How To Make a Blue Plasma: Impurities in WHAM

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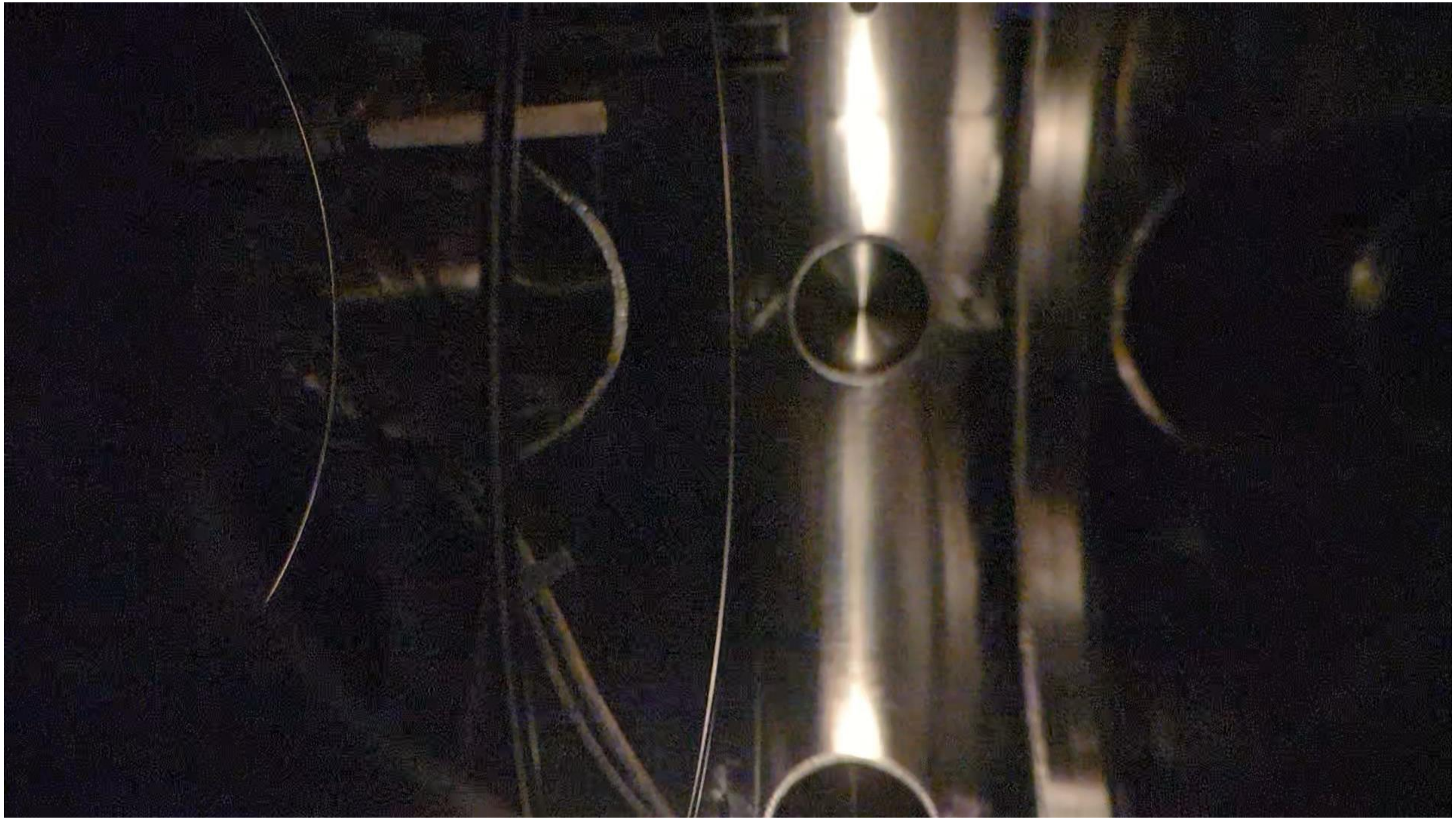
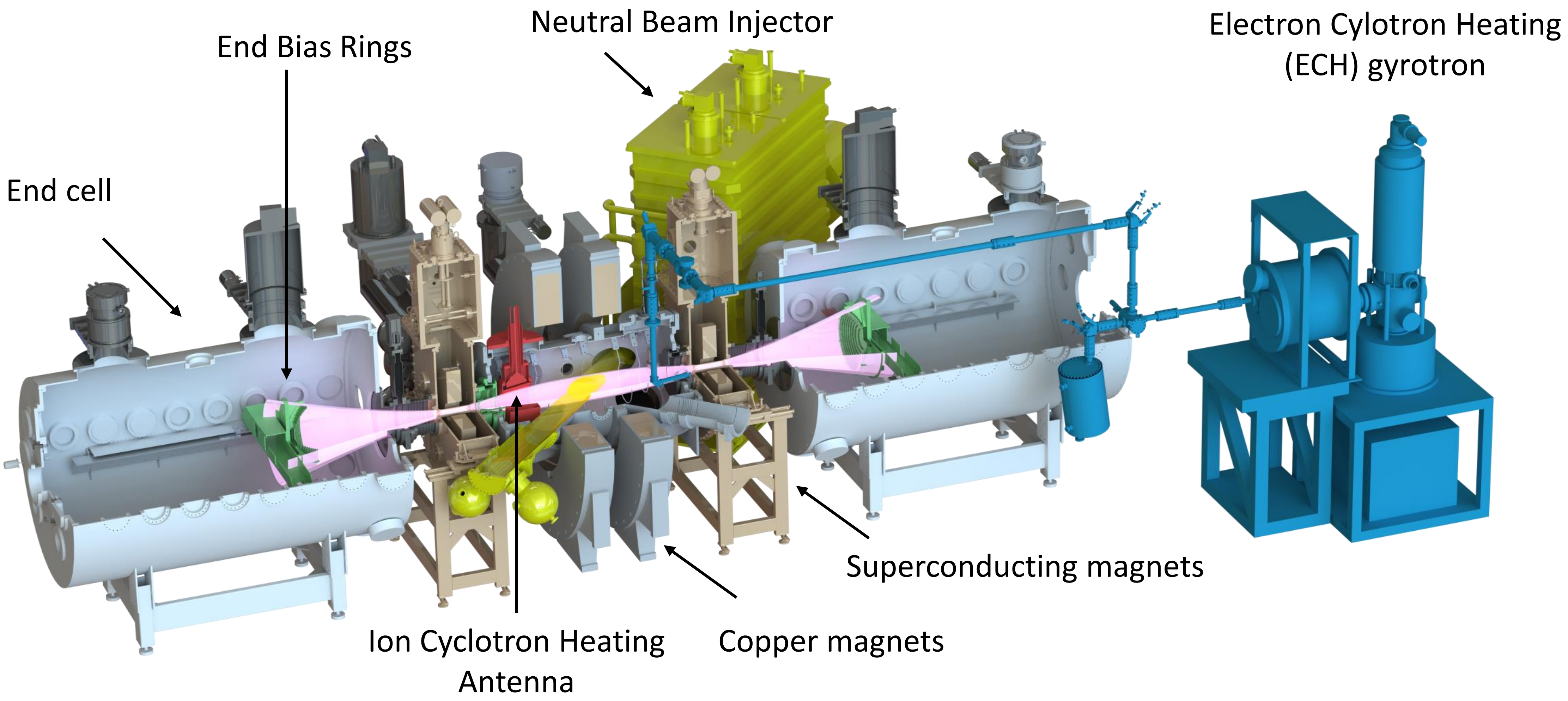
05-28-25



Tiny Plasma + Lots of Heating = Impurities



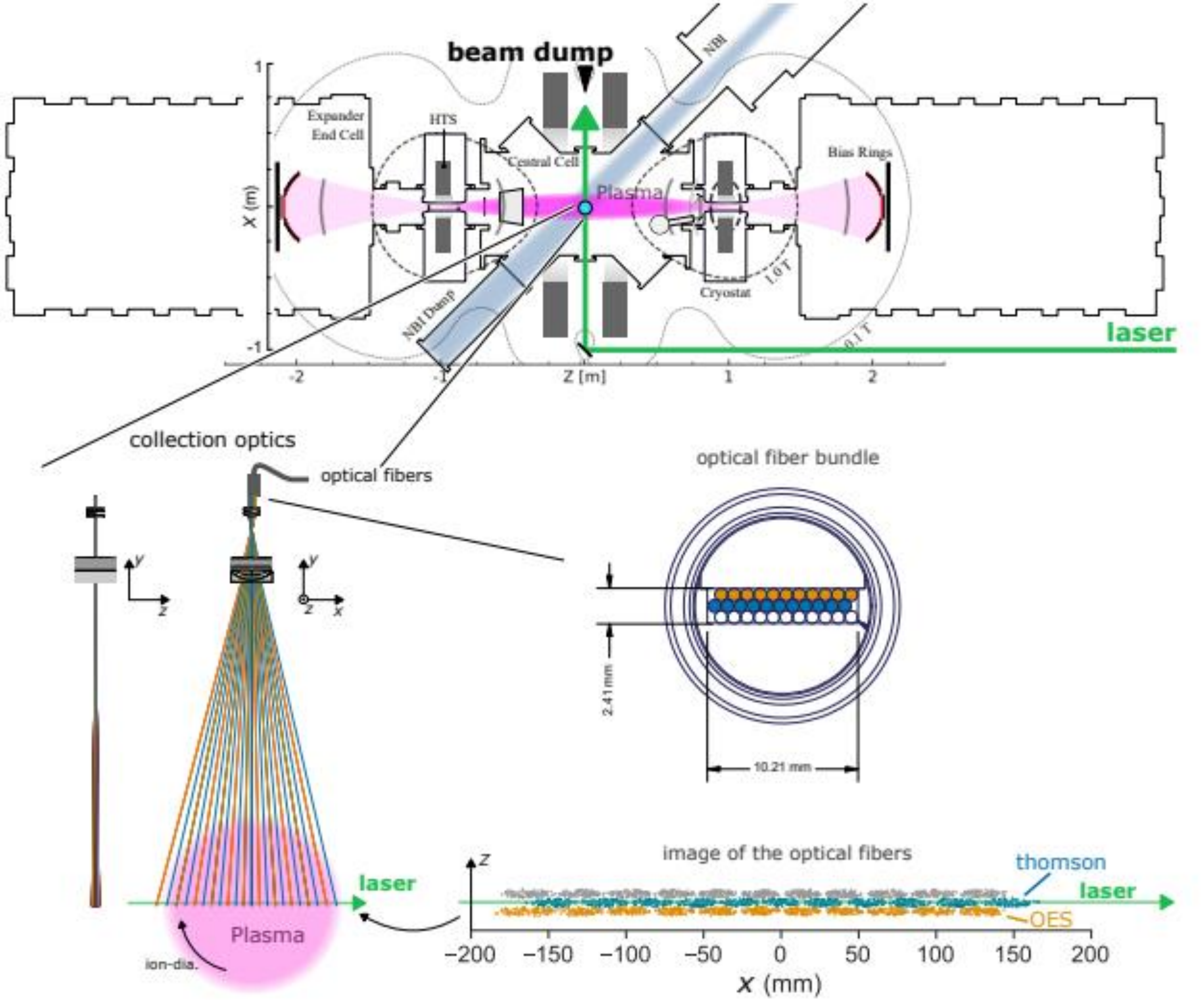
Outline

- Identifying impurity elements
  - Optical spectroscopy (visible range)
  - Collisional radiative modeling
  - Residual gas analysis
  - Soft X-Ray pulse height spectroscopy
- Identifying impurity sources
  - Inspection of plasma facing components (PFCs)
  - High speed and long exposure videos of plasma
- Future work

