Two-Dimensional Temperature Measurements of Nanocrystalline Diamond Stripper Foils at SNS

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Outline

- Motivation
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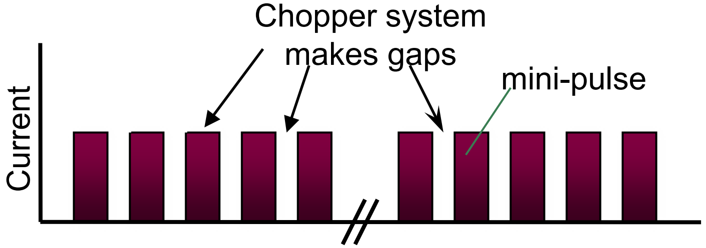
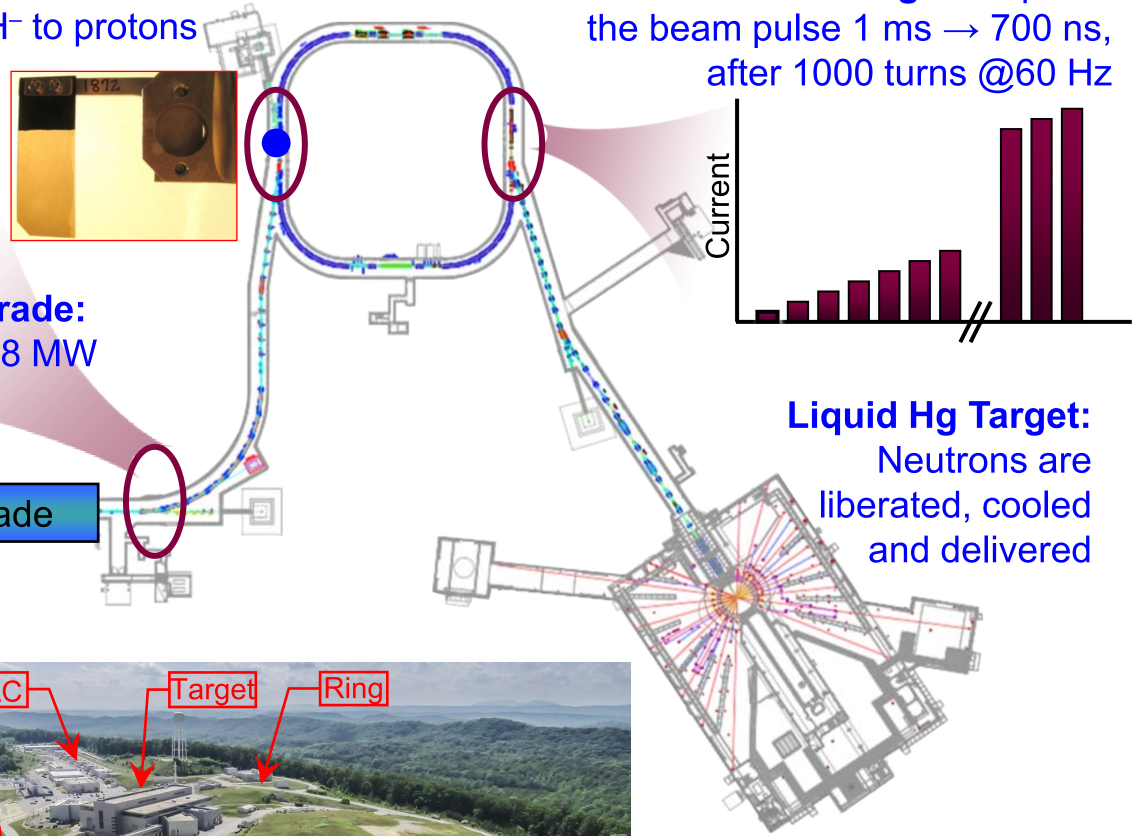
  - Nanocrystalline Stripper Foils at SNS
  - Foil Heating & Material Property Change
- Foil Temperature Measurement System
  - Two-Color Pyrometry
  - Optical System Configurations
  - System Calibration
- Experimental Results
  - Temporal Measurements with Integrating Pyrometer
  - Imaging Pyrometer Configurations
  - Spatial Temperature Profile with Imaging Pyrometer
  - Time Resolved Temperature Profiles
- Summary

The Spallation Neutron Source

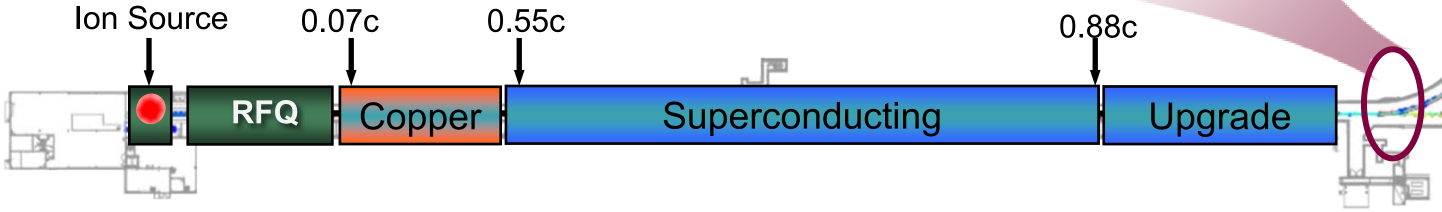
Front-End: Produce the H⁻ beam pulse



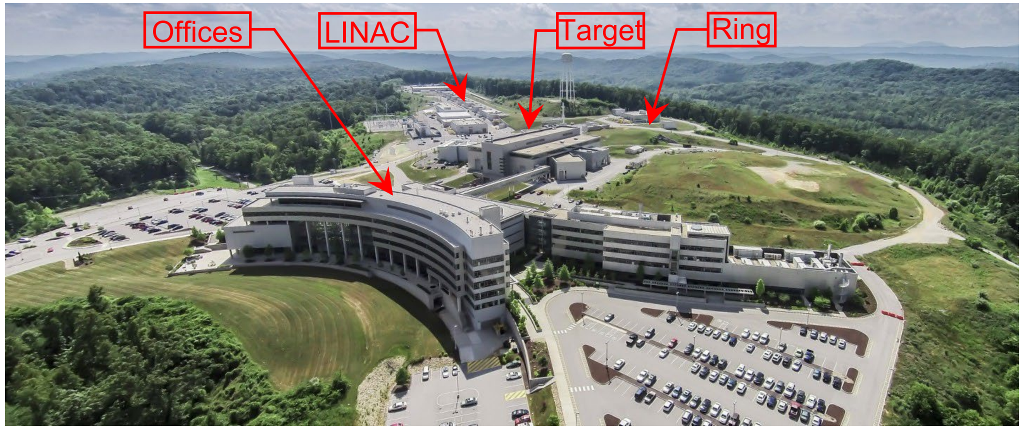


LINAC: Accelerates the beam to 1.0 GeV, ~90% speed of light

After Upgrade: 1.3 GeV, 2.8 MW



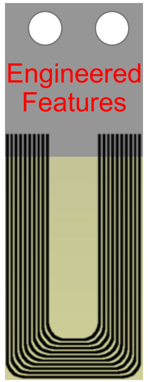
- **1 GeV, 1.7 MW** proton beam for producing neutrons (2.8 MW @1.3 GeV after upgrade)
- H⁻ Multi-Turn Charge-Exchange Injection to create a short pulse of protons in the Ring
- **1.8×10^{14} protons/pulse** in the Ring
- **Beam power limiting factors**:
  - Injection foil survivability; Beam loss



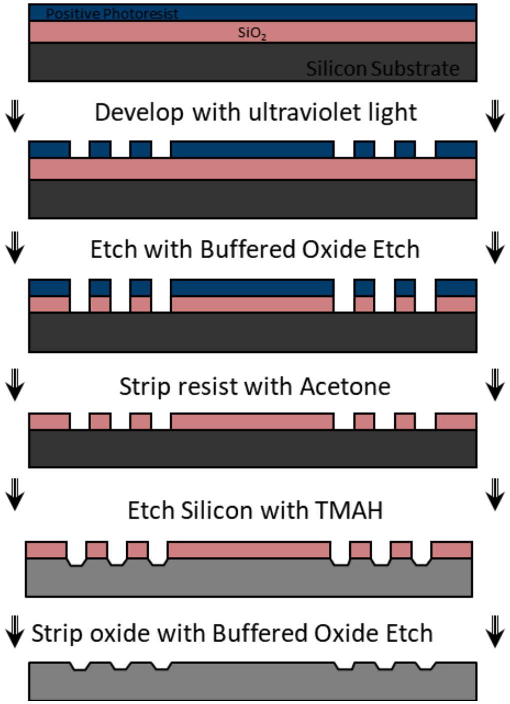
Nanocrystalline Diamond Foils at SNS

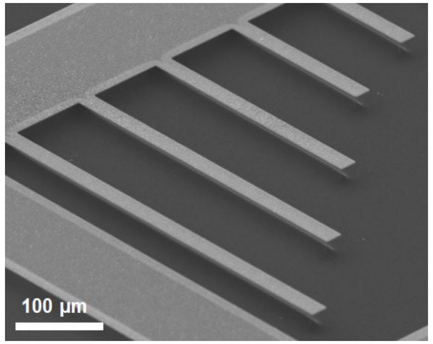
- Foils are nanocrystalline diamond grown on Si substrates.
  - Thickness: 250 – 400 µg/cm^2 (or 1 – 2 µm).
- SNS overcame early years of foil issues that limited beam power.
- R&D partnership with Center for Nanophase Material Science (CNMS) on foil production & characterization
- Foil corrugation method developed
  - Thermal expansion mismatch (diamond vs. silicon)
  - Grain size uniformity: residual stress changes during conditioning
- SNS effort:
  - Foil characterization: Foil Test Stand
  - Study foil behavior: Foil flutter, Holes, Curling, Buckling, Tearing
  - Foil Temperature Measurements

