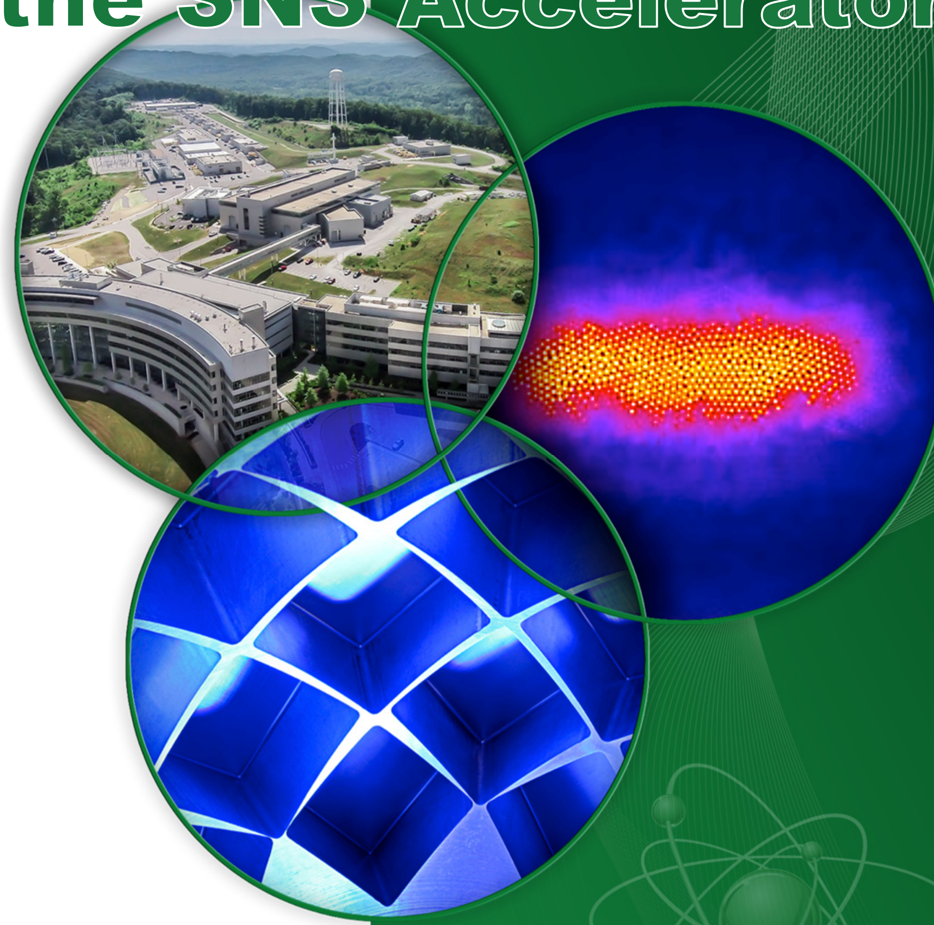
Injection Foil Temperature Measurements at the SNS Accelerator



W. Blokland

N. Evans

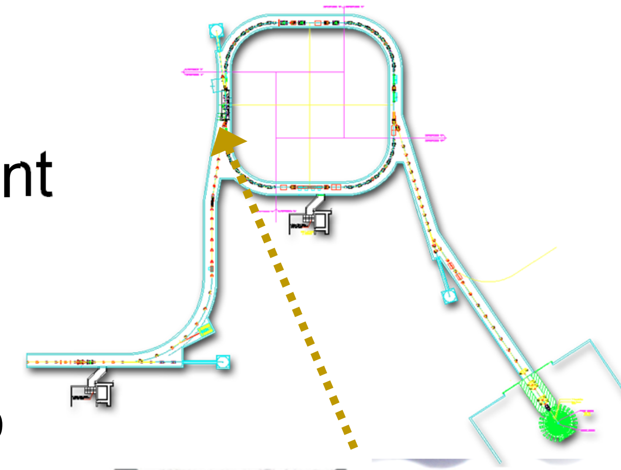
C. Luck

A. Rakhman

SNS/RAD

Introduction

- The SNS uses a stripping foil to implement a charge-exchange injection scheme to accumulate beam in the ring
- A nano-crystalline diamond foil is used to strip the electrons from the H^- particles
- Current lifetime of a foil is ~3 months (2500 MWHr) at 1.2 MW
- We want to estimate the foil lifetime for higher beam powers, up to 2.8 MW for possible STS upgrade

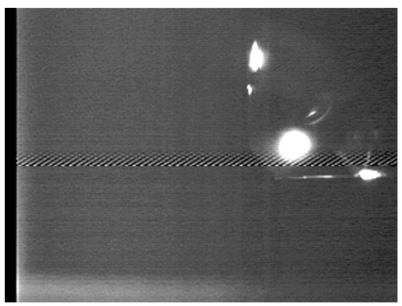


New Used

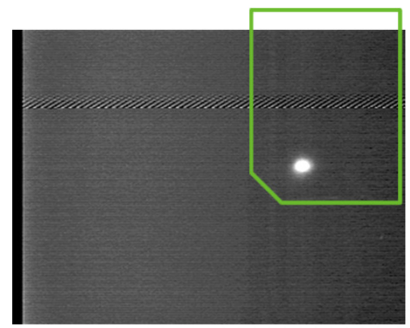
→ Measure the temperature and compare to sublimation threshold (> 2100 K)

Setup

- In the tunnel: very high radiation
  - Previous attempts over the years showed that the radiation instantly kills infrared cameras near the foil and quickly disrupts shielded digital cameras 10 meters away
- Foil conditioning
  - Nano-crystalline diamond foil changes to have graphite-like properties
- Beam spot has 2-D Gaussian shape, ~2 mm



Light on and 10% filter



Light off and 1% filter

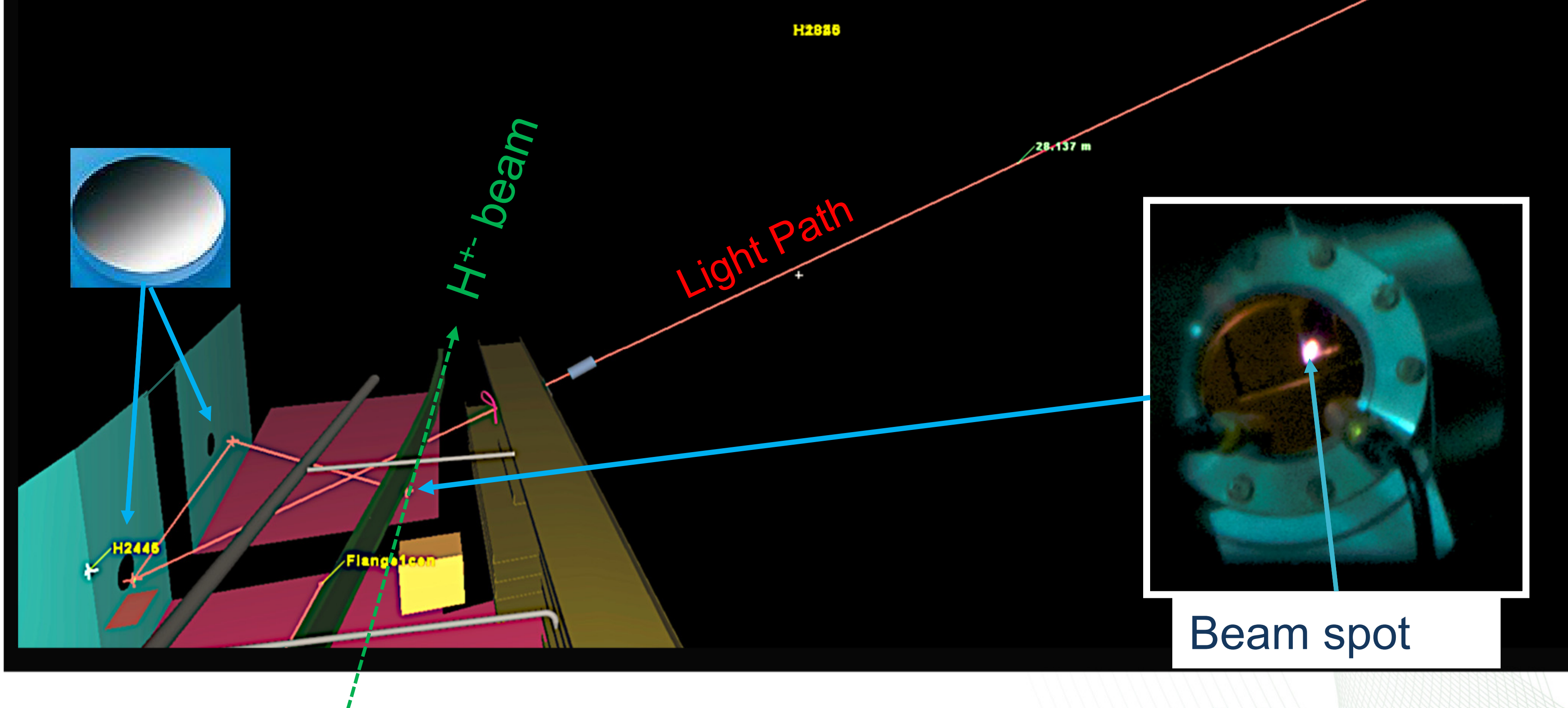
- Analog camera in tunnel cubby hole last for several years but is not suitable for temperature measurements
- Use existing infra-structure to minimize costs

Setup

We can see the foil from the service building through a cable chase with only two mirrors

- First used to implement a digital foil video system

Path length is 40 meters with about 8 cm aperture in chase



Methods considered

- To use the chase for temperature measurements, we need to deal with the limited aperture and long path. Options:
  - Infrared camera
    - Expensive and needs very expensive telephoto lens to get constant temperature over the surface of each pixel
    - Need to know emissivity and calibration with optical elements
    - Need short exposure (~50 μs)
    - Need infrared compatible optical elements (vacuum window)
  - Two-wave pyrometer
    - Emissivity does not need to be known (but needs to be constant)
    - Need two photodetectors with bandpass filters (cheap)
    - Use available amplifiers and telescope
    - Use existing vacuum window and mirrors
  - Visible light cameras with bandpass filters
    - If foil hot enough this could work (but presently not enough light)

→ We will build a two-wave pyrometer using bandpass filters, photodiodes, and amplifiers

Two-Wave Ratio Pyrometer

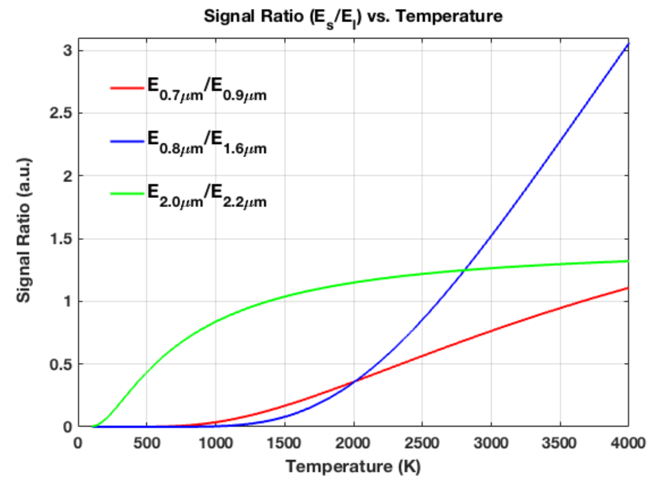
$$I(\lambda,\epsilon,T) = \frac{2hc^2}{\lambda^5}\frac{\epsilon(\lambda)}{e^{\frac{hc}{\lambda kT}}-1}$$