Optical Emission Spectroscopy

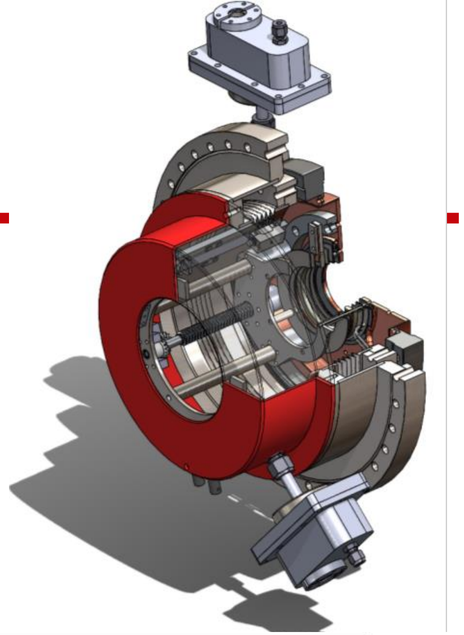
Optical Emission Spectroscopy at Mid-Plane

- ORNL Portable Diagnostics Package (PDP) [1]
- Mainly for **Thomson scattering**
- 1x fiber bundle with 10 sightlines dedicated to Optical Emission Spectroscopy (OES)
- 2x Teledyne Princeton Instruments IsoPlane 320 Czerny-Turner spectrometers
  - Instrument function with 2400 l/mm grating ~0.1 nm
  - Pixel pitch ~0.008 nm
  - Span ~ 8 nm
  - Adjustable gating and amplification with ICCD
- **One exposure per shot**
  - Repeat many shots to get rough time-dependence
- **Visible only**: limited by window and fiber ~400-800 nm
  - ~30 shots to scan across entire visible range
- 2x **Ocean Optics USB spectrometers**

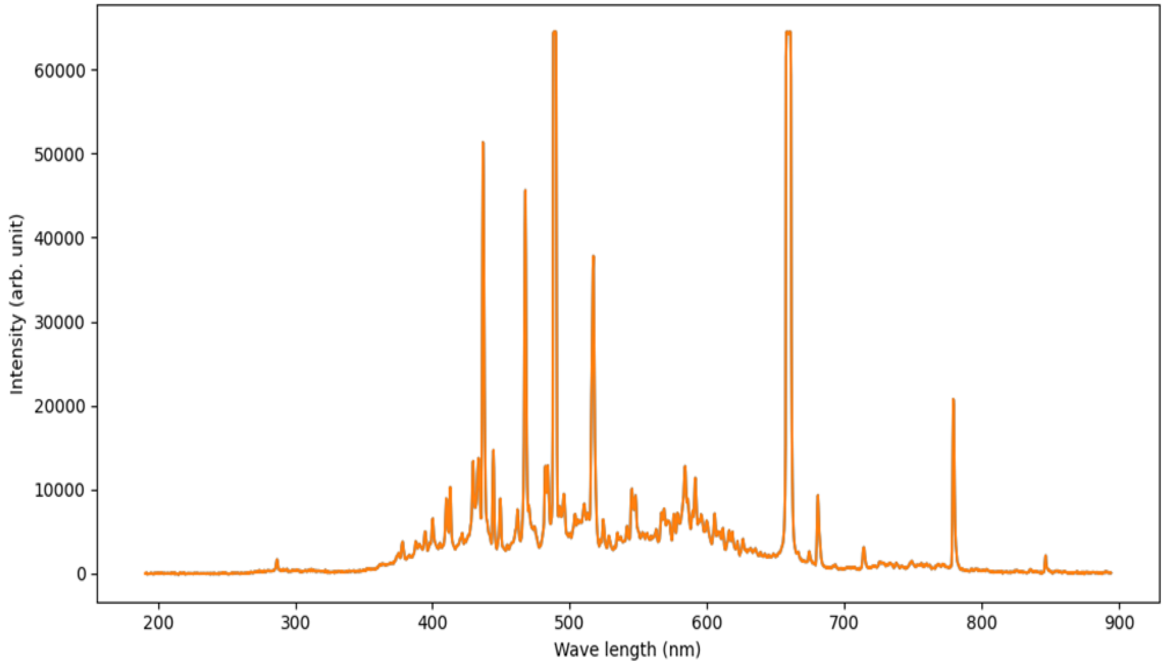


*[1] K. Fujii et al. "*Application of a Portable Diagnostic Package to the Wisconsin HTS Axisymmetric Mirror" Rev. Sci. Instr. (under review)

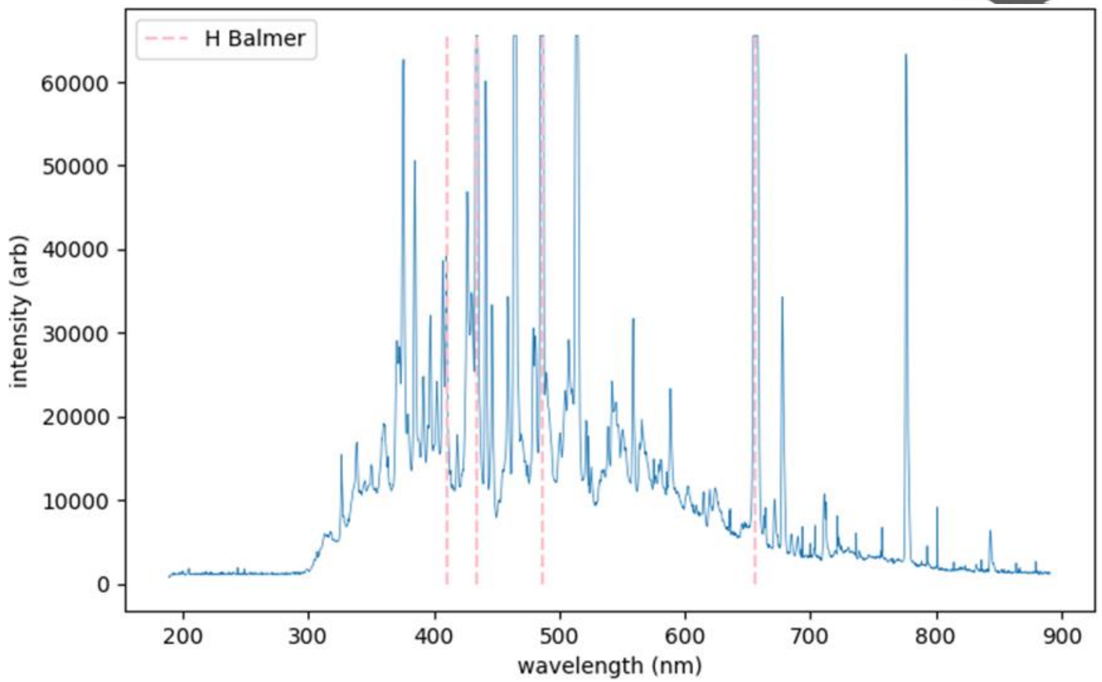
A Very Active Visible Spectrum!



- H-Balmer series by far the brightest
- Very bright line from C-III at 465 nm
- → **Large dynamic range** required
- → **Resolution >0.5 nm is insufficient** to accurately identify impurity peaks



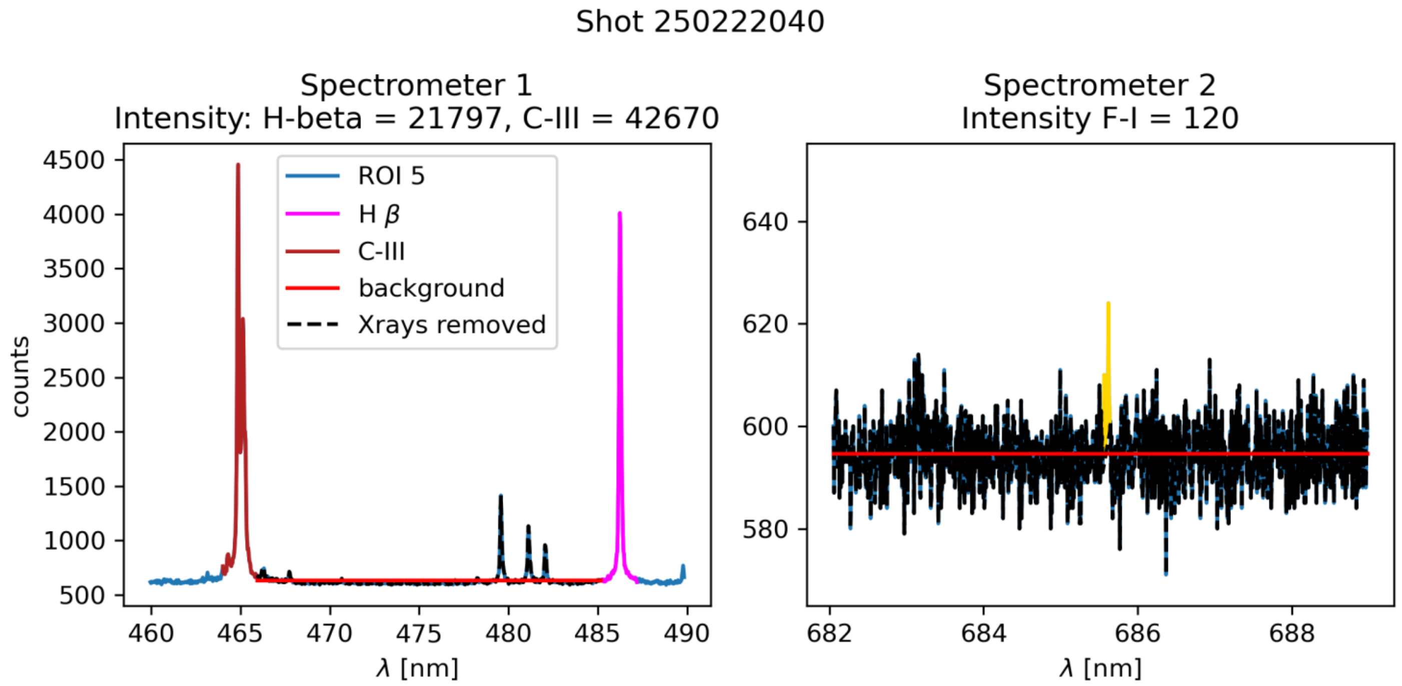
Spectrum at z=25 cm

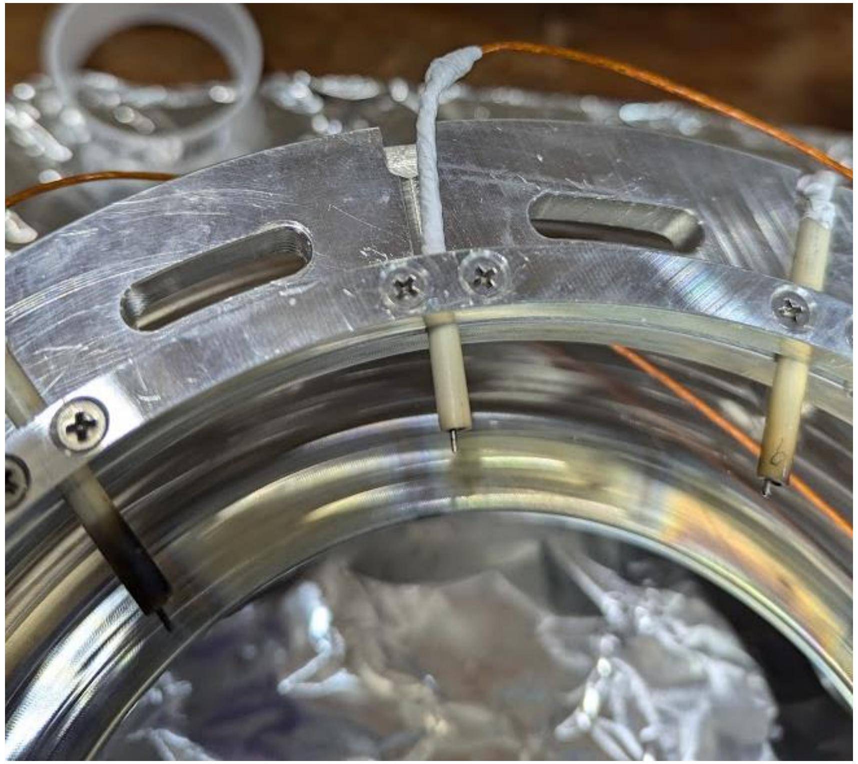


Spectrum inside gas baffle (prior to plastic removal)

