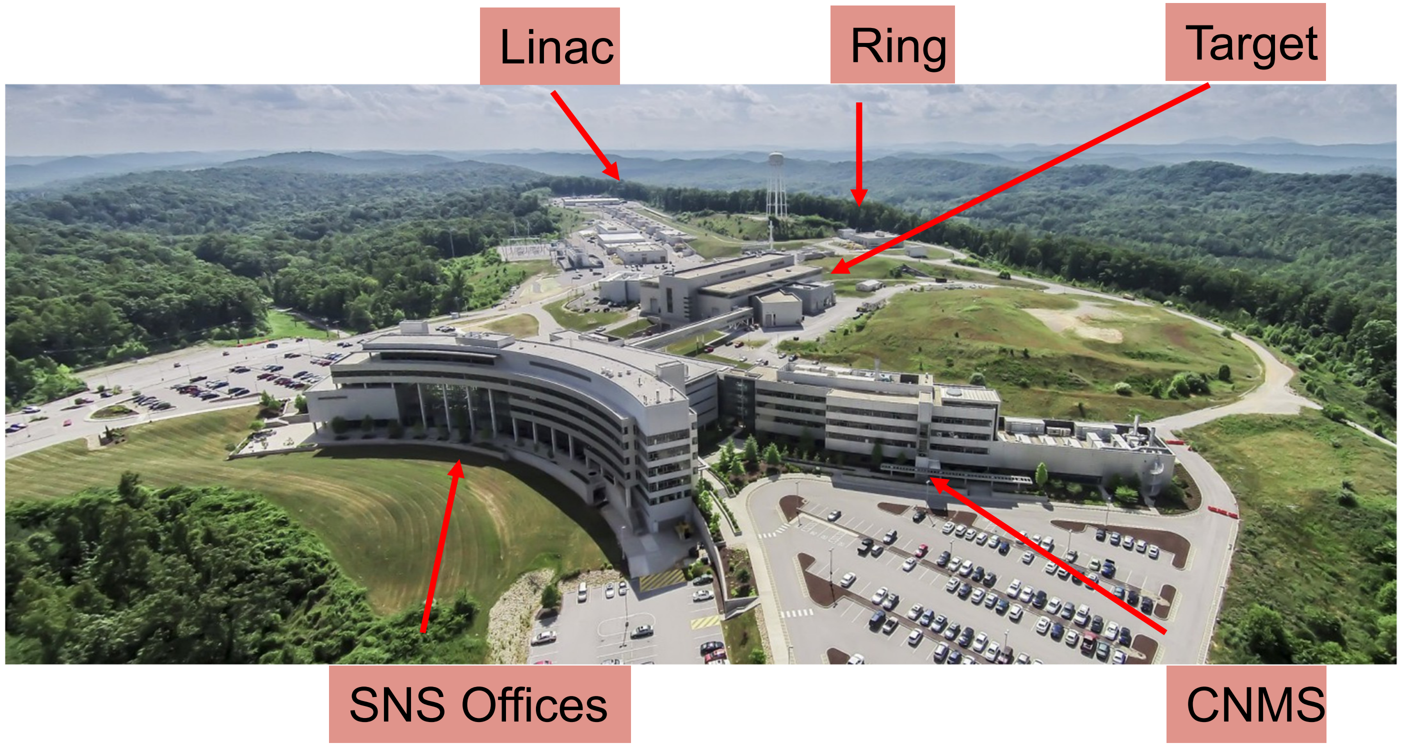
- Attractive qualities are:
  - Low Z to reduce scattering
  - High melting/sublimation point
  - Uniform thickness in effective area
    - thin to minimize loss, heating
    - thick for +95% stripping, no holes
  - Mechanically stable
  - Self-supporting
- Variety of materials have been tried: poly-paraxylene, plastic food wrap* (does not work), Al_2O_3, Boron-doped carbon, carbon nanotubes, etc.

*Joy, FNAL TM-699, 1976

SNS Foils - Fabrication

- MWE CVD tool used to grow SNS foils at CNMS

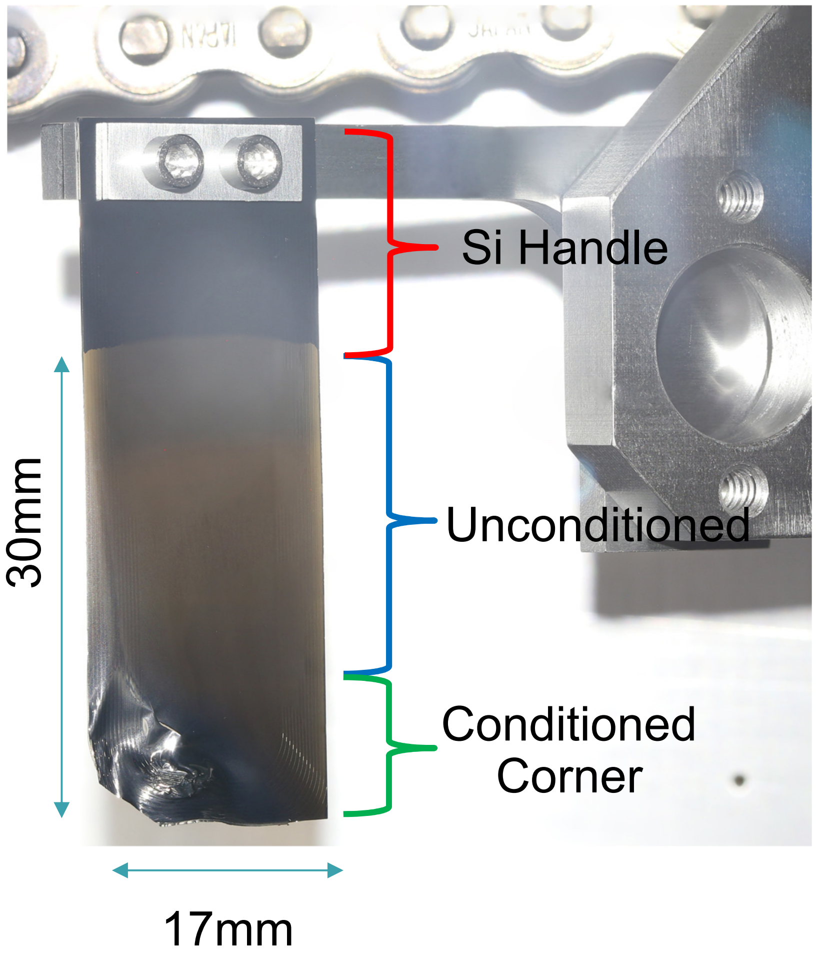
- SNS foils are nano-crystalline diamond grown by microwave CVD at the Center for Nano-Materials Sciences (CNMS) located next door
- Facilitates collaboration in production, and analysis of foils



SNS Foils - Operations

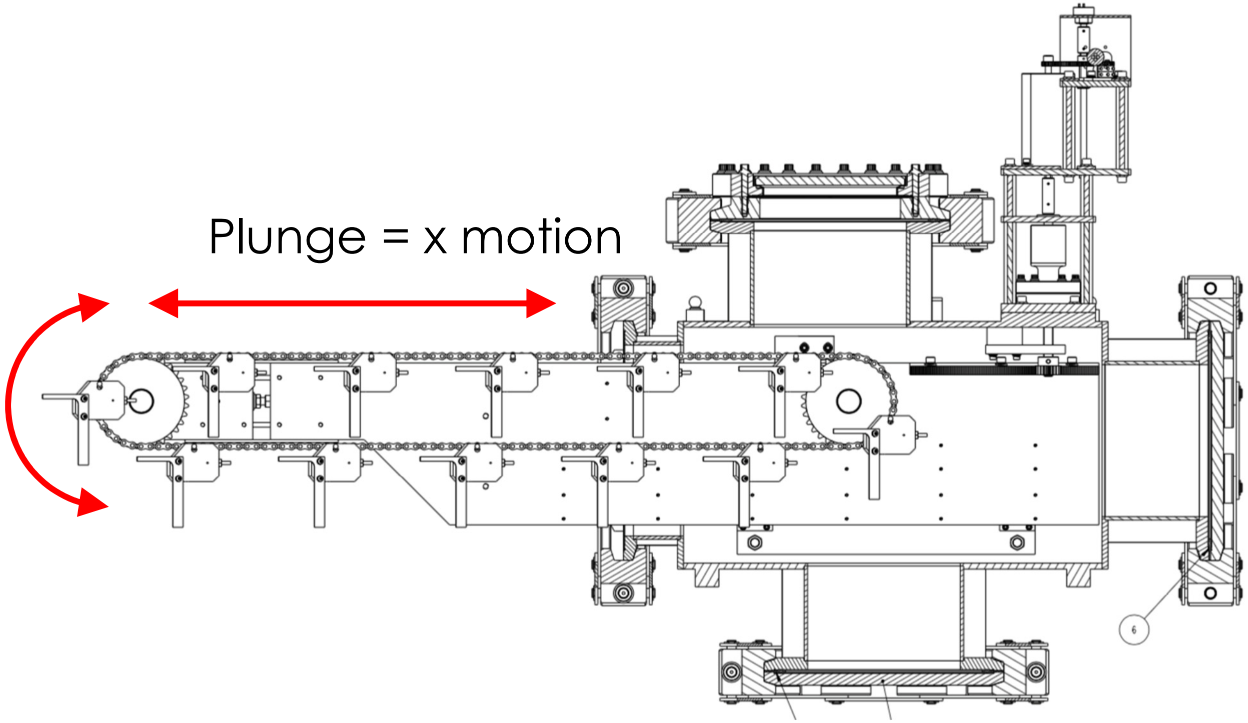
- 250-400 $\mu g/cm^2$ foils grown on Si substrate – thickness depends on energy, mechanical stability
- Around 350 $\mu g/cm^2$ is ideal for stripping at 1.0 GeV, but we tend to use 400 $\mu g/cm^2$ for mechanical stability (this is optimal thickness for stripping at 1.3 GeV)
- Substrate is partially etched away, remaining substrate is used as 'handle' for mounting
- With new MWE CVD tool thickness is uniform to within 0.04 um across foil (vs. 0.4 um with old tool)
- CNMS Foil #3073 ran for 2448 MW·Hr at 1.2 MW (almost a full run) – a new record – but looks pretty battered