Planck radiation

With Wien's approximation:

$$Ratio_{1/2} = \frac{s_1 I(\lambda_1,\varepsilon(\lambda_1),T)}{s_2 I(\lambda_2,\varepsilon(\lambda_2),T)}$$

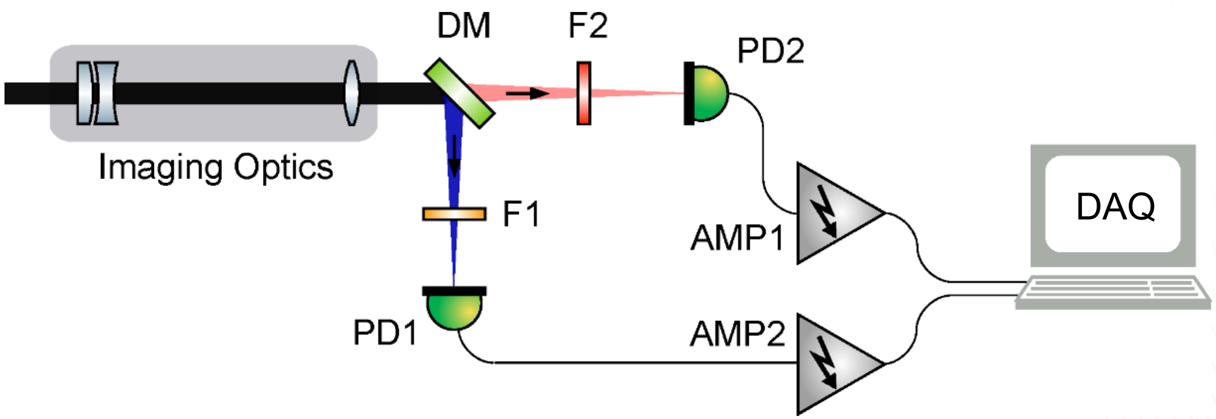
$$= \frac{s_1}{s_2}\left(\frac{\lambda_1}{\lambda_2}\right)^{-5} e^{\frac{2hc^2}{T}\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)}$$



Ratio curves

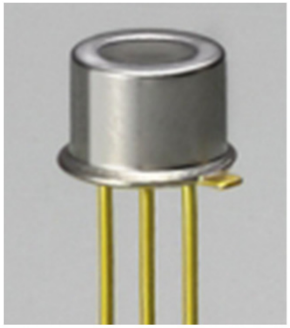
With s_1 and s_2 the spectral transmission coefficients

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

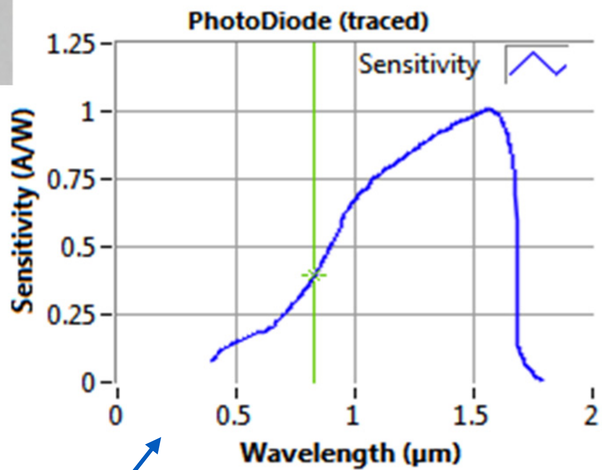


Optical elements

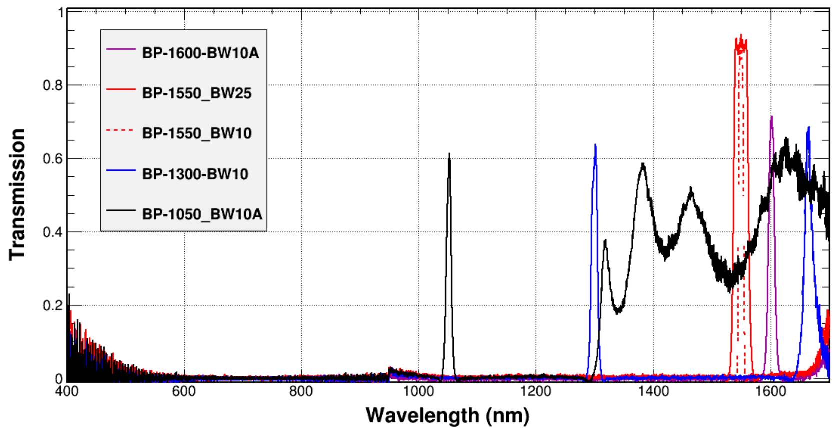
- Vacuum window in tunnel
- Two mirrors in tunnel
- Glass window in chase
- Telescope
- Longpass dichroic mirrors
- Bandpass filters
- Sensors
  - G10899 Indium Gallium Arsenide (InGaAs) PIN photodiode
  - Need to correct for its wavelength dependent sensitivity
  - Use with available current amplifier
  - Linear response within our range



photodiode

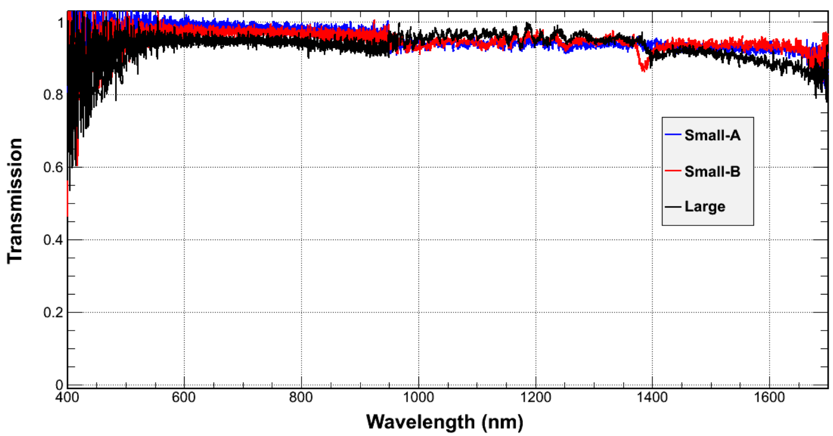


Optical Path: Filters & Windows

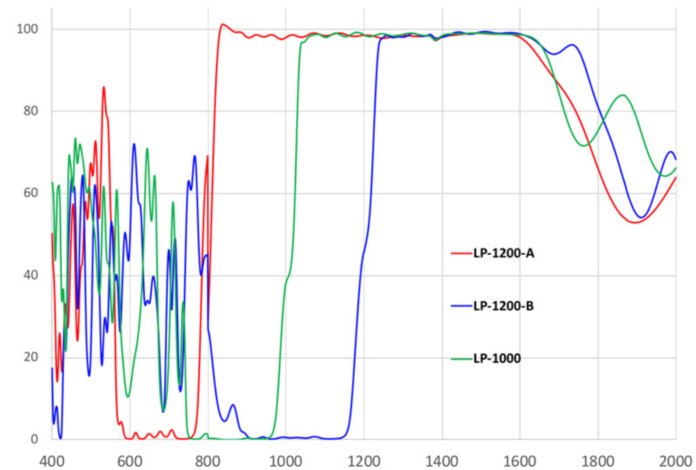


Bandpass filters

- Some vendors do not fully specify the spectral response of their filters for a broad spectral range
- We want to verify them for the spectral range of interest (0.4 µm – 1.7 µm)
- Many bandpass filters turned out to be leaking light outside their pass band



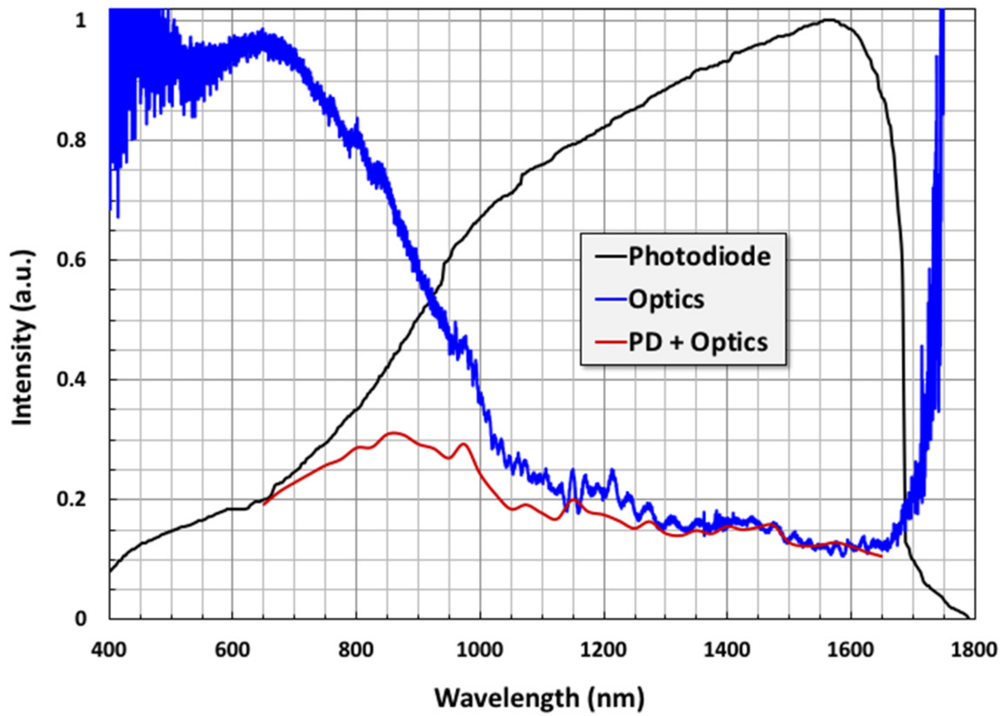
Windows



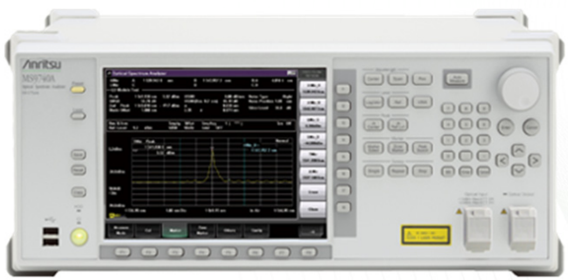
Longpass mirrors

Optical Path: Telescope

- It was extremely hard to get the absolute transmittance of the telescope due to its size and difficulties in coupling the same light to the fiber based optical spectrometers
- Small offset leads to ~100 K error
- Absolute transmittance of the telescope must be verified