Initial Identification: Fluorine and Carbon

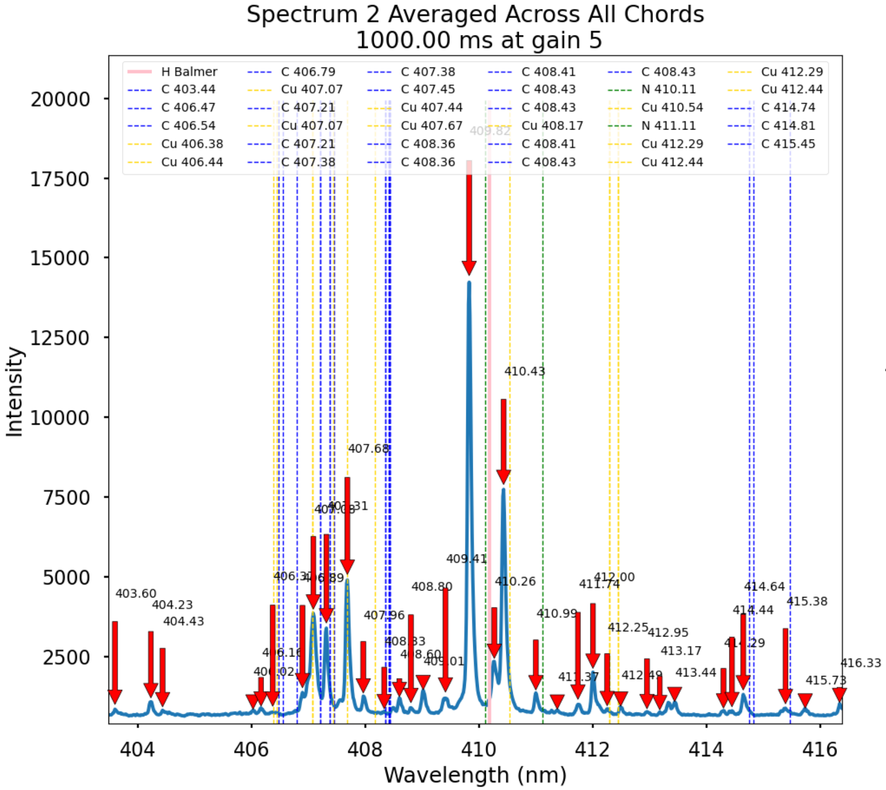
- **C-III line always present and very bright** with ECH heating
- Strong fast electron tail with low pressure → **F-I line** appears
- → **Removal of Teflon components** near the plasma reduced F-I brightness to near zero
  - Flux loop support and edge electrostatic probes
- → Removal of **3D printed plastic reduced C-III brightness, but not to zero**
- → **X-rays** from fast electrons hitting sensor directly cause sharp lines

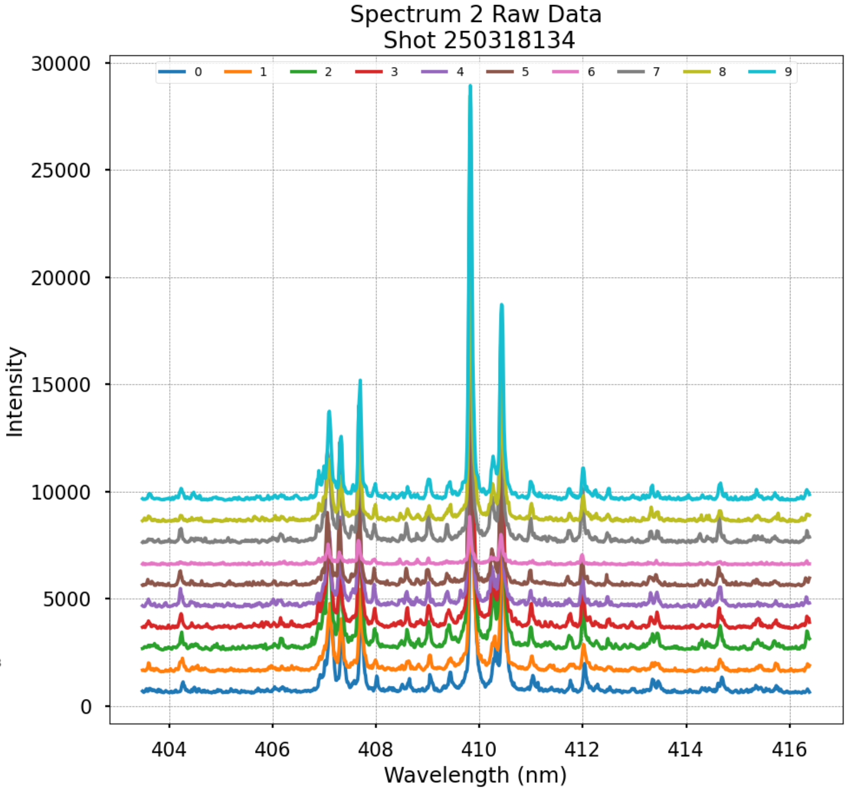




After Baking and Conditioning: Still, Lots of Lines

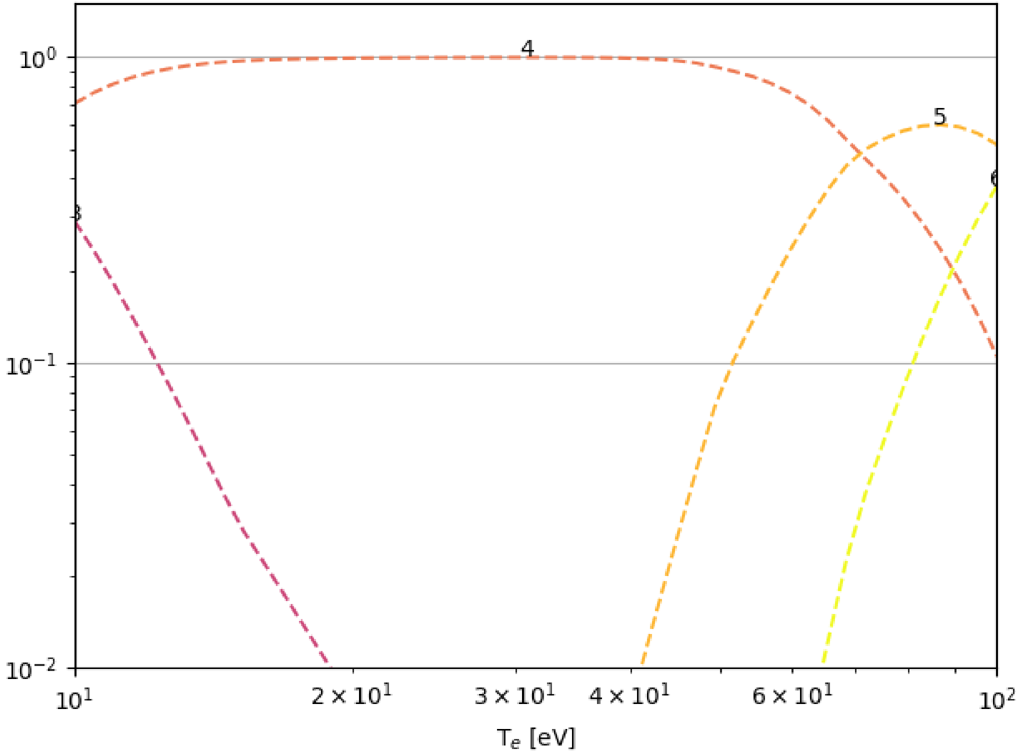
- Concentrated in the UV/blue range for **high-Z impurities: Fe, O, Cu, N tentatively identified**
  - Wavelength calibration of spectrometer is non-linear
- Shot-to-shot repeatability is good for plasma parameters, but not necessarily for spectra
  - X-rays? UFOs? Wildly different dynamic range required for different regions in visible
- → **Collisional Radiative Model** required for accurate interpretation



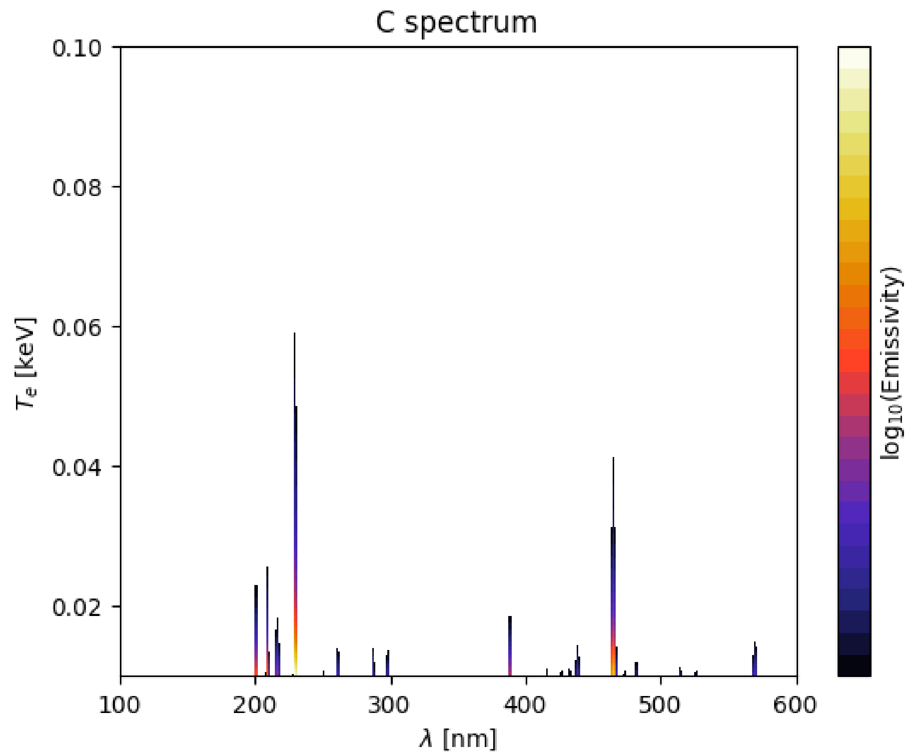


CR Model in Thermal Equilibrium Is Insufficient

- WHAM should be hot enough to burn through C-III
  - Assuming thermal equilibrium with constant population (zero source, zero sink)
- But only **20 ms pulse length** + heating power correlates with both **source rate and temperature**
- ColRadPy used to model the thermal equilibrium case
- → Even at low temperatures, **radiated power can be extreme**!