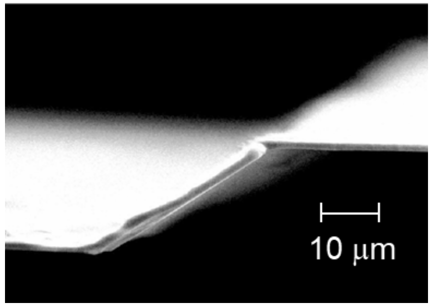
Early Years
at SNS (2010)



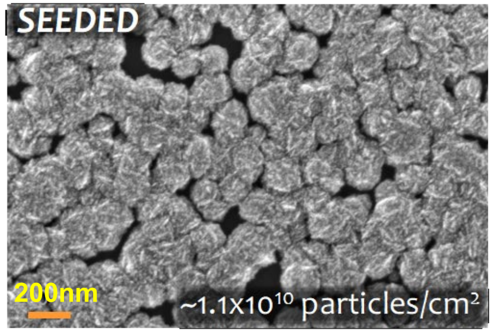
Patterning Process

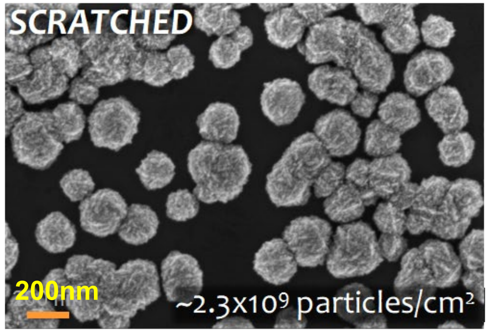






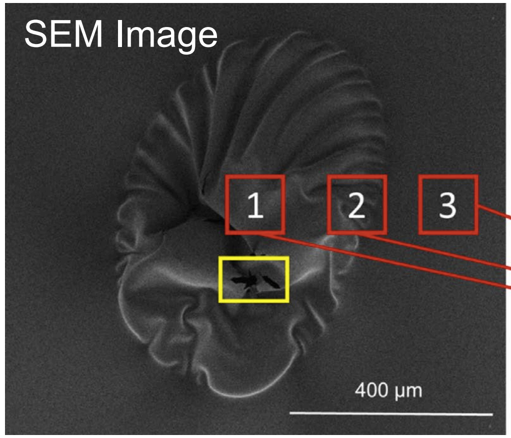
SEM Analysis of Nanocrystalline Diamond Foil Nucleation Processes



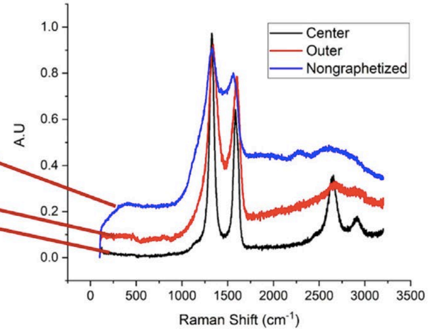


Foil Heating & Material Property Change

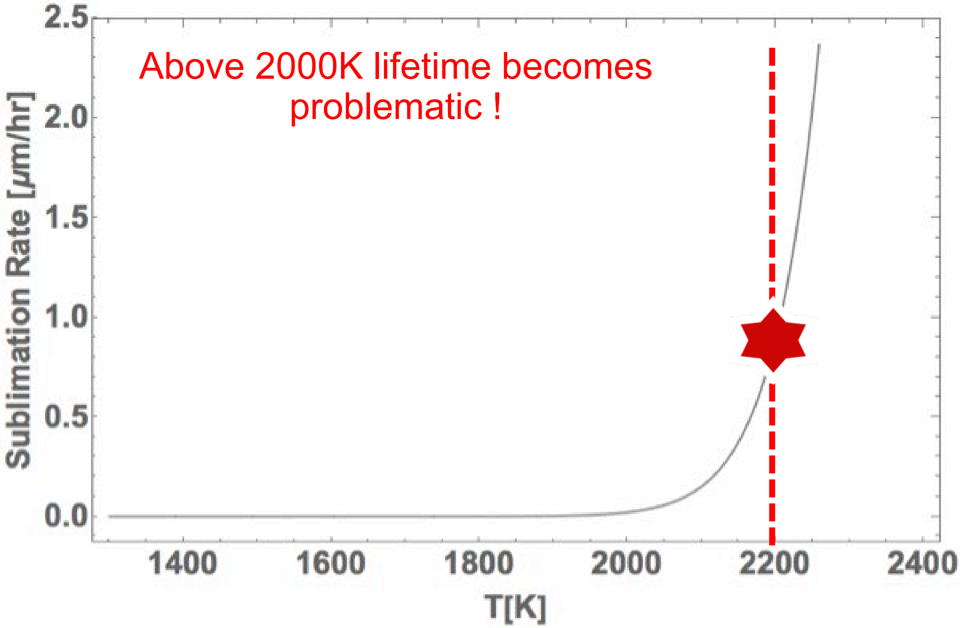
- Power deposited in the foil cause heating, beam loss and material changes.
- Energy deposited causes material change:
  - nanocrystalline diamond → polycrystalline graphite
  - Increase in **emissivity** ($\varepsilon_{diamond} < \varepsilon_{graphite}$)
  - Reduces foil heating (thermal conductivity increases)
- Foils have two major limitations:
  - Radiation Damage (beam loss, scattered particles hit beam pipe cause radiation)
  - **Sublimation** (Thinning, crystal lattice destruction, mechanical deformation)
- There is a practical beam power density limit for foil use.
- Calculation must be verified by measurements to estimate lifetime of foil for power upgrade at 2.8 MW.



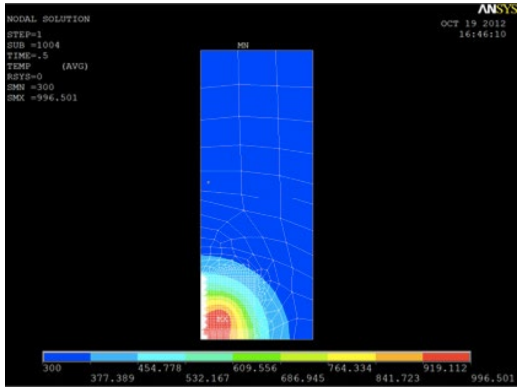
Raman Spectra

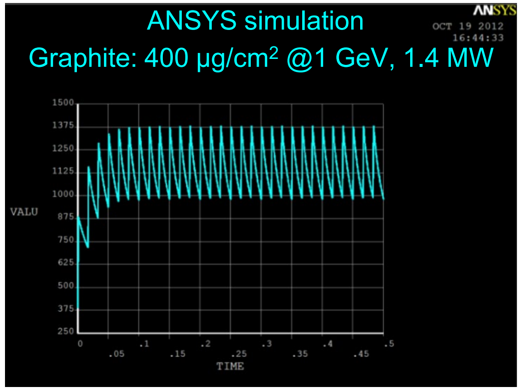


L. Saturday, *et al.*, *NIMA* 2022)



(S. Lebedev & A. Lebedev, *PRSTAB* 2008)



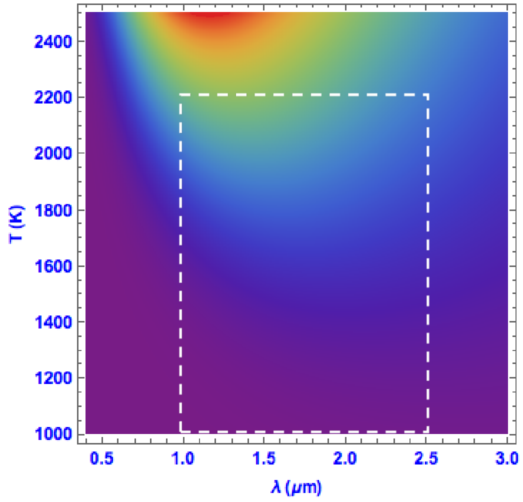


(Y. Takeda & M. Plum, *IPAC* 2013)