Thorlabs CCS200
Spectral range: 0.2-1.0 μm
Multi-mode fiber coupling



Anritsu MS9740A
Spectral range: 0.6-1.7 μm
Single-mode fiber coupling

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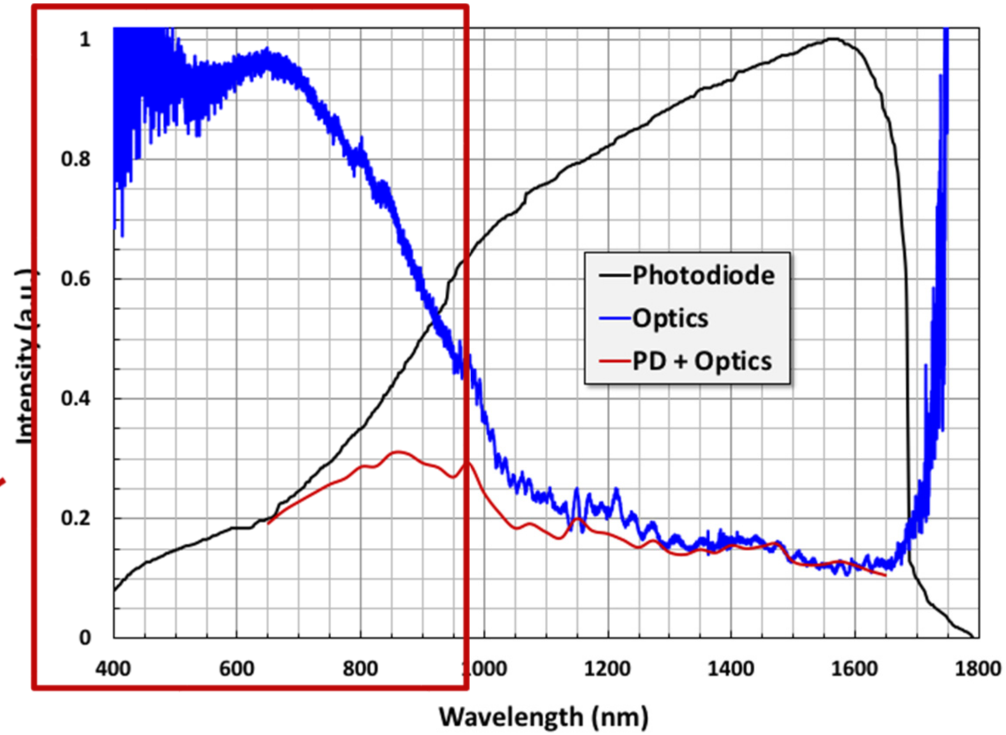

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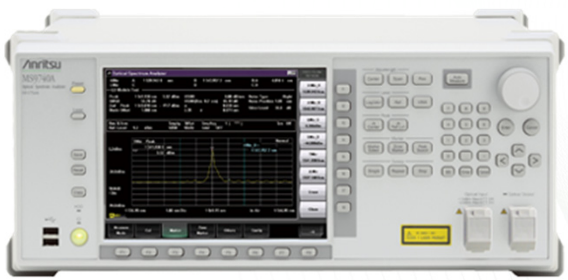

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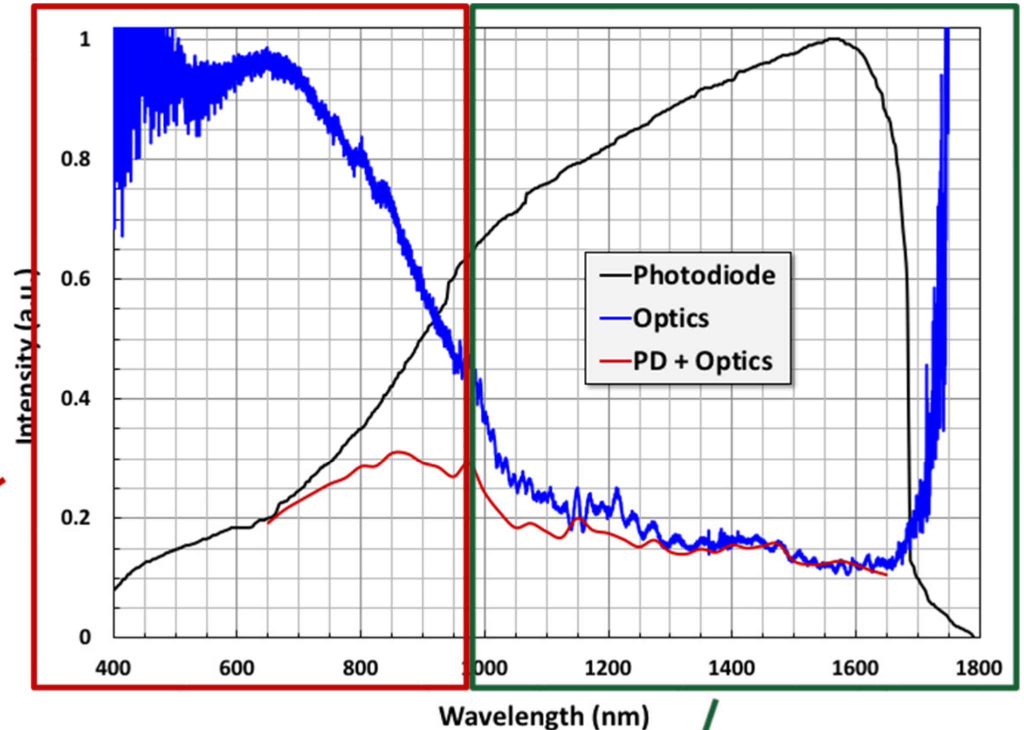

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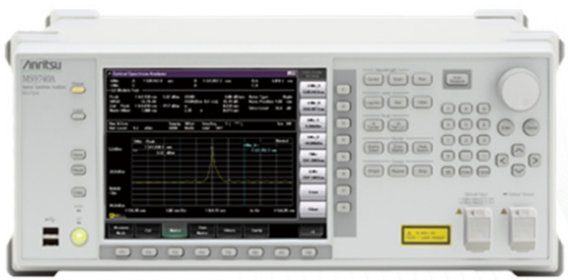

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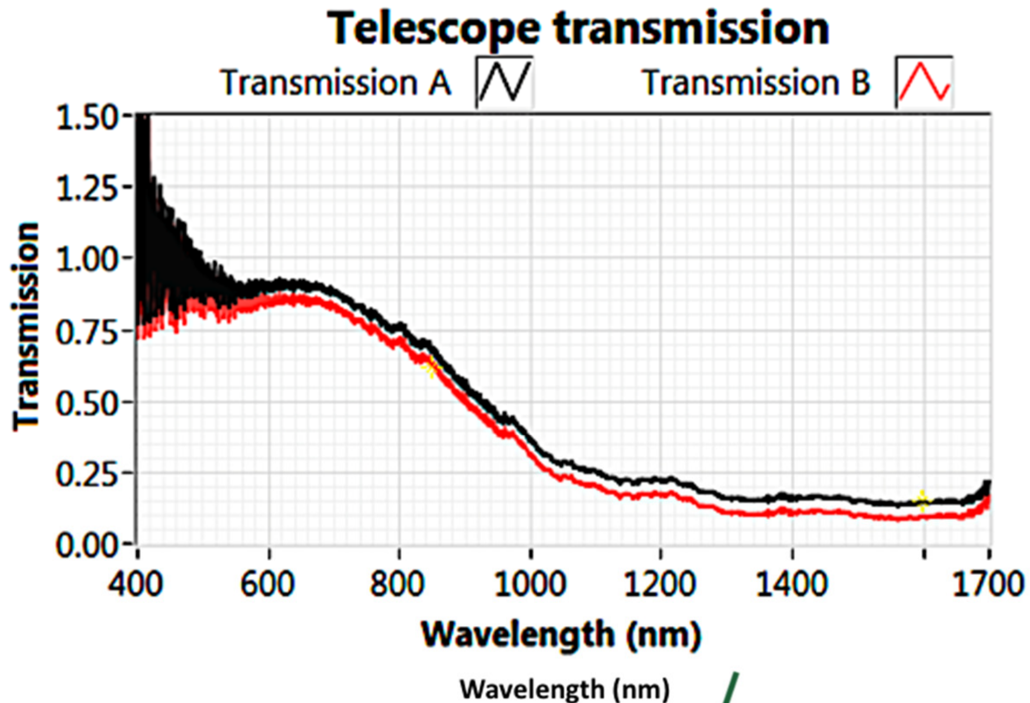

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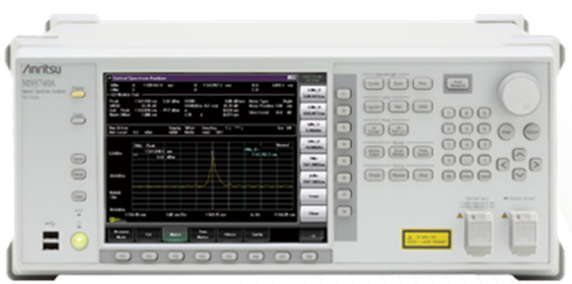

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Blackbody Source

- In April, the foil lab got a Blackbody Source
  - Up to 1000 ℃
  - We used it to calibrate two optical heads:
    - 850 nm and 1600 nm with a longpass dichroic mirror at 1000 nm
    - 1000 nm and 1310 nm with a longpass dichroic mirror at 1180 nm
  - Measured at 800, 900, 1000 ℃ (can take hours to stabilize)

Calibrating the pyrometer in the foil lab

Blackbody Radiator

Blackbody Temperature (℃)	Measured Ratio	Calibration (s_1/s_2)	Calibrated Ratio	Calculated Temperature (℃)	Error	Step (℃)
800	0.181	**0.895**	0.162	799.85	-0.02%	
900	0.238		0.213	901.85	0.21%	102
1000	0.298		0.267	1000.85	0.09%	99

Blackbody calibration for 1000/1310/LP1180

- We obtained a calibration factor (s_1/s_2) for the optical path including sensor
  - We tested the optical heads for focus and alignment requirements for both photodiodes
  - For the optical head 850/1600, difference with the optical transmission measured was ~1.8x (~100-150 K)

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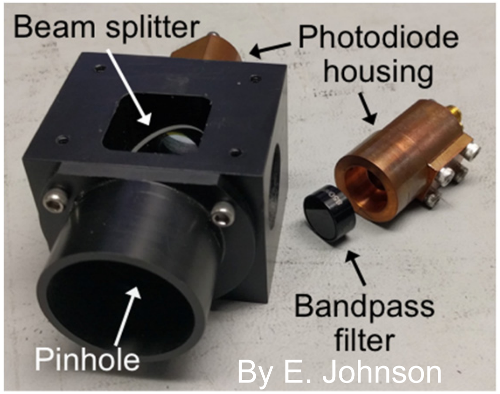
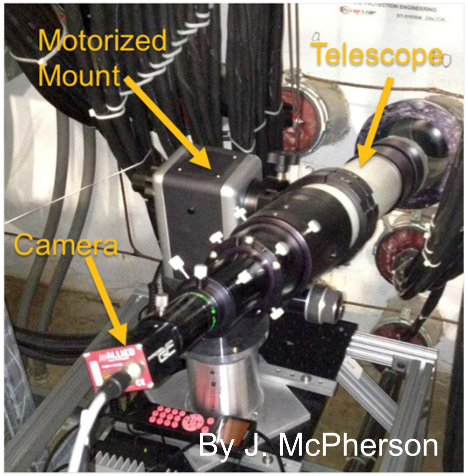
Two-wave pyrometer

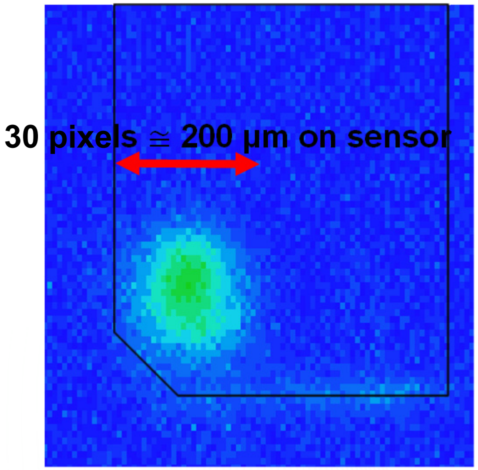
- Initial idea was to scan the foil with a motorized telescope and a pinhole in front of the photodiodes. But:
  - there was not enough light after the pinhole (unless sized 200 μm or larger)



Optical head



telescope



Projected image

- Can we collect all the light from the beam spot and still derive the peak temperature?

