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He discharges with transition on GOLEM - spectroscopic study

Beatriz García[1]

Supervisors: Diana Naydenkova[3] ,Vladimir Weinzettl[3]
Helpers: GOLEM team[2]

Affiliations:
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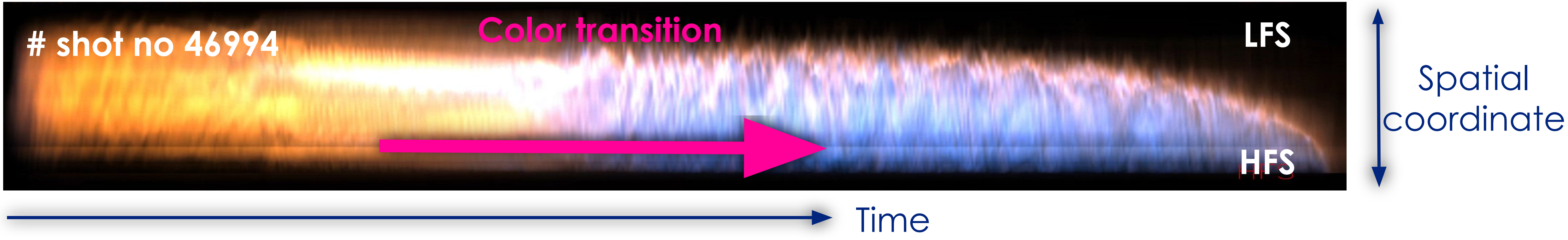
MINISTRY OF EDUCATION,
YOUTH AND SPORTS

Motivation

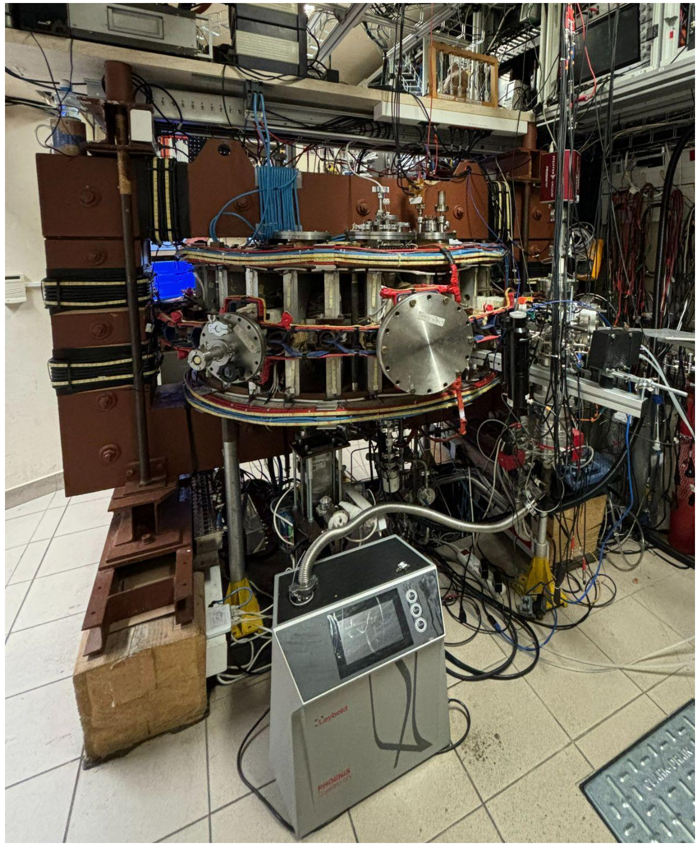
What is behind the transition in He discharges in GOLEM?



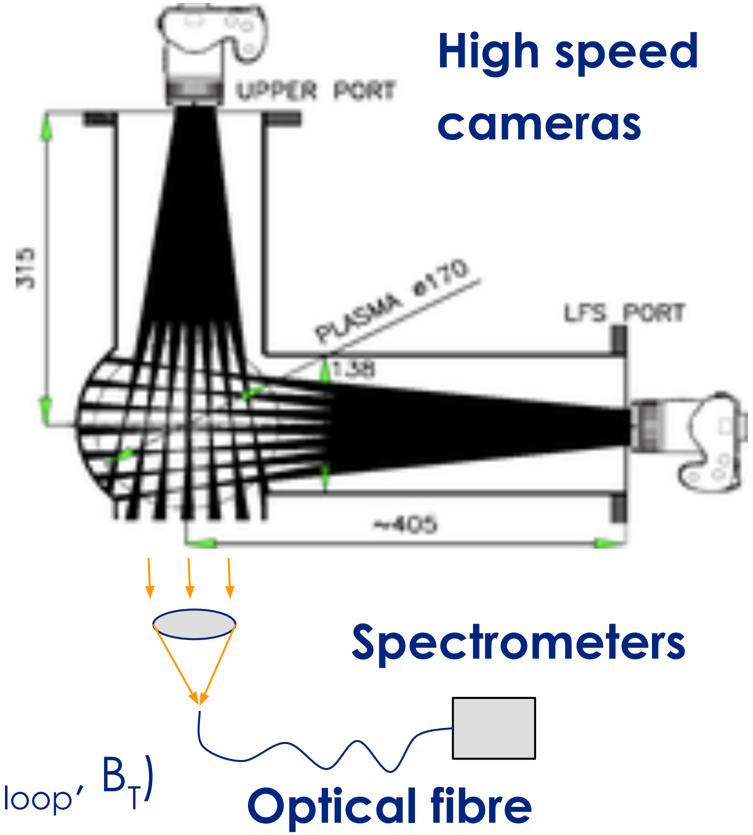
High-speed camera (40 kfps, time evolution of the narrow spatial stripe)

Set up: GOLEM TOKAMAK

- Small university tokamak at FNSPE CTU in Prague



I_p	< 5 kA
B_T	< 0.5 T (sinusoidal)
$\langle n_e \rangle$	< 3×10^{19} m^{-3}
$T_e(0)$	< 100 eV



Plasma diagnostics used for the task:

- Basic magnetic diagnostics (I_p, U_{loop}, B_T)
- High speed cameras
- Compact spectrometers (NUV-NIR spectral range)

Compact spectrometers (Czerny-Turner type with grating & CCD)

Halpha
630 - 680 nm
0.025 nm/px

UV
248 - 472 nm
0.11 nm/px

VIS
460 - 663 nm
0.10 nm/px

IR
654 - 1084 nm
0.21 nm/px

IRVISUV
185 - 1110 nm
0.45 nm/px

Spectral range

Spectrometers at GOLEM connected with the tokamak via optical fibers

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Previous Work

EMTRAIC 2024

Beatriz García, Momoko Kato

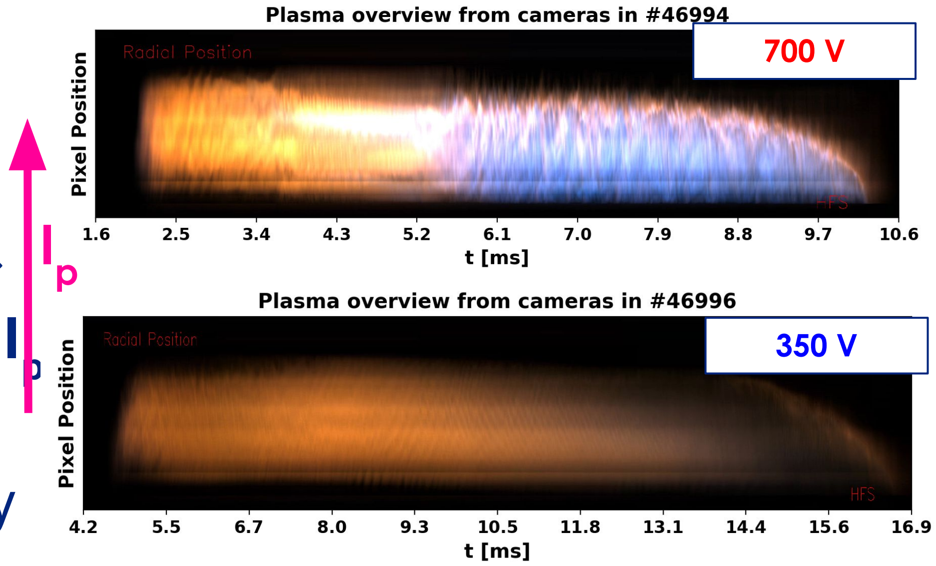
Supervisors: Vladimir Weinzettl[3], Diana Naydenkova[3]
Helpers: GOLEM team[2]

EMTRAIC 2024

1) I_P **Scan** → **Smooth behaviour in I_p ($I_{p,crit}$ not found)**
→ **Color transition more intense for higher I_p**

2) Effect of breakdown and B_T → no B_T dependence.
→ changes MHD activity

3) Spectra analysis (IRVISUV) → Light (Z<20) impurities found to be responsible for color transition 😃
→ Lines of higher ionization states not confirmed (but not ruled out either)



EMTRAIC 2024

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3) **Spectra analysis (IRVISUV)** → **Light (Z<20) impurities found to be responsible for color transition** 😃 → **H I, O I, O II, N II, C II, Cl II**
   → Lines of higher ionization states not confirmed (but not ruled out either)

EMTRAIC 2024

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He II, O III, N III, C III, Cl III?

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Research Internship
August 2025

Beatriz García

Supervisor: Diana Naydenkova[3]
Helpers: GOLEM team[2]

GOAL

→ **Search for higher ionized ions:** He II, C III, Cl III, O III, N III

HOW?

→ **Use Higher Resolution Spectrometers:**

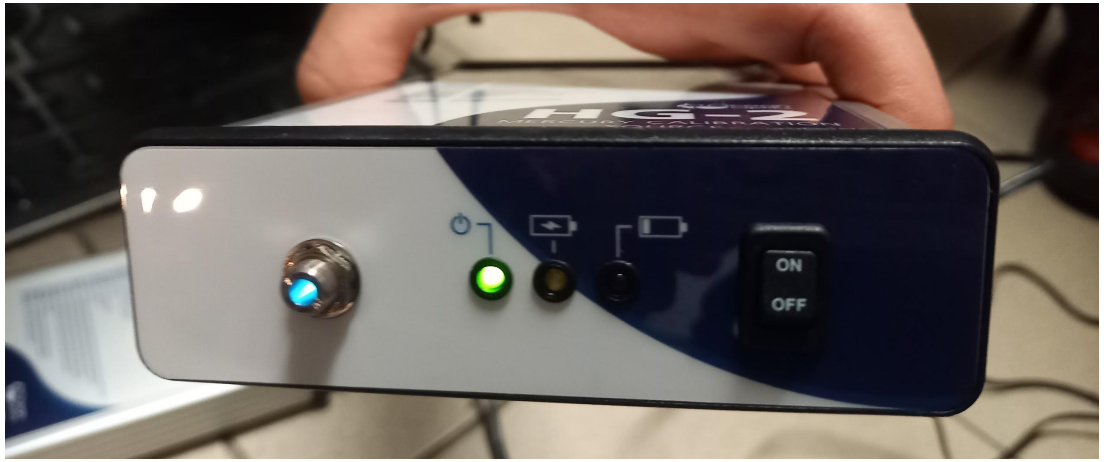
Minispectrometer name	Spectral range, nm	Optical resolution, nm
HR2000 UV	247 - 473	0.17
HR 2000 VIS	460 - 663	0.15
HR 2000 H alpha	630 - 680	0.04
HR 2000 IR	659 - 1084	0.23