Used foil on bracket in SNS



SNS Foils – Foil Placement

Photo: C. Luck

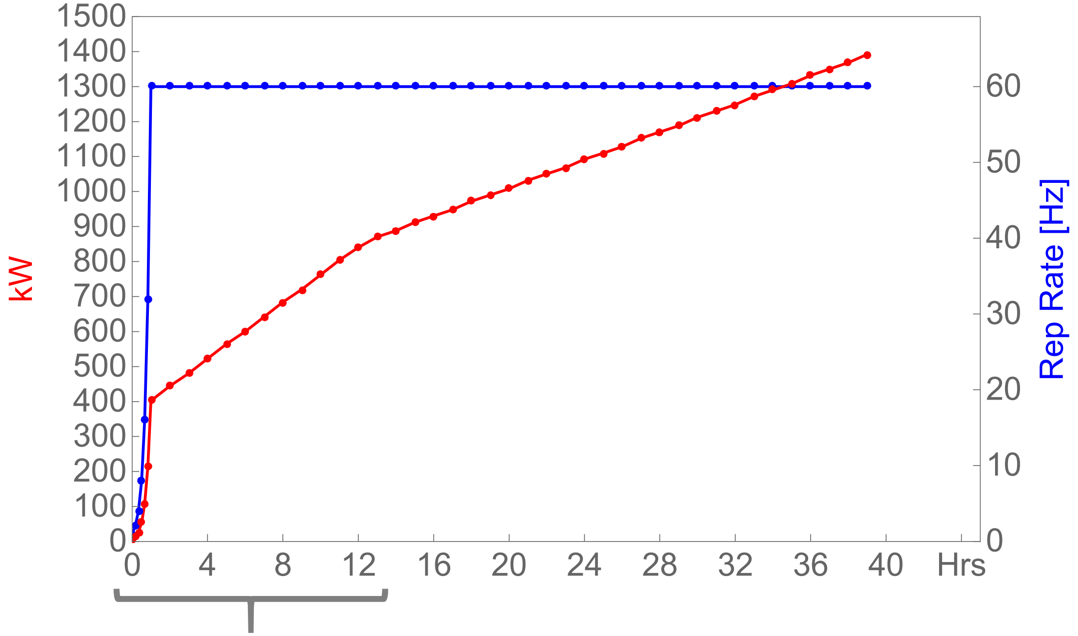


- Foil changer is capable of holding 12 foils – changed once per year or so
- Changer allows movement of foil horizontally and vertically
- Typically 1-2 foils needed for a run (~2500 hrs)

SNS Foils - Conditioning

- Conditioning Time ~40 hours
  - Slow ramp to prevent vacuum trips from outgassing
  - Diamond to pyrolytic graphite, increase in emissivity – reduces foil heating – has implications for temperature measurement
  - 12 foils = 575 hours of conditioning, ~23% of the run!
- Uniformity/Predictability
  - Sometimes we find out after hours of conditioning foil is bad - flutter, curling, twisting – can we predict/prevent/reduce bad foils?
  - Combination of making better foils, better QA, new lithography, modified conditioning, etc.

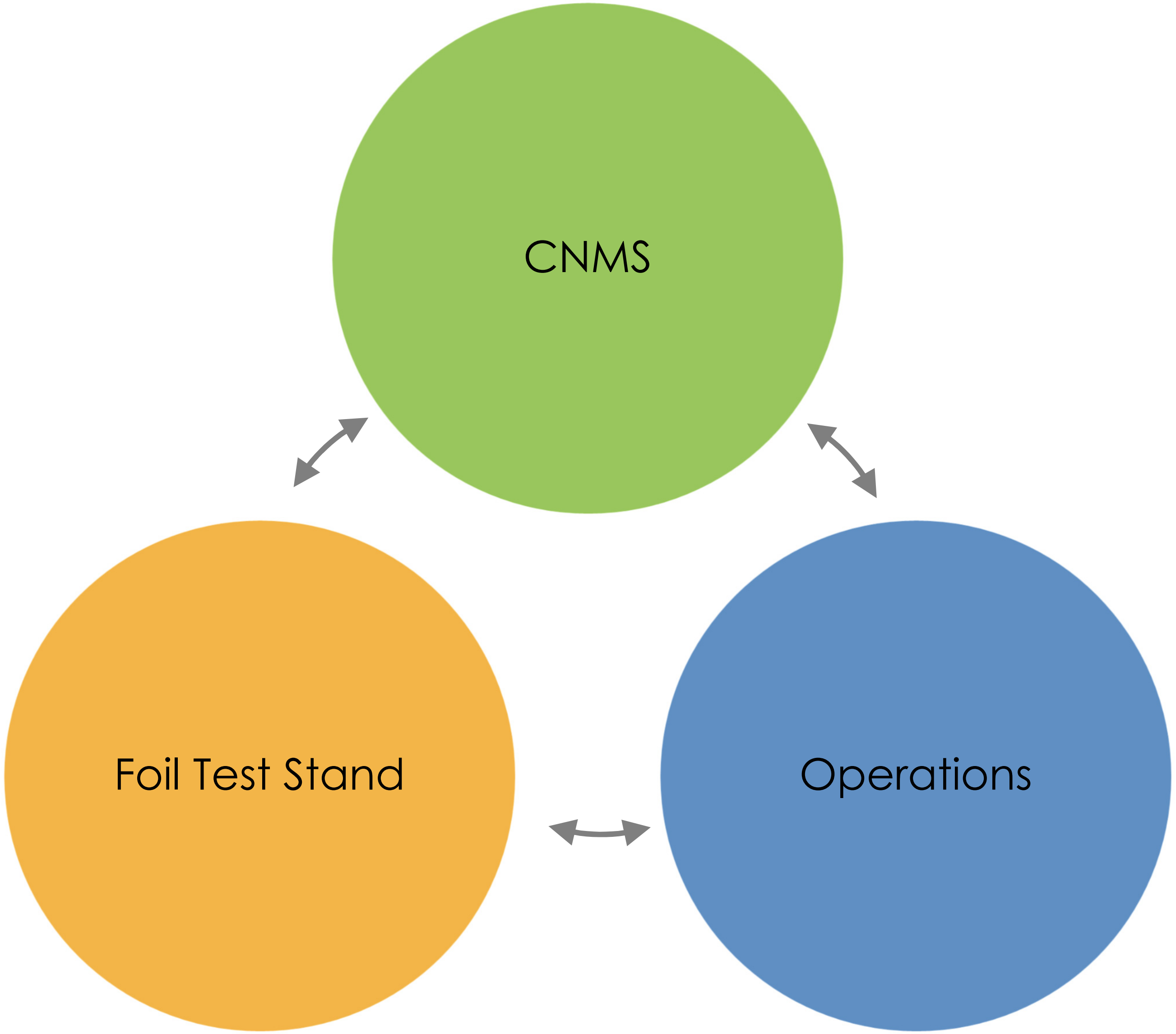
Rep rate and pulse width are used to control power



Beam is moved from corner to corner during 1 hr rep rate ramp, and 40 kW/hr ramp

Foil R&D at SNS

- Three main efforts:
  - Materials science and engineering at CNMS – prod./characterization*
  - Foil Test Stand – Controlled experiments, easy analysis, quick turn around*
  - **Operational Data**
- What do we want to know?
  - Can we reduce the conditioning time?
  - What affects deformation during conditioning, ops?
  - Can we engineer foils for better performance – either through new materials, more advanced deposition, new recipes?

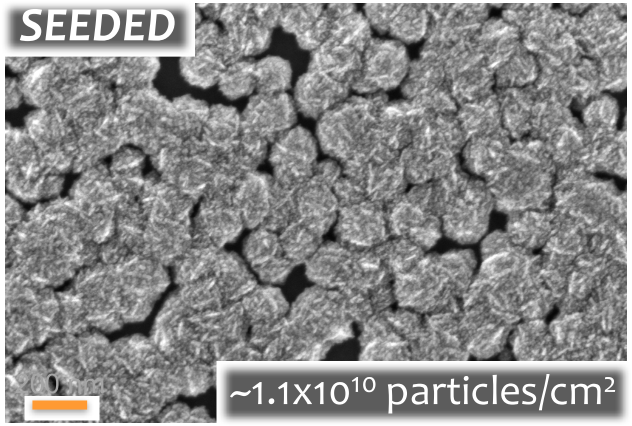


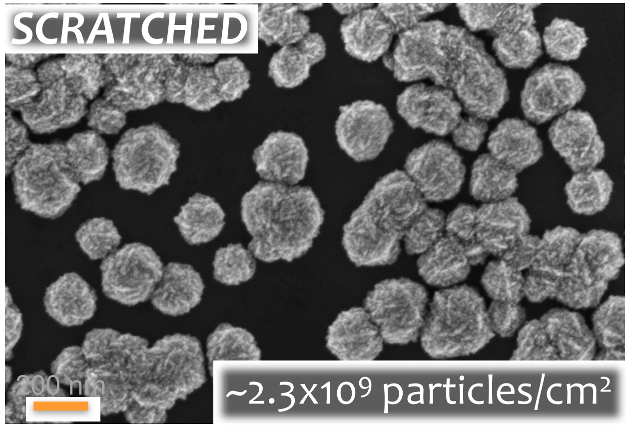
*See talk WEBZA4 L. Saturday for details

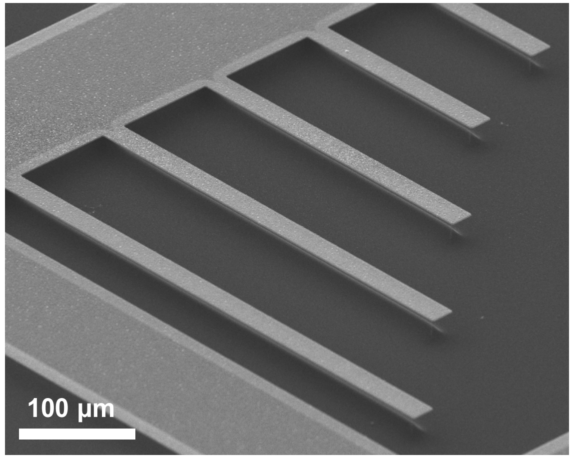
CNMS – Foil Production and Characterization