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Beam spot blackbody radiation

- Assumptions:
  - Foil has graphite-like properties with constant emissivity
  - Temperature ≡ deposited energy ≡ beam intensity
  - Beam is 2-D Gaussian shape about 1.6 x1.8 mm:

$$T_G(x,y) = I_0 \cdot \exp(-x^2/2\sigma_x^2) \cdot \exp(-y^2/2\sigma_y^2)$$

  - Received light is sum of different temperatures and all light is projected on the photodiode's sensitive area

→ Create new BB curve as sum of BBs at different temperatures:

$$BBS(T) = \sum_{\substack{-l<x<l \\ -k<y<k}} BB(TG(x,y))$$

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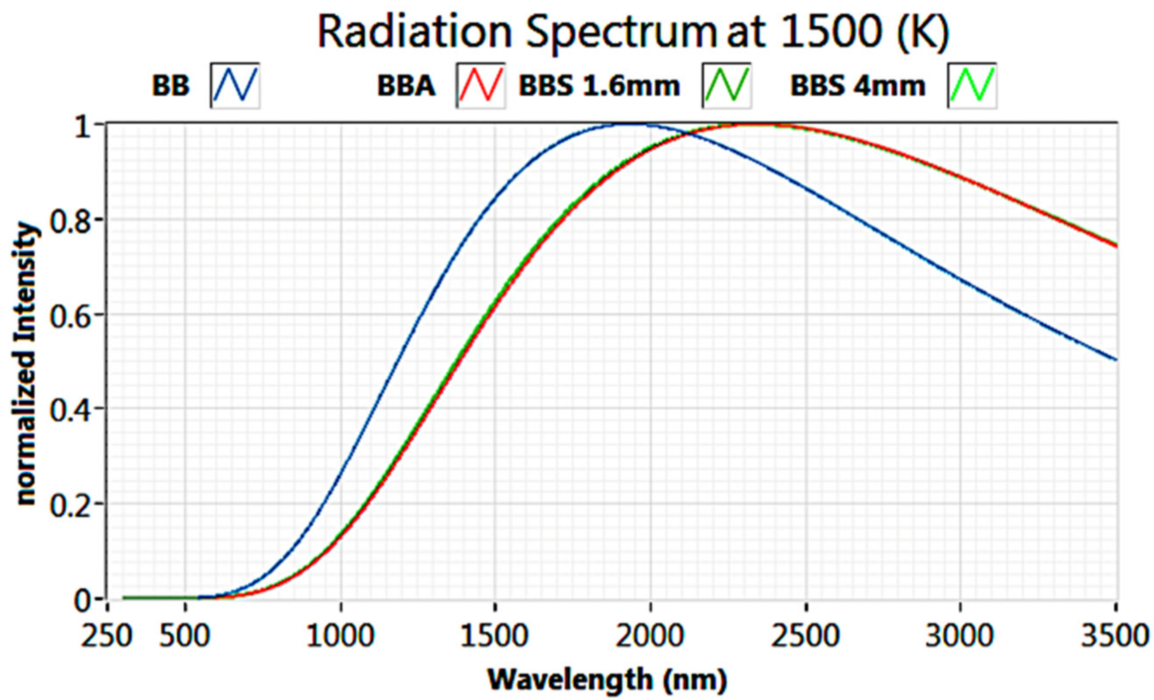
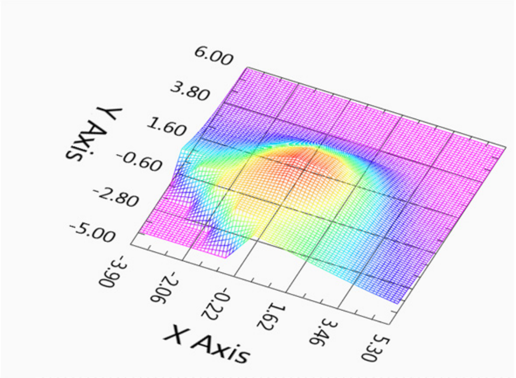
Summed blackbody radiation curve



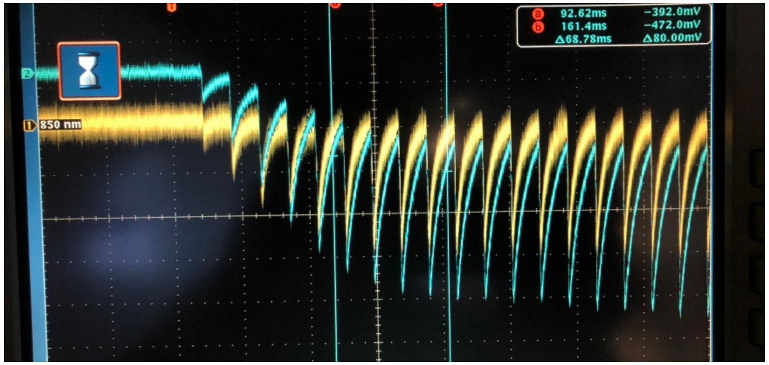


Calculated beam spot

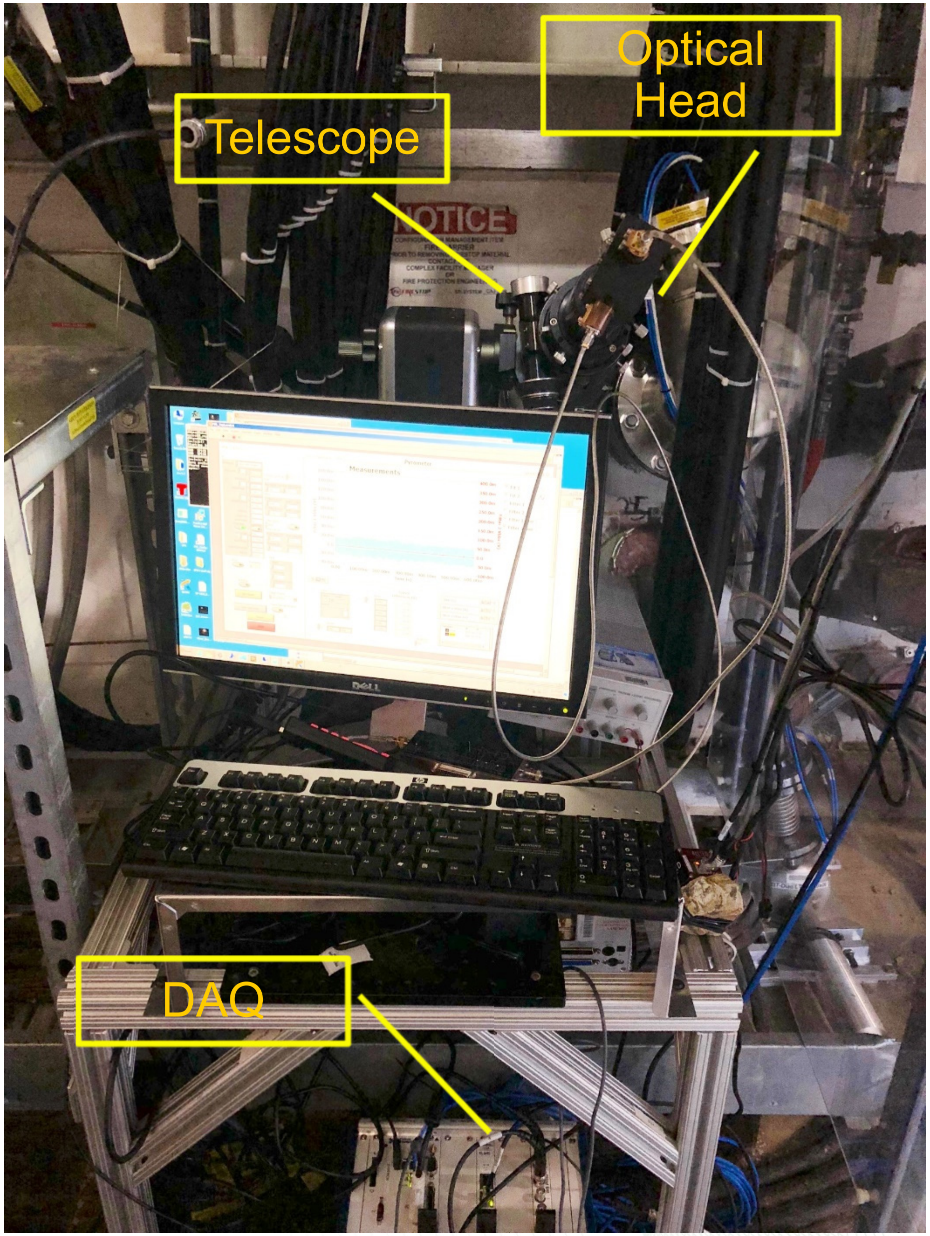
- Summed blackbody (BBS) and for calculated beam spot (BBA)
  - Very small difference between AP calculated and 2-D Gaussian sum
  - Obtained radiation curve shifts towards longer wave lengths
- Derive new ratio curve for two-wavelength combination
  - Measure each wavelength's signal and correct for transmission

Setup in the field

- Alignment with handhold controller and camera to get the beam spot in the middle of the image
- Replace camera with optical head and test if alignment is optimal (both signals are maximized)