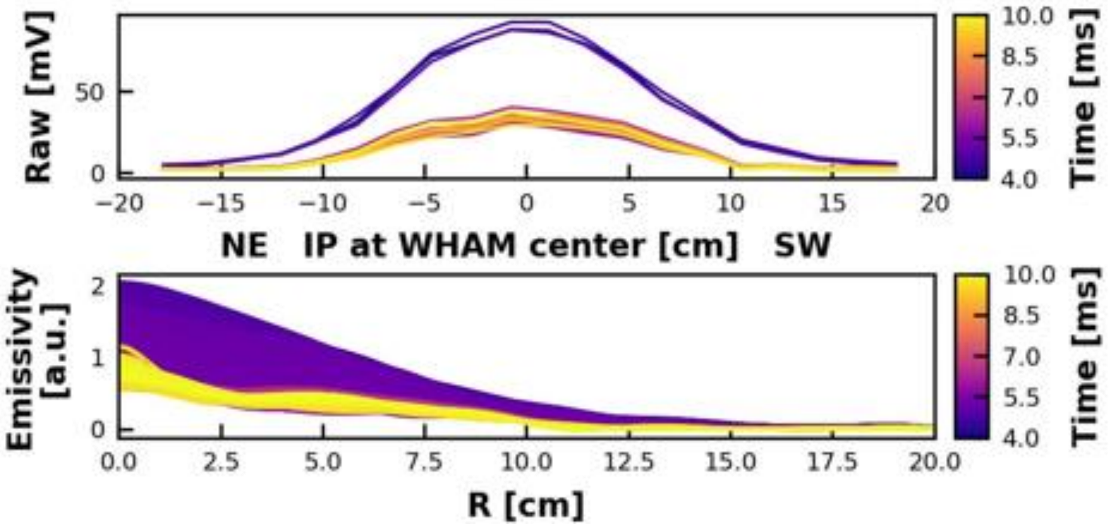
Carbon Ionization State Portion as Function of Temperature in Thermal Equilibrium



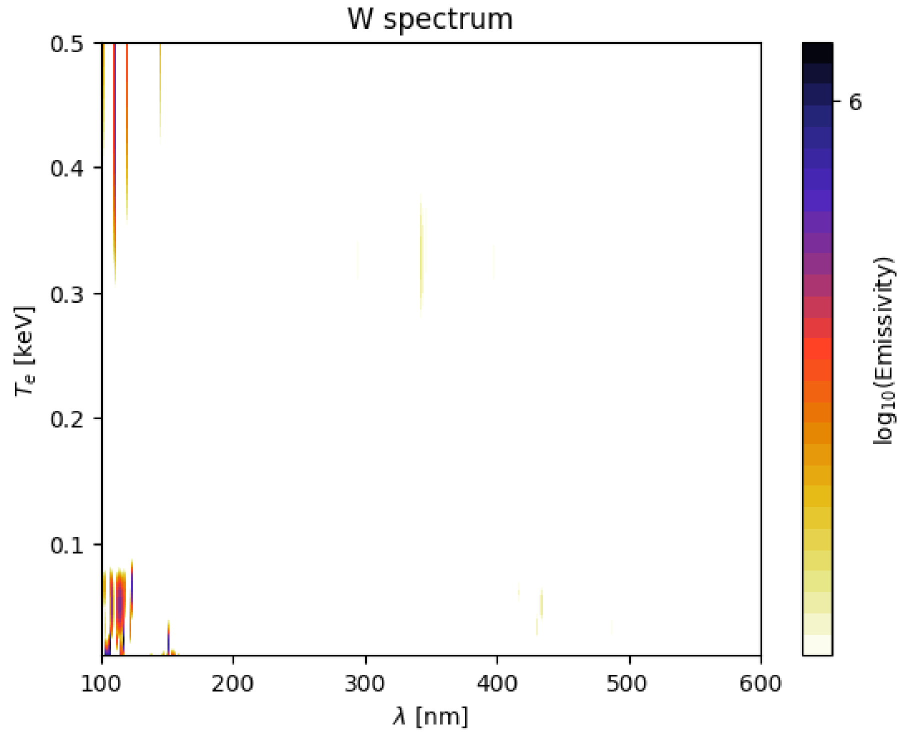
Predicted Carbon Spectrum as Function of Temperature in Thermal Equilibrium

Difficult to Identify high-Z Impurities Without UV Spectroscopy

- High-Z impurity lines in the UV and soft x-ray range is invisible to OES spectrometer
- Use of AXUV diodes and soft x-ray pulse height spectroscopy as proxies for impurity level
  - Current filter in 40-70 nm
- ECH heating increases core AXUV emission
  - Hot electron tail or bulk electron temperature increase?
- Low-Z impurities lines always there



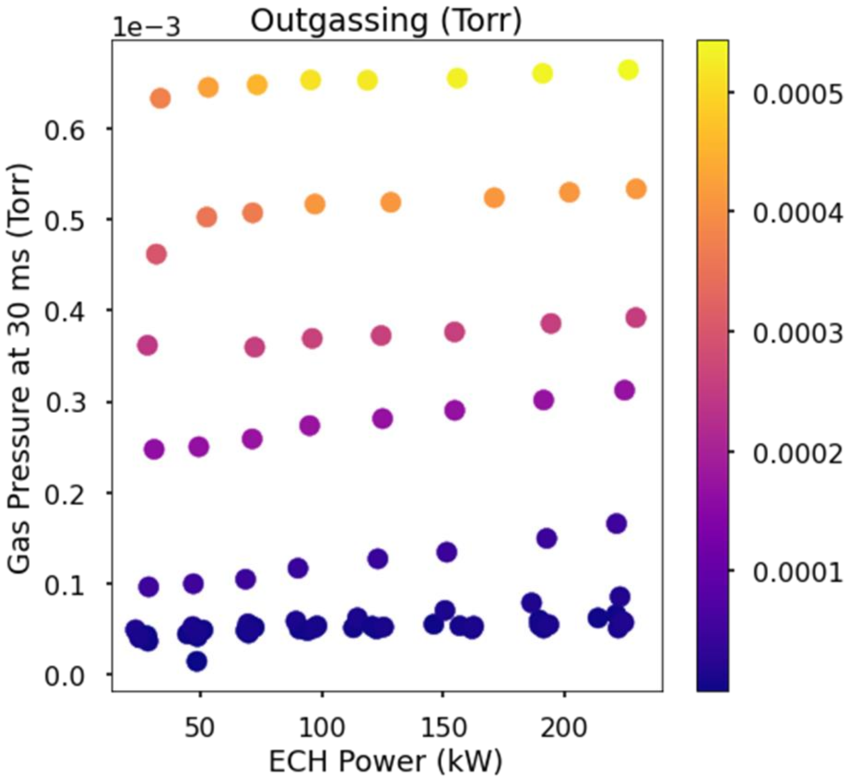
AXUV Signal and Radial Emissivity Profile with ECH+NBI and NBI only

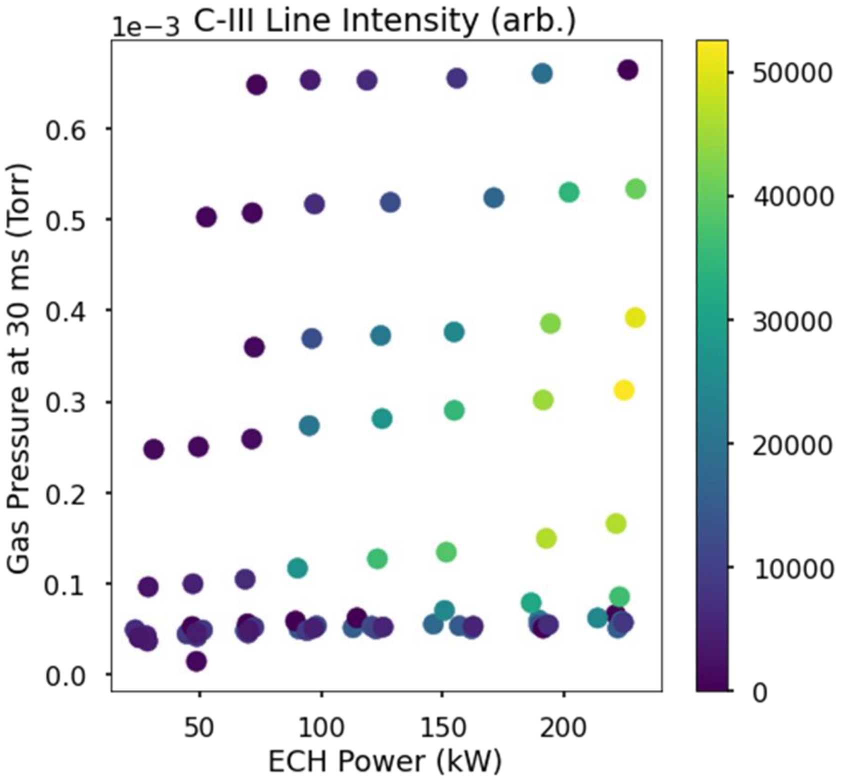


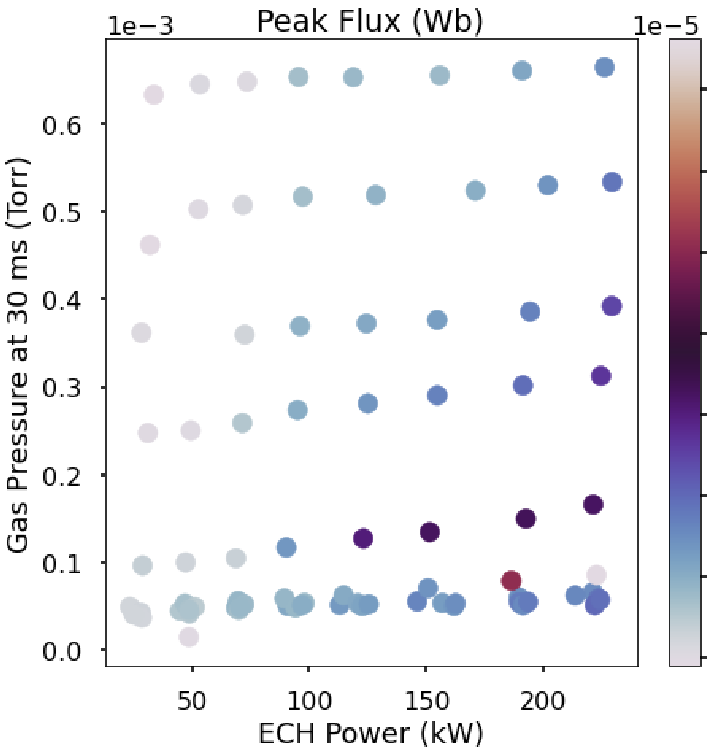
Predicted W Spectrum as Function of Temperature in Thermal Equilibrium

Intensity and Out-gassing Proportional to ECH Power

- → Source rate of gas and impurities **depends on heating power**
- → More heating may not be able "burn through" impurities **if sources are not under control**
- Adding **more gas puff tends to suppress C-III line**, likely by lowering bulk temperature