Photo: C. Luck

Analysis of Nanocrystaline Diamond Foil Nucleation Techniques







Photos Courtesy of S. Retterer

Test stand and
SNS Operations

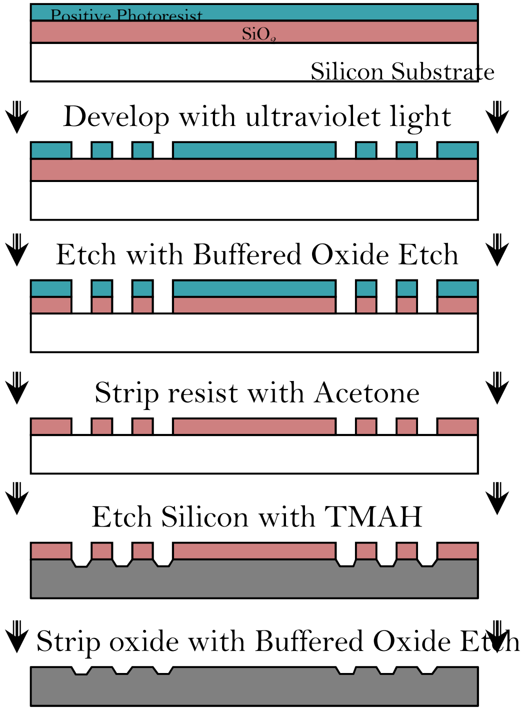
Foil Flutter
Holes
Curling
Buckling
Tearing

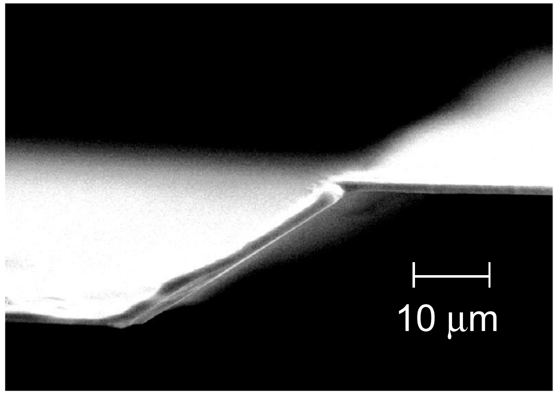
CNMS
Nano-scale Characterization

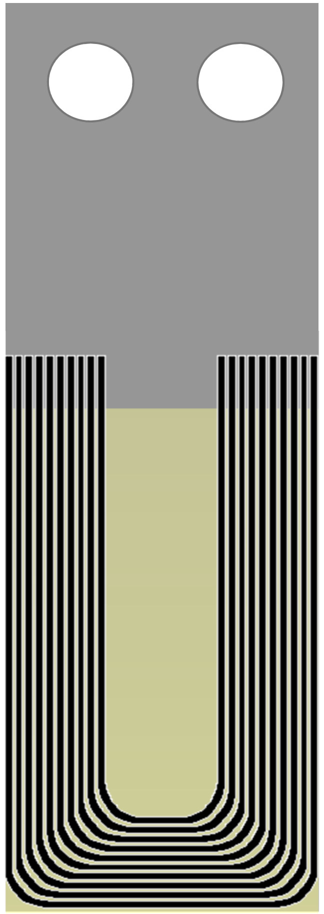
Grain Size Uniformity
Residual Stress
Changes during
conditioning

Connect observations to improve foil uniformity and reliability, and understand how performance is related to structure

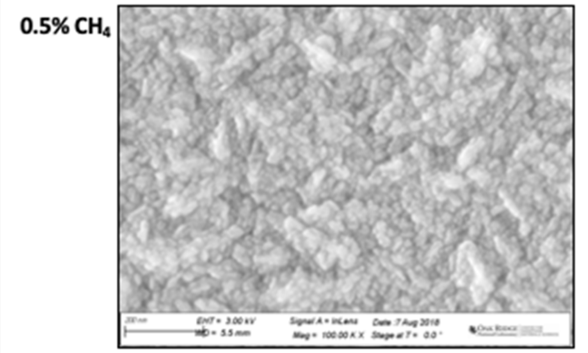
CNMS – Foil Production

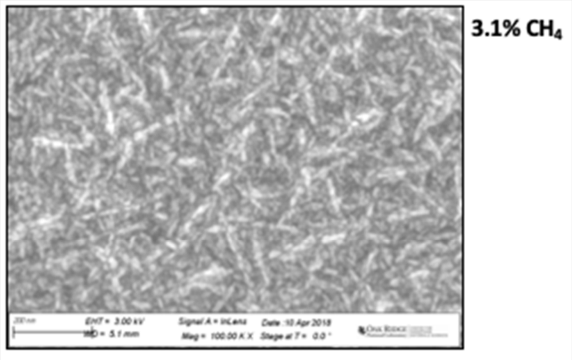


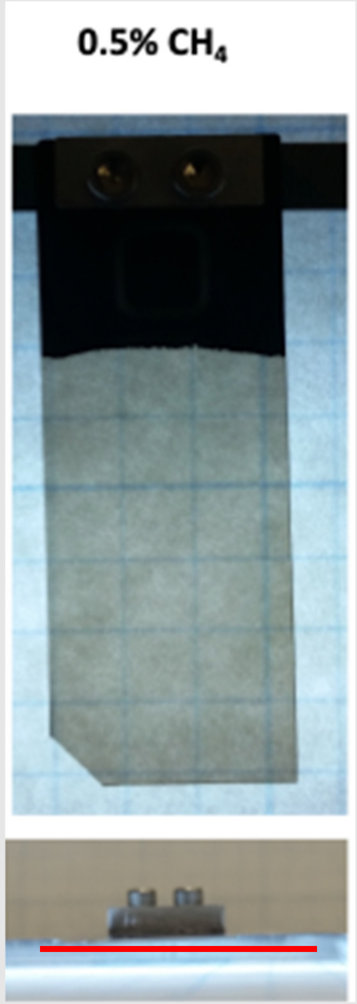




Recipe Development





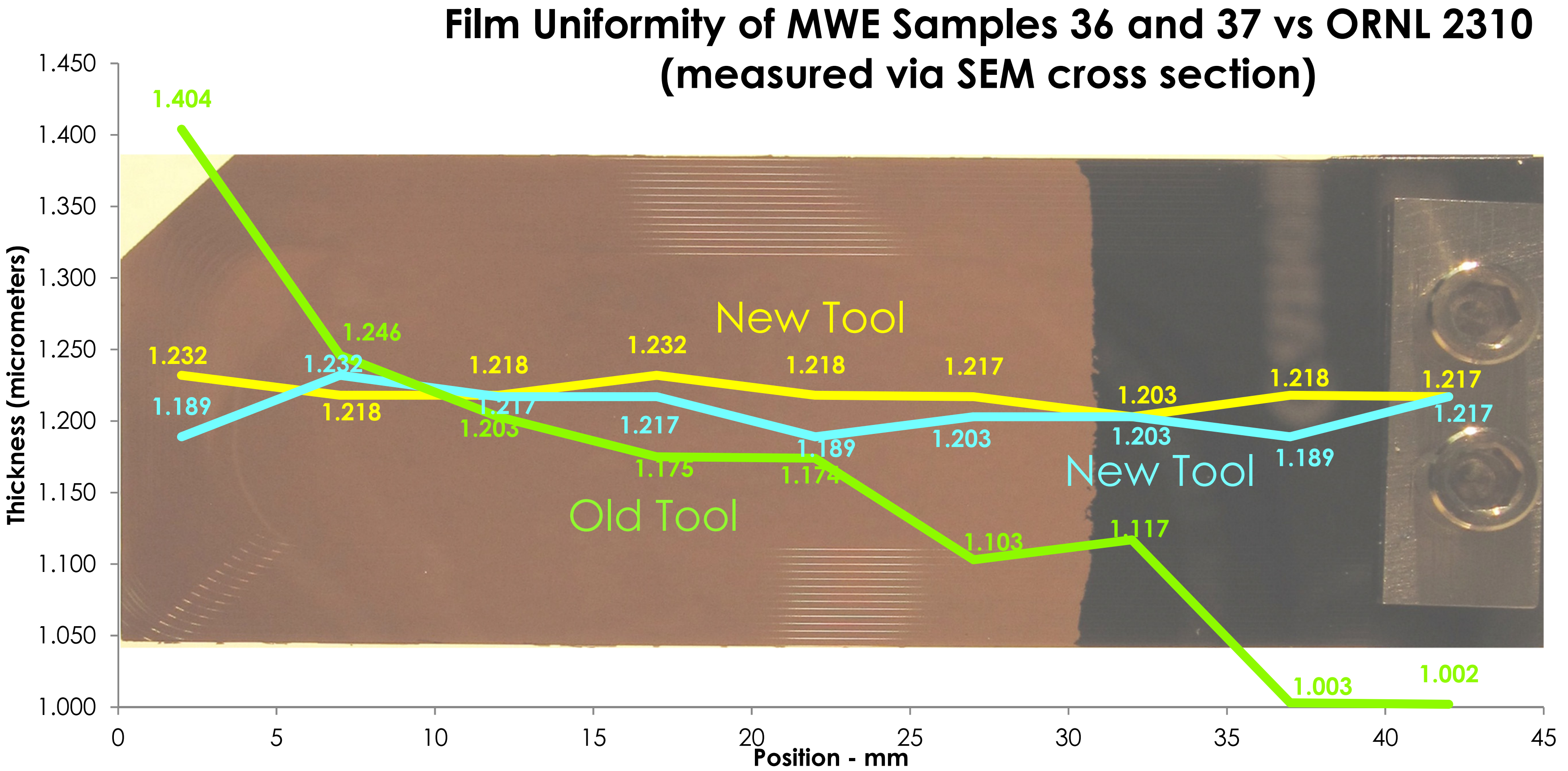


Engineered features

Images : B. Shaw, L. Wilson

CNMS – Foil Production - Uniformity

MWE foils are using the new CVD tool – uniformity is much better due to larger effective area for foil growth