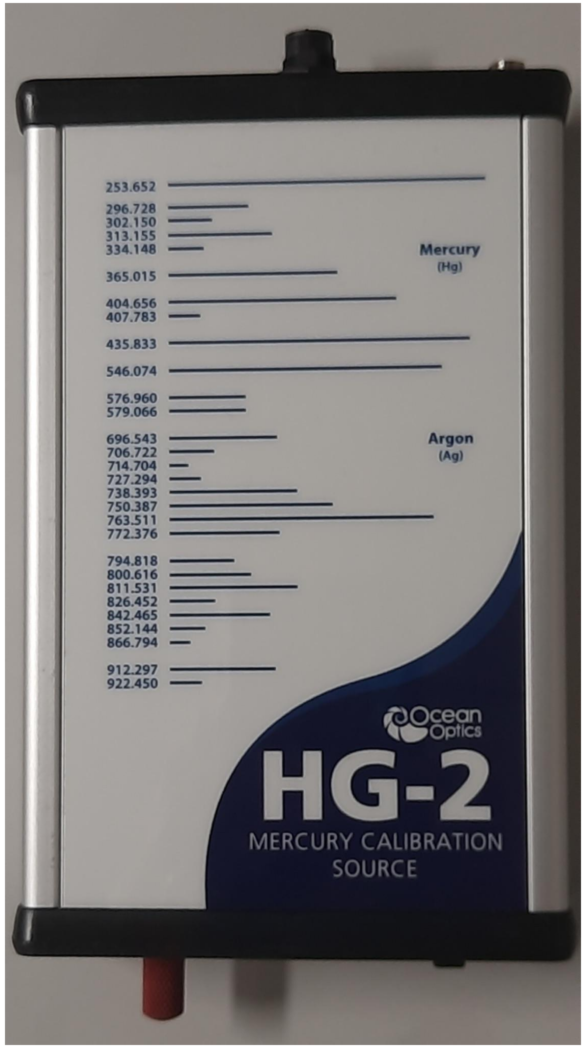
→ **Calibration of Spectrometers!**

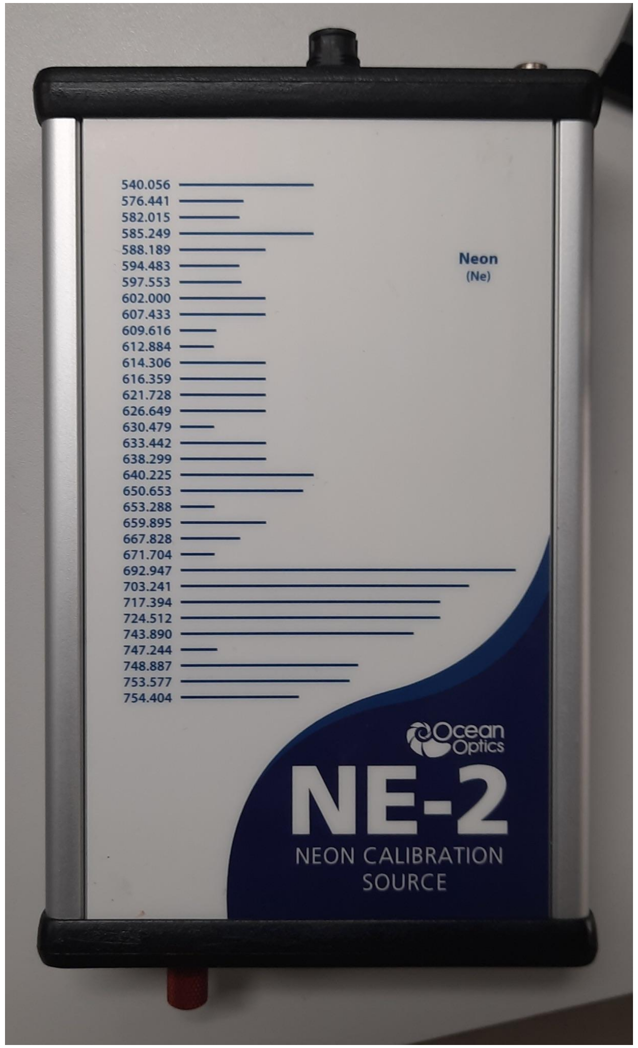
Spectral Calibration

allows precise wavelength assignment

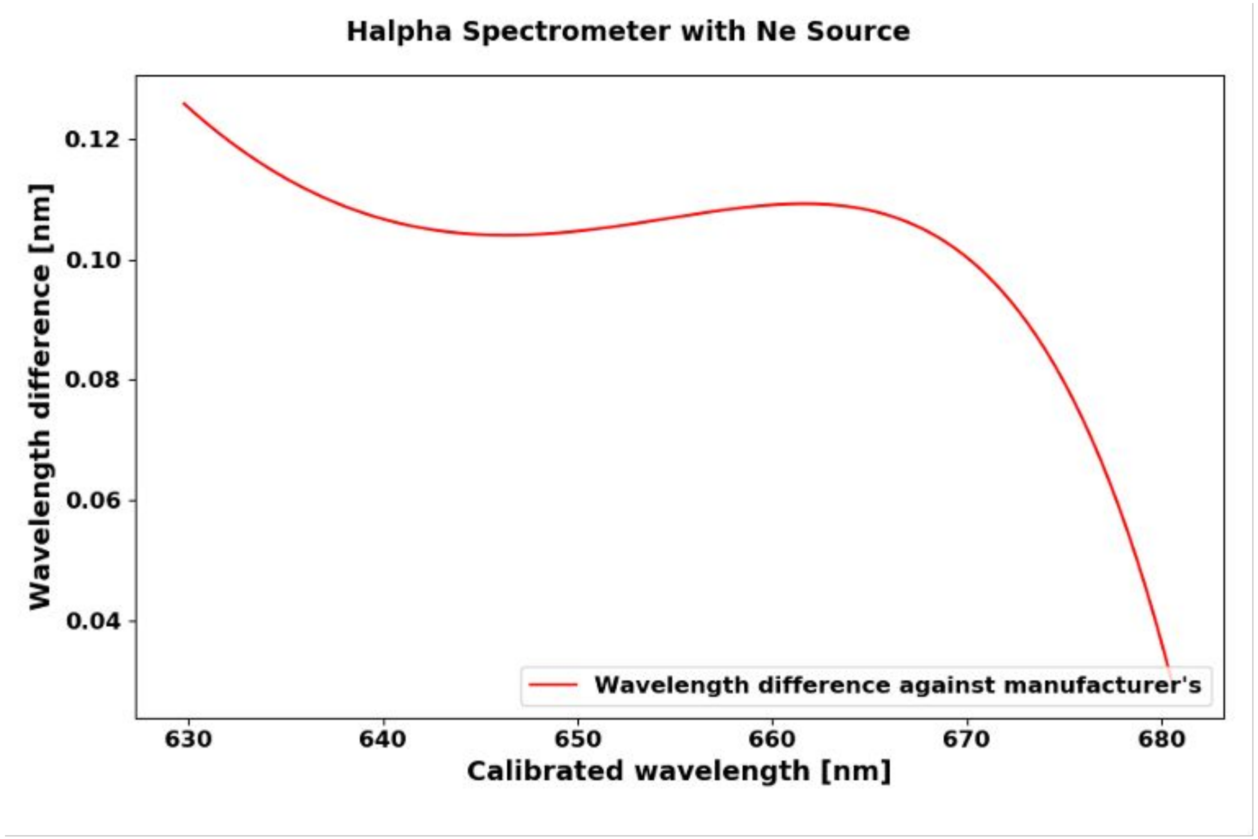
- **Hg-2 (Hg+Ar) spectral calibration source:**
  Usable for UV, IR and VIS
- **Ne-2 spectral calibration source:**
  Usable for VIS and Halpha

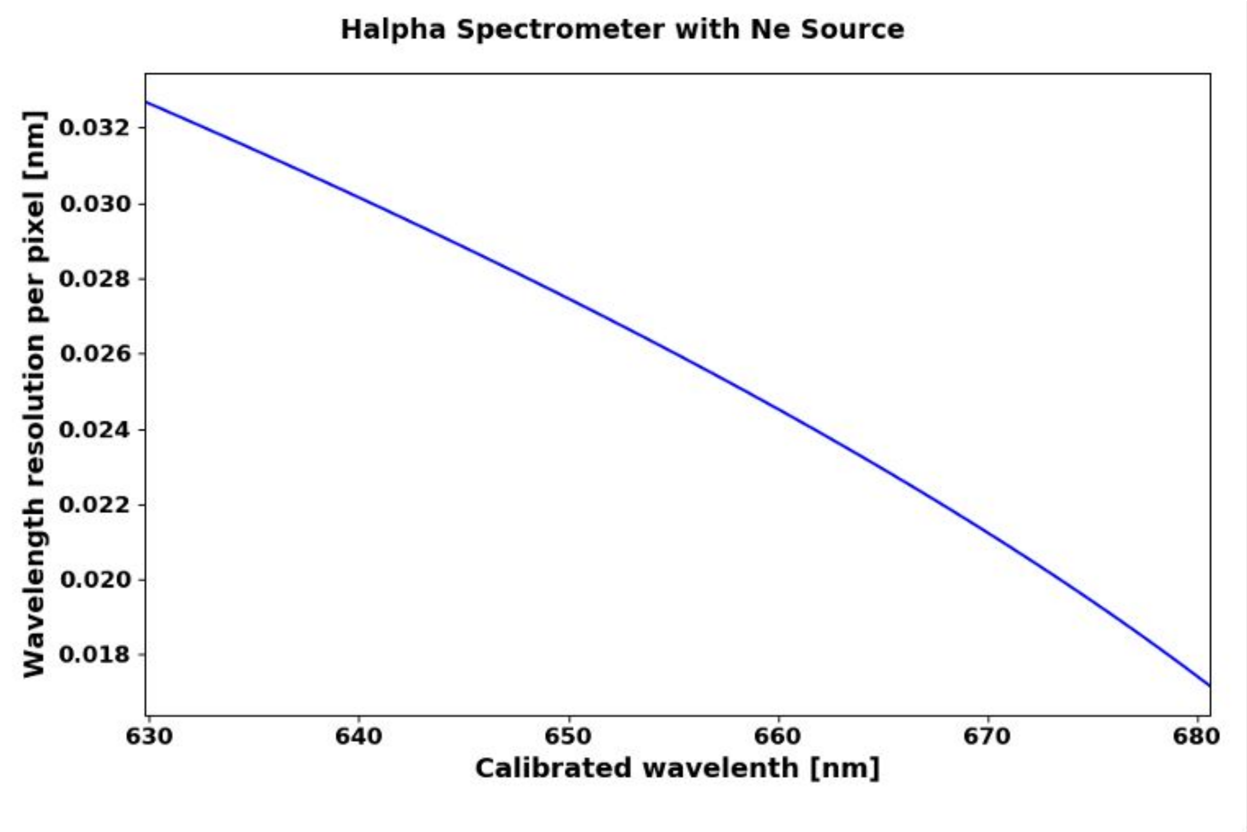






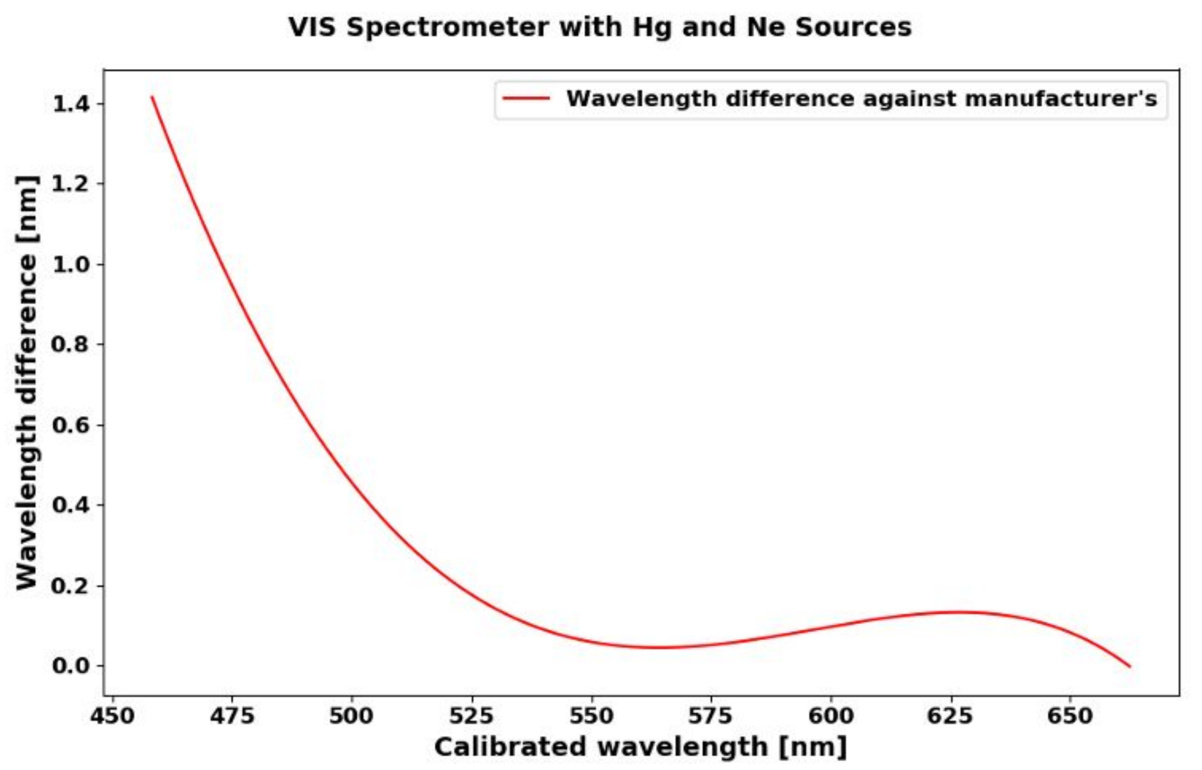
Spectral Calibration

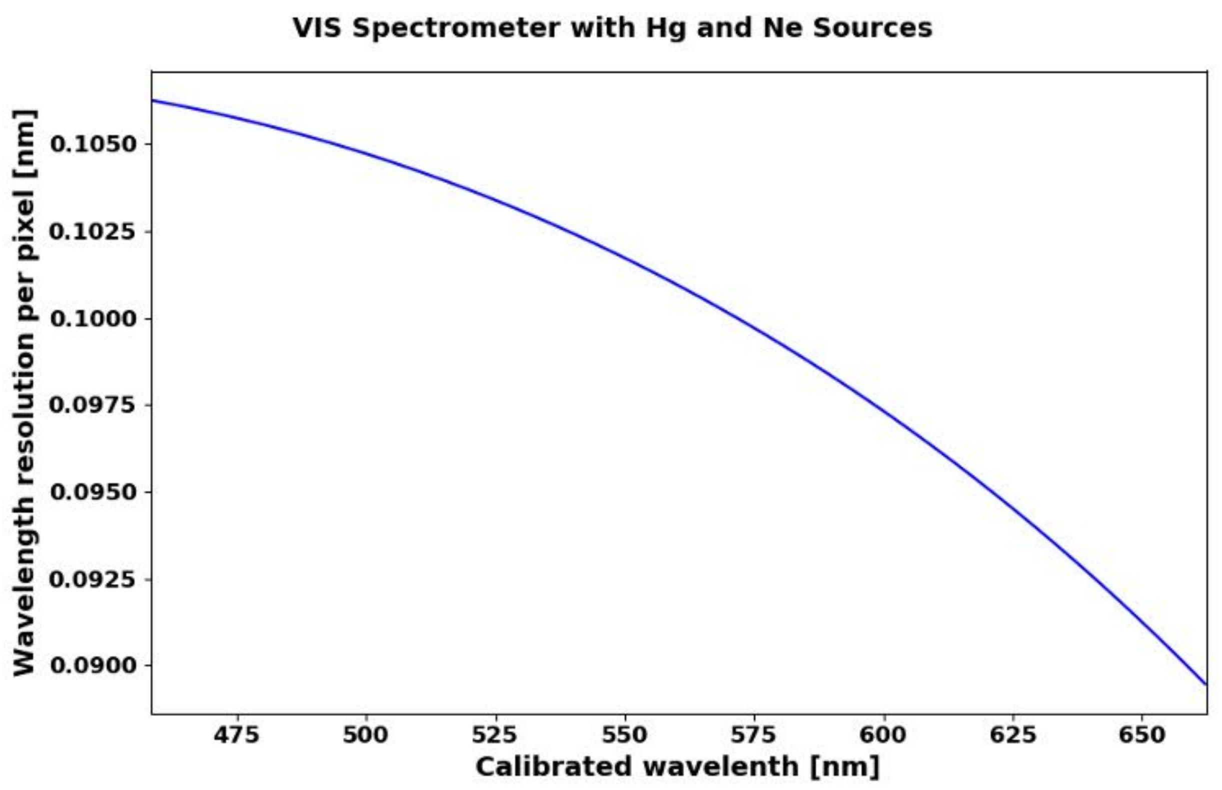




- **Wavelength difference Δλ ~ 0.1nm** against the manufacturer's calibration
- Resolution per pixel ~ 0.026 nm/pixel → ~ 4 pixels systematic error → **Use new spectral calibration!**
- FWHM ~ 0.062 nm