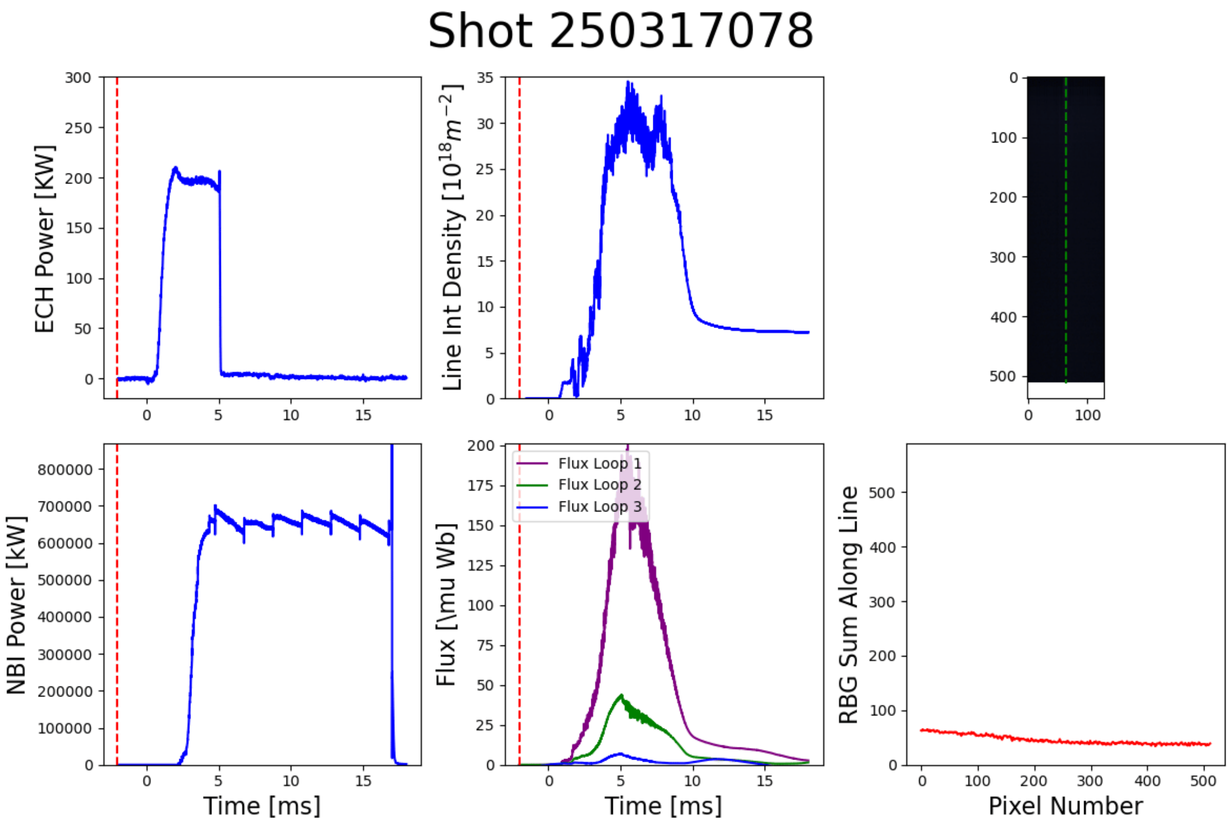


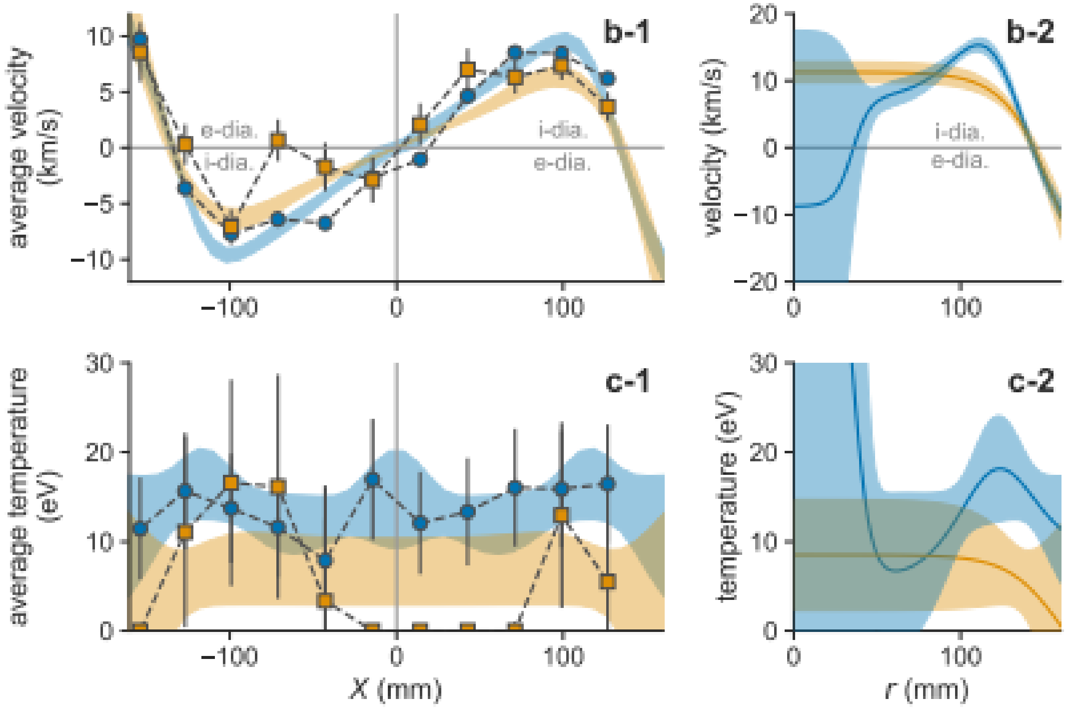




Impurity Ions Rotation and Broadening Driven by NBI

- Doppler broadening and shifting allows determination of impurity ion temperature ~30-50 eV
- Radial bias driven rotation up to ~10-20 km/s
- Phantom video shows plasma **immediately turns blue upon NBI turn-on**
- → Possible beam dump recycling? Effect of biasing?

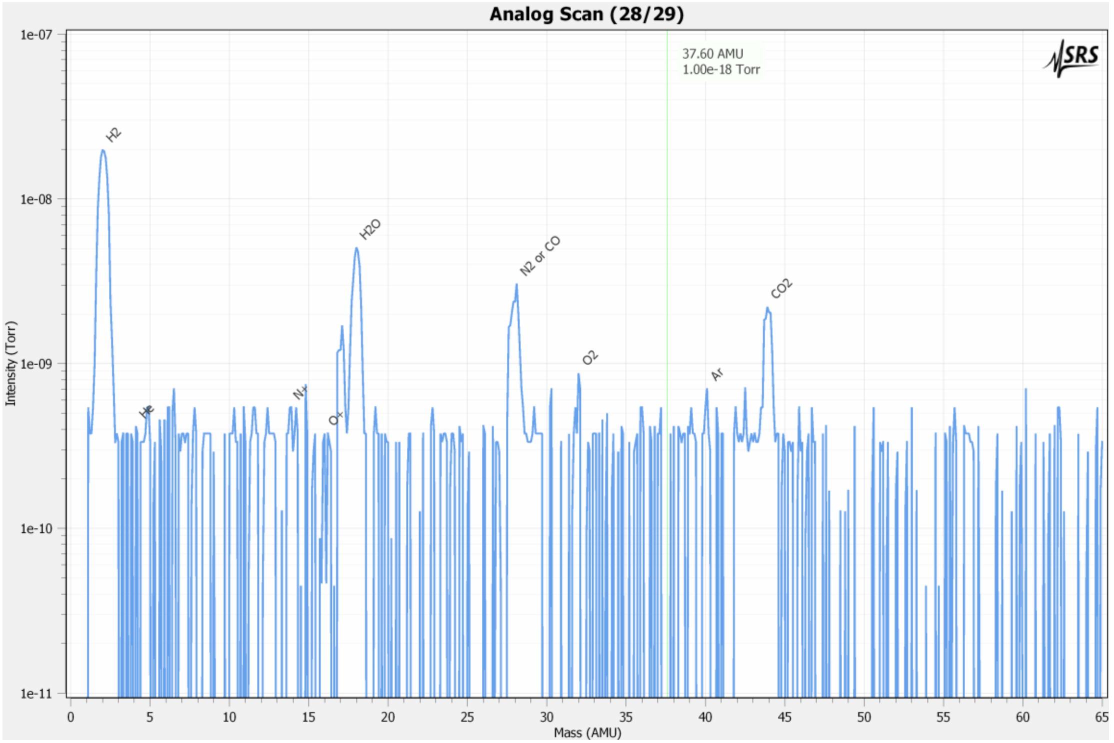


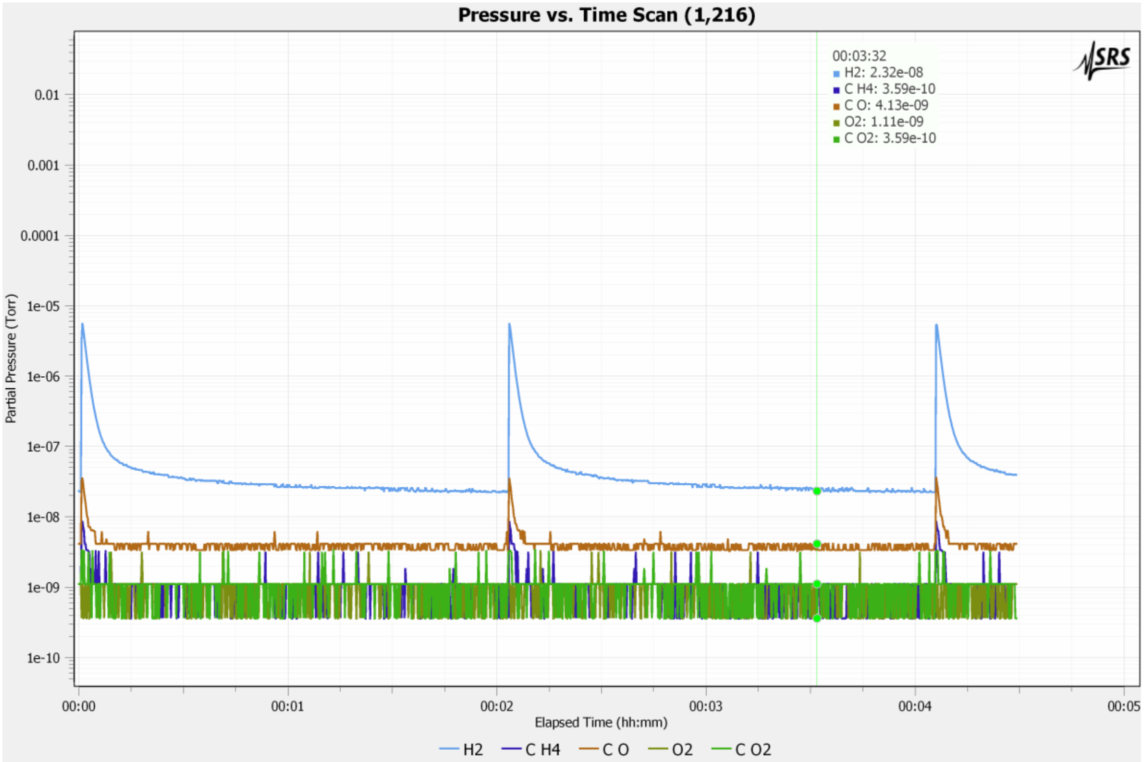


Residual Gas Analysis

RGA Cannot Identify Non-Gaseous Compounds

- SRS-100 RGA logged at 3 Hz frequency is sufficient to identify some gaseous impurities
- Requires significant distance and magnetic shielding to obtain accurate partial pressures
- → H_2O, N_2 ***or*** CO, O_2, CO_2, CH_4 are tracked and logged 24/7
    - No baking for this experiment, but carbon compounds are always observed with/without baking
- → Suitable for tracking long term trends and carbon content between shots