Foil	Avg. Thickness(um)	Range (um)	Std Dev. (um)
MWE 36	1.219	0.029	0.009
MWE 37	1.206	0.043	0.016
ORNL 2310	1.159	0.401	0.124

*Credit: L. Wilson

CNMS – Foil Production - Features

Corrugation pattern here is U shaped all the way around, plus channels in the central region of the foil crossing the handle/foil boundary – seems to help with stability, tearing

U shaped all the way around, no channels in the central region of the foil crossing the handle/foil boundary – notice tearing

Photos: C. Luck

Foil Test Stand (FTS)

- To test new foil technology, characterize foils quickly
- Pulsed, rastered 30 keV electron beam, 5 mA, 0.3 mm^2spot size can simulate 2.8 MW equivalent heat loads on small spot
- Foils are not highly activated – making post-mortem easier
- Combined with analysis in CNMS facilities to correlate NEMS characterization with performance relevant to SNS operation
- calibrating in-situ temperature measurements

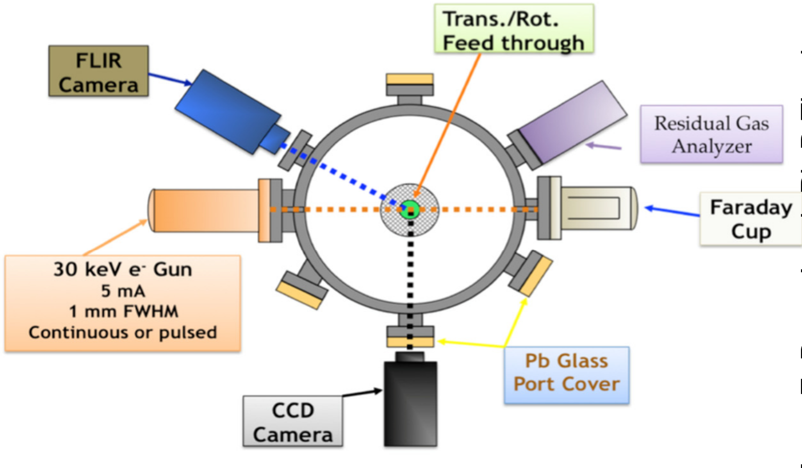


Figure 2.1 - Illustration of the Foil Test Stand

From: E. Barroclough Ph.D Thesis

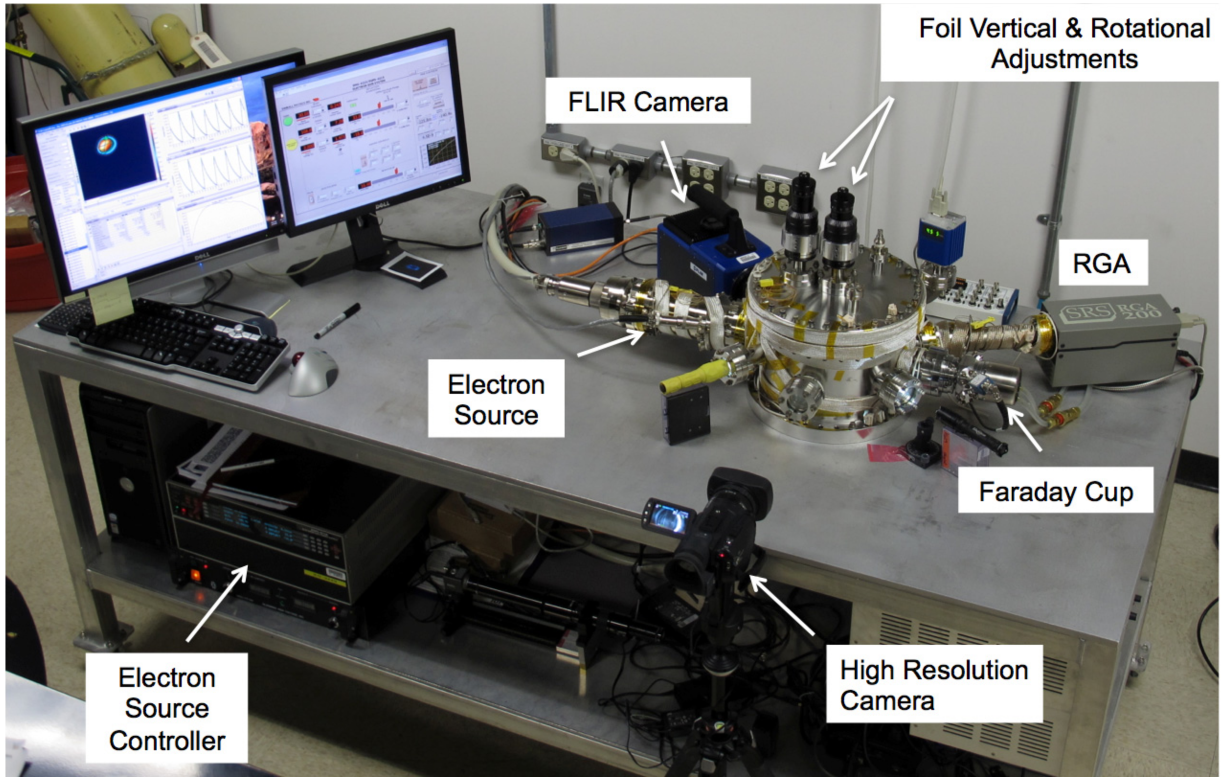
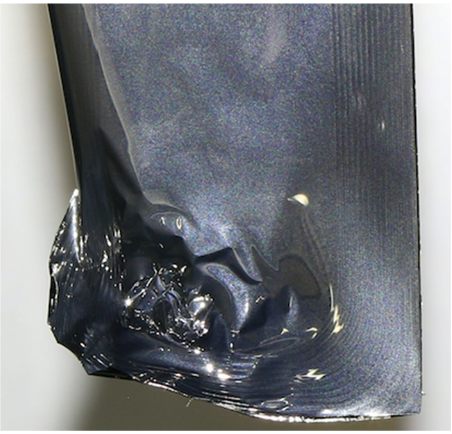


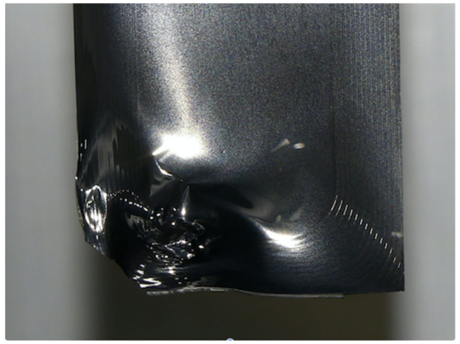
photo by C. Luck

Foil Test Stand Goals: Deformation and Performance

Foil 3162

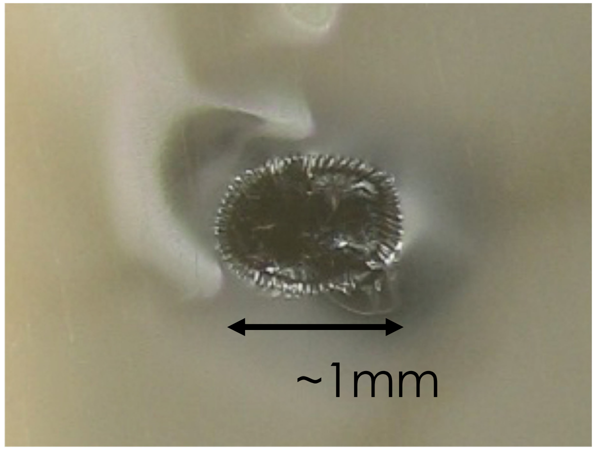


Foil 3073



Deformation can vary from foil to foil affecting operation

- Conditioning causes swelling, and puckering, and larger scale deformation
- Deformation causes some foils to 'flutter' after conditioning
- Is this deformation something we can control to minimize flutter?
- Talk WEZBA4 by L. Saturday will have more detail on test stand investigations and CNMS



Close up image of Foil Test Stand foil showing larger scale deformation and puckering near the edge of the beam spot, not present in the center

If conditioning is too fast, stress on material can cause tears

Photos: C. Luck, L. Saturday

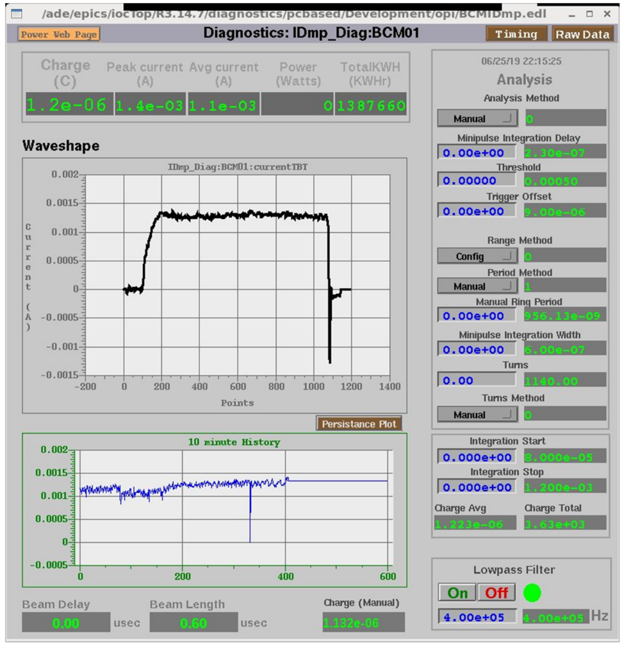
Operations Challenges

- Three primary challenges in evaluating the efficacy of foils:
  1. limited number of data points
  2. difficulty in performing post-mortem analysis on SNS foils because of activation, and difficulty handling conditioned foils
  3. they already work so well
- Long conditioning time contributes to 1 – we tend conservative in operations and try to time conditioning periods with unused study cycles, or slow ramps required by other equipment
- The test stand is crucial for testing ideas, but somethings are still not apparent until you get full beam power