Spectral Calibration

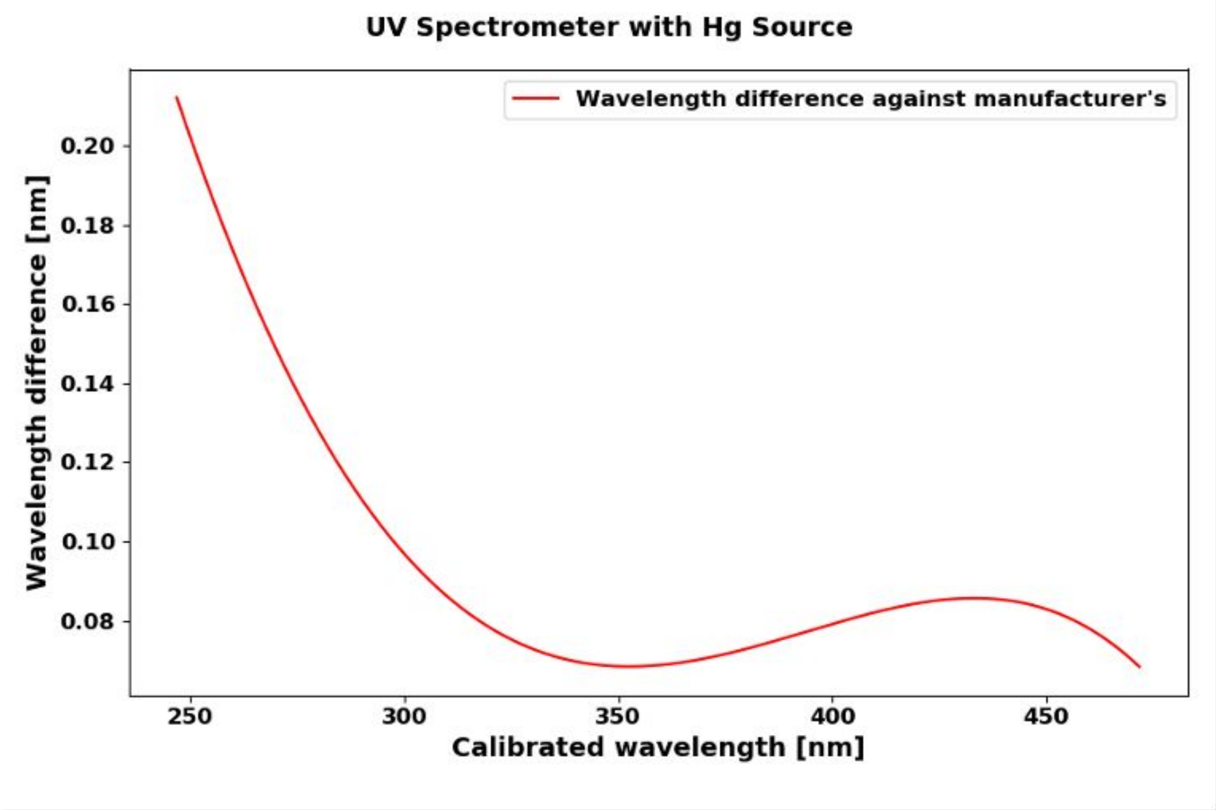


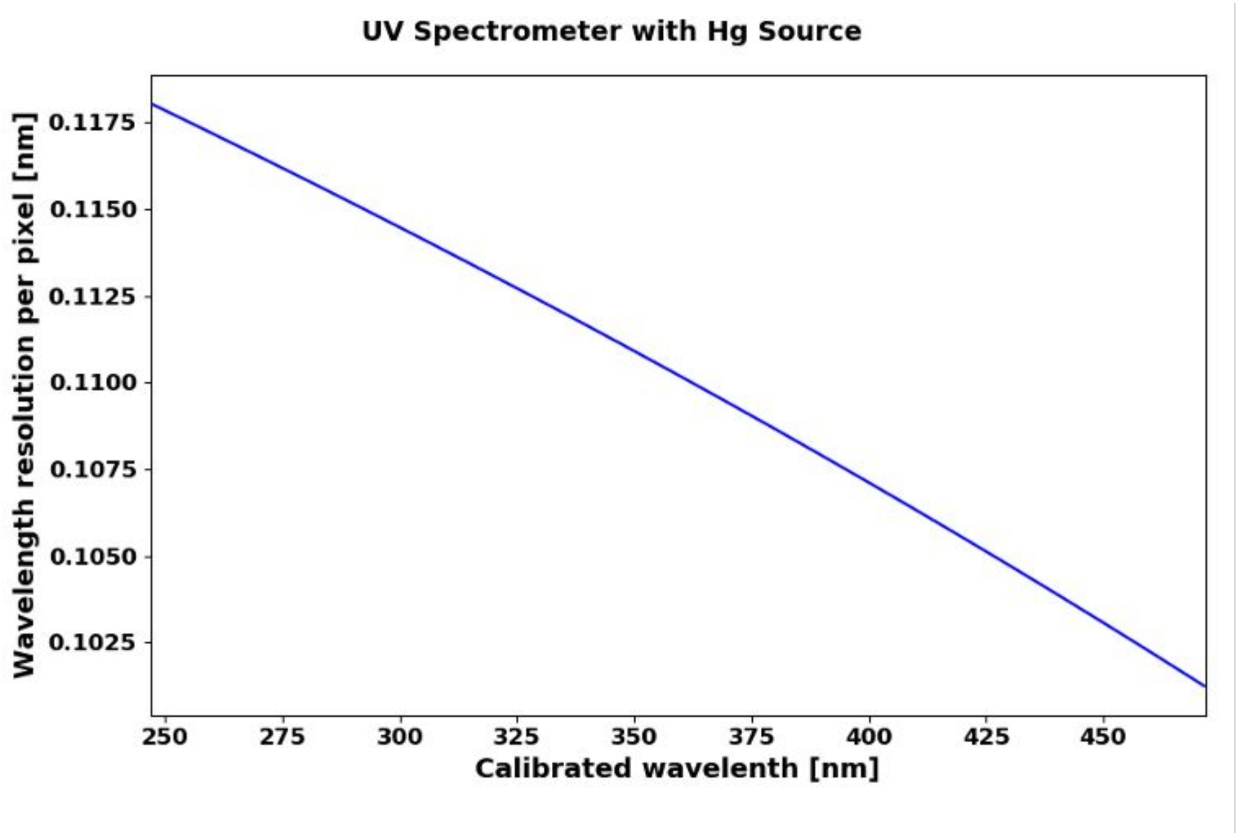


- **Wavelength difference negligible** (at 545-660 nm) against the manufacturer's calibration
- Resolution per pixel ~ 0.1 nm/pixel
- FWHM ~ 0.23 nm

→ **Source is non ideal for this spectrometer**
Use manufacturer's calibration

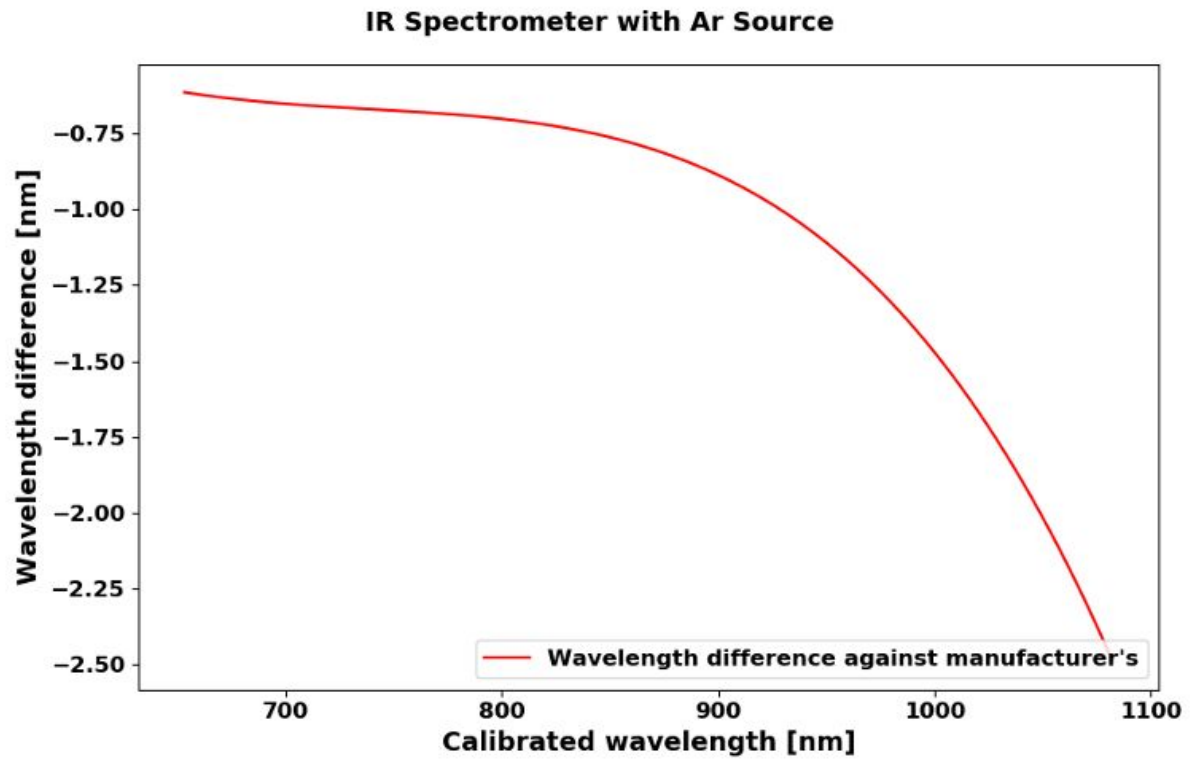
Spectral Calibration

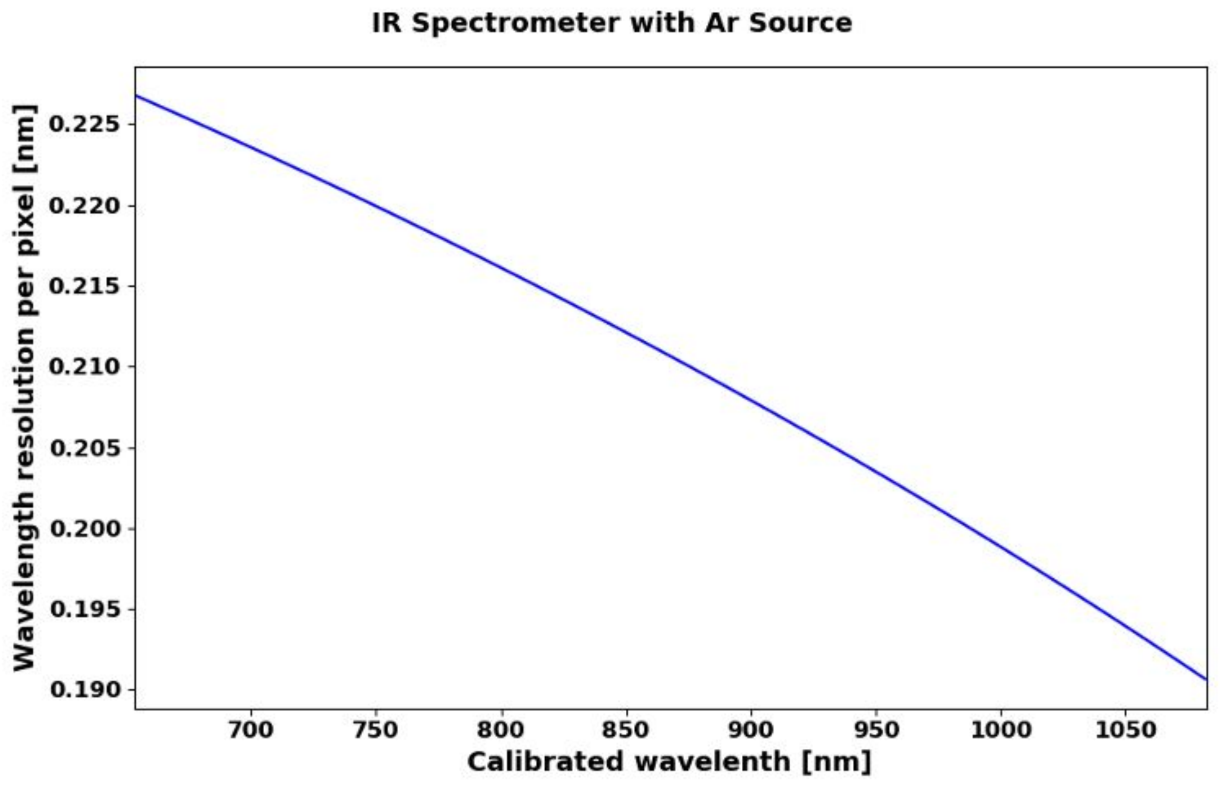




- **Wavelength difference Δλ ~ 0.07nm** (at 296-436 nm) against the manufacturer's calibration
- Resolution per pixel ~ 0.1 nm/pixel → **Use manufacturer's calibration!**
- FWHM ~ 0.23 nm