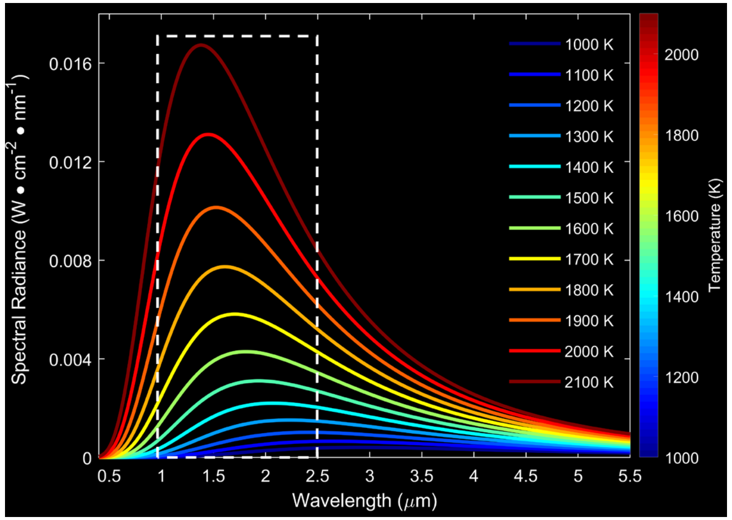
Two-Color Pyrometry

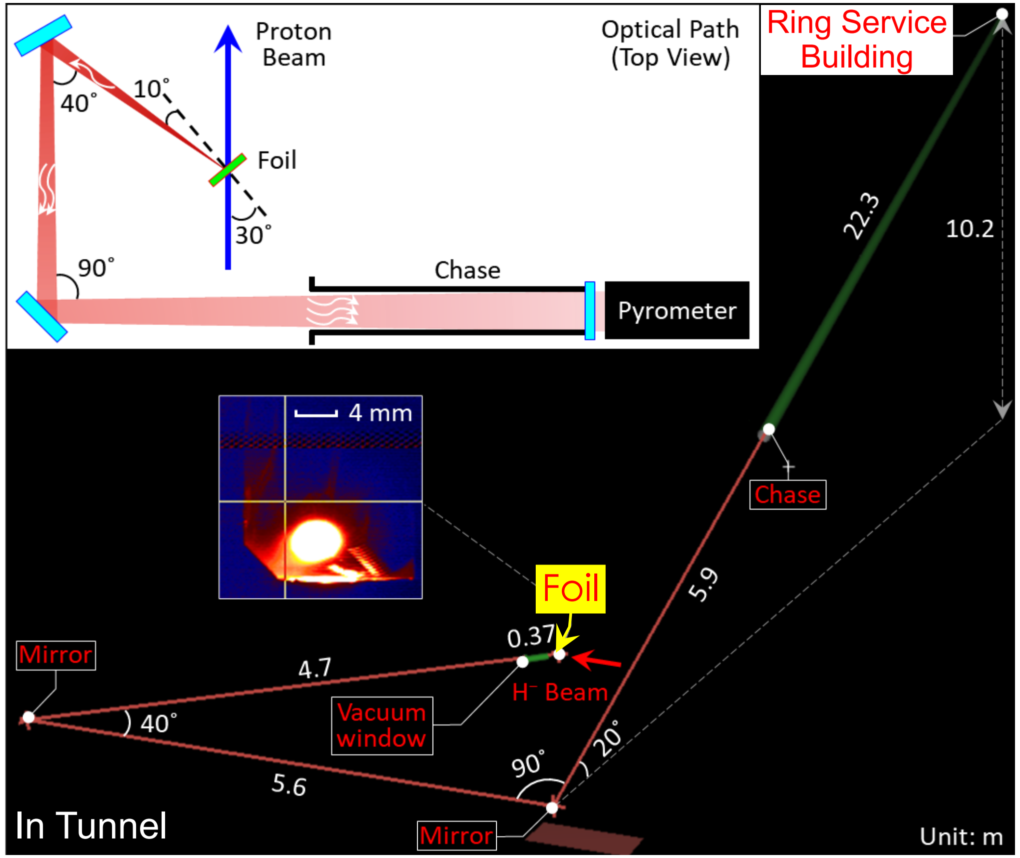
- Need only two wavelengths and based on the ratios of the measurements with calibration constants σ_i and σ_j to extract the temperature values.
- Do not need to know emissivity as long as two wavelengths are close enough to cancel in the ratio.
- Foil temperature range (1000 – 2100K), required to work 1.0 – 2.5μm region.
- Challenges:
  - High radiation (~10Rad/hour, highest radiation area in accelerator).
  - Limited Accessibility: Restricts placing our instrument closer to the foil area.
  - Total optical path length: ~40m, usable aperture size: ~Ø100mm.

Planck's Law: $I(\lambda, \epsilon, T) = \frac{2hc^2}{\lambda^5} \frac{\epsilon(\lambda)}{e^{\frac{hc}{\lambda kT}} - 1}$



Distribution of Blackbody Spectrum





Ratio of Two-Color Measurement:

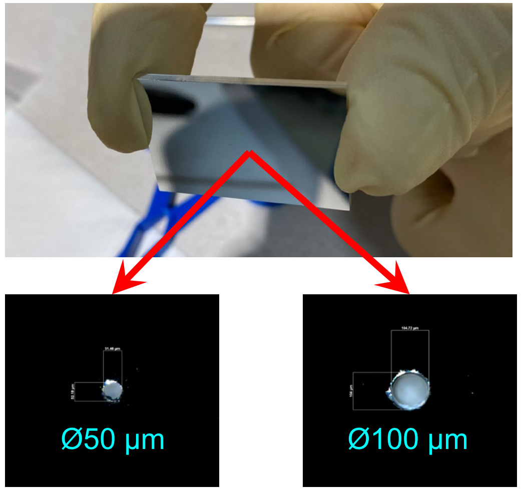
$$R_{i,j} = \frac{\sigma_i I(\lambda_i, \epsilon(\lambda_i), T)}{\sigma_j I(\lambda_j, \epsilon(\lambda_j), T)} = \frac{\sigma_i \lambda_i \epsilon(\lambda_i)}{\sigma_j \lambda_j \epsilon(\lambda_j)} e^{\frac{2hc^2}{T}\left(\frac{1}{\lambda_j} - \frac{1}{\lambda_i}\right)}$$

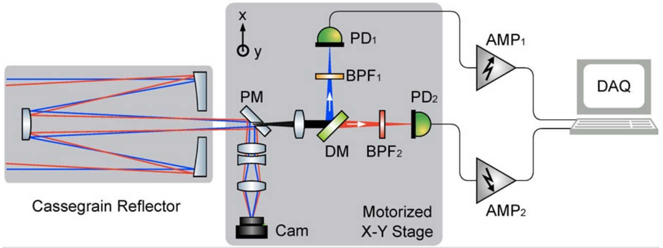
Temperature:

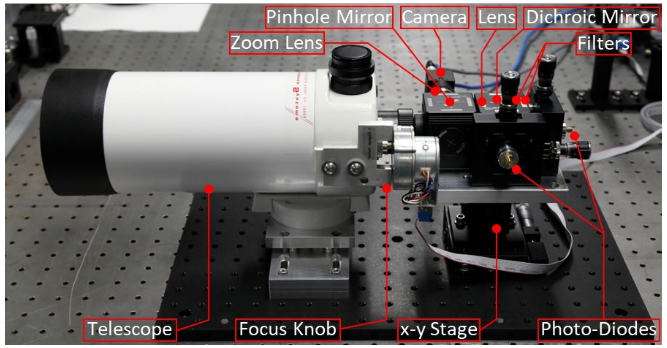
$$T = \frac{2hc^2[(1/\lambda_i) - (1/\lambda_j)]}{\ln R_{i,j} - 5\ln(\lambda_i/\lambda_j)}$$

Optical System Configurations

- Integrated Optical System:
  - Ø4.0” Cassegrain, f/10, EFL = 1010 mm, BFL = 180 mm, Coating: protected. Ag, 0.4 μm–20 μm.
  - Image sampling pinhole mirror size: Ø50 μm.
  - Dichroic beam splitter, 36 mm x 25 mm.
  - High throughput bandpass filters (1072nm & 1300nm, T>0.95), Ø1.0”.
  - Two photodiode based integrating pyrometer.
- Pinhole mirror to allow spatial sampling of beam spot on foil, reduces background light, therefore measurement uncertainties.