Useful Diagnostics

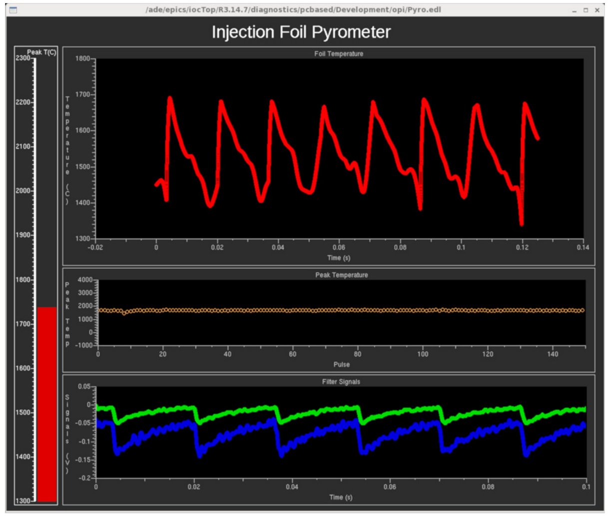
- Injection Dump Current
- Camera
- Foil Position
- Loss Monitors
- Vacuum Gauges
- Wirescanners – not during operation
- **Temperature - Pyrometer**

Injection Dump Current

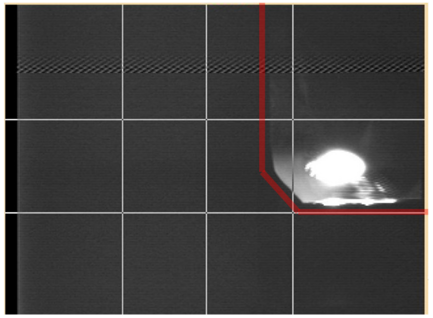


Measure sum of H- and H0 waste beams – can measure independently with wire scanners, but not during operation

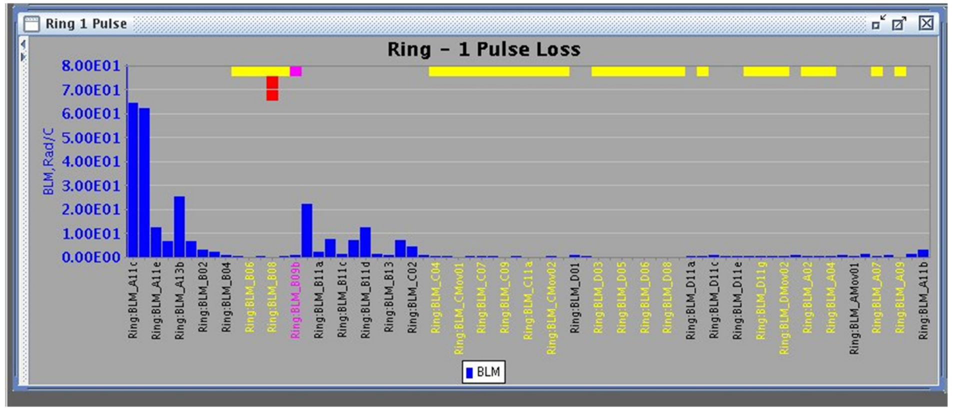
Temperature - pyrometer



Camera



Loss Monitors



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Two Wave Ratio Pyrometer

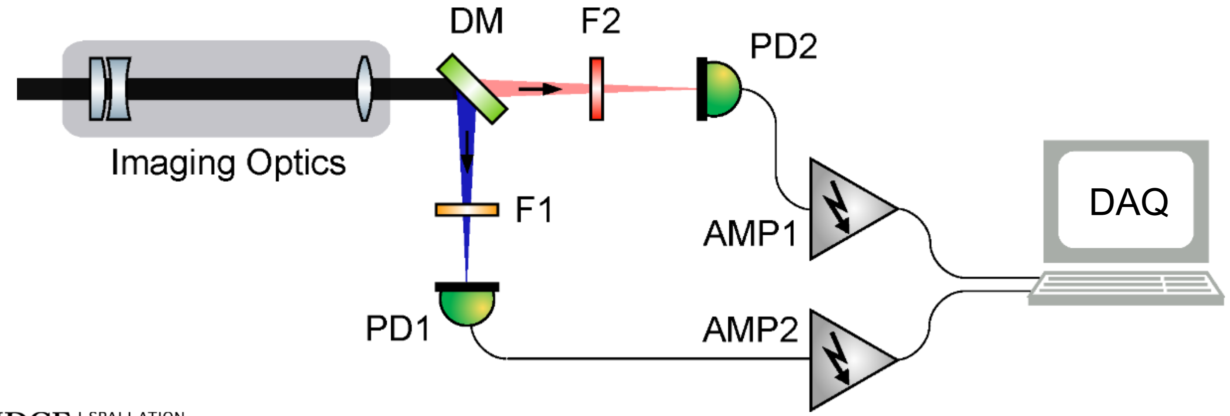
$$I(\lambda,\epsilon,T) = \frac{2hc^2}{\lambda^5}\frac{\epsilon(\lambda)}{e^{\frac{hc}{\lambda kT}}-1}$$ Planck radiation

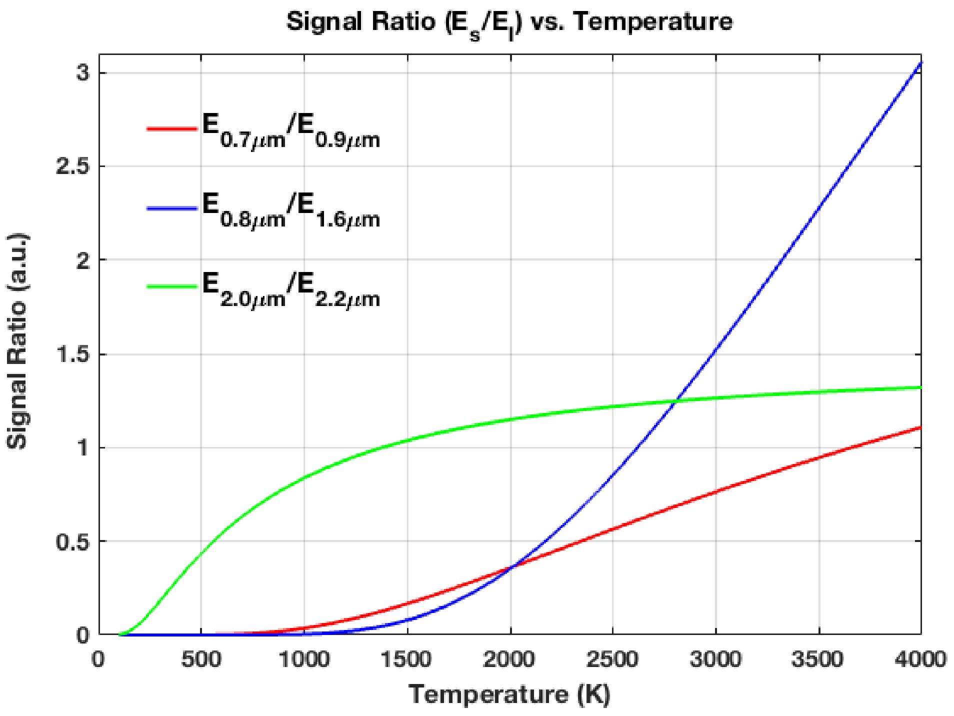
With Wien's approximation:

$$Ratio_{1/2} = \frac{s_1 I(\lambda_1,\varepsilon(\lambda_1),T)}{s_2 I(\lambda_2,\varepsilon(\lambda_2),T)} = \frac{s_1}{s_2}\left(\frac{\lambda_1}{\lambda_2}\right)^{-5} e^{\frac{2hc^2}{T}\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)}$$

With s_1 and s_2 the spectral transmission coefficients

- Don't need to know the emissivity as long as $\varepsilon(\lambda_1)$ and $\varepsilon(\lambda_2)$ are equal



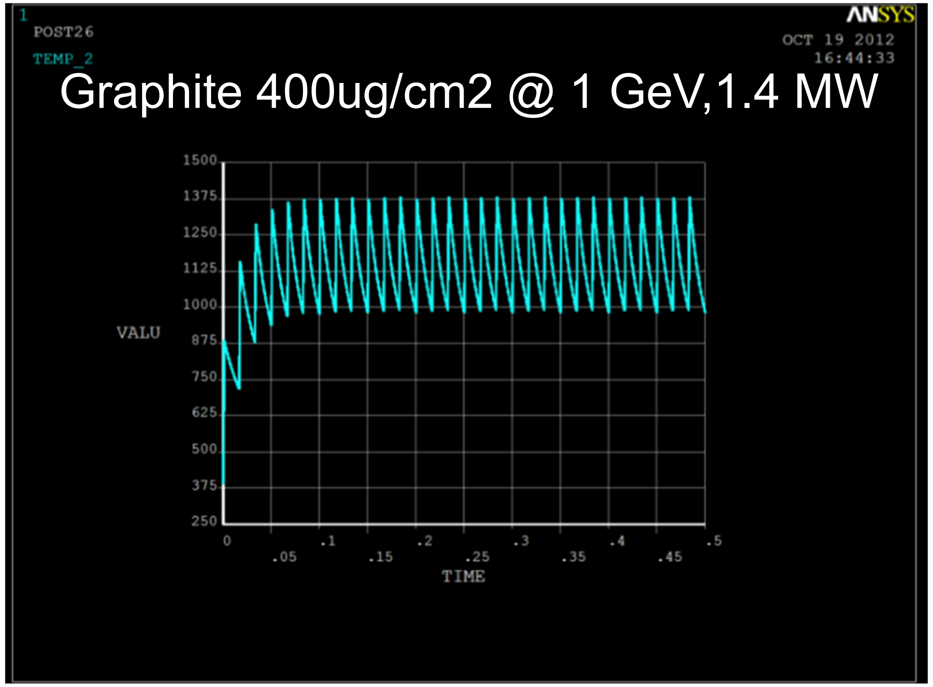


Ratio curves

Choice of wavelengths depends on temperature range of interest, 1500 - 2000 K for foils