Spectral Calibration

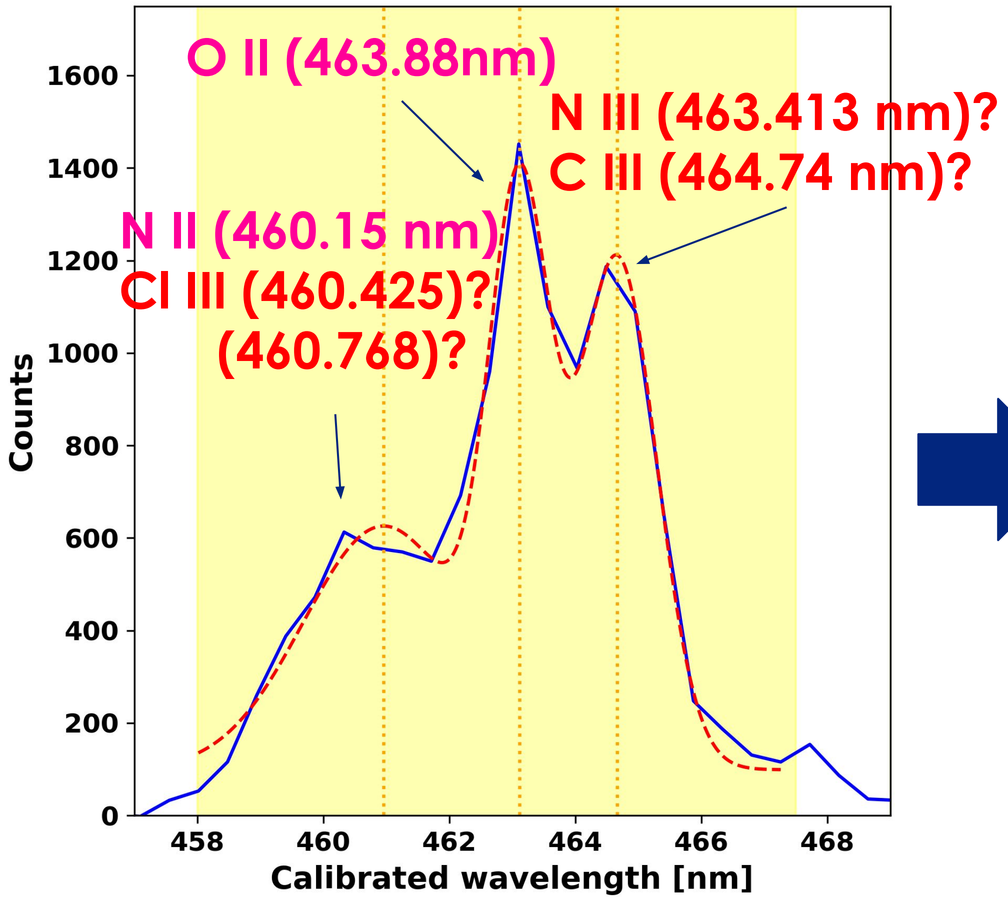




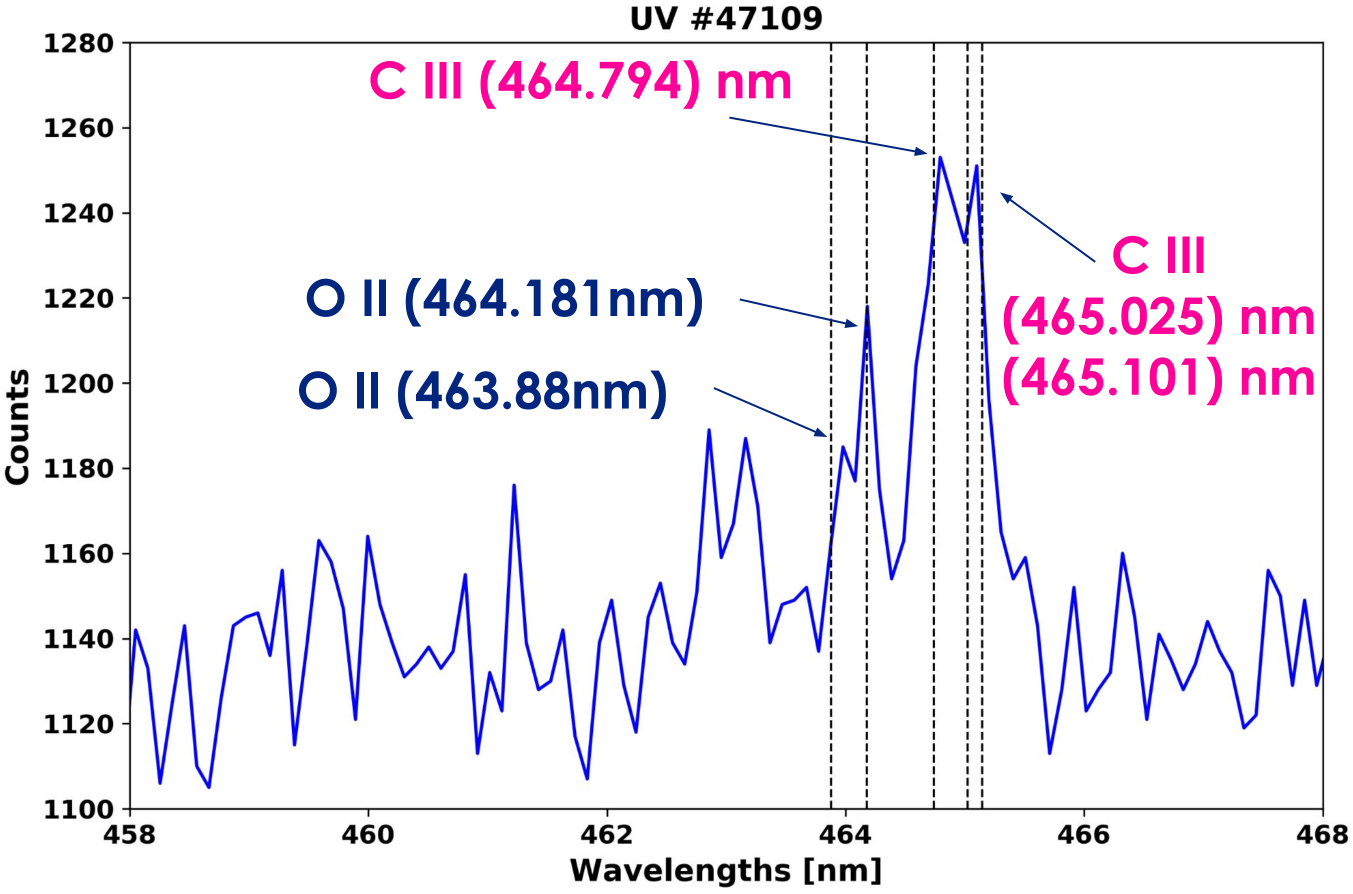
- **Wavelength difference Δλ ~ 0.75 nm** (at 696-966 nm) against the manufacturer's calibration
- Resolution per pixel ~ 0.1 nm/pixel → ~ 4 pixels systematic error → **Use new calibration up to 1000!**
- FWHM ~ 0.39 nm

High Ionized Ions

Previously (IRVISUV)

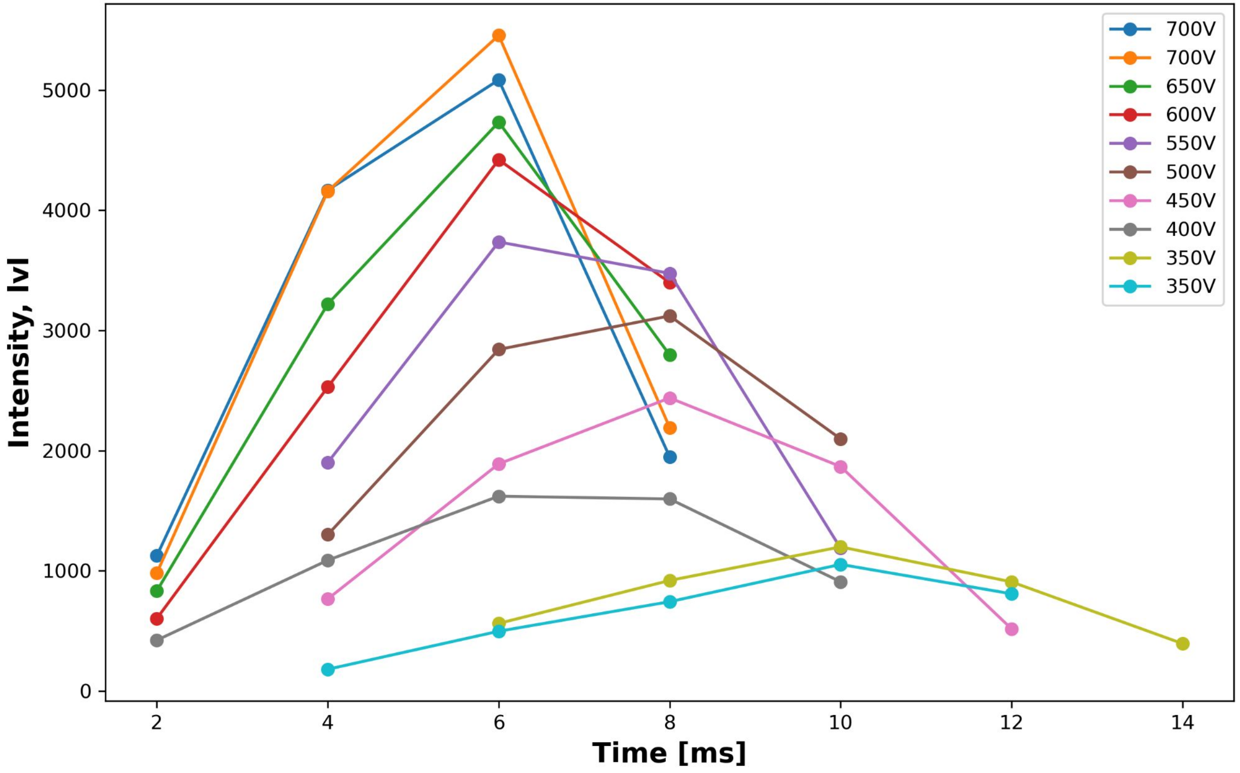


C III triplet FOUND!

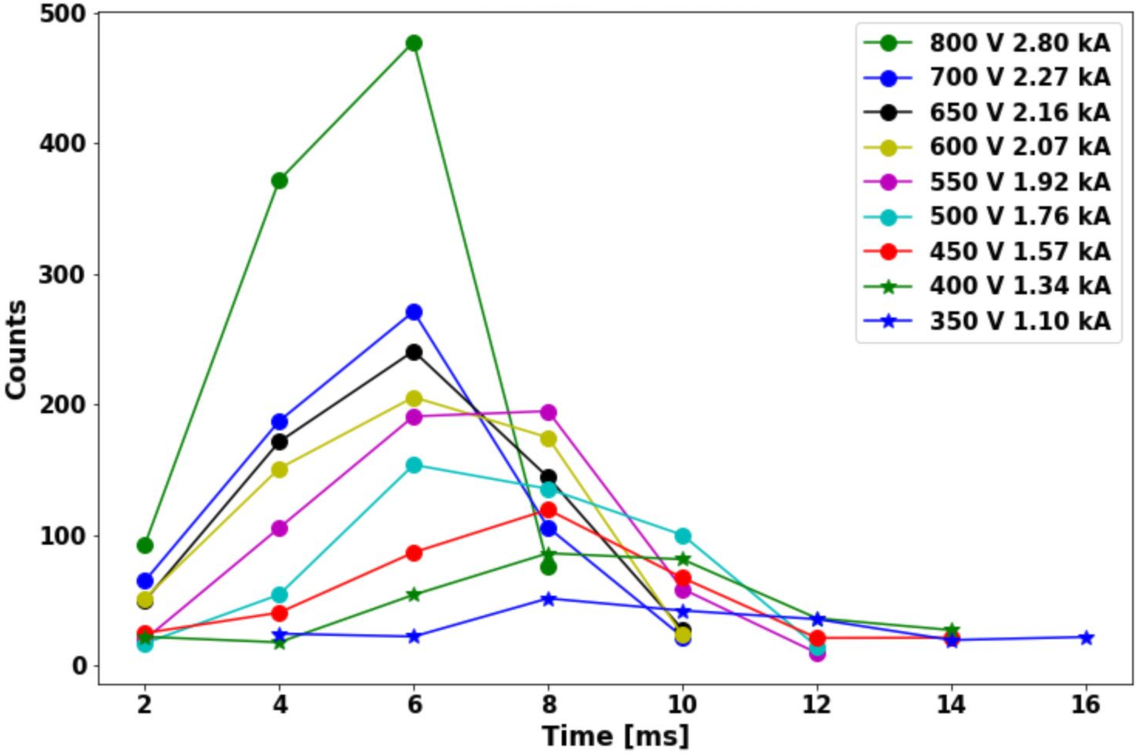


High Ionized Ions

Big Peak Time Evolution (IRVISUV)

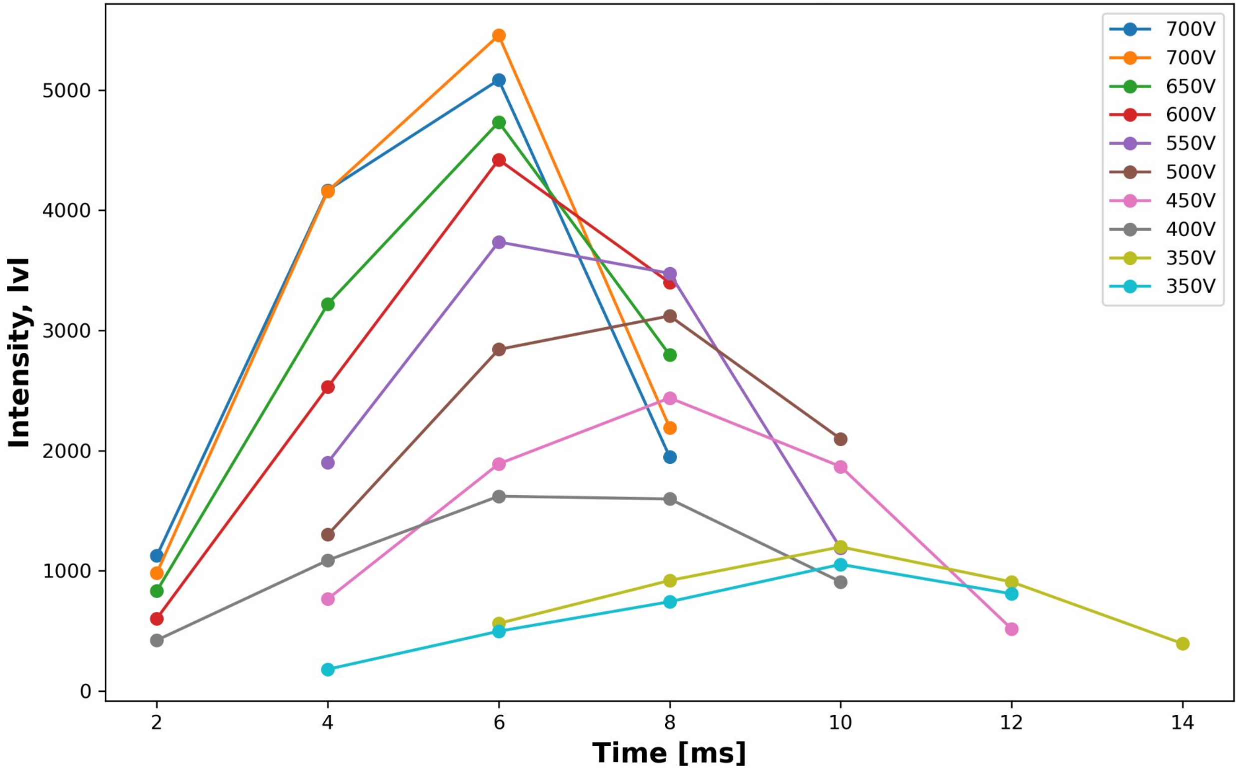


O II Time Evolution (IRVISUV)