System Calibration with Blackbody Source (1000 – 2000K)

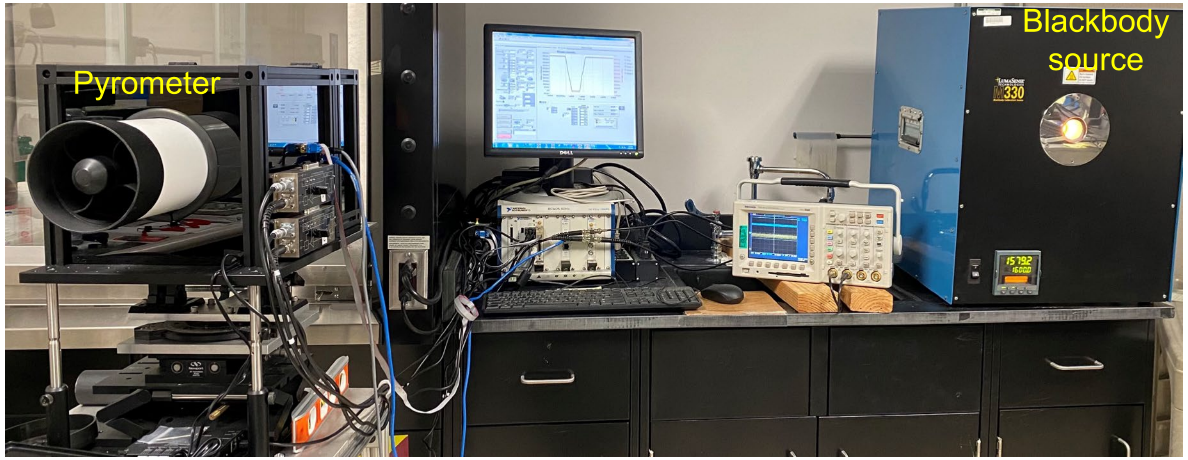
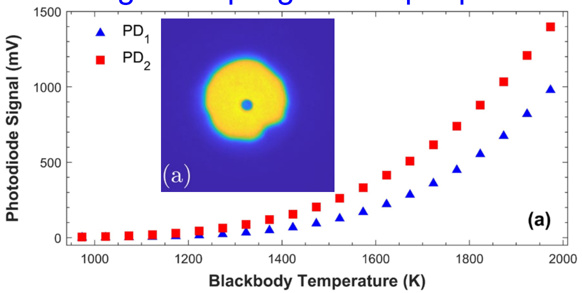
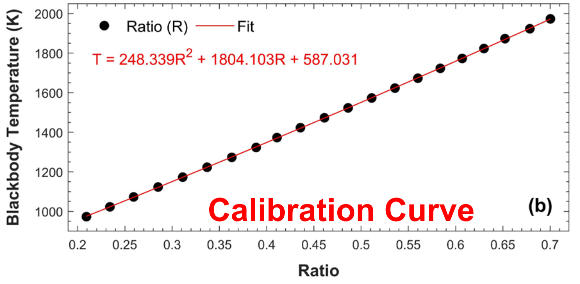
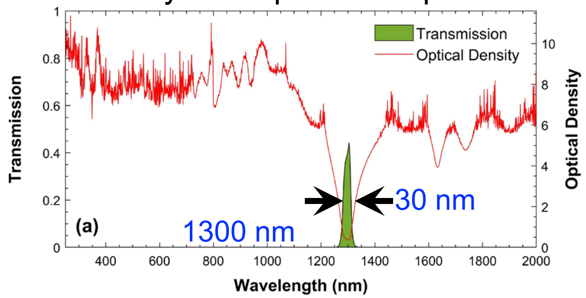


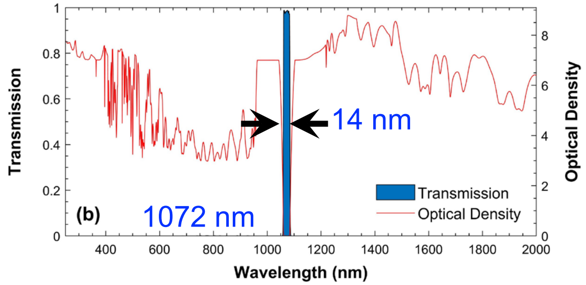
Image Sampling with 50μm pinhole





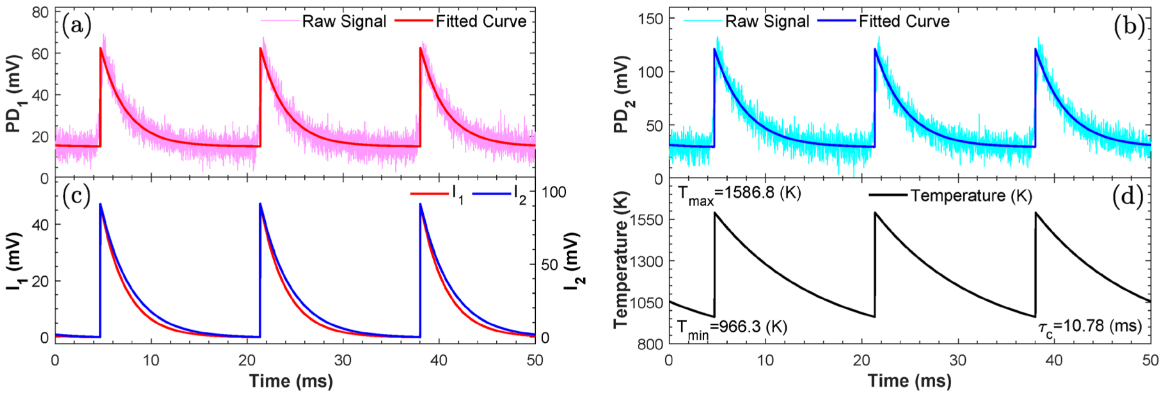
System spectral output

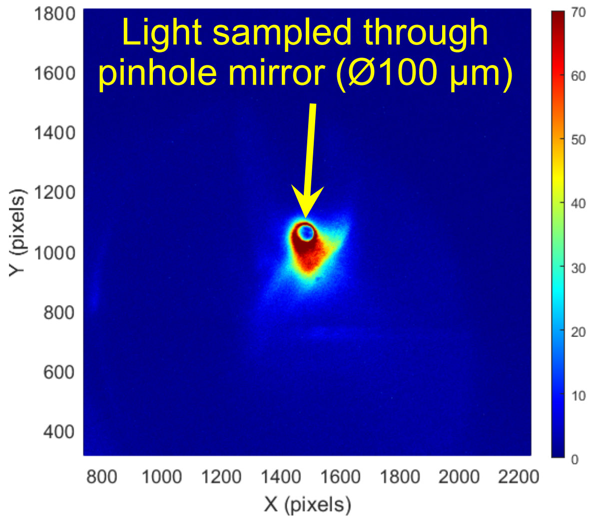




Foil Temperature Temporal Measurements

- Algorithm for obtaining T_{max}, T_{min} and $\boldsymbol{\tau}_c$ (colling constant):
  - Calculated for 1 second time interval, *i.e.* averaged over 60 pulses, using fit routine.