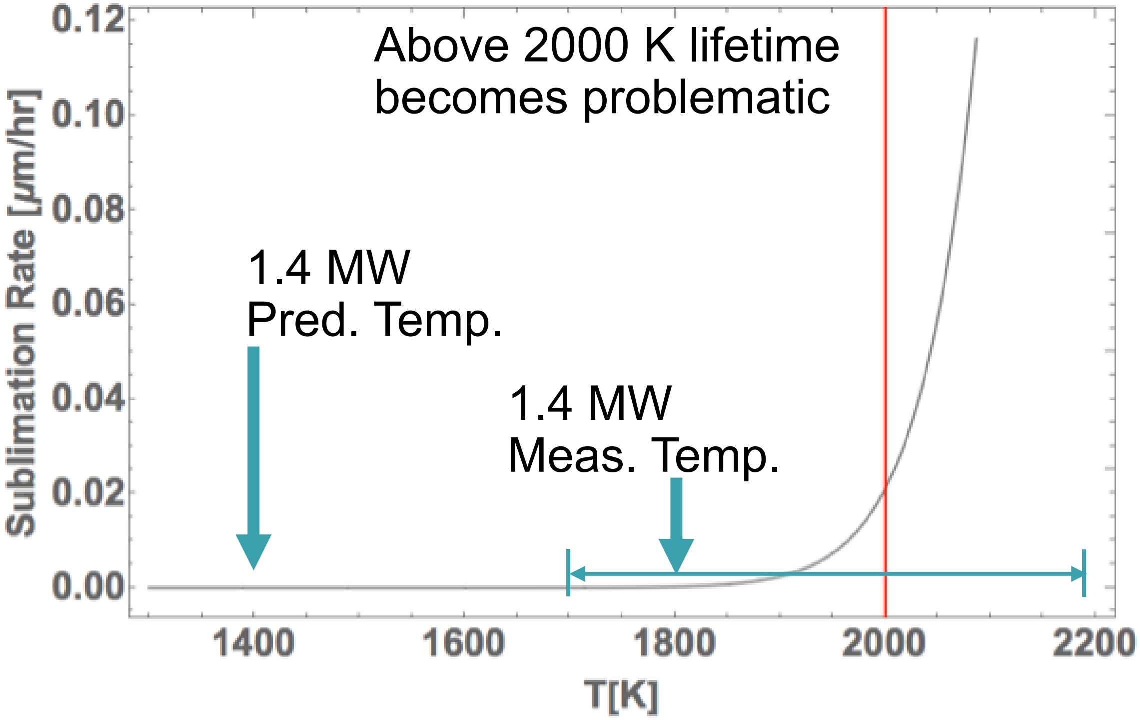
Slide courtesy of W. Blokland

Temperature Measurements: Models



Simulations show max temperature
1403 K at 1.4 MW

From: Y. Takeda ANSYS Simulations for SNS



$$\frac{dh(t)}{dt} = -8.12 \times 10^{10} \frac{[g\sqrt{K}]}{[\mathrm{cm}^2\ \mathrm{sec}]} \frac{\exp[\frac{-83\,500}{T}]}{\sqrt{T}}.$$

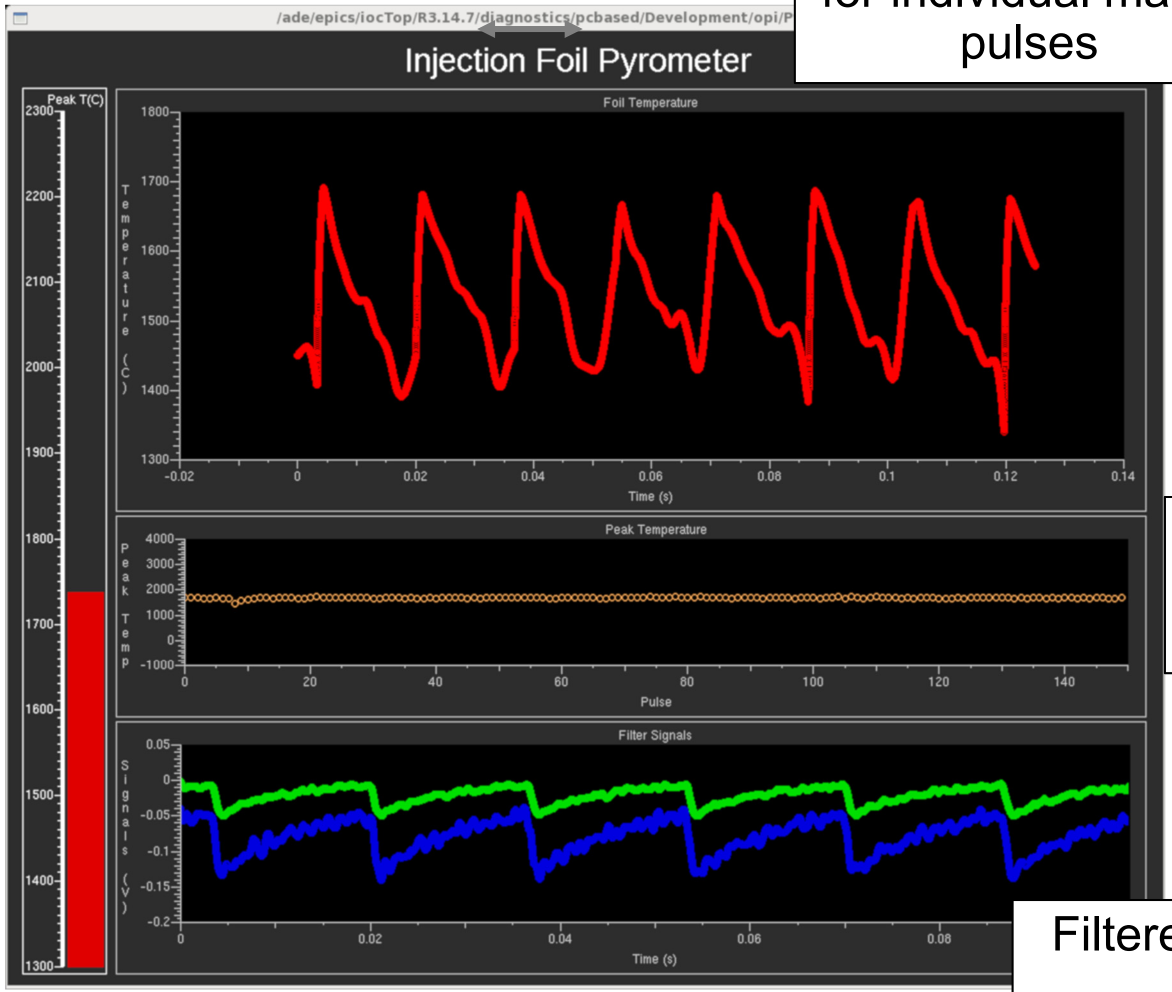
(Lebedev, and Lebedev, PRSTAB 2008)

Discrepancy is due to smaller beam on foil than design

Operational Diagnostics – Pyrometer Prototype

Avg peak Temp (K)

Temperature curve for individual macro pulses



Peak temperature for the last 150 pulses

Filtered photo diode signals

Allows us to monitor temperature in real time

Particularly helpful in determining cause of high injection dump current – are we missing the foil, or is the foil thinning?

Should provide feedback for conditioning cycle – we have not tested this yet

Prototype system has ±150 K error

Foil Conditioning with Pyrometer

Outgassing, conversion to graphite-like diamond, and possible sublimation

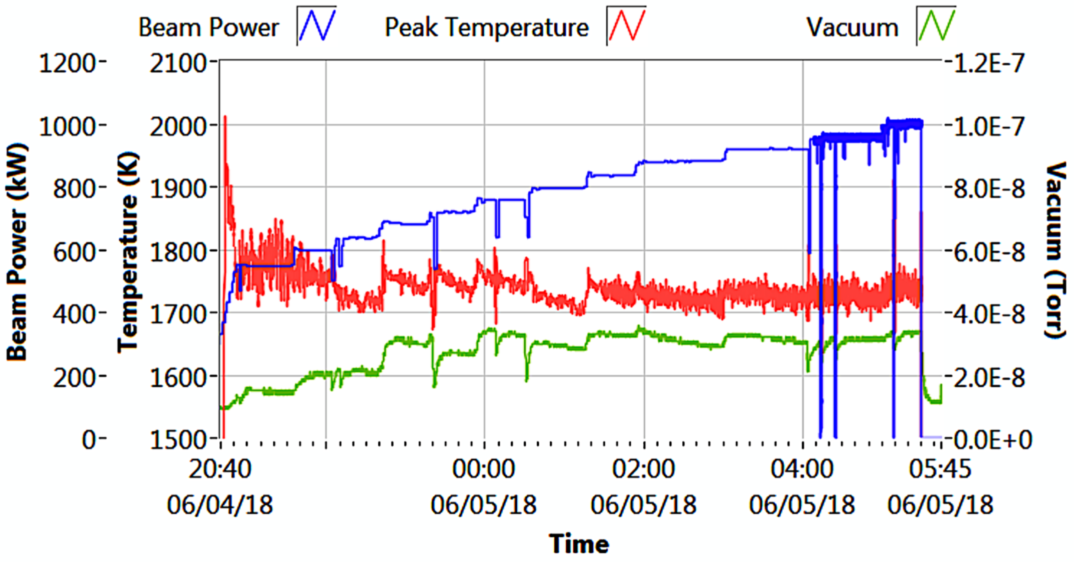
High initial temperature: foil camera shows very bright spot, vacuum up

For each beam power increase (blue) the temperature (red) and vacuum (green) change but recover

We have made observations of foil temp during conditioning, but have not yet used the pyrometer as feedback during foil conditioning