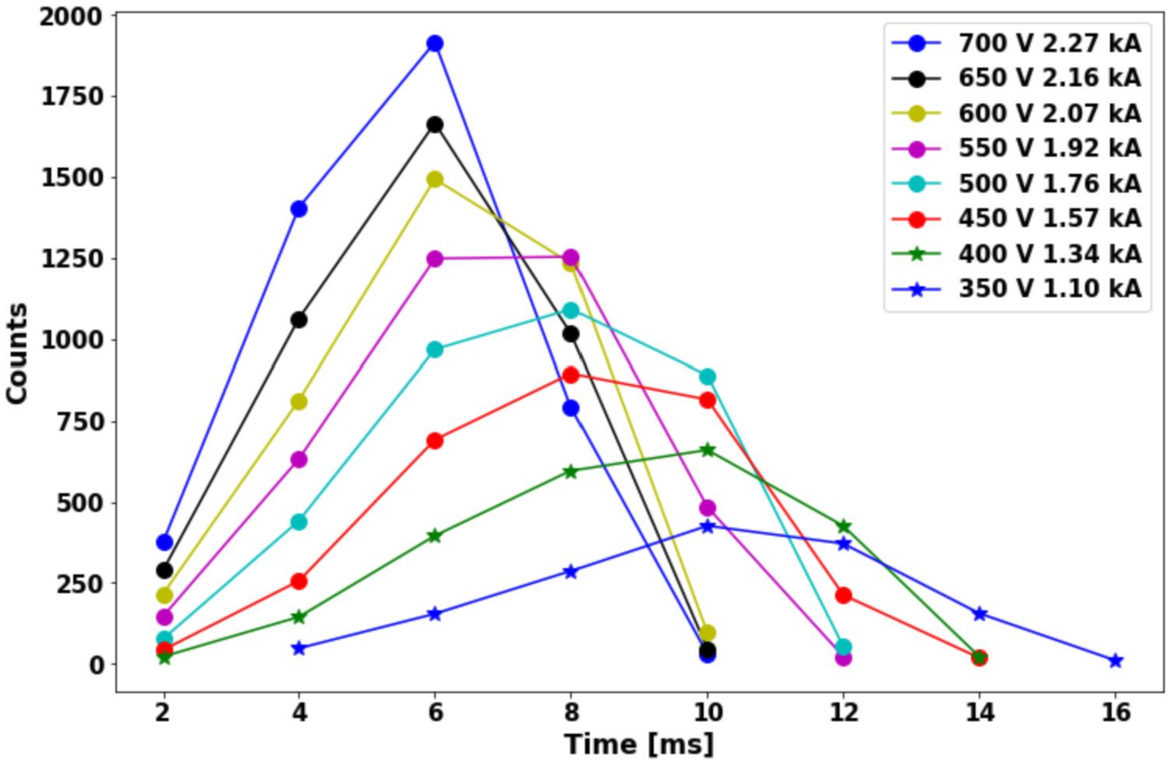


High Ionized Ions

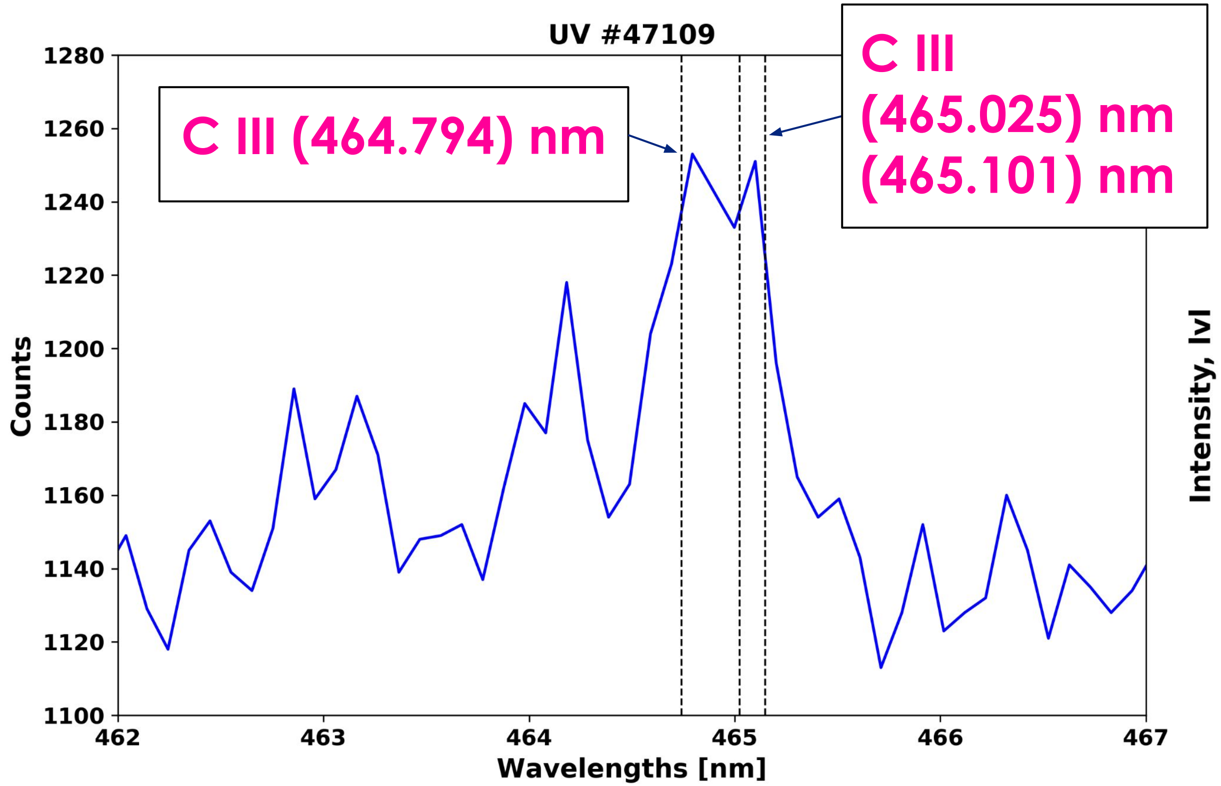
Big Peak Time Evolution (IRVISUV)

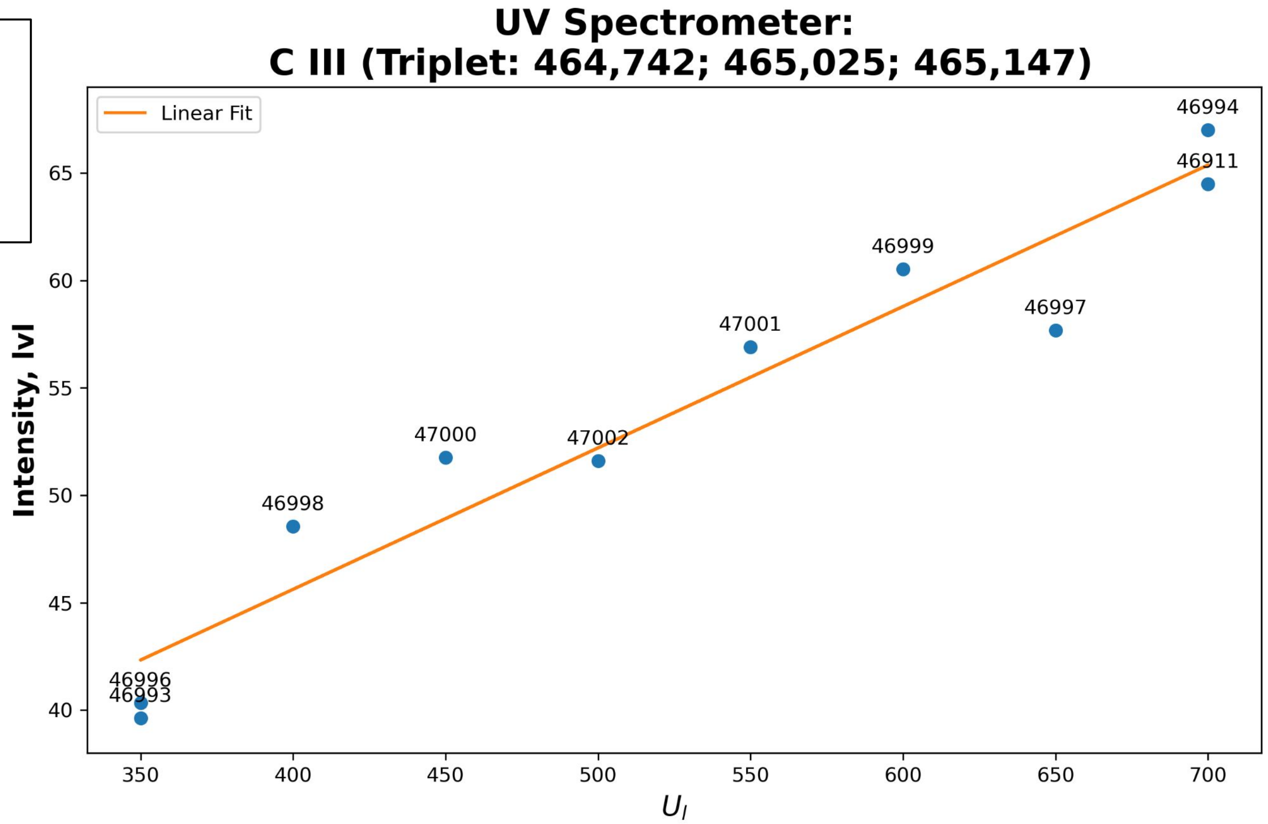


N II Time Evolution (IRVISUV)

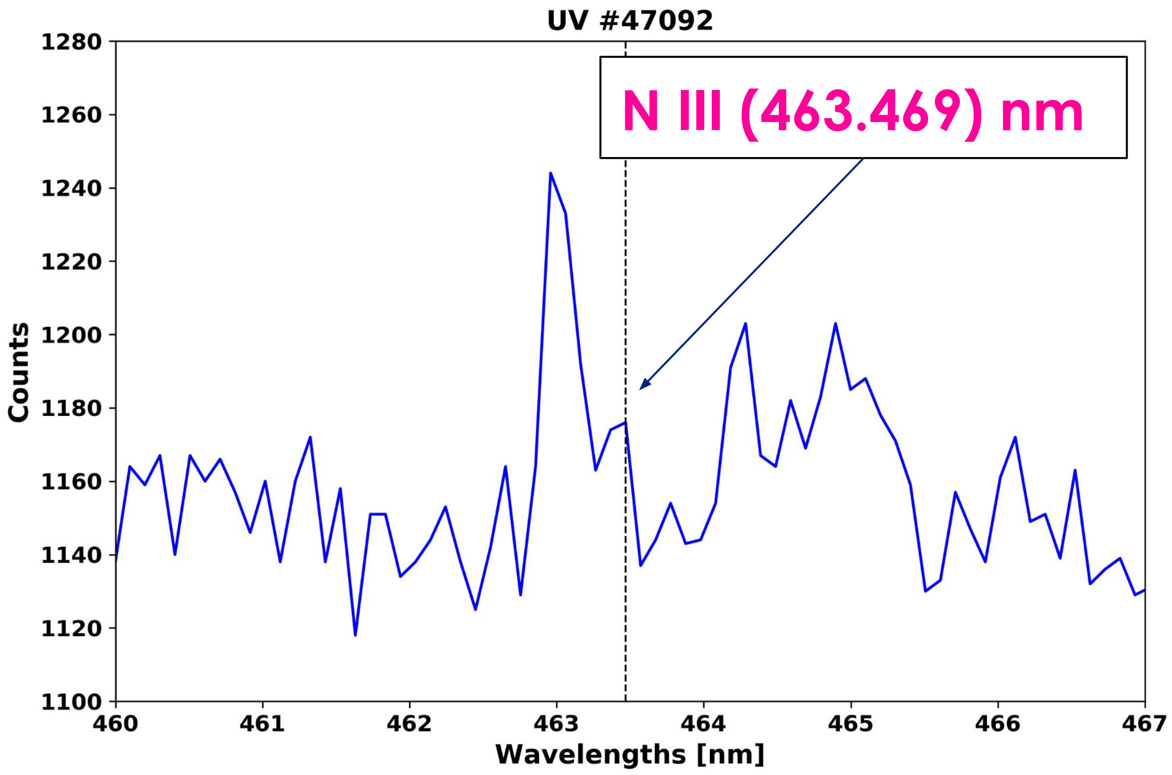


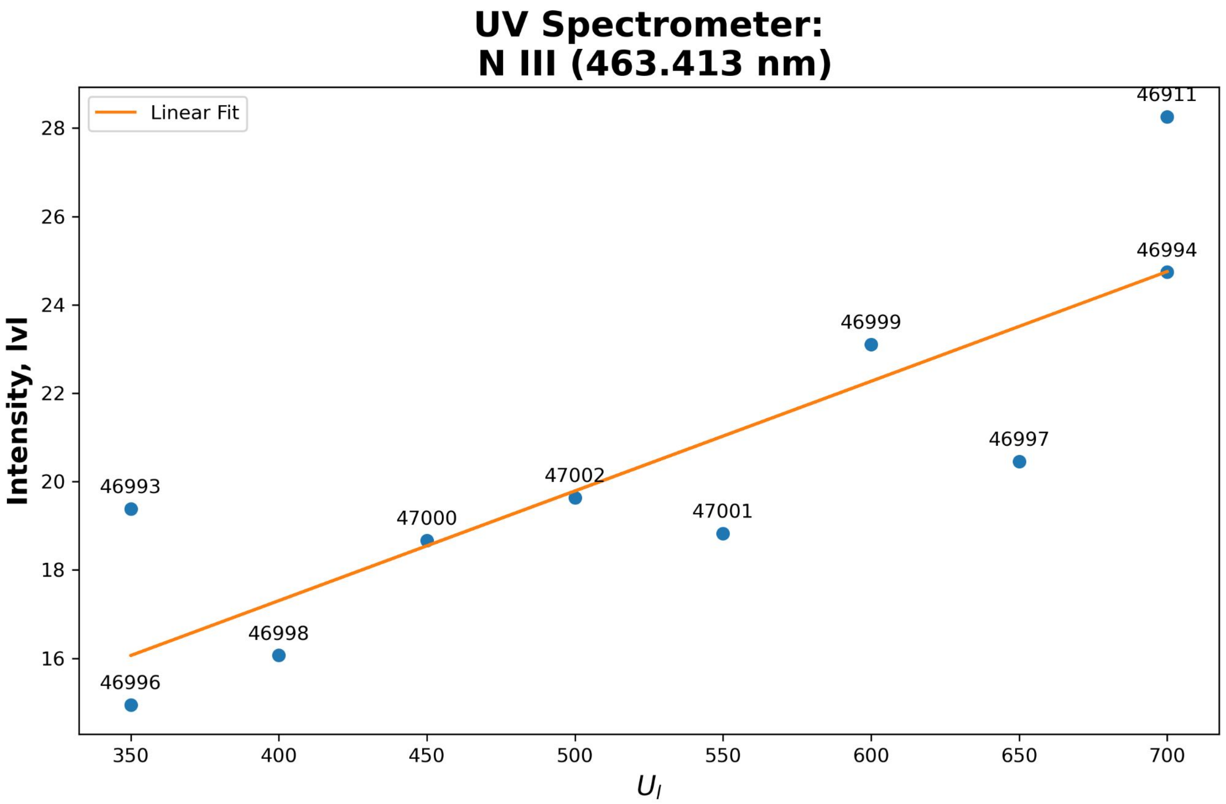
C III triplet: 464.742, 465.025, 465.147 nm (UV: Δλ=0.17 nm)