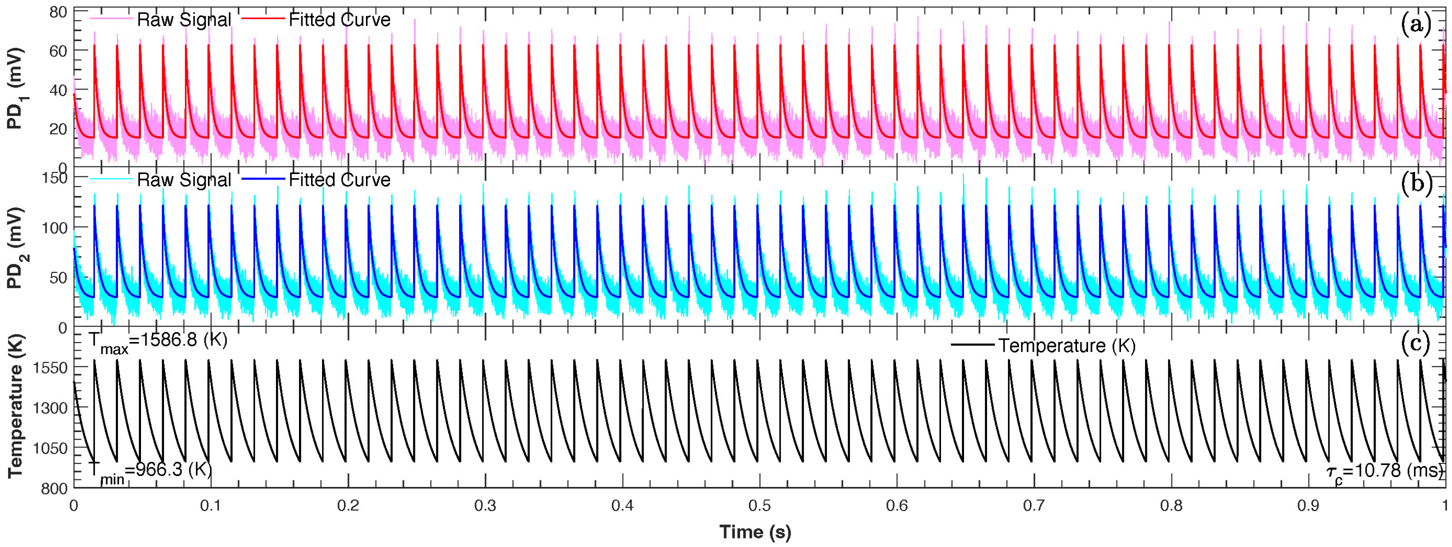


Ratio: $$R = \frac{V_1(t) - V_{1o}}{V_2(t) - V_{2o}}$$

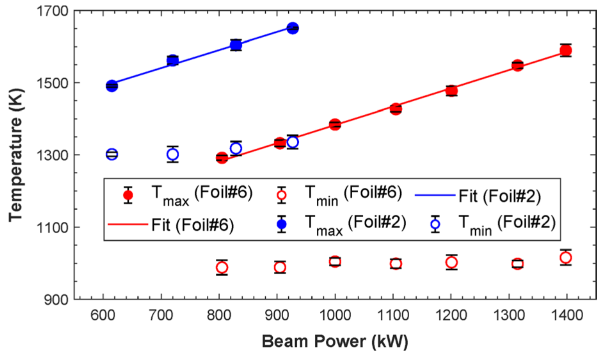
Fit function to extract cooling constant:

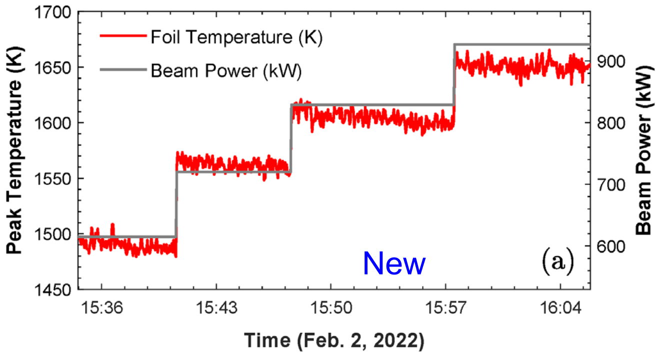
$$T(t) = \frac{T_{max}}{1 - e^{-\frac{f}{\tau_{cool}}}}\left[e^{-\frac{mod(t-t_o,f)}{\tau_{cool}}} - e^{-\frac{f}{\tau_{cool}}}\right] + T_{min}$$

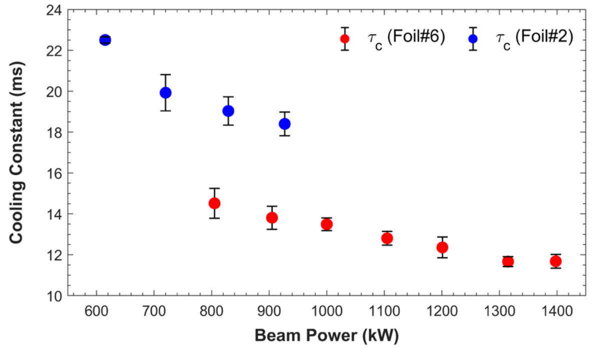
Calibration Equation: $$T = 248.34R^2 + 1804.1R + 587.03$$



Foil Temperature vs. Beam Power (2022)







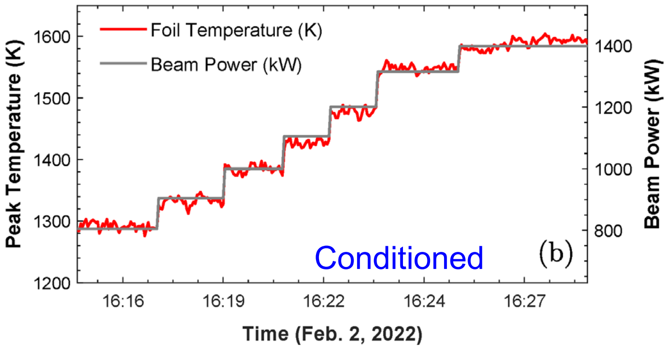
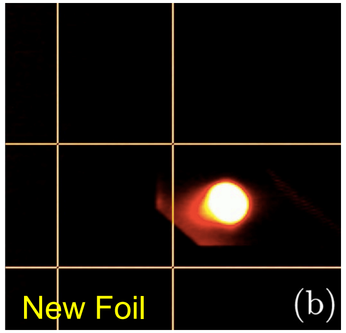
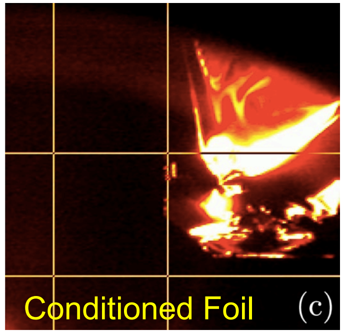


TABLE II. Averaged peak (T_{max}) and minimum (T_{min}) temperature and cooling constant (τ_c) as well as associated RMS values of Foil#2 and Foil#6 under various beam power settings.

P_b (kW)	T_{max} (K)	T_{min} (K)	τ_c (ms)
Foil#2:			
615	1490.9 ± 3.5	1301.6 ± 5.5	22.5 ± 0.2
720	1561.9 ± 10.7	1301.5 ± 21.6	19.9 ± 0.9
829	1604.3 ± 14.2	1318.0 ± 19.2	19.0 ± 0.7
927	1650.7 ± 2.9	1335.7 ± 18.5	18.4 ± 0.6
Foil#6:			
805	1291.8 ± 6.9	988.6 ± 20.4	14.5 ± 0.7
905	1332.4 ± 8.6	988.9 ± 16.1	13.8 ± 0.6
1000	1384.3 ± 5.8	1004.9 ± 10.3	13.5 ± 0.3
1105	1427.0 ± 7.7	998.9 ± 12.4	12.8 ± 0.3
1201	1477.2 ± 12.7	1002.9 ± 20.2	12.4 ± 0.5
1315	1547.9 ± 7.6	998.6 ± 9.5	11.7 ± 0.2
1398	1589.9 ± 17.1	1016.0 ± 20.9	11.7 ± 0.3

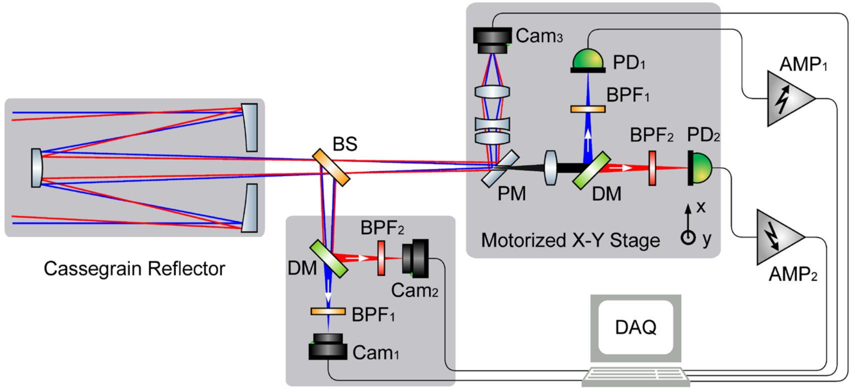
- Unconditioned foil (Foil#2) heats up quickly as compared to old foil (Foil#6)
  - Diamond to graphitization process still ongoing ($\varepsilon_{diamond} < \varepsilon_{graphite}$)
  - Lower emissivity means less ability to release the heat (or radiative cooling)
- Cooling constant:
  - Longer time to cool for new foil (Foil#2) than old foil (Foil#6)
  - Higher beam power speeds up graphitization process (shorter cooling time)

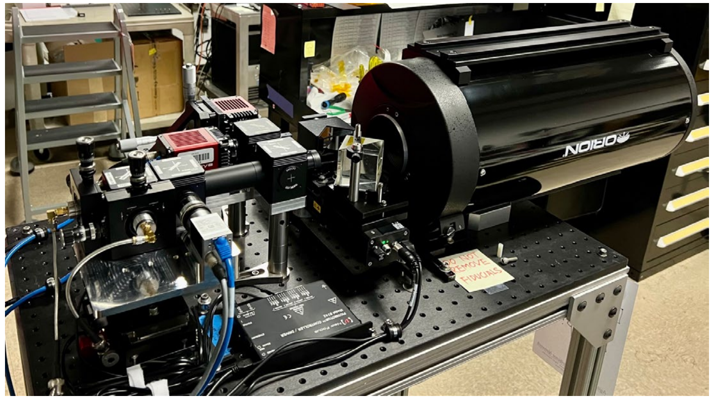




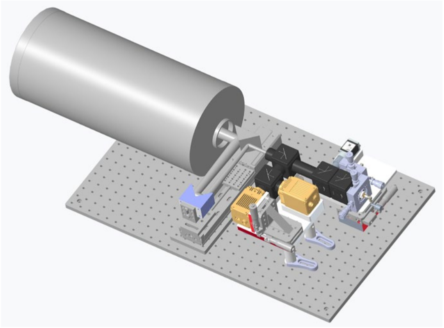
Two-Color Imaging Pyrometer (2023)