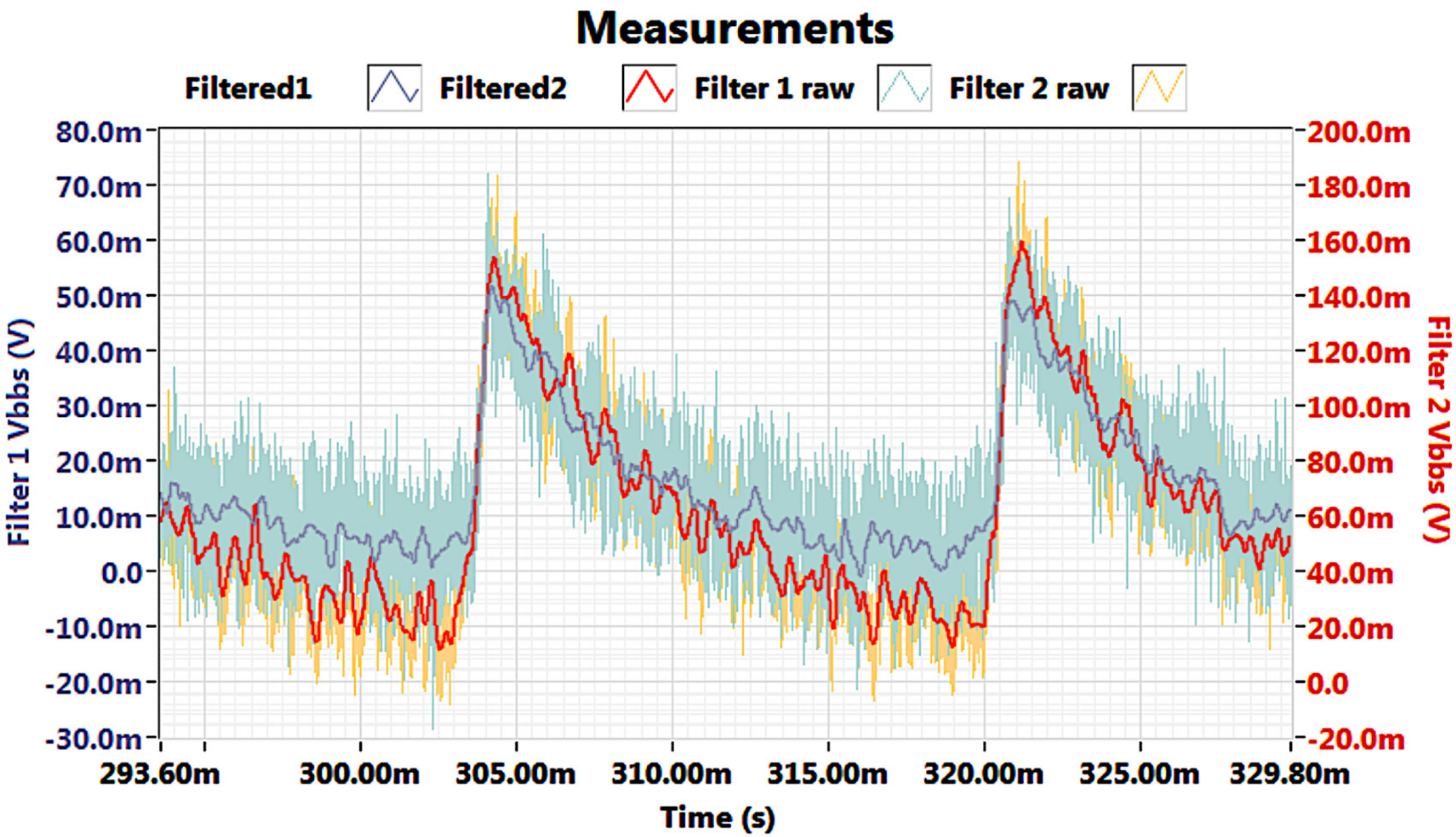
Photodiode signals



Pyrometer setup

Data Processing: example

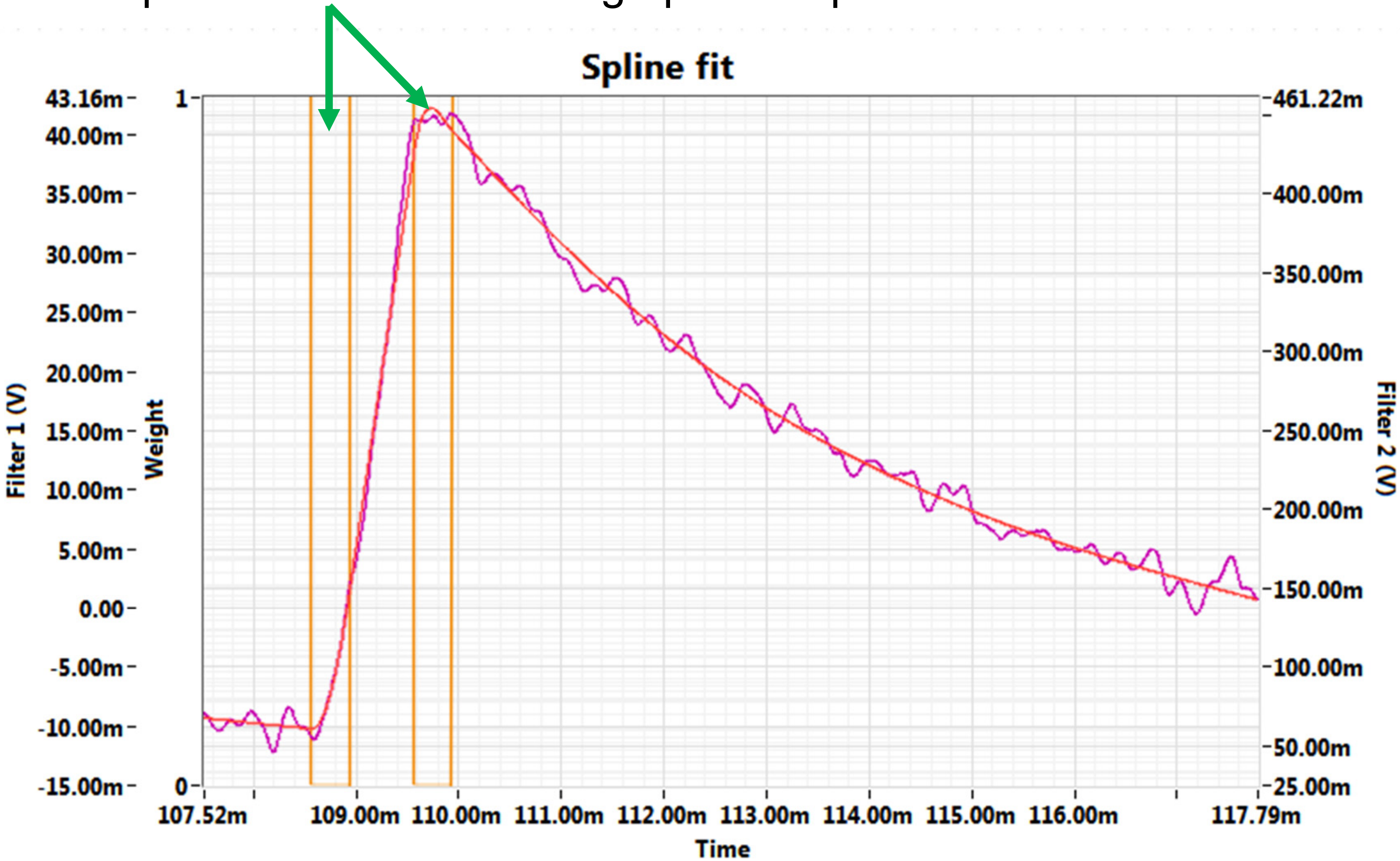
- There is a lot of noise in the signals
  - data is first filtered (no phase shift: median or Savitzky-Golay filter)



Example of raw and filtered data

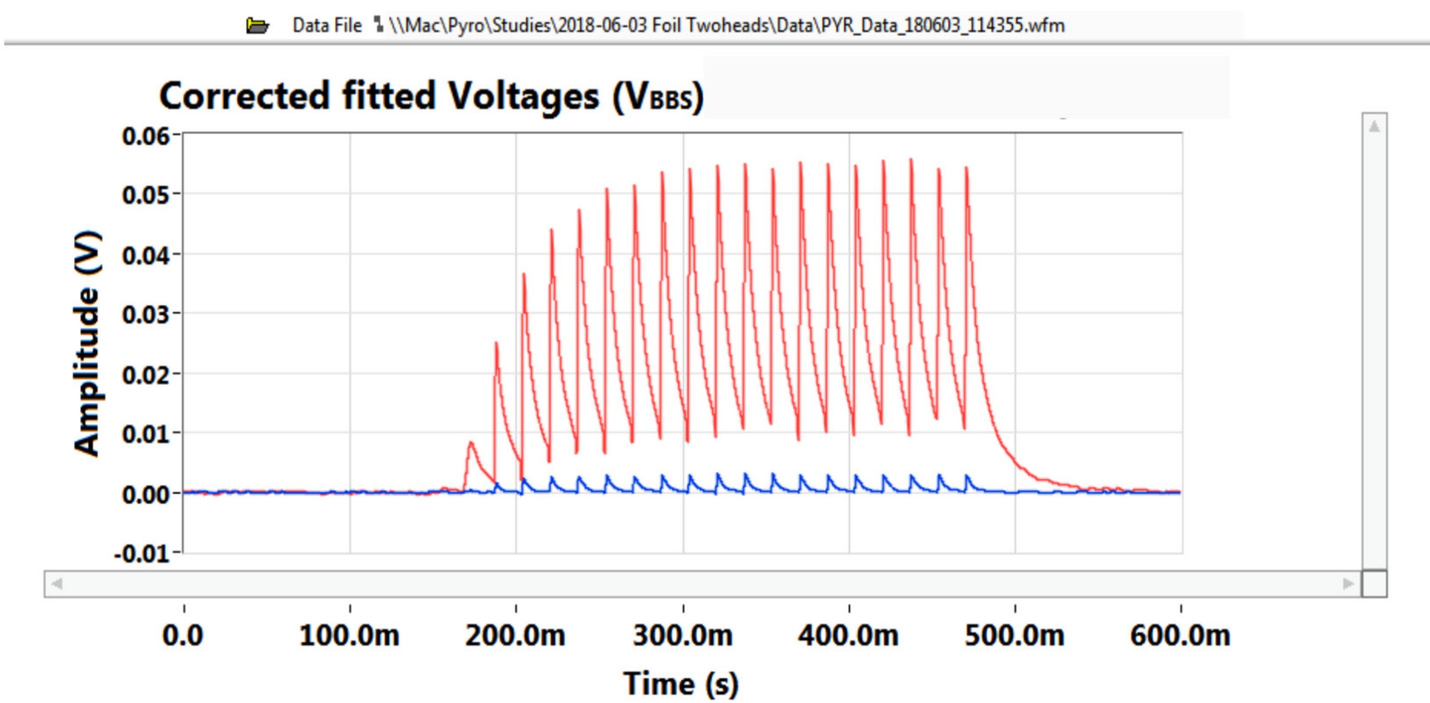
Data Processing: Spline Fit

- Filtered signal is still too noisy to take ratio → spline fit
  - Peak of the fits for both signals are forced to be at the same location to get better peak temperature
  - Spline fit has relaxed hinge points: spline is more flexible within the intervals



Studies: Pulse trains

- 20 pulses at 16.6 ms apart
  - Allows us to see baseline
  - Shows response of foil as it warms up
  - Shows cool down curve



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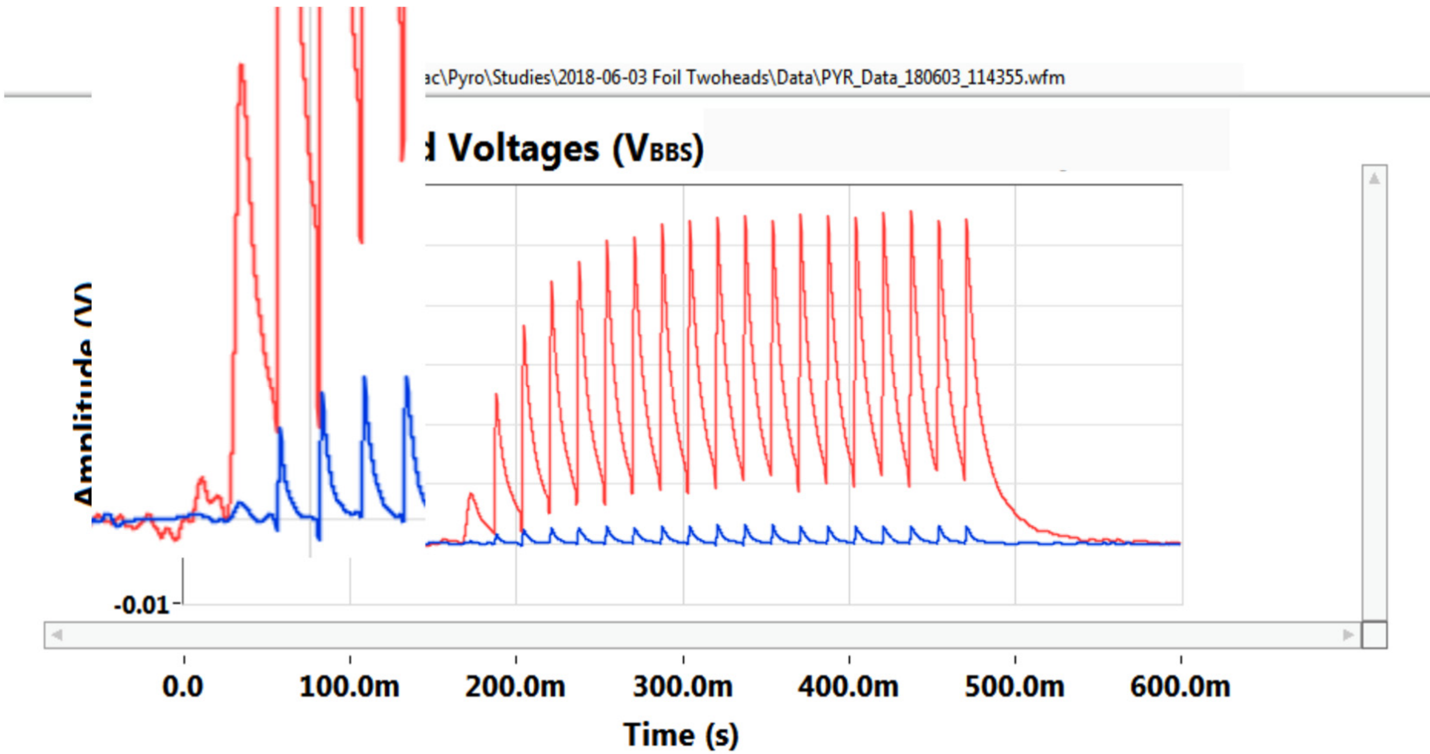