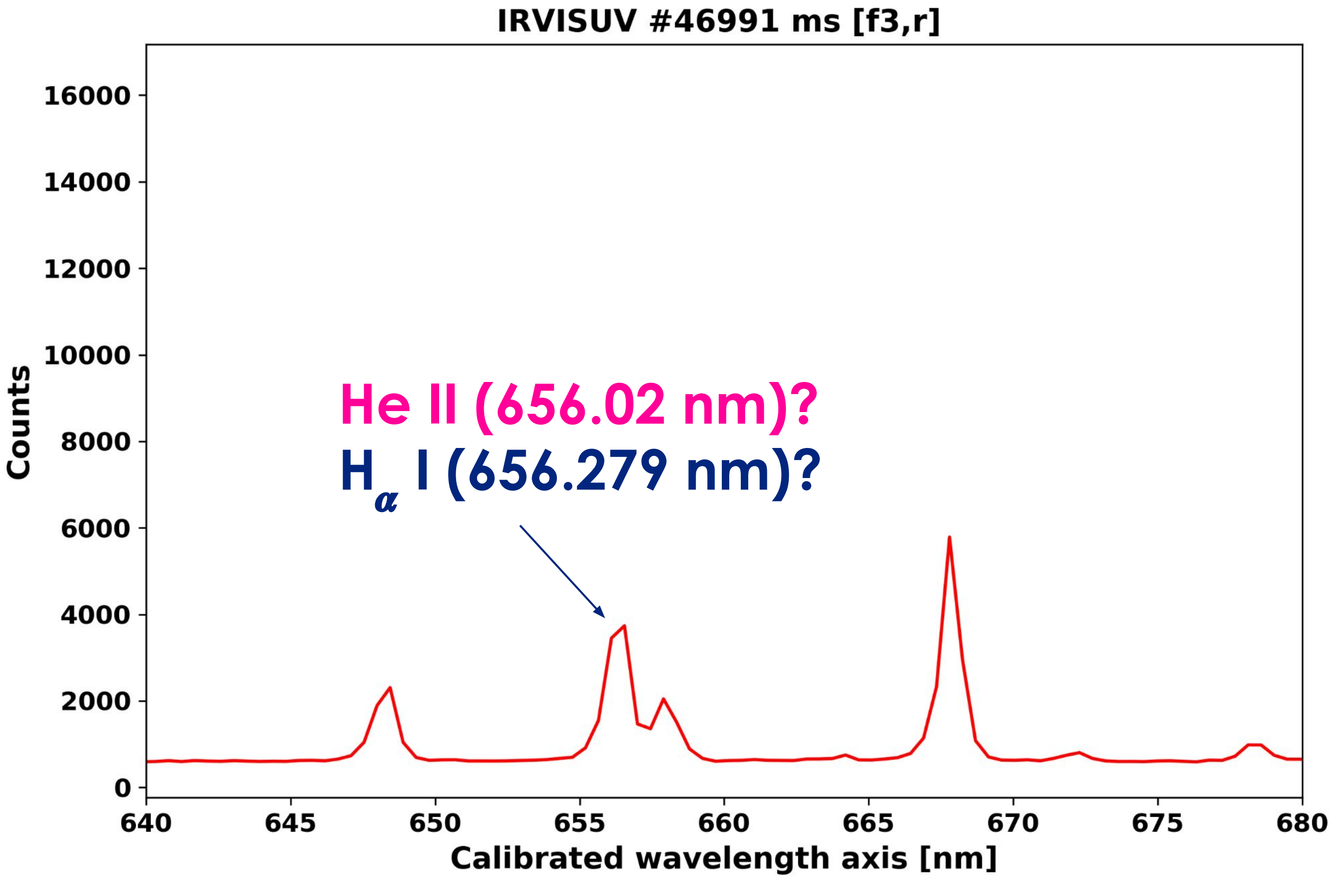
N III doublet ?: 463.413 nm



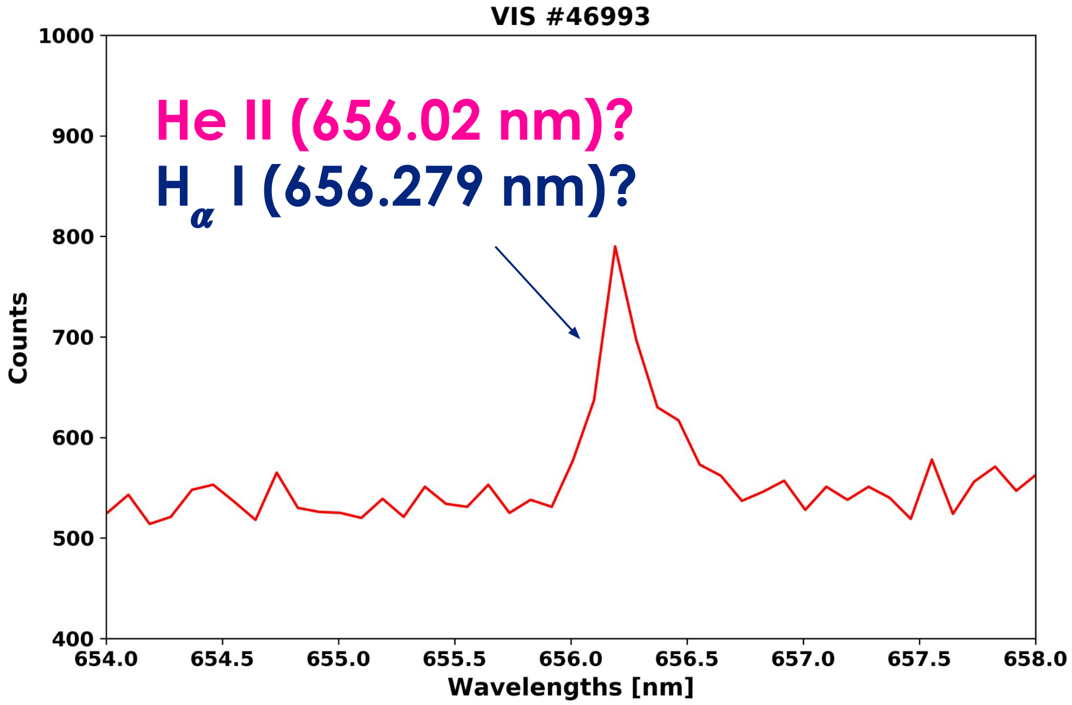


He II?

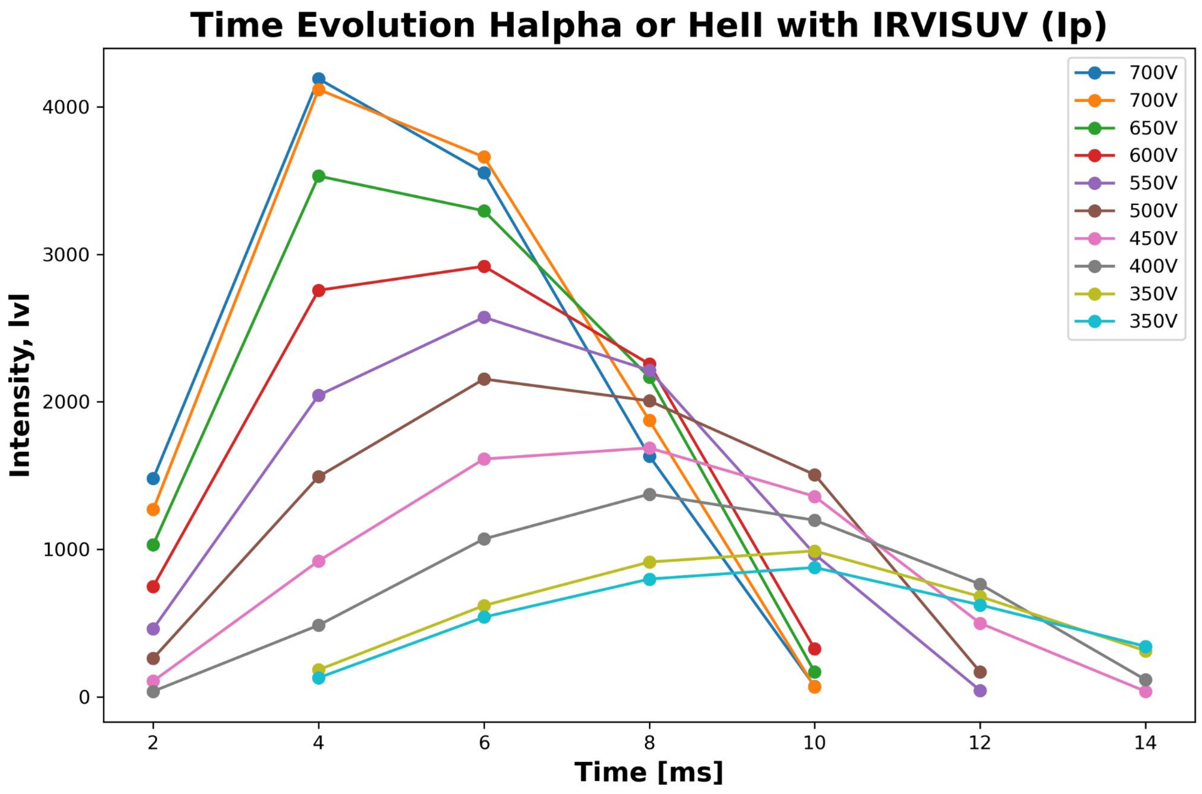
Previously:

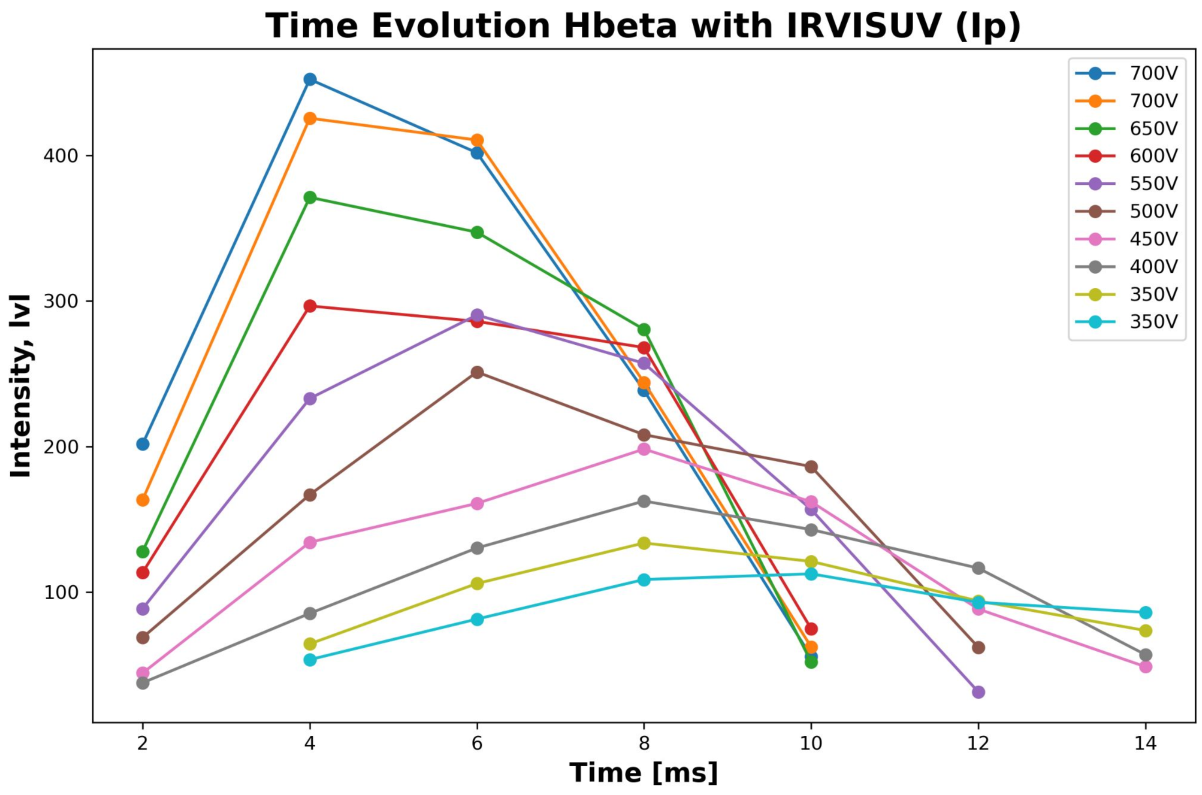


VIS: Δλ=0.15 nm

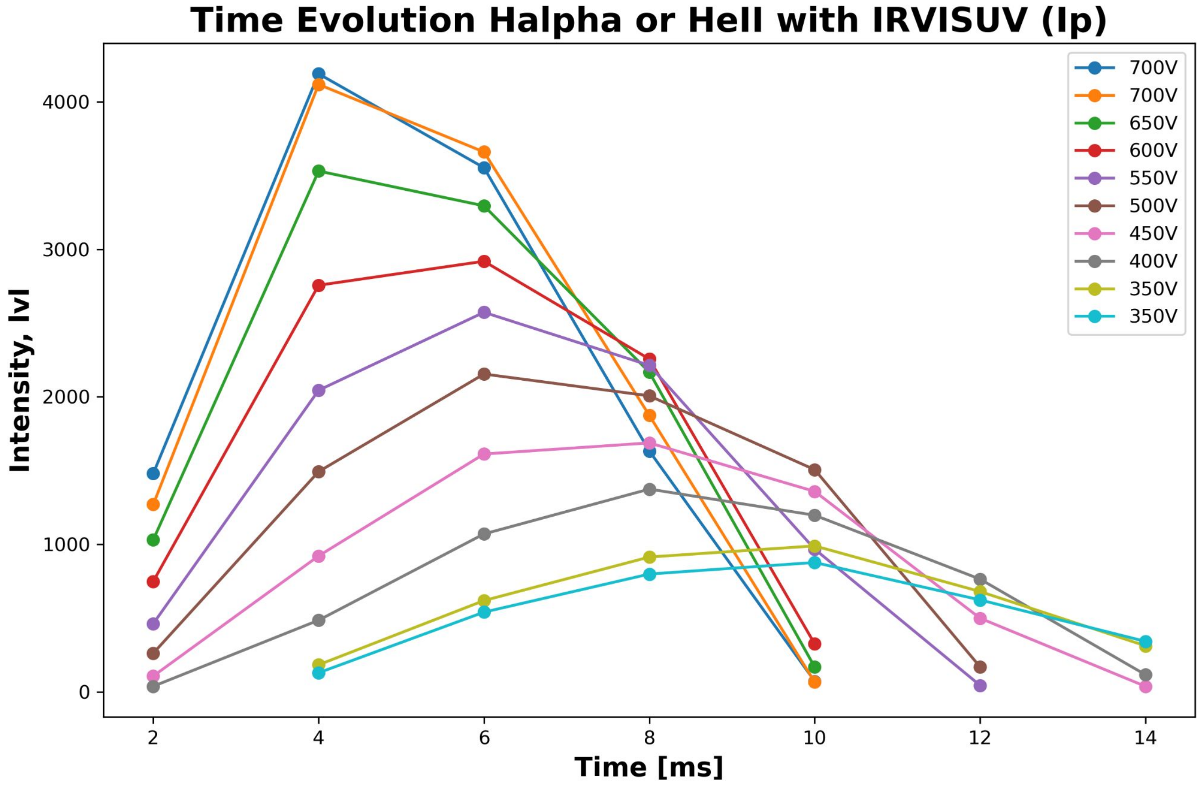


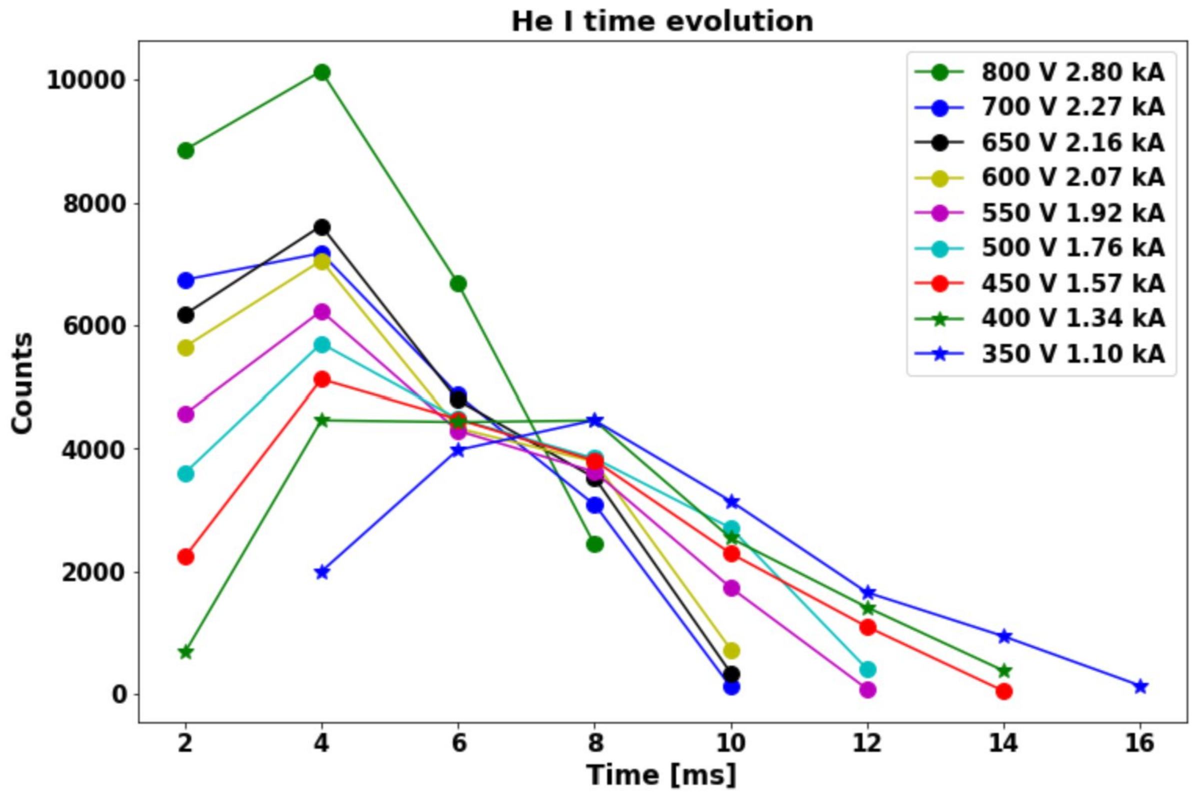
Comparison with H_β(486.135 nm)