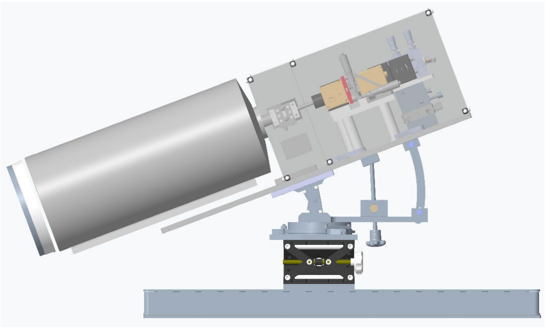
- Ø8.0”, EFL=2.4m, Cassegrain telescope
  - Increased light collection efficiency
  - Increased resolution
- Spatio-Temporal (**2D**+**1D**) measurement
  - Spatial 2D: SWIR Cameras
  - Temporal 1D: Photodiodes
- Improved SNR
  - High throughput filters (Δλ = 70nm, T = 0.98)
  - Smaller detectors (Ø3.0 mm → Ø0.3 mm)
- Two independent systems work side-by-side

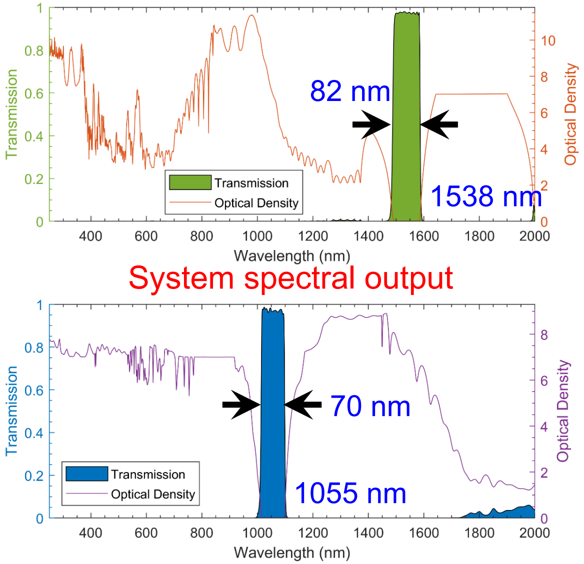


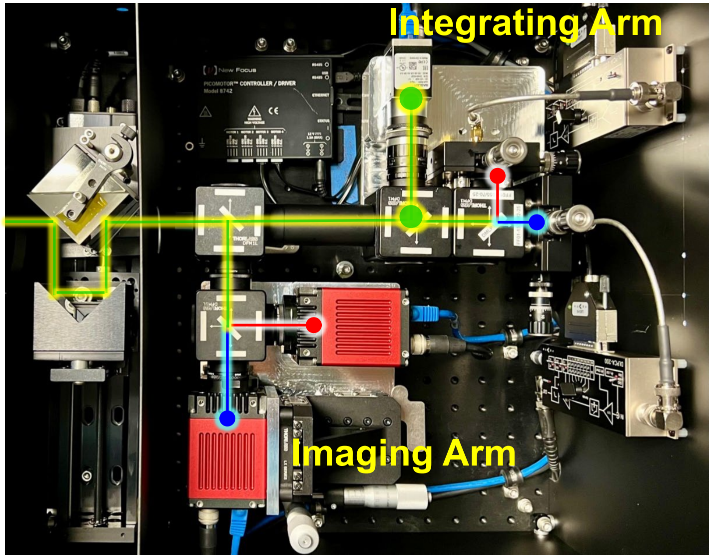


System CAD model



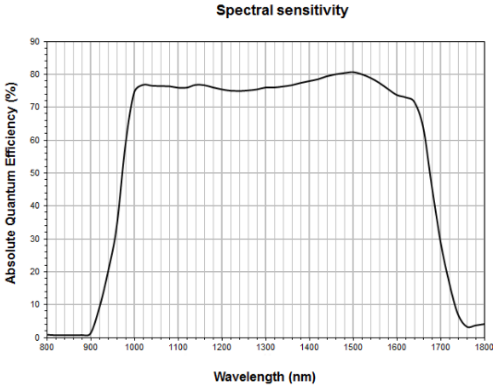






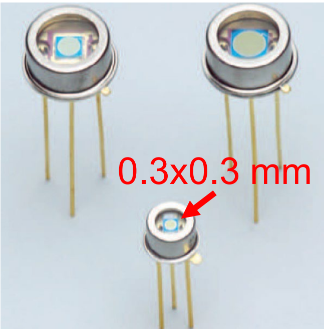
System Optical Specs

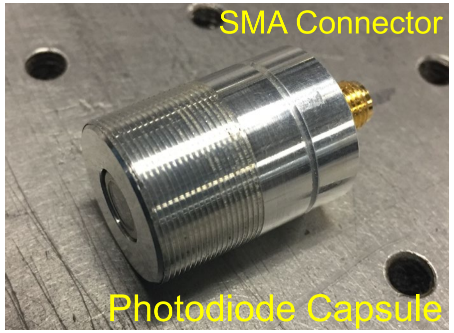
SWIR Camera: Allied Vision Goldeye G-033 TEC1

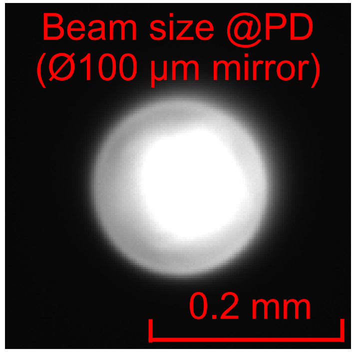


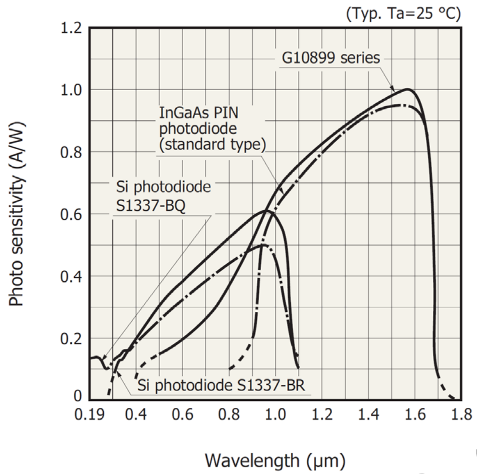
Specs	
Resolution	640 (H) x 512 (V)
Spectral Range	900 – 1700 nm
Sensor Type	InGaAs
Pixel Size	15 μm x 15 μm
Max. Frame Rate at Full Res.	301 fps
ADC	14 bit
Cooling Temperature	5 °C
Image Buffer (RAM)	256 MB
Dark Current	110 ke⁻/s (20°C)