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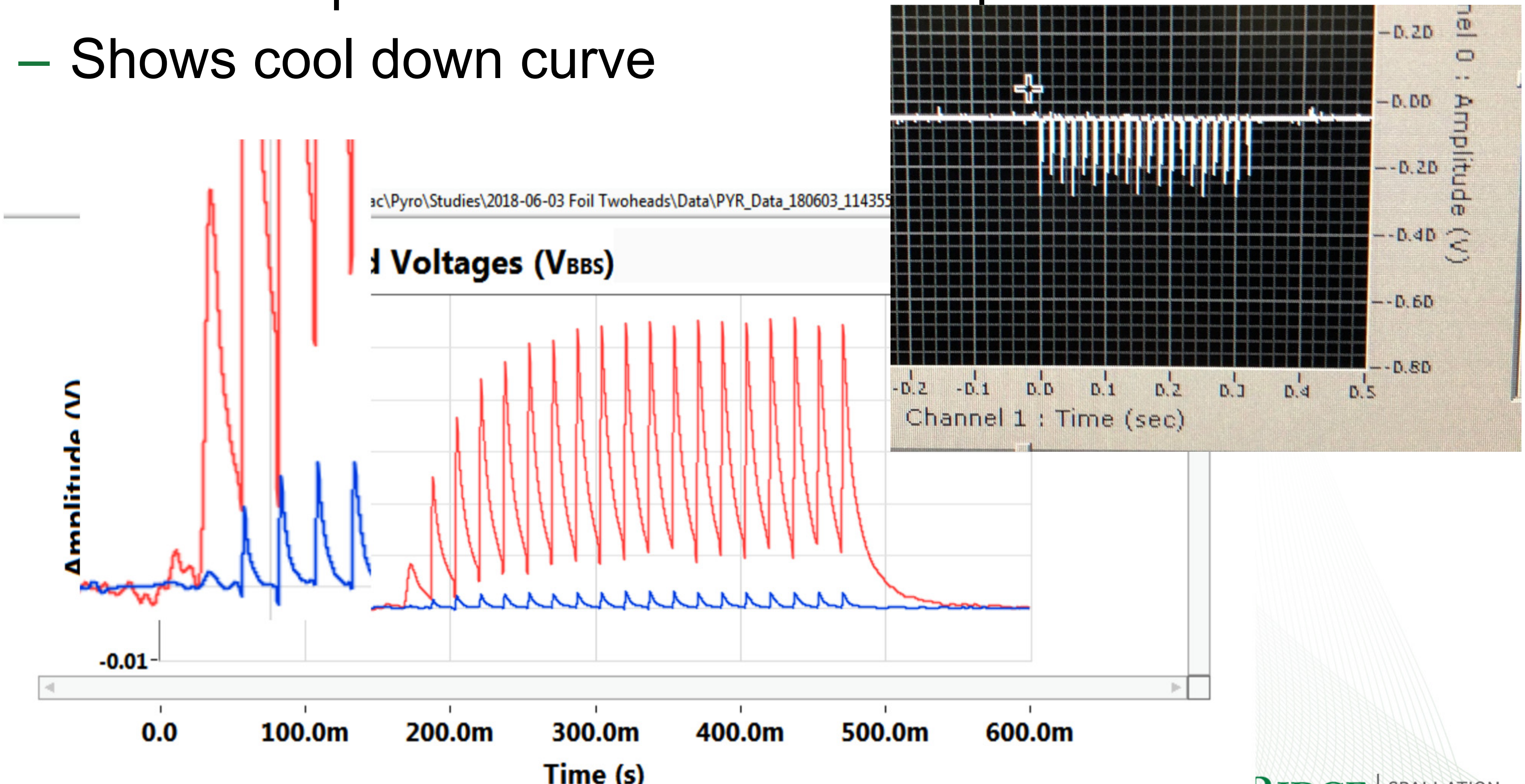

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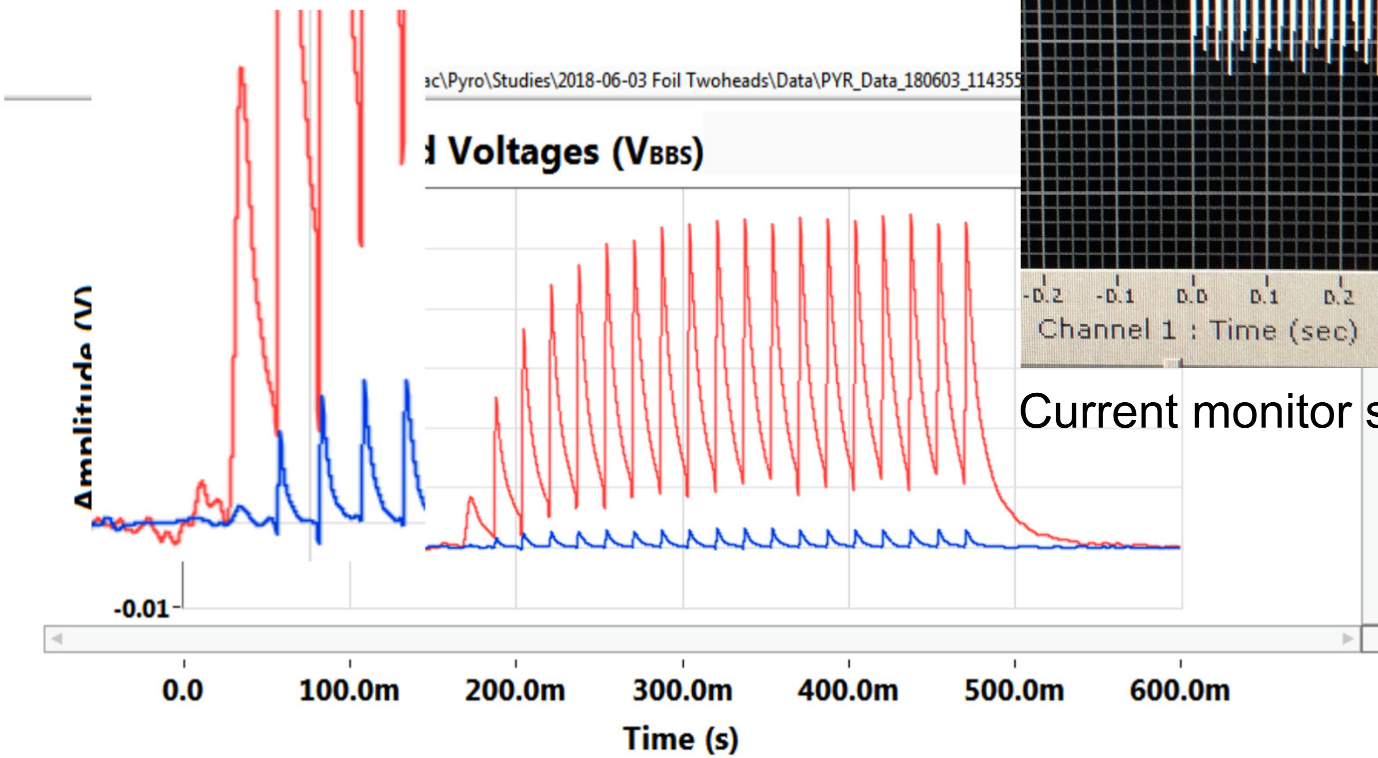
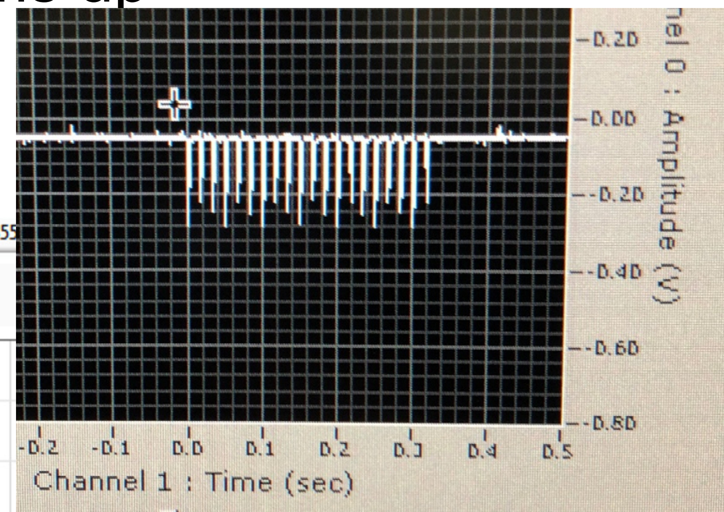
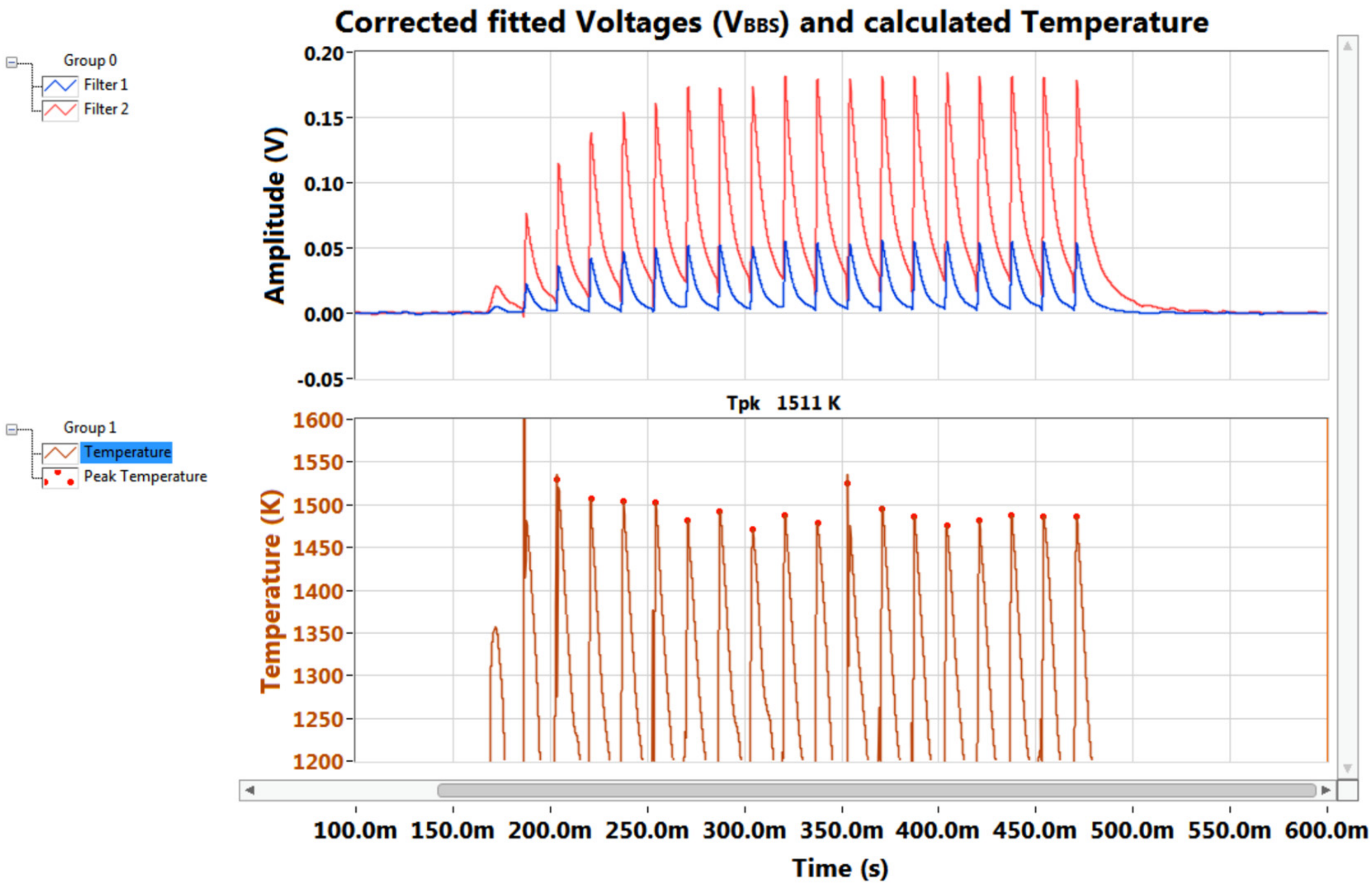