New Foil

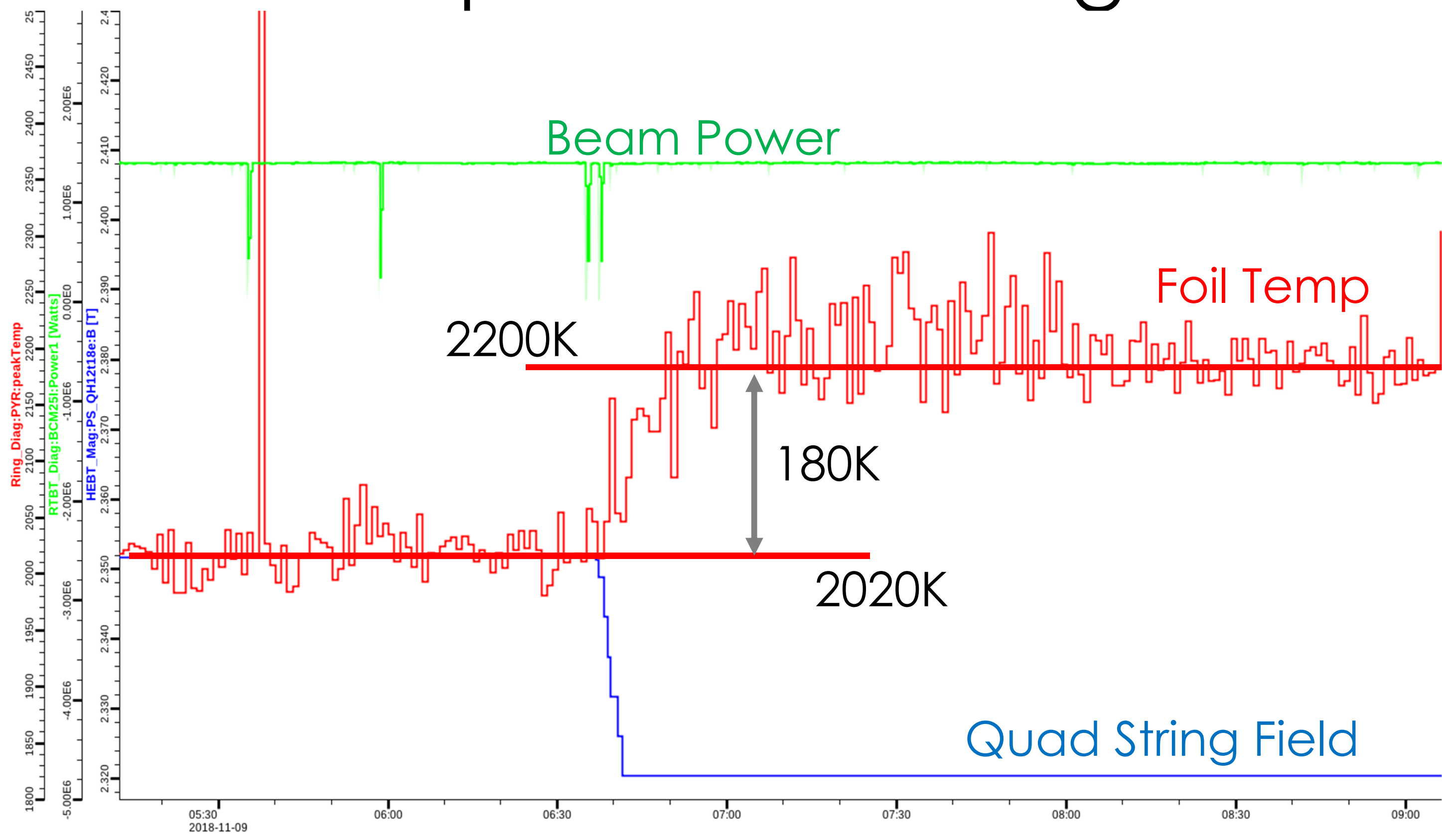

Used Foil



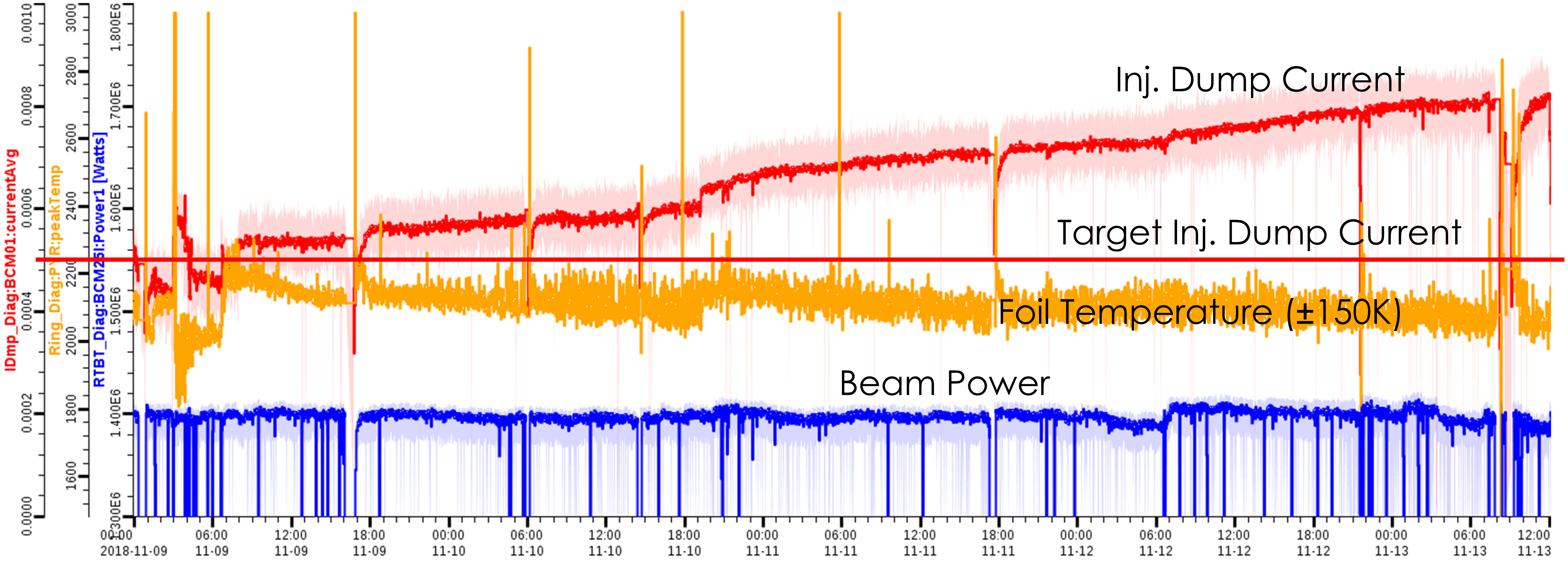
Data: Wim Blokland, Photos: Chris Luck

Observations from Operation – Temperature Changes

- Temperature changes due to small tweaks to beam size on foil in predictable ways
- We trust the trends we see, particularly when close in time and correlated with known changes
- Notice the temperature is much hotter than predicted 1400 K
- Upgrades to pyrometer will improve signal, aiming, stability



Noticeable Thinning During Production



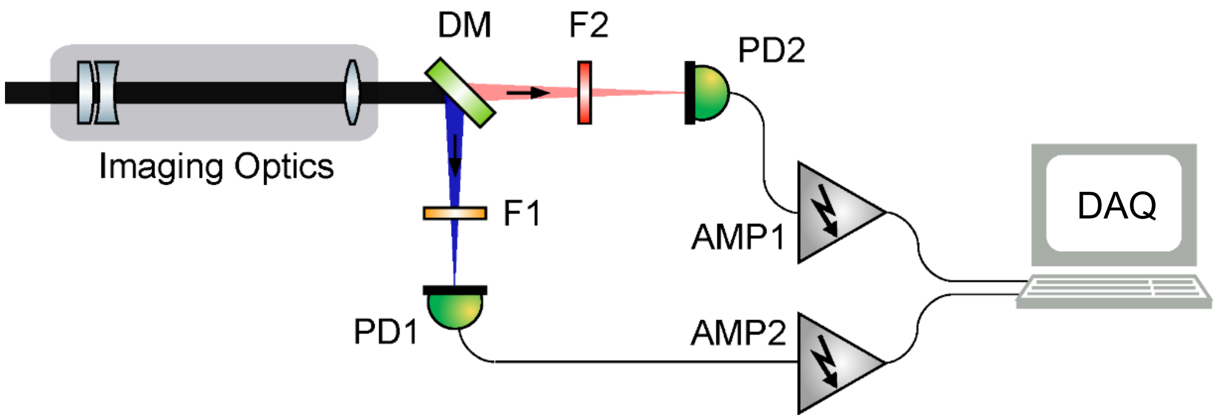
November 9,2018 November 13,2018

- Inj. dump current increases, temperature decreases probably foil thinning
- Peak temperature around 2200 ±150 K with 3-4x design current density on foil
- There are additional clues that we are thinning – counter-intuitive behavior as we move closer to the edge of the foil – but this could still be due to deformation and not thinning – Leo will discuss our effort to measure thinning directly