Photodiode: Hamamatsu G10899-003K

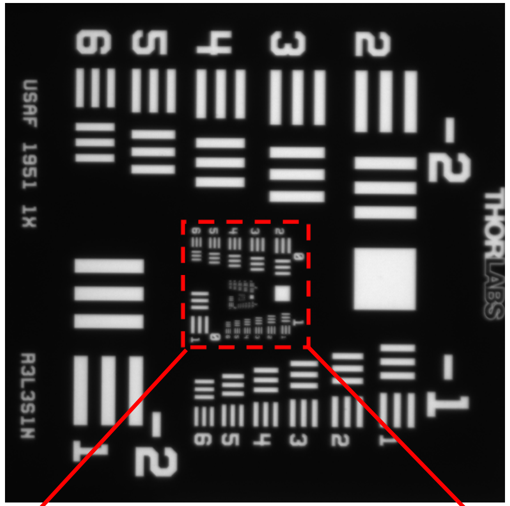




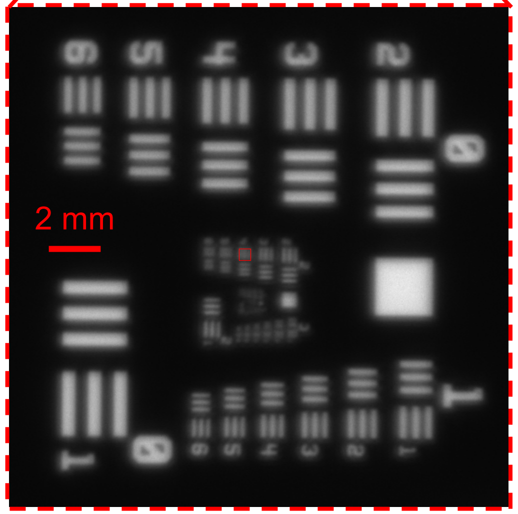




Imaging Resolution Test w/
3.0”x3.0” USAF Target @40m

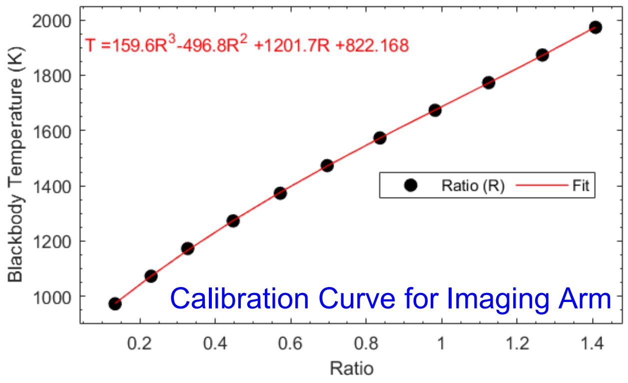


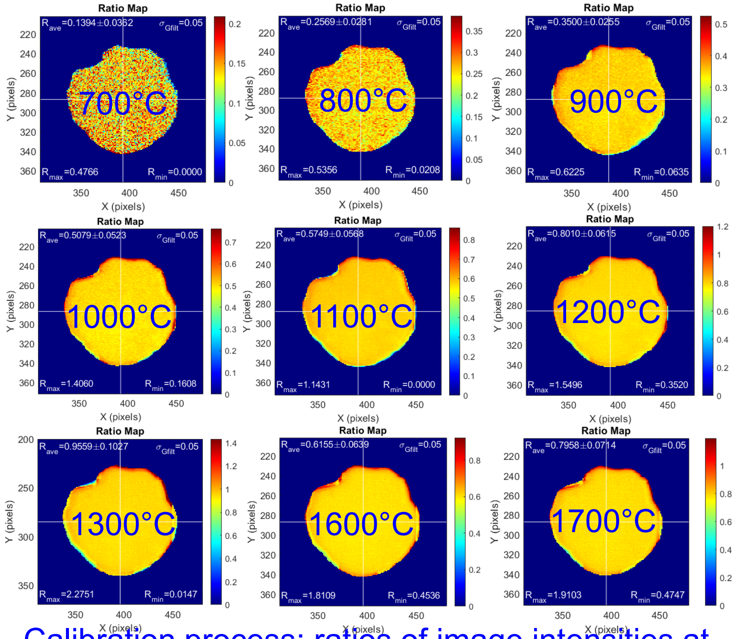
Magnification: 0.0625



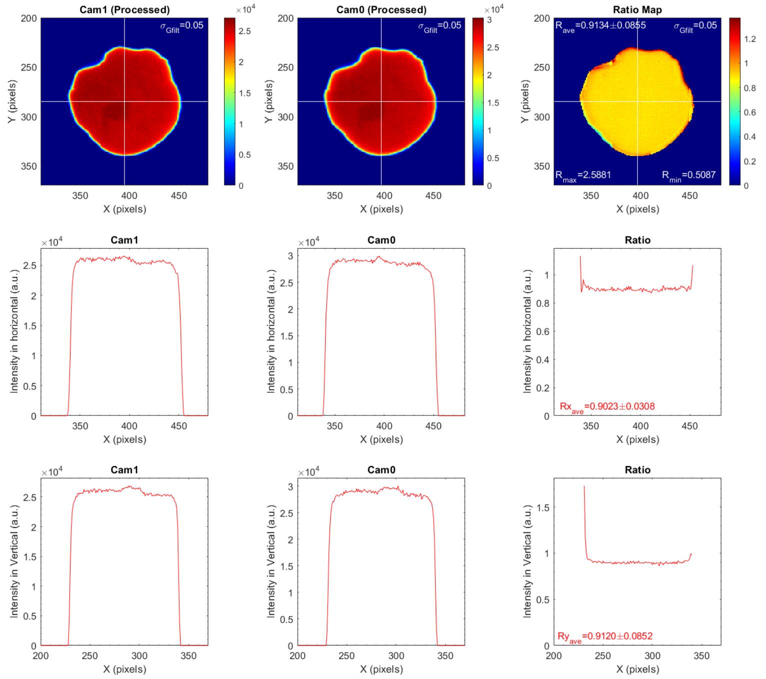
Imaging Pyrometer Calibration with Blackbody Source

- Blackbody source:
  - 0.1 °C stability, emissivity: 0.999 (0.6 – 2.0 μm)
- Measured:
  - SWIR camera 2D array ratio signal
  - Photodiode ratio signal with pinhole size: Ø100μm
  - Distance: 40 m

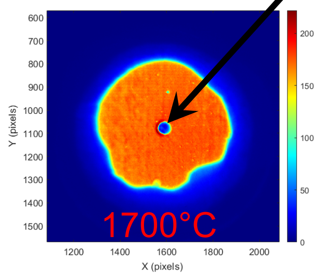


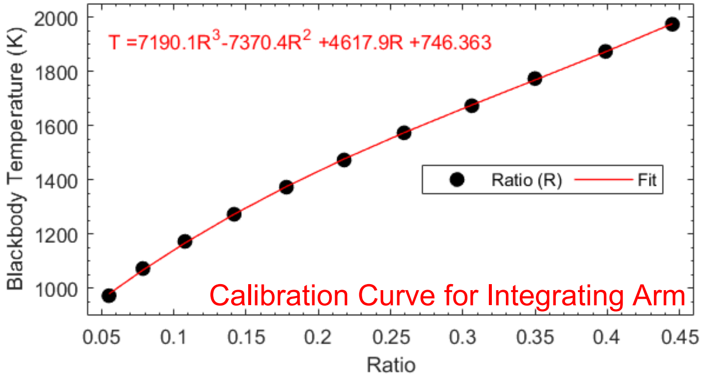


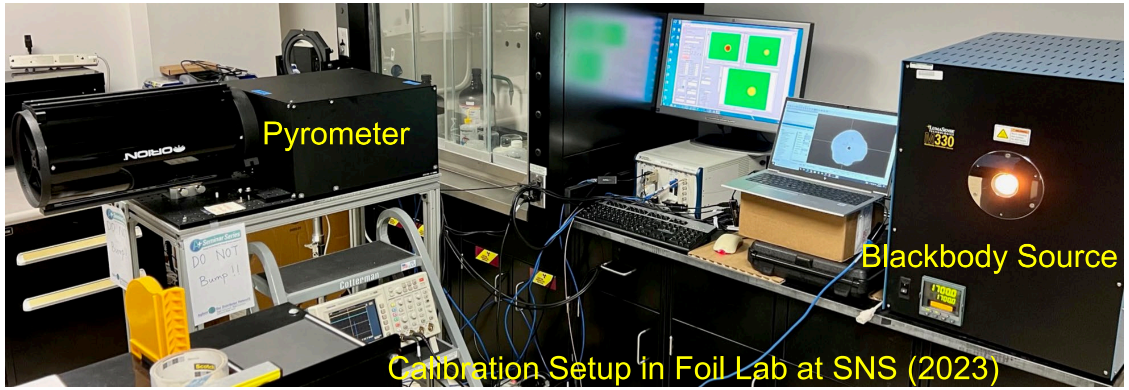
Calibration process: ratios of image intensities at two-wavelengths measured at respective blackbody temperature



Visible Camera Image: blackbody image sampled through pinhole (Ø100um)