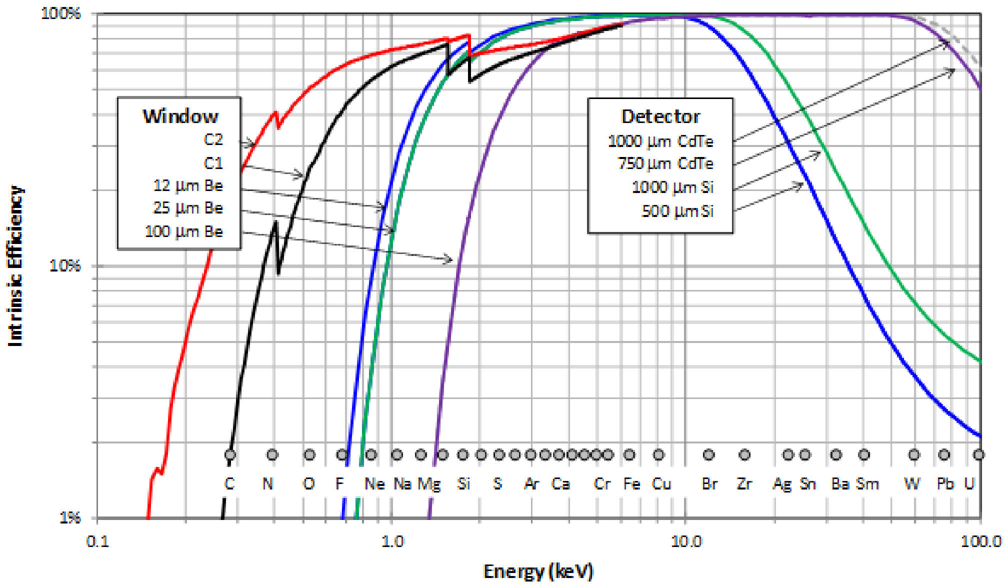


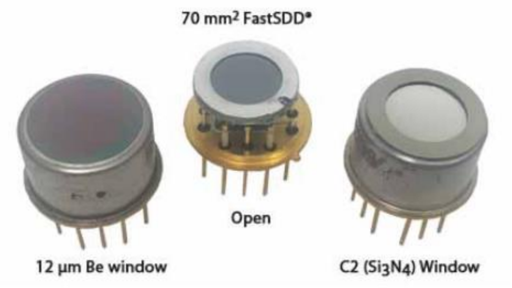


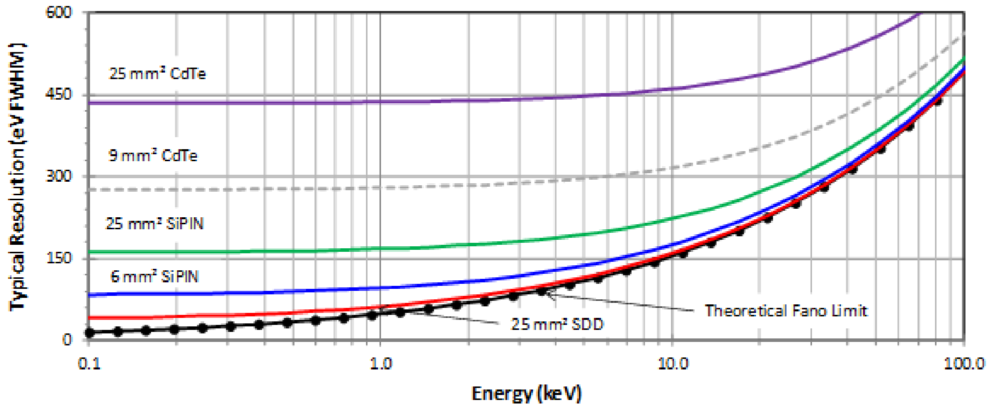
Soft X-ray Spectroscopy

Pulse Counting Detector Resolves ~1 keV X-rays

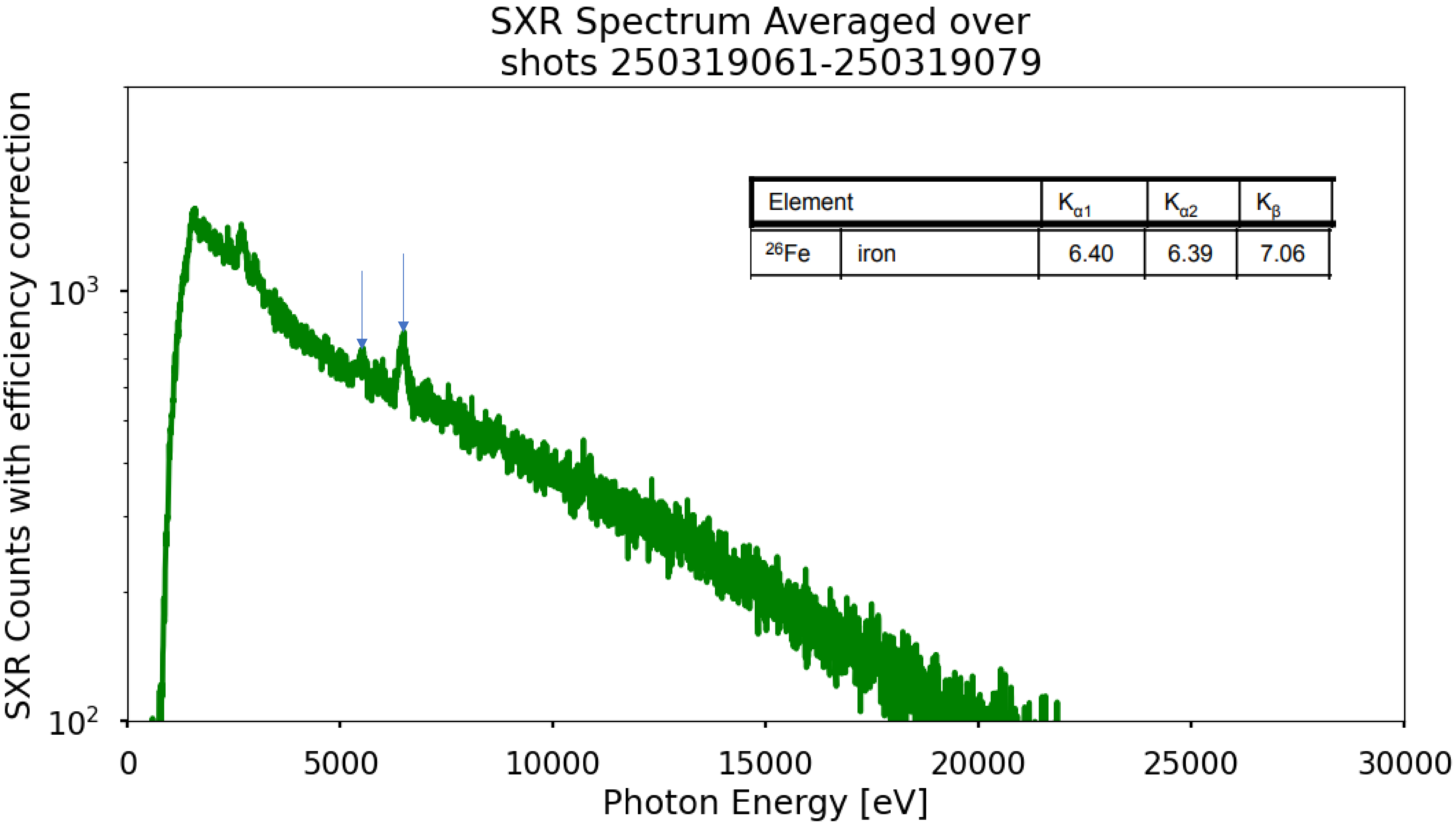
- **Amptek Silicon Drift Detector SDD-123** acquired second-hand
  - 12 um Beryllium window, with fast count rate option to 1 MCPC
  - C2 window is transparent to XUV photons and can overwhelm detector
- Magnetic shielding allowed electronics to function
  - Installed at NW 4-5/8" port looking at ECH launcher
- Configured for **low gain, max. count rate**
  - Max cooling, achieving -43 C in field
  - 8192 Multichannel Analyzer bins
  - Fastest shaping time: 0.4 us
- Start integration at t=-20 s, integrate for 30 seconds
- **Careful calibration and tuning** requir
  - In-situ due to background magnetic field
  - Sensitive to baking