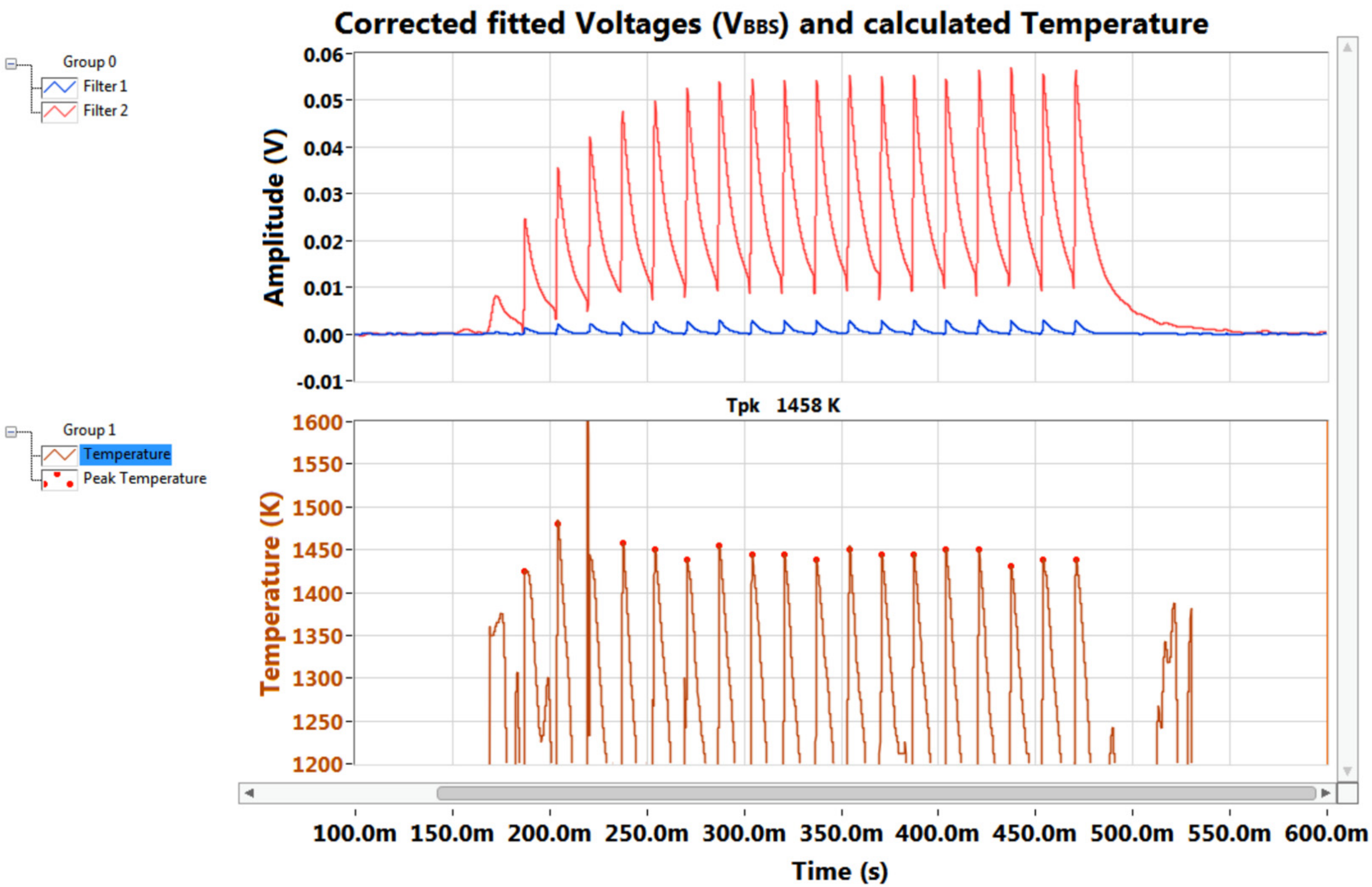
Current monitor showing 20 pulses

Data: 1000/1310



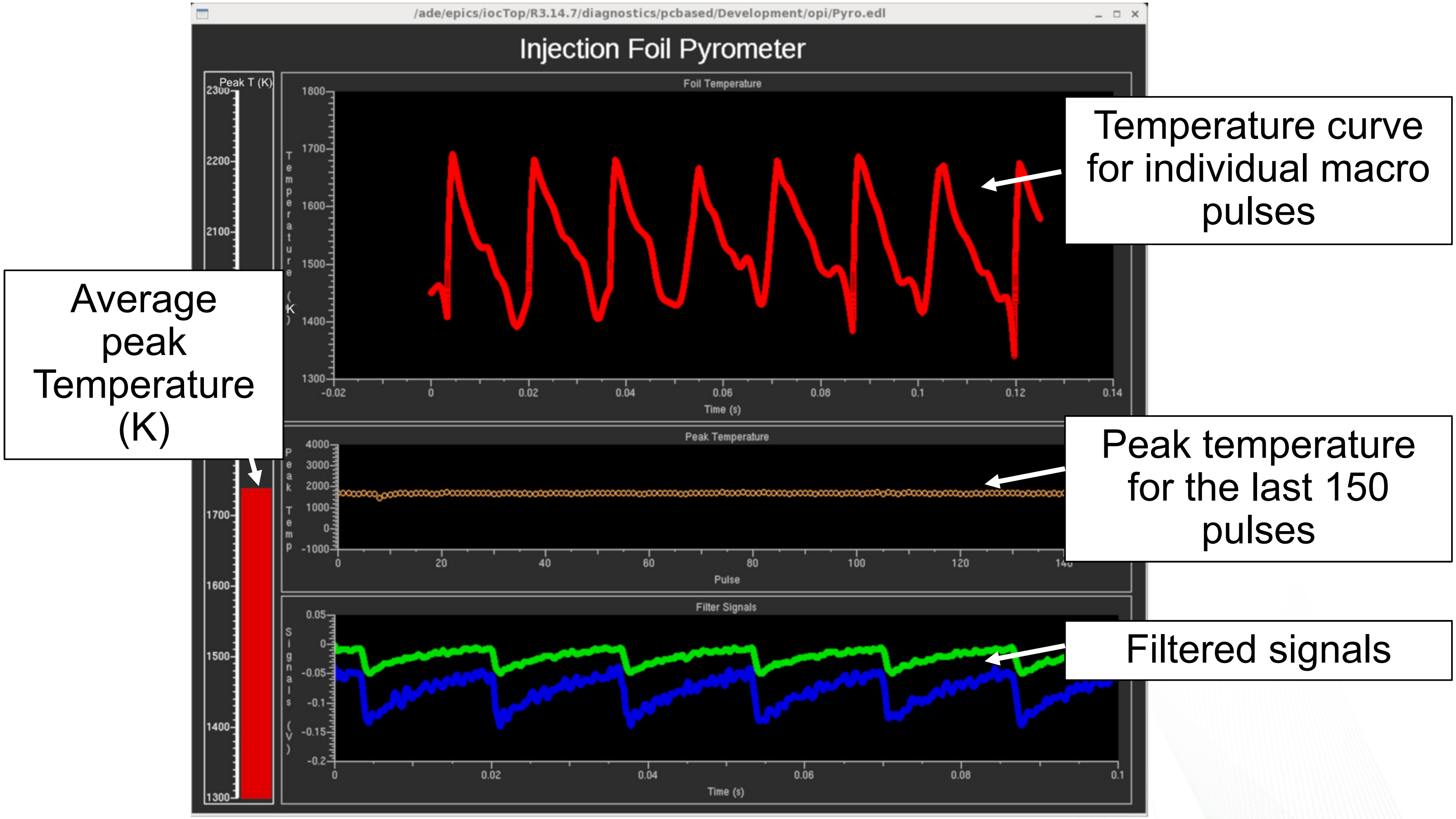
- Very similar temperatures compared to 850/1600

Data: 850/1600



- Fairly low temperature for the foil at 1450 K
  - Was about 1600 K earlier

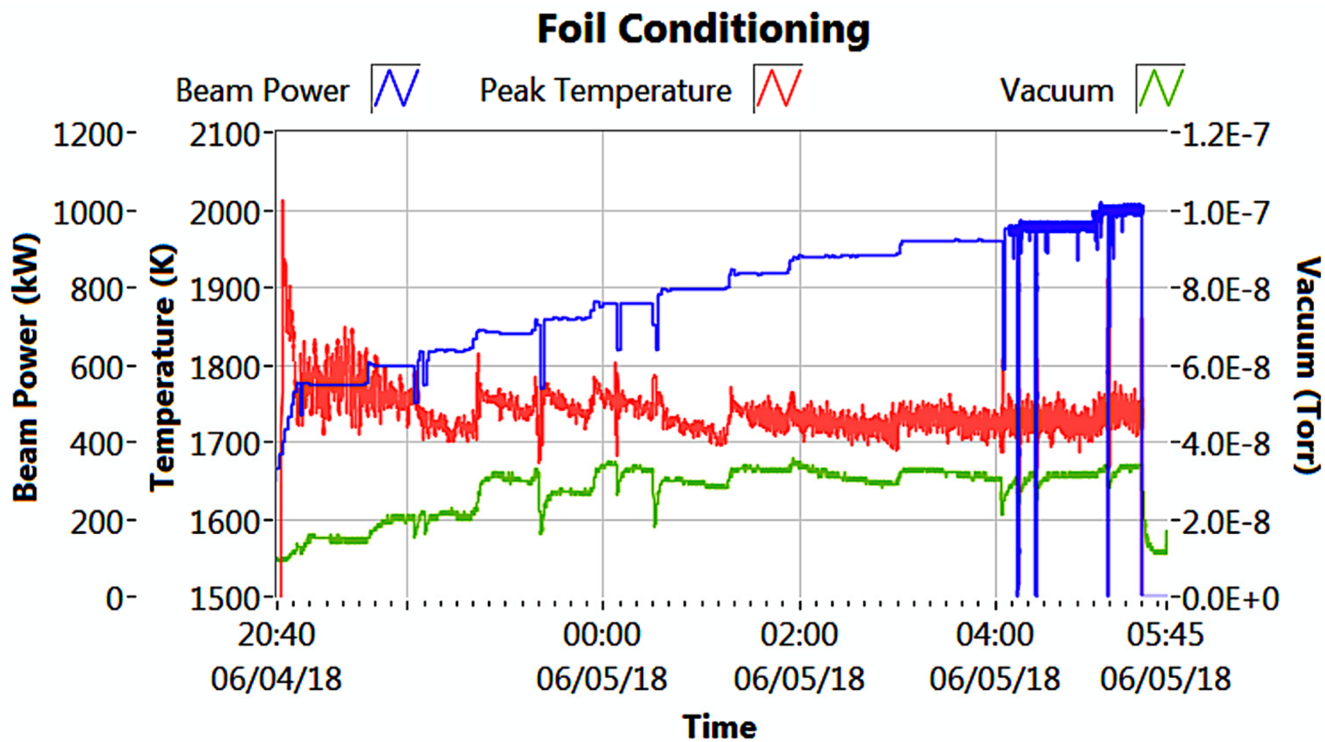
Foil Pyrometer in the control room



Foil Pyrometer EDM Screen

- We now have a on-line prototype pyrometer

Data: Effect of foil conditioning



Foil conditioning is done by slowly raising the beam power on the foil over about half a day:

- 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

Foil sublimation

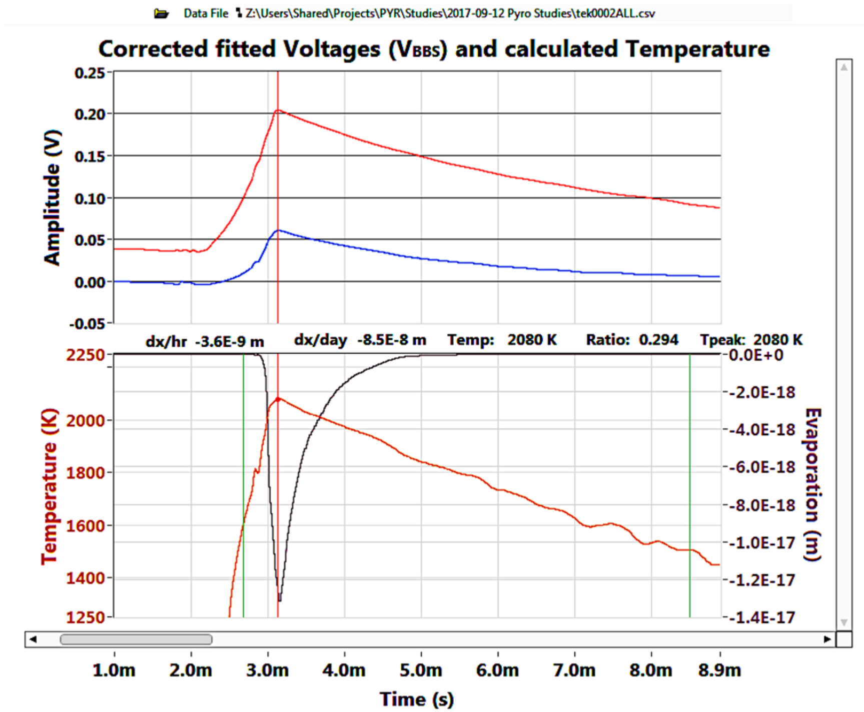
Equation:

$$\frac{dh(t)}{dt} \cdot \frac{1}{\rho} = -4.06 \cdot 10^{8} \cdot \frac{e^{\left(-\frac{83500}{T}\right)}}{\sqrt{T}} \quad {}^{m}/_{s}$$

S. G. Lebedev and A. S. Lebedev

(Density diamond is 3.5 g/cm^3)

(Density graphite is ~2.2 g/cm^3)



Example data

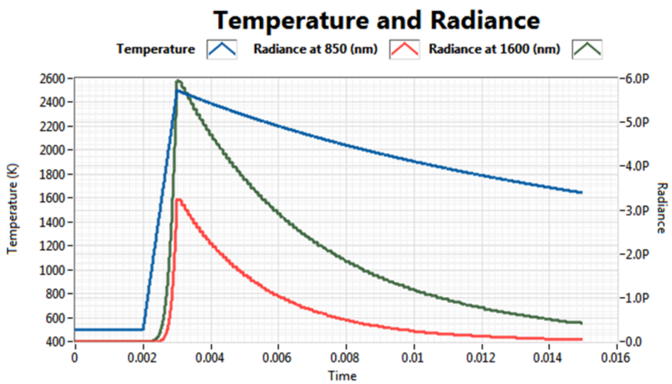
- Foil sublimation: integrated over time to determine dx over day
  - Foil is only 1 µm thick, can loose maybe 30%, or 0.3 µm but rate at, for example 2100K is high: 0.085 µm/day → 3 days (depending on foil density)
  - We see over months of lifetime for certain foils
  - Peak temperature should be lower than 2100 (~ 3 days lifetime)
  - Accuracy/applicability to be studied

Radiative cooling

- During beam pulse $T = T_{low} + C \cdot Beam_I \cdot dt$
- During cool off: $T = {T_{pk}} \Big/ {\sqrt[3]{1+3kT_{pk}^3 \cdot t}}$ with $k = \frac{2\varepsilon\sigma A}{3Nk_B} = 1.82\ 10^{-8}$ *(At 1 μm)*
- Use equation with the sum-of-blackbodies curve to calculate the measured signal

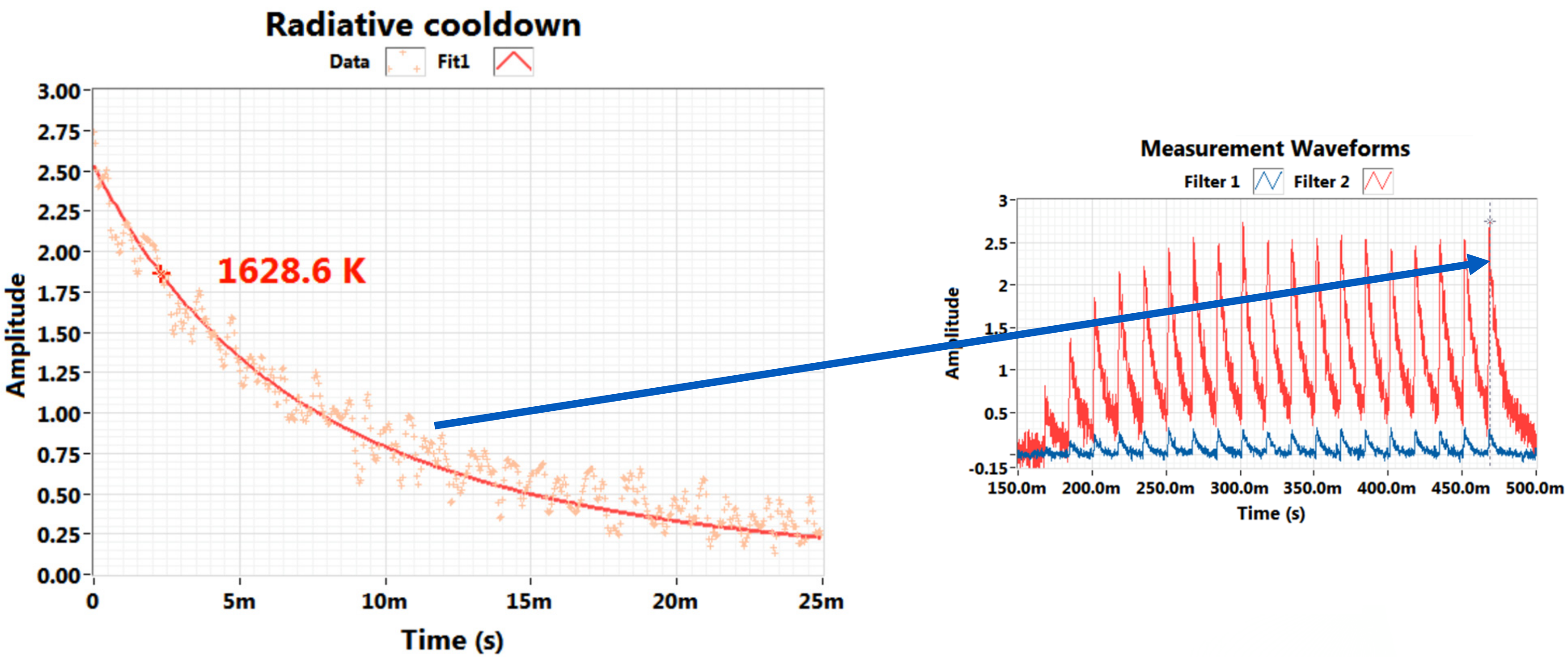
$$V_{BBS}(T, \lambda_c, \lambda_{ws}) \approx G \cdot \sum_{\substack{\lambda=\lambda_c-\lambda_{ws} \\ \lambda+=\Delta\lambda}}^{\lambda_c+\lambda_{ws}} BBS(T, \lambda) \cdot \Delta\lambda$$

- Use the measured data and iterate to determine temperature



Example curve for specific temperature

Peak temperature from cooling curve

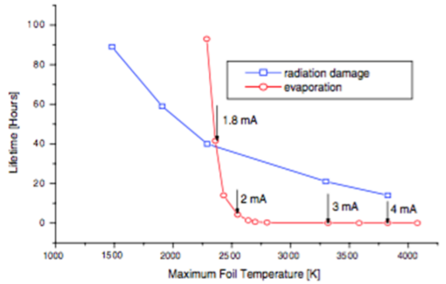


Without using the second signal:

- Fitting to temperature: other parameters, scale and k, are hold to a tight range so all variation is mapped into the temperature
- While we have estimates to calculate k, estimate scale, at this point the uncertainties are too great and too wide a temperature range can be fitted
- With using second bandpass, second optical head, more data from the foil lab, we expect to improve estimates

Summary and future

- We have installed a prototype foil temperature measurement system and started correlating temperature with foil conditioning, accelerator setup, and variations in beam parameters
- Temperature as it stand now 1500-1600 at 1.3 MW
  - Accuracy?
    - Signal processing: ± 100 K
    - Assumptions to check:
      - No heat conduction
      - Perfect capture of beam spot light
      - Constant emissivity



S. G. Lebedev and A.S. Lebedev

- Sublimation minimal at 1500-1600 K (but we already knew this from how long a foil survives)

Summary and future

- Future Improvements
  - Improve the calibration:
    - Using free space optical spectrum analyzer to redo spectral measurements
    - Compare foil lab's infrared camera with pyrometer
  - Improve optical head and add pinhole
  - Better signal-to-noise to support 2-D temperature profiles:
    - Wider bandpass filters
    - Different detectors (cooled)
  - Improve optical path:
    - Increase light collection: requires in tunnel optics and will be expensive
    - Reduce shimmering

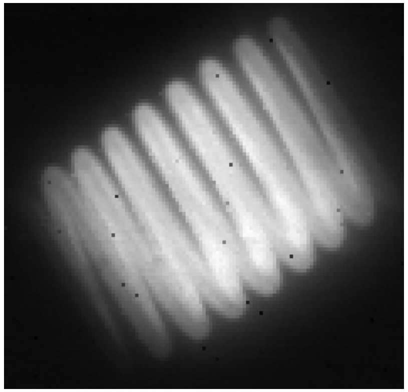


Image of filament using programmable pinhole

- Future R&D
  - With foil lab testing we hope to determine sublimation point, density, and verify emissivity measurements