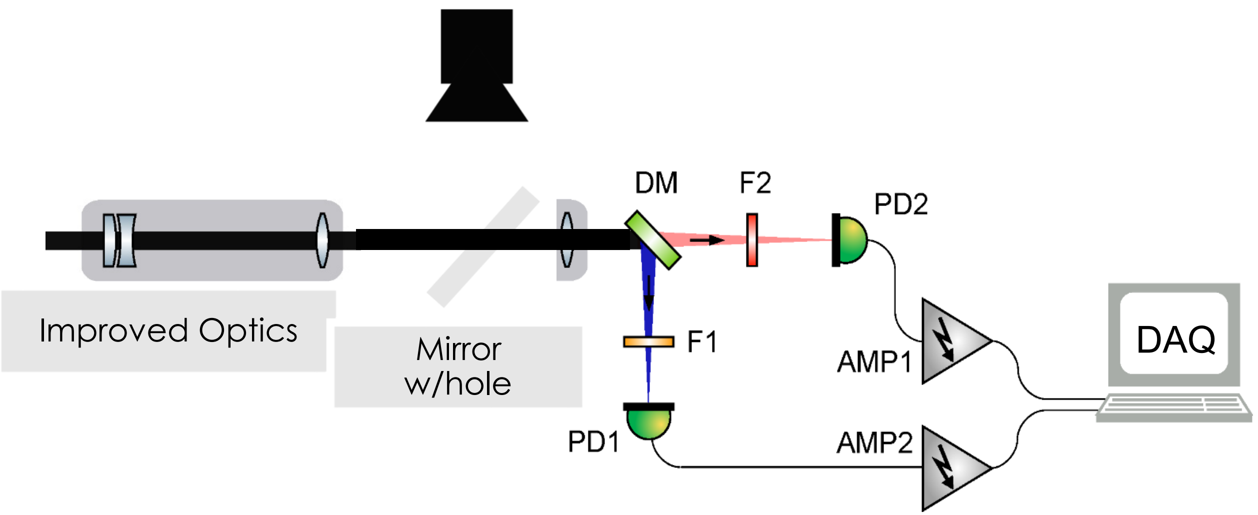
Pyrometer Upgrades

- Optics upgrades will increase number of photons gathered
- A mirror with a hole has been added, a camera will image the foil area except where beam is present – this will help with alignment
- Expected precision is ±50 K at 2000 K
- Higher T Blackbody source would improve precision

Prototype



Camera



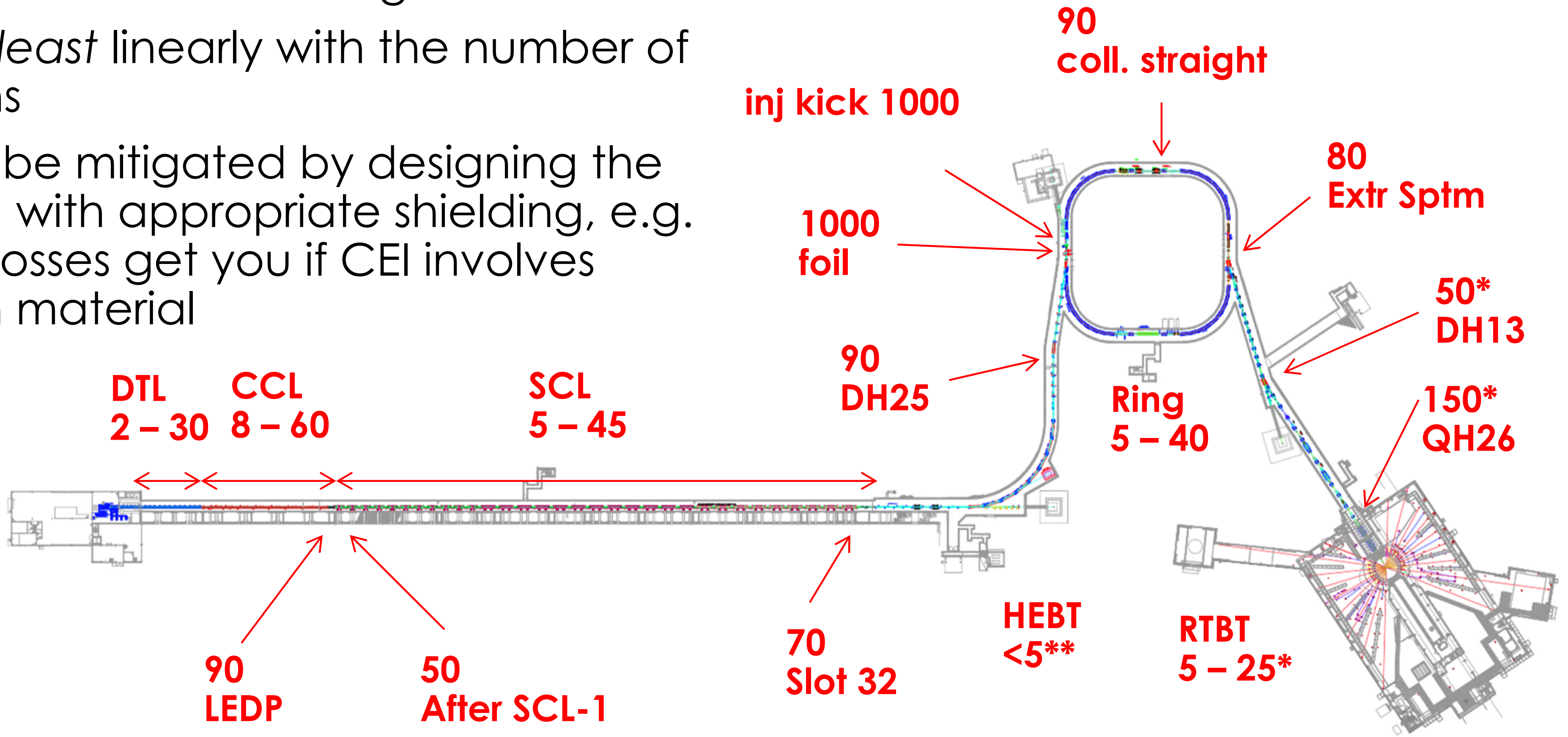
Thoughts on the Limits of foils for CEI

- Foil Limitation
  - CEI limited by foil sublimation on time-scales comparable to the conditioning time
  - At SNS we see failure due to sublimation when beam size is too small
  - If we assume design beam size, but scale to similar beam densities at 1.3 GeV max power for SNS would be between 6-8 MW based on foil sublimation alone

Thoughts on the Limits of foils for CEI

- Operational Limitation
  - Activation from losses is main issue
  - ~20 days cool down for foil change
  - Losses scale *at least* linearly with the number of injected protons
  - Activation can be mitigated by designing the injection region with appropriate shielding, e.g. but eventually losses get you if CEI involves interaction with material

* 3 days after 1.3 MW
** No survey near this time, indicated does rates are typical



Laser Assisted Charge Exchange Injection

- Laser based methods are the future of high-power CEI*
- Feasible technology has been demonstrated at SNS** on μs duration pulses with >90% stripping efficiency – no immediate plans for operational implementation
- Technical challenges remain, but no obvious show stoppers apparent, path forward identified

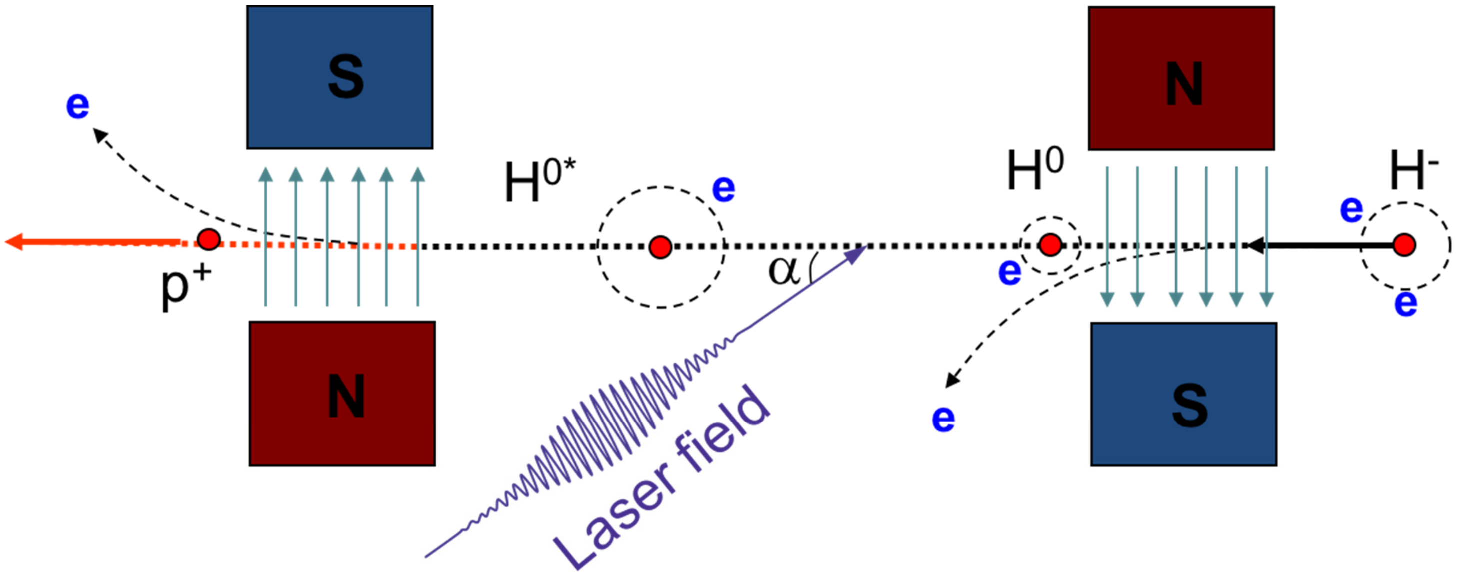


Figure: S. Cousineau

*See talks WEYBB5 (Aleksandrov) and TUYBB2 (Rakhman) for some discussion of laser developments at SNS
** Cousineau et al. Phys. Rev. Lett. **118**, 074801 (2017)
Cousineau et al. Phys. Rev. Accel. Beams **20, 120402 (2017)

Summary

- Nanocrystalline diamond foils behave well for MW level operation and will survive 2.8 MW at design beam density
- Current R&D is aimed at reliable, predicable operation and establishing the limits of the technology – for SNS design, limit is 6-8 MW based on onset of foil thinning
- Current research is concerned not just with material used, but with nano-scale properties, and microscale structure, and material changes during conditioning
- Next order of magnitude power, CEI based on interaction with materials likely to be superseded as the state-of-the-art by laser-based methods, largely because of losses

Acknowledgements

I would like to thank my colleagues at SNS: Chris Luck, Charles Peters, Wim Blokland, Jeff Holmes, Mike Plum, Jeremy Price

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And the University of Tennessee: Leo Saturday, Philip Rack

For contributing to this project