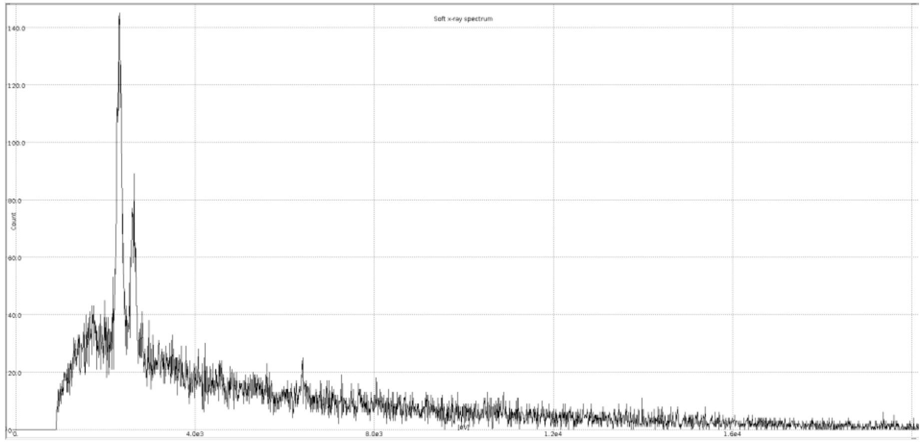
Confirmed Iron lines 6.4 keV, 7.06 keV

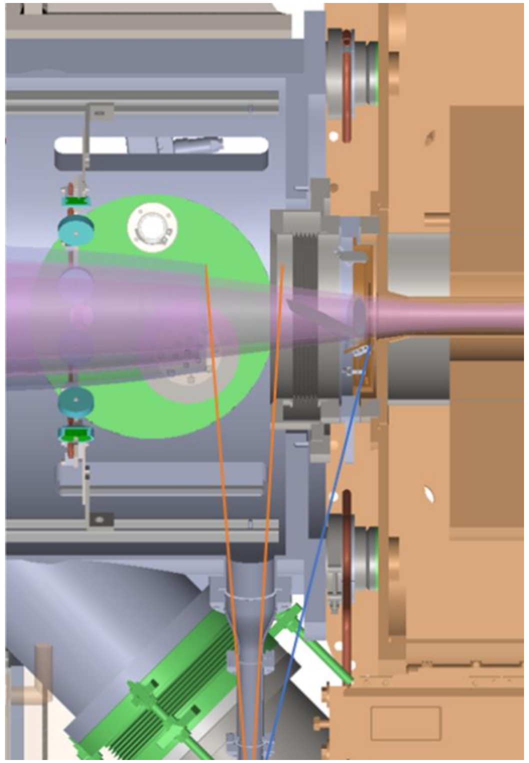


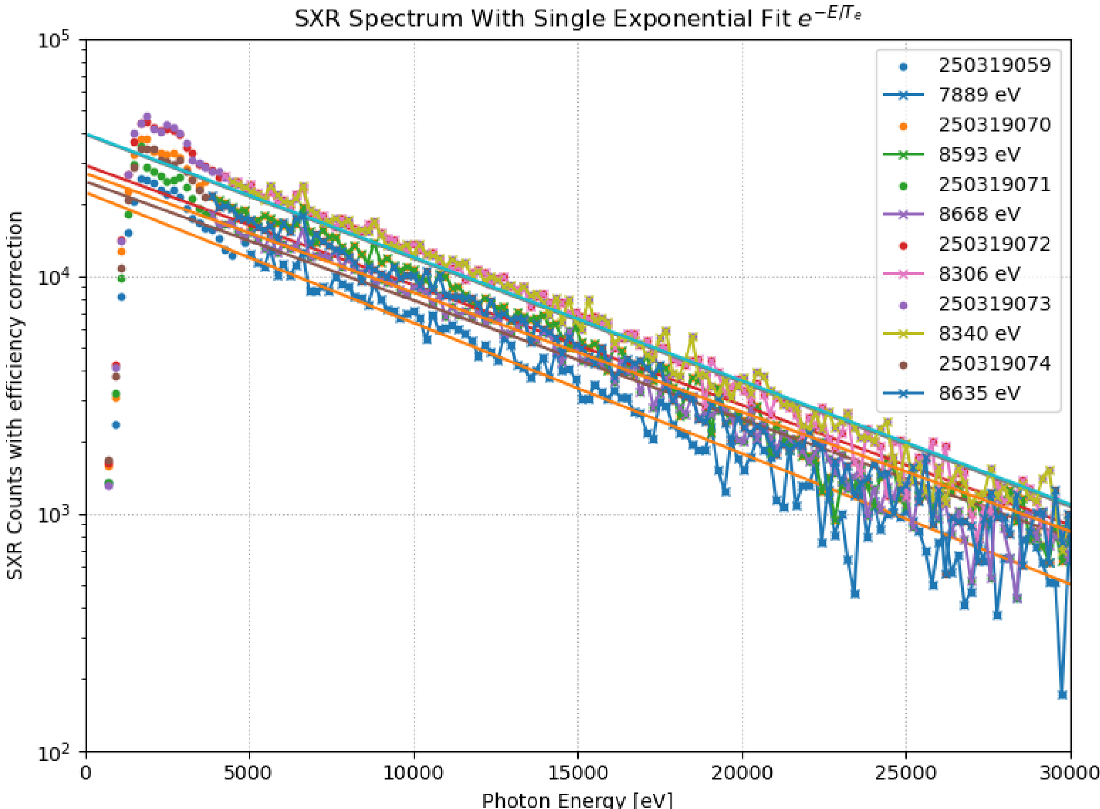
Element		$K_{\alpha 1}$	$K_{\alpha 2}$	K_{β}
^{26}Fe	iron	6.40	6.39	7.06

Measurement of Hot Electron Tail/EEDF

- → Clear **distinction between bulk and tail population**: two slopes
- Bulk T_e still too low to be an effective bulk electron temperature measurement
  - At least will require **calibration against Thomson scattering**
- Line-of-sight is limited, does not see any high-Z PFCs directly
- **Inversion of EEDF** in-progress
- Observation of **Mo K_α lines**
  - Disappeared/weakened after limiter fix



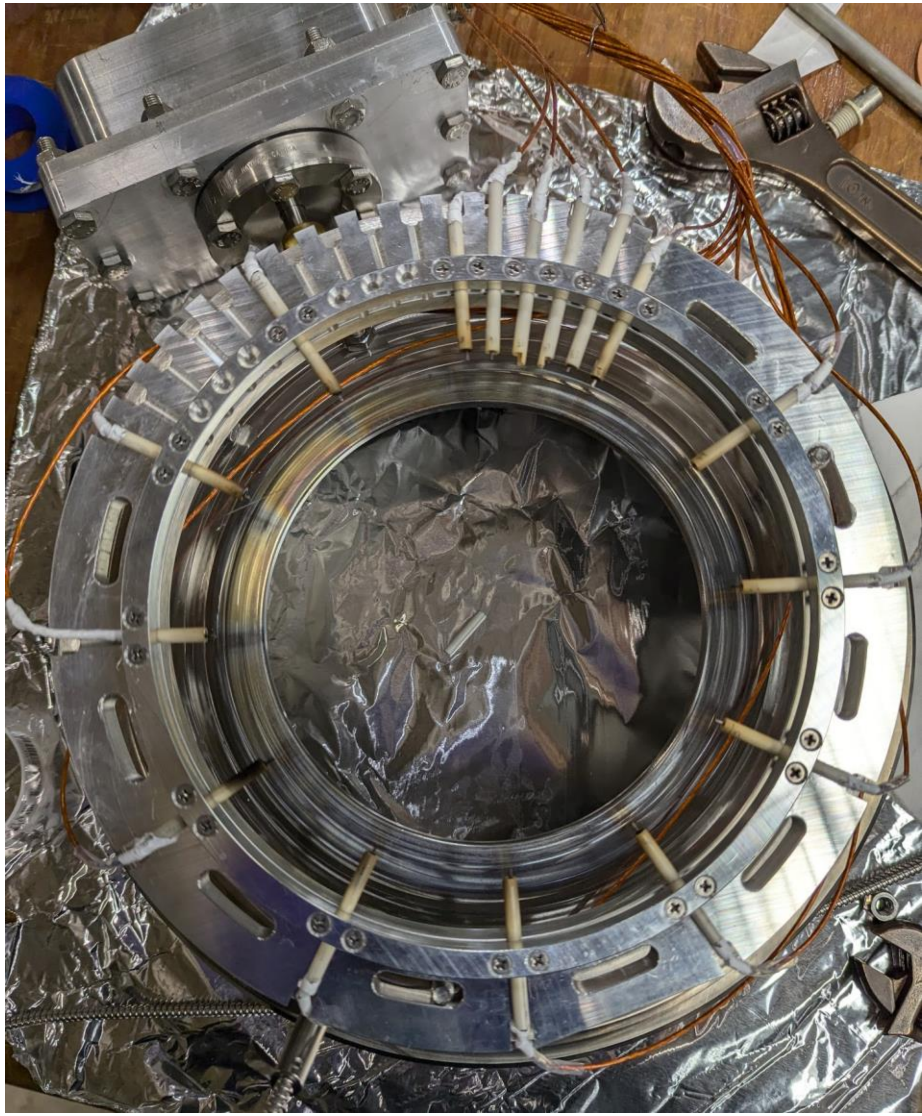




Identifying Impurity Sources

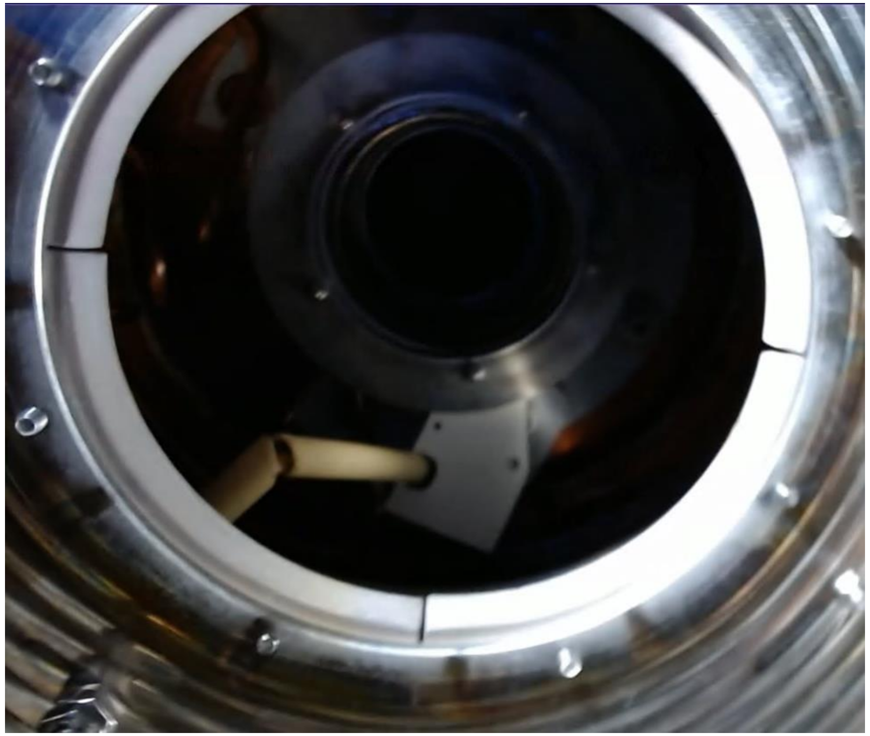
Post-mortem of PFCs

Diagnostics-Rich Plasma



Unintended PFC/Limiting Surfaces

Metal PFCs Could be Source of Carbon?

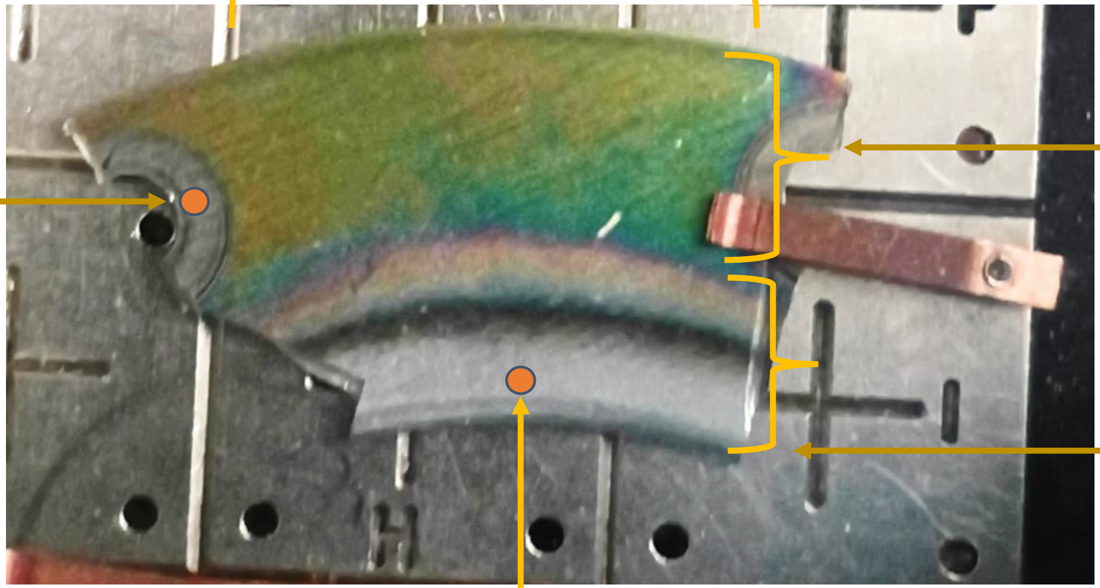


Surface Analysis Revealed Impurity Profile

- Results from Ishita Kemeny
- Flux surfaces sometimes can't be trusted in the presence of instabilities and radial transport