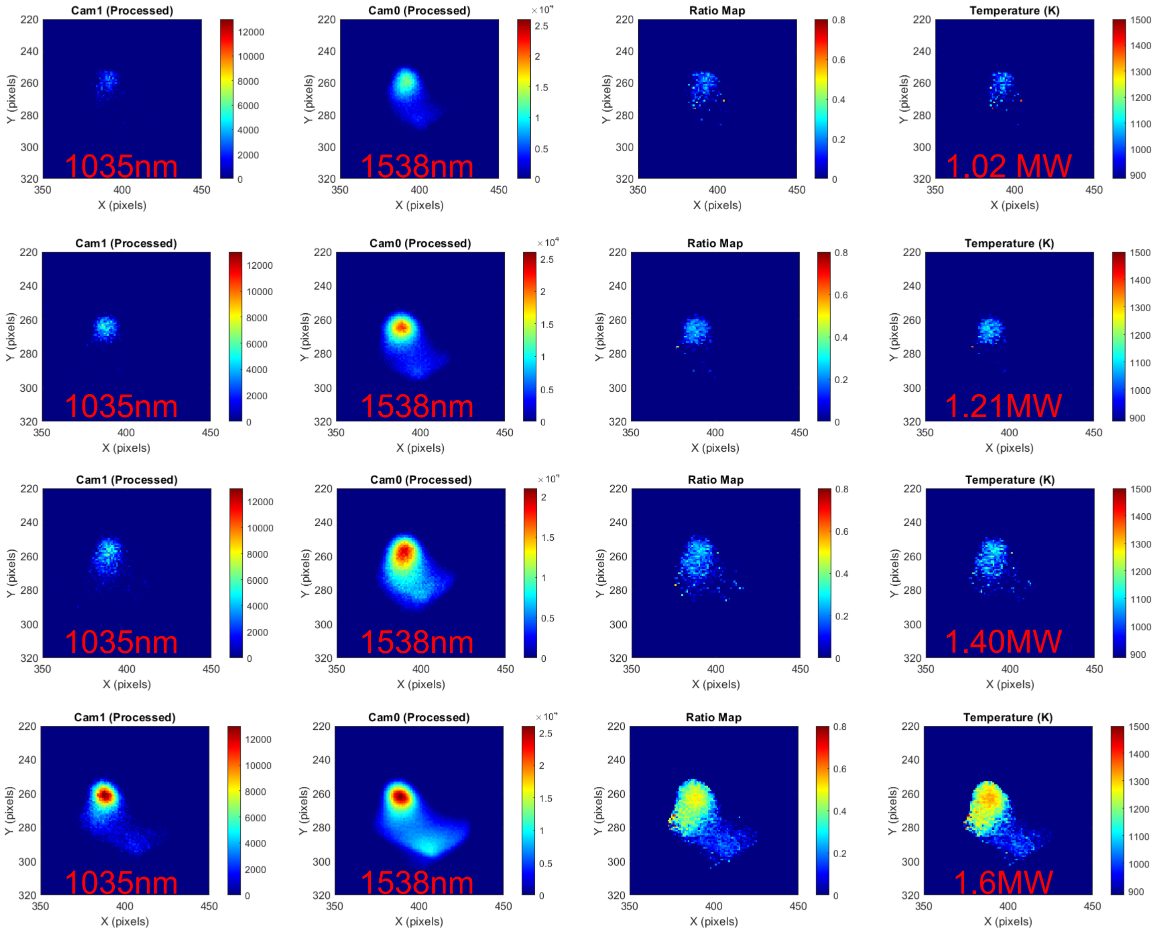




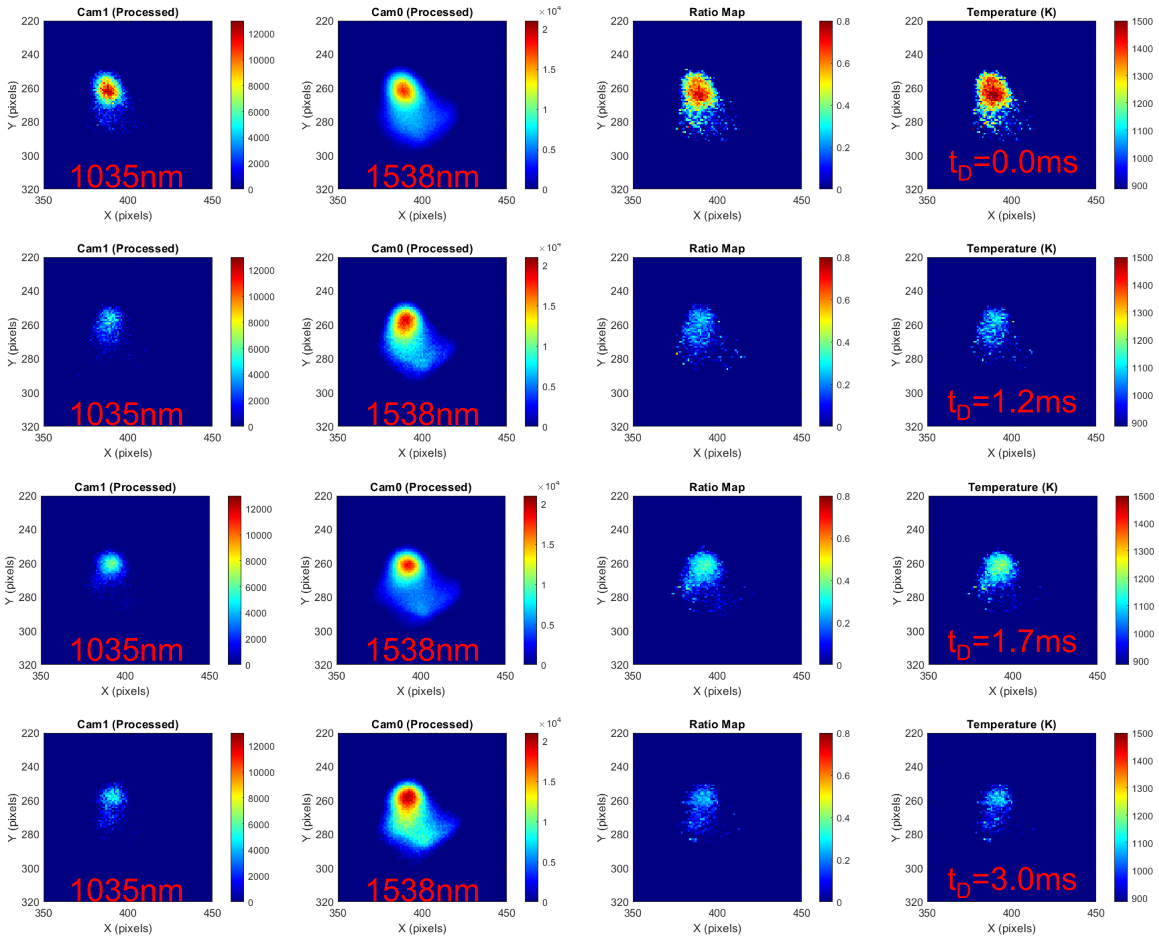


Temperature Profile

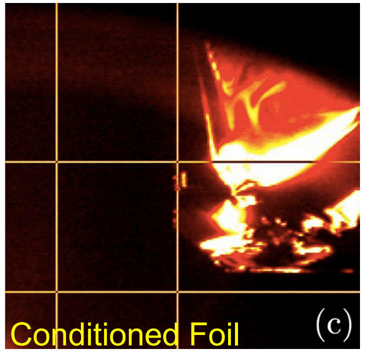
Temperature vs. H⁻ beam power

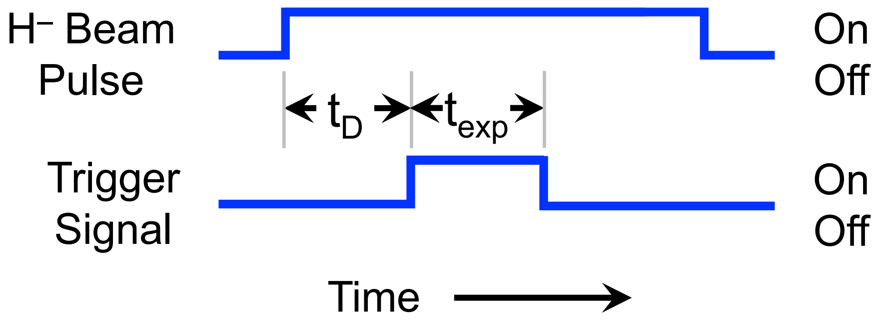


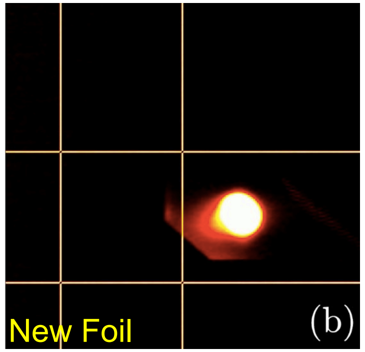
Temperature vs. time @1.4MW



Time-Resolved Temperature Profile







Summary

- Designed, built & calibrated two-color imaging pyrometer with a wide working range (900 – 2000K).
- We have spatio-temporal measurements of foil temperature at various H^- beam power (0.6 – 1.7MW).
  - First-hand temperature map of stripper foils under high-intensity beams have been obtained.
  - Temporal evolution of temperature profile obtained.
- Developed an effective & reliable data analysis algorithm to extract foil temperature.
  - Foil cooling constant shows good correlation with beam power & foil conditioning status.
  - Would offer more insight on foil graphitization process under different beam conditions.
- Temperature measurement uncertainties:
  - Integrating pyrometer: ±15 K
  - Imaging pyrometer: TBD
- 2D Pyrometer Status:
  - Data is still being analyzed.
  - Optimization of filter choices will be next (SNR in shorter wavelength can be improved).
  - Thorough calibration and more studies will follow.