Mo
O
C
Si

O, C, Si, ~~Mo~~, N
Cu , F, Cl, Fe

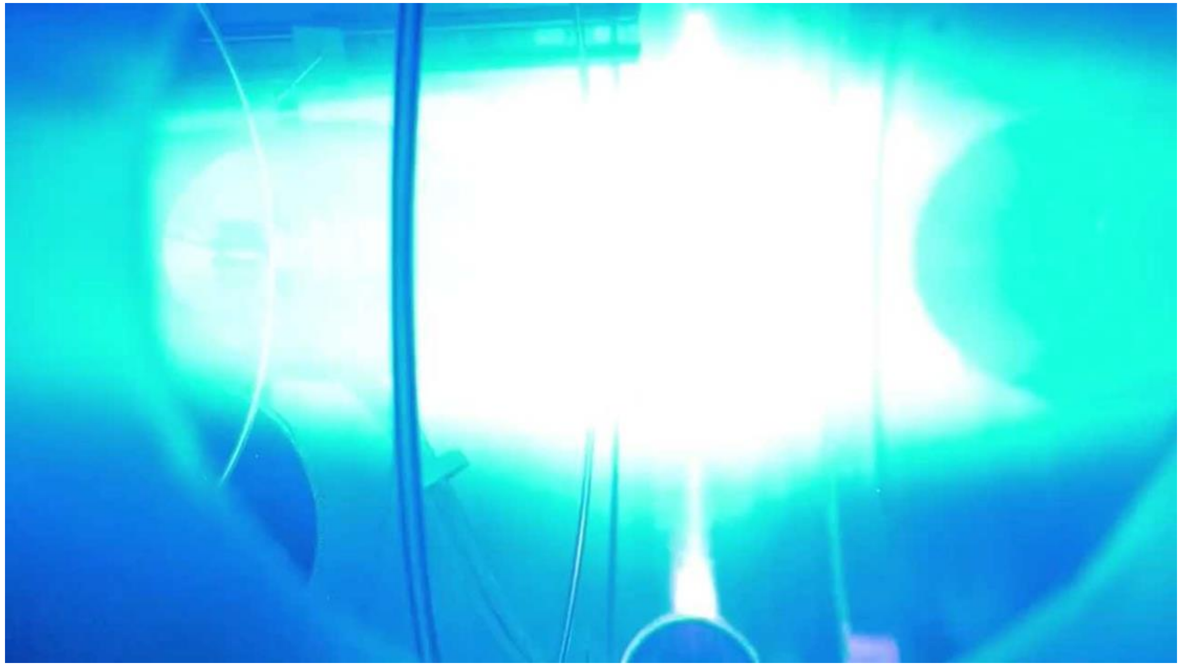


C 1s, O 1s, Si 2p,
~~Mo~~
N 1s
Cu 2p3*, F 1s, Cl 2p, Fe 2p*

O ,Mo, C, ~~Si~~
Cu
Fe, Cr, Ru, Sn, Zn

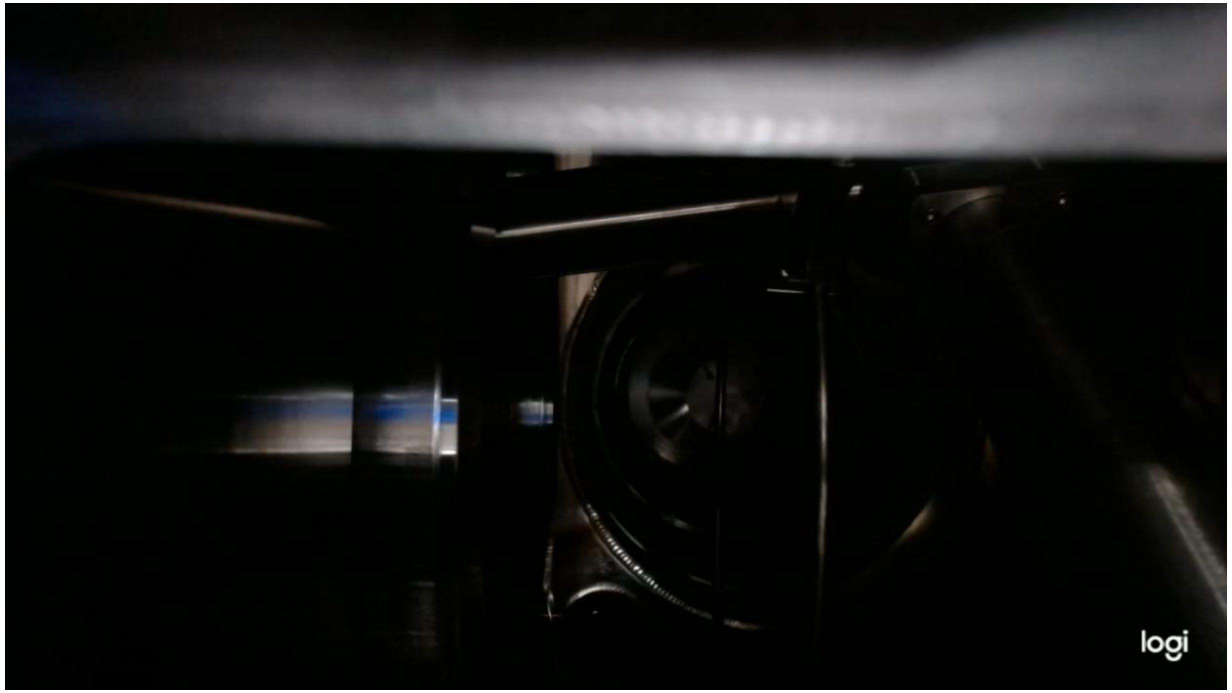
O 1s, Mo 3d, C 1s, ~~Si 2p~~
Cu 2p, *Fe 2p /2p3, Cr 2p, Ru 3d, Sn 3d5, Zn*

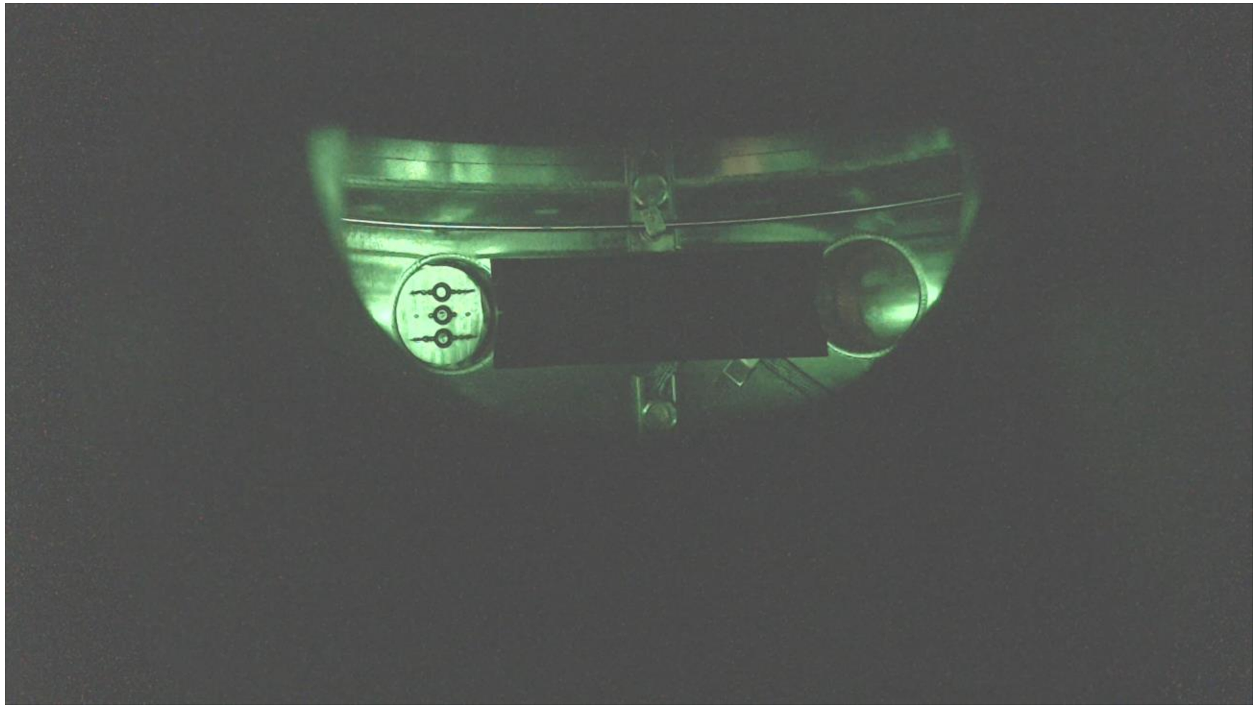
Videos of UFOs



Long Exposure Video Reveal UFOs

- $\rightarrow$ Cheap but highly integrated **USB webcams can function at extremely high magnetic fields** $> 7\ T$
- Streaks never goes in front of foreground objects
- **Comes from all directions**
- Some curve in the magnetic field

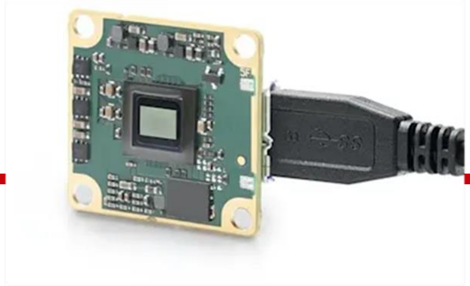


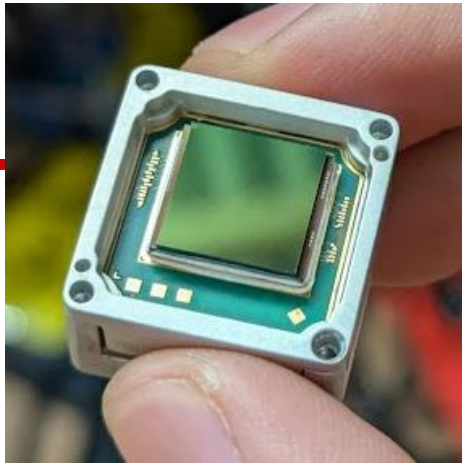


Large Amount of Dust and Debris Recovered

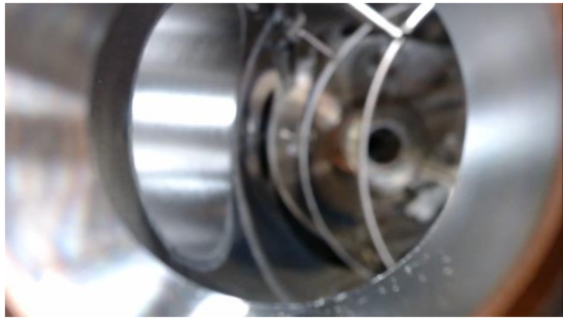
Future Work

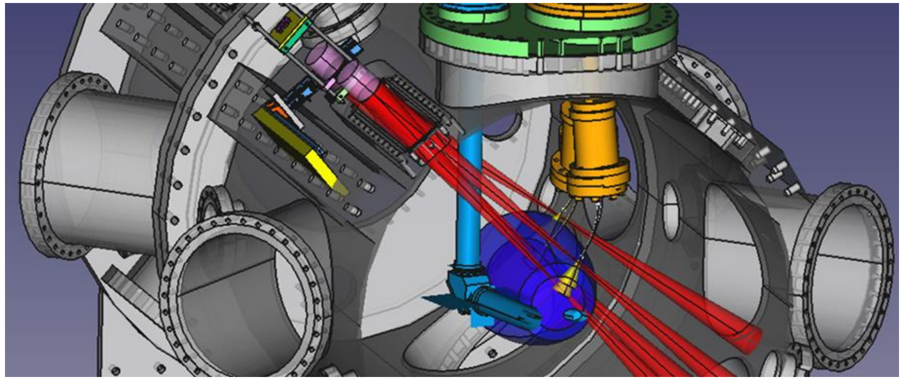
Diagnostic Improvements





- **Time-resolved** spectroscopy data
  - Use of filterscopes to digitize intensity of strong lines of impurities (C, Fe, N, O)
- **High resolution**, time-resolved spectrometer dedicated to OES (?)
  - McPherson 1.33 m Czerny-Turner spectrometer with 5 pm resolution
  - iStar 334T intensified CCD to give 4 pm pixel resolution and 55250 spectra per second
- **Line ratio measurement** for edge temperature estimation and impurity transport
- Improved **IR and visible imaging of all PFCs**
  - FLIR Boson camera and Basler CMOS camera modules
- **Time-resolved soft x-ray** data
- Installation of multiple **WISP gauges**





Future PFC Strategy and Tracking Effects

- Removal of all plastics
- Thorough cleaning and inspection of metal surfaces
- Systematic removal of PFCs:
  - Probe array: reduced fluorine lines to nearly zero, and reduced carbon line brightness
  - Gas baffle: further reduction in carbon line brightness
- Full Ti wall gettering
- Beam dump improvements
- Conditioning with glow discharge and Ion Cyclotron Wall Conditioning (ICWC)
- Remove high-Z impurities in favor of carbon/low-Z materials?
  - Graphite limiter? BN protection?
- Use 316LN wherever possible
- Time-dependent CR model to aid analysis of OES spectrum