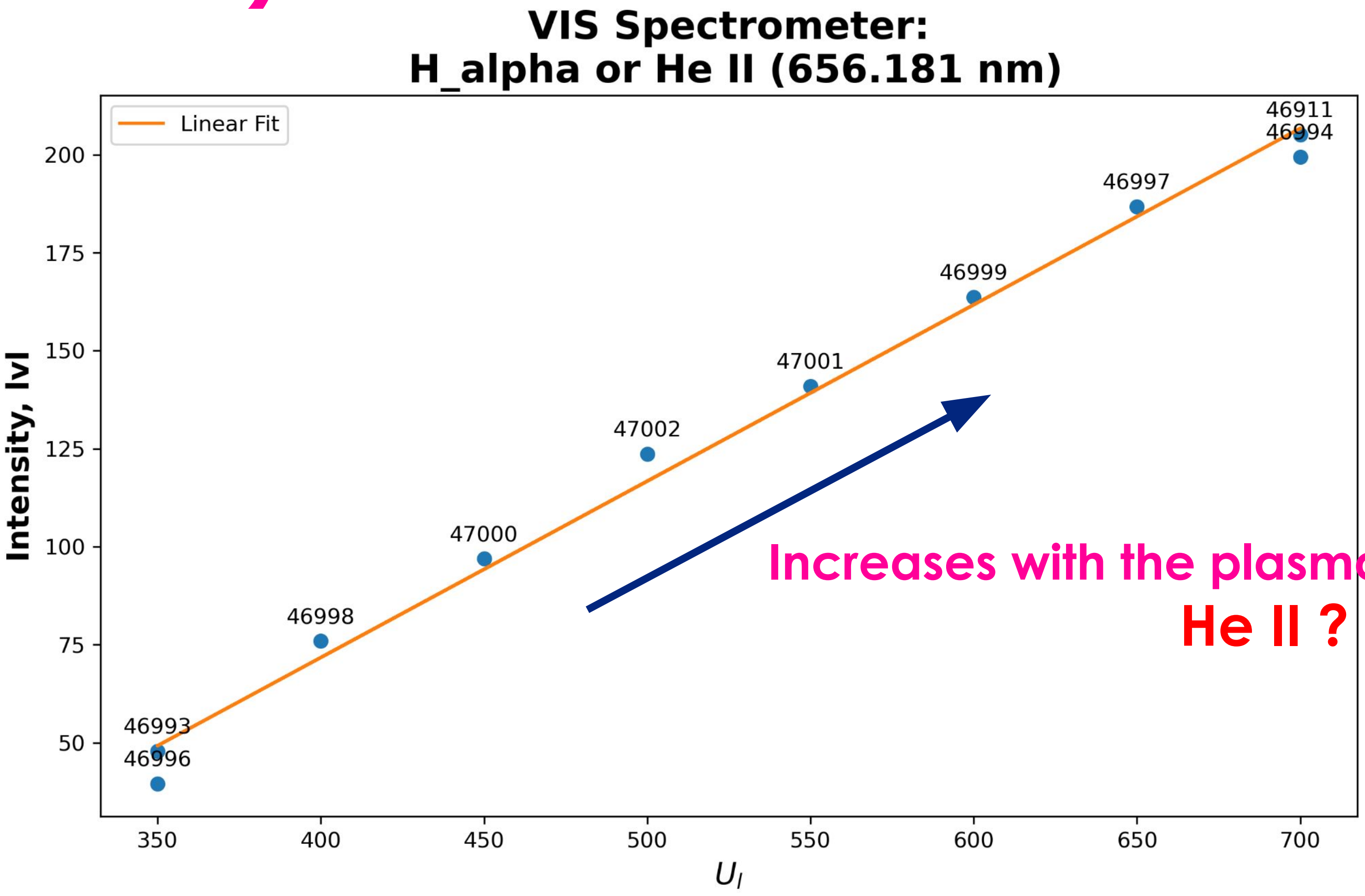
Comparison with He I (667.8 nm)





High Ionized Ions

He II (656.02 nm) FOUND!

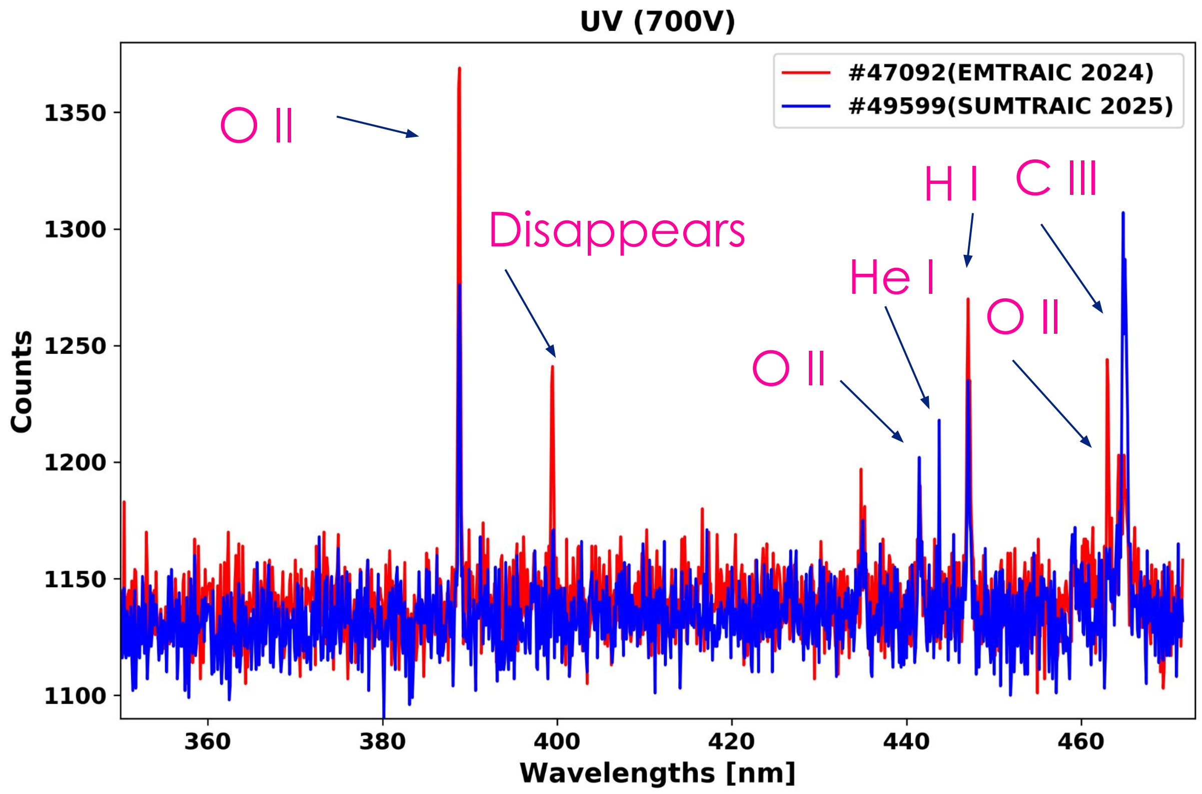


Increases with the plasma current → ion

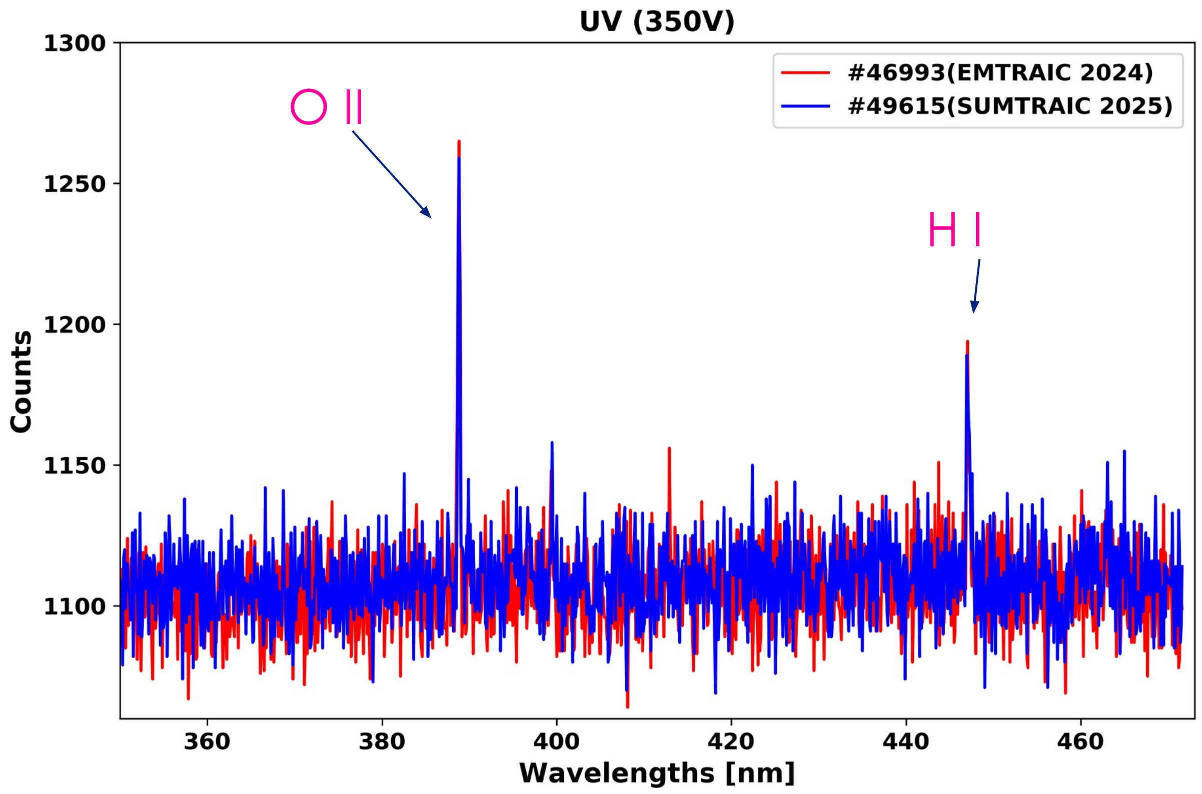
He II ? ✅

EMTRAIC (CABLE) VS SUMTRAIC (NO CABLE)

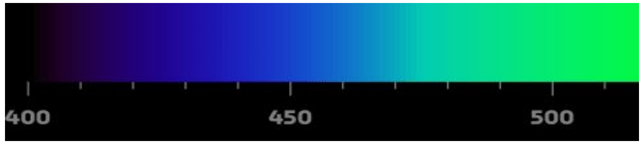
Transition:



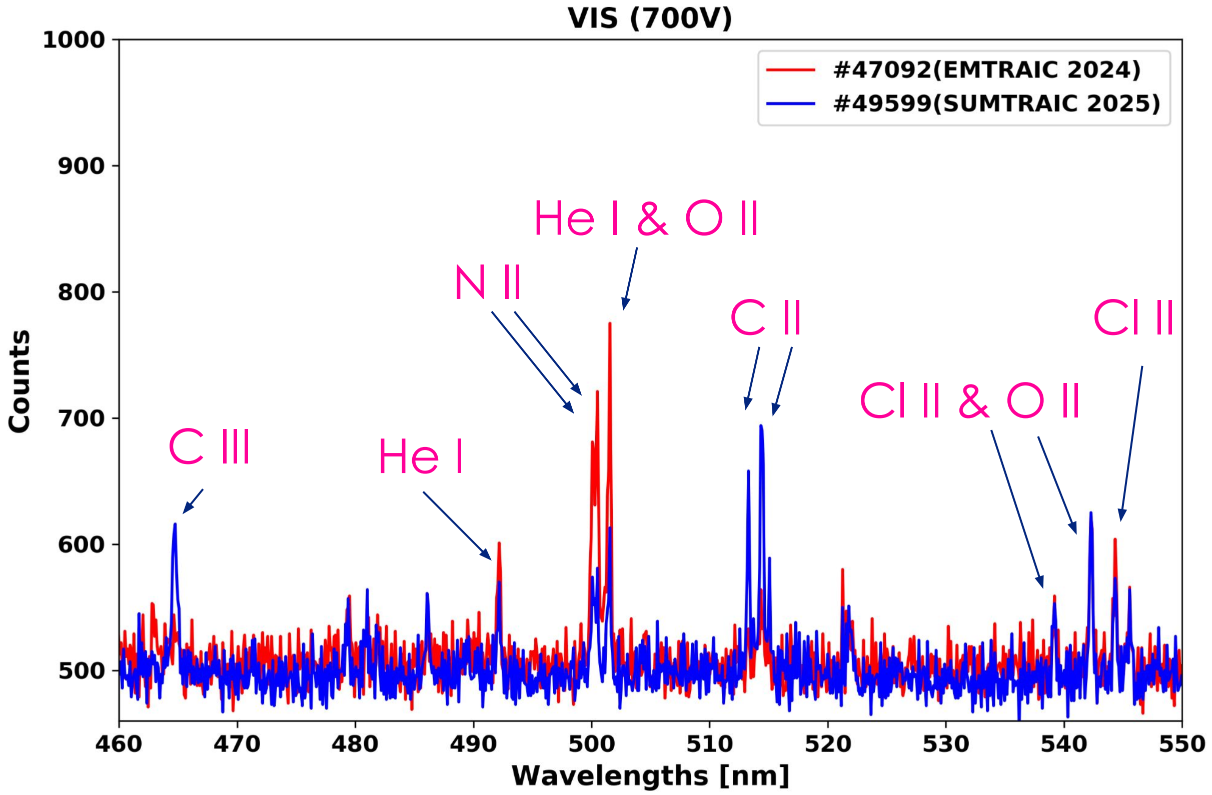
No Transition:



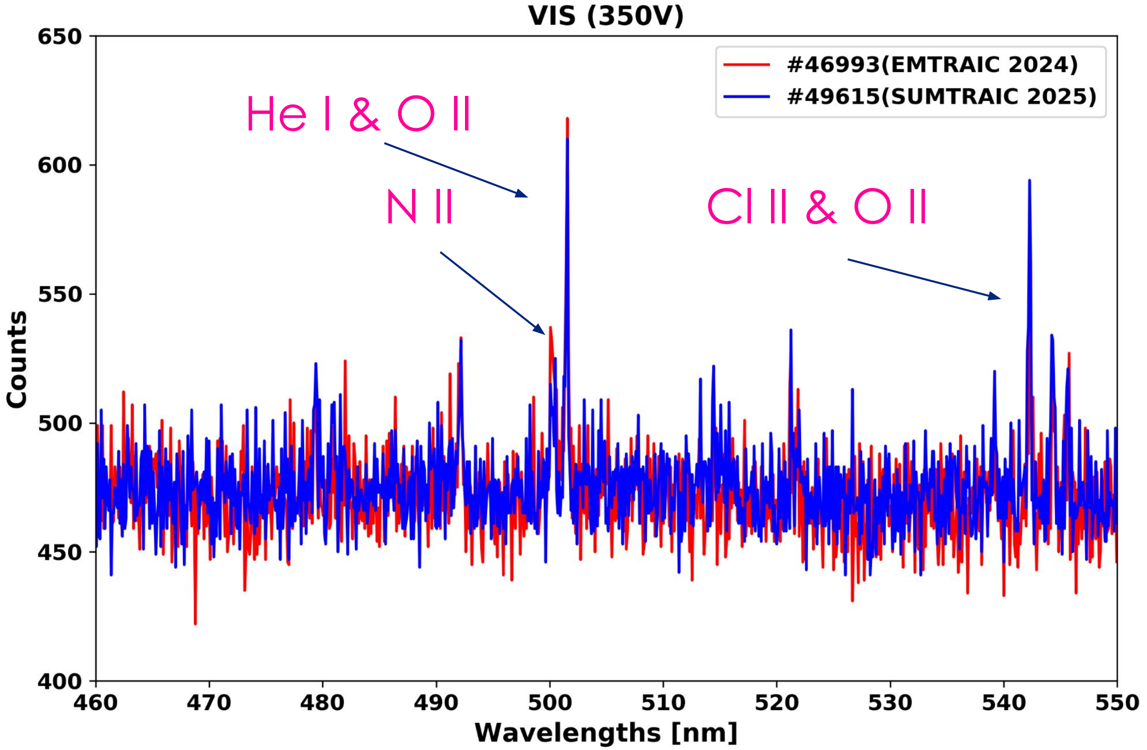
EMTRAIC (CABLE) VS SUMTRAIC (NO CABLE)



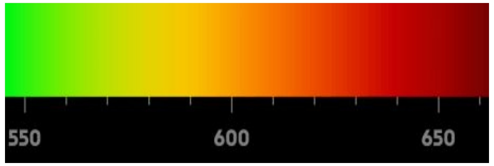
Transition:



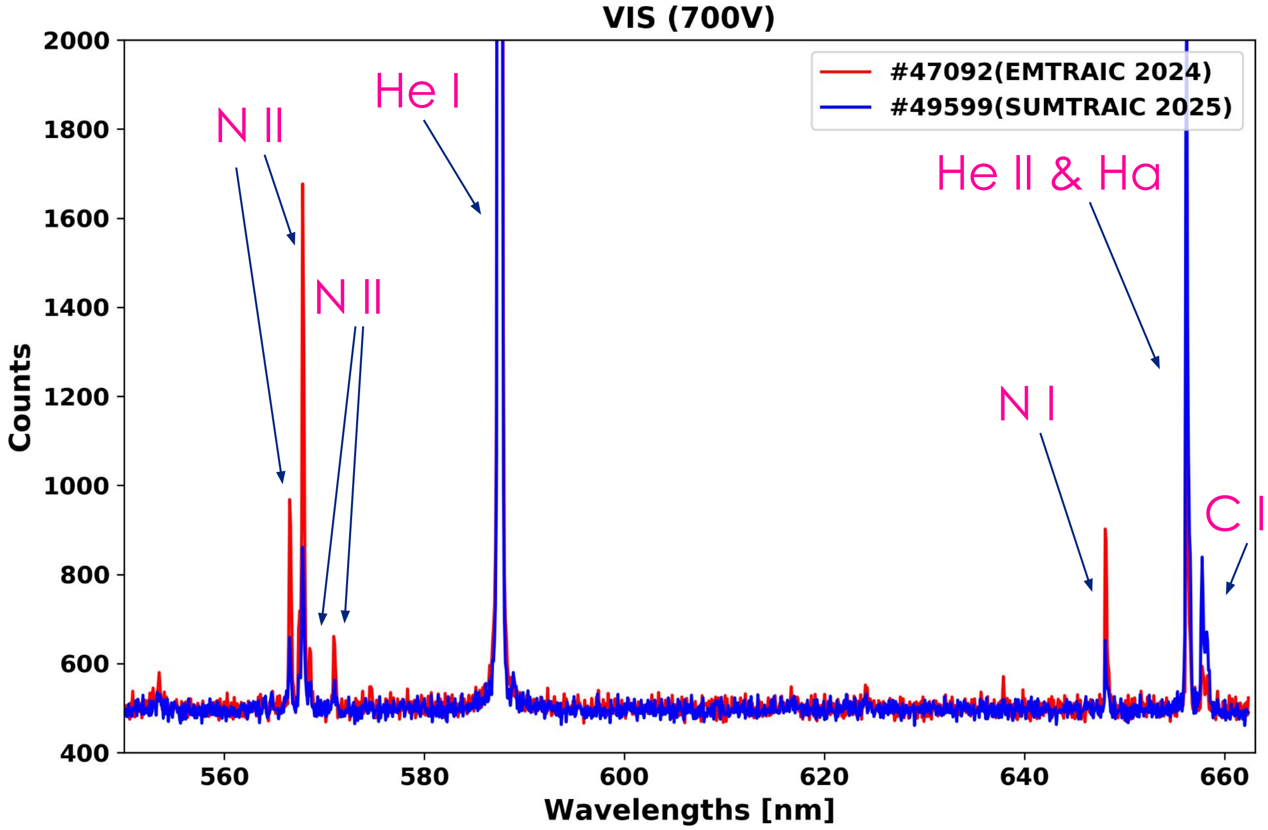
No Transition:



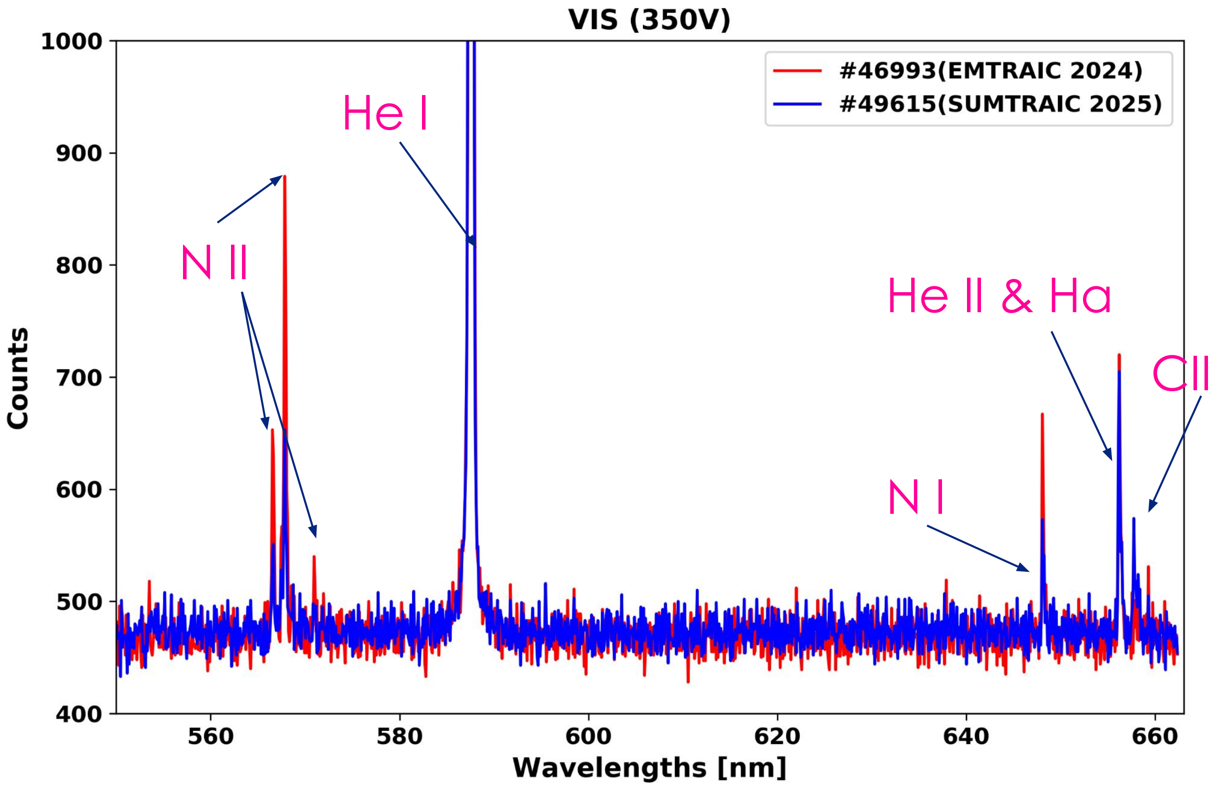
EMTRAIC (CABLE) VS SUMTRAIC (NO CABLE)



Transition:



No Transition:



Conclusion

- Found
- Not found?

Neutral (I)	Ionization energy [eV]	1st ionic state (II)	Ionization energy [eV]	2nd ionic state (III)
He	24.59	He^{+}		
H	13.60			
C	11.26	C^{+}	24.38	C^{2+}
O	13.62	O^{+}	35.12	O^{2+}
N	14.53	N^{+}	29.60	N^{2+}
Cl	12.97	Cl^{+}	23.8	Cl^{2+}

- Spectroscopy diagnostic system should be updated→not enough QE of high resolution spectrometers .
- Occasional presence of power cord → Impurity influx + Edge condition change → Repeat experiment
- Similar improvements in particle confinement were reported by Finken et al. (2007) in TEXTOR, where opening of flux tubes connected deeper rational surfaces to the wall led to edge cooling, core density peaking, and barrier formation.
- Our results suggest that even in a small device like GOLEM, analogous barrier-formation mechanisms may be at play, with impurities serving as tracers of changing edge topology.

References

[1] P. Macha et al 2023 Nucl. Fusion 63 104003; https://doi.org/10.1088/1741-4326/acf1af
[2] Kramida, A., Ralchenko, Yu., Reader, J. and NIST ASD Team (2024). NIST Atomic Spectra Database (version 5.12), [Online]. Available: https://physics.nist.gov/asd [Mon Dec 09 2024]. National Institute of Standards and Technology, Gaithersburg, MD. DOI: https://doi.org/10.18434/T4W30F
[3] GUIRLET Rémy, providing graph of the fractional abundances of Carbon
[4] Finken et al. (2007) Improved Confinement due to Open Ergodic Field Lines Imposed by the Dynamic Ergodic Divertor in TEXTOR. Physical review letters. 98. 065001. 10.1103/PHYSREVLETT.98.065001.

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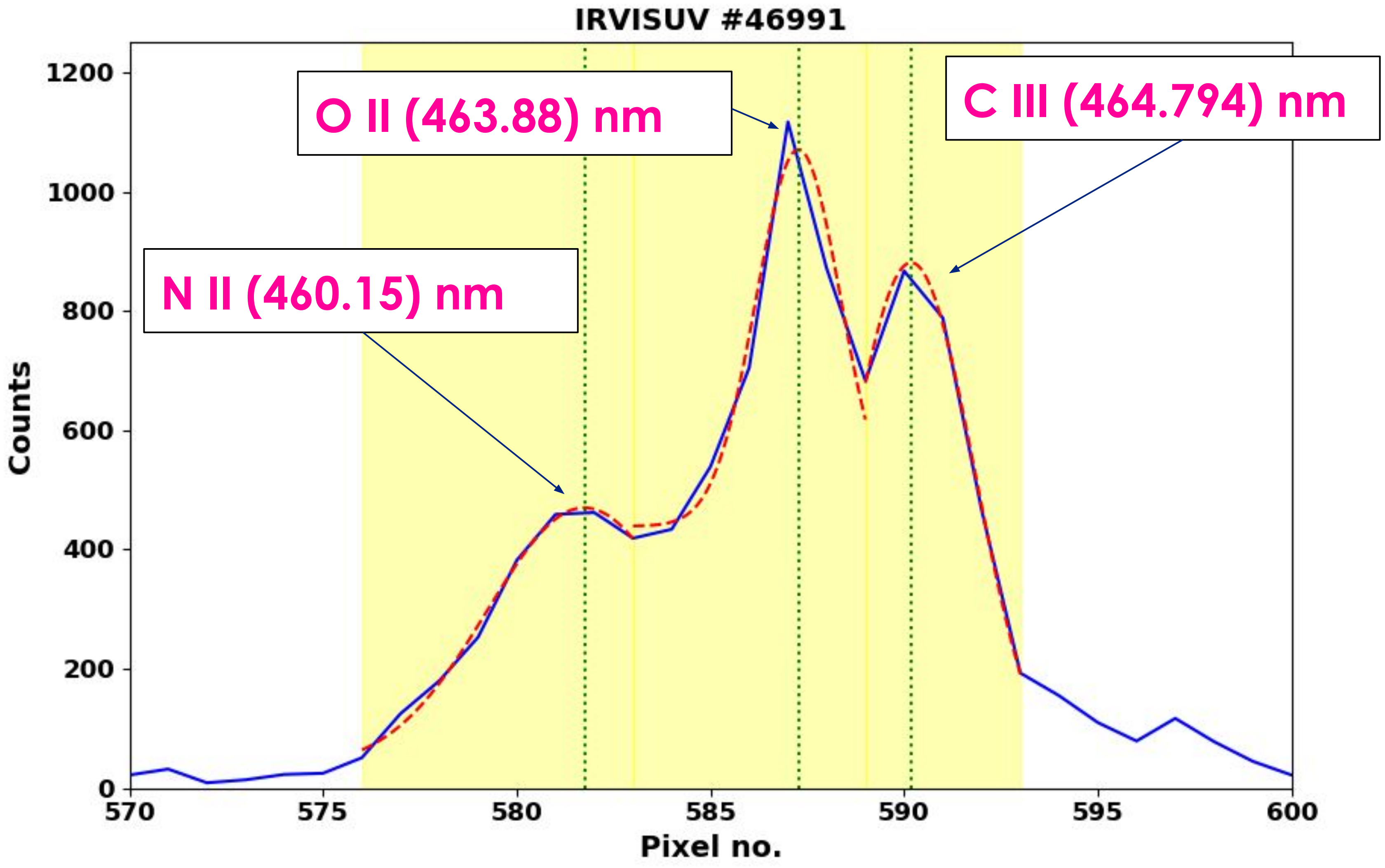
Extra slides

Big peak →

Fit of all peaks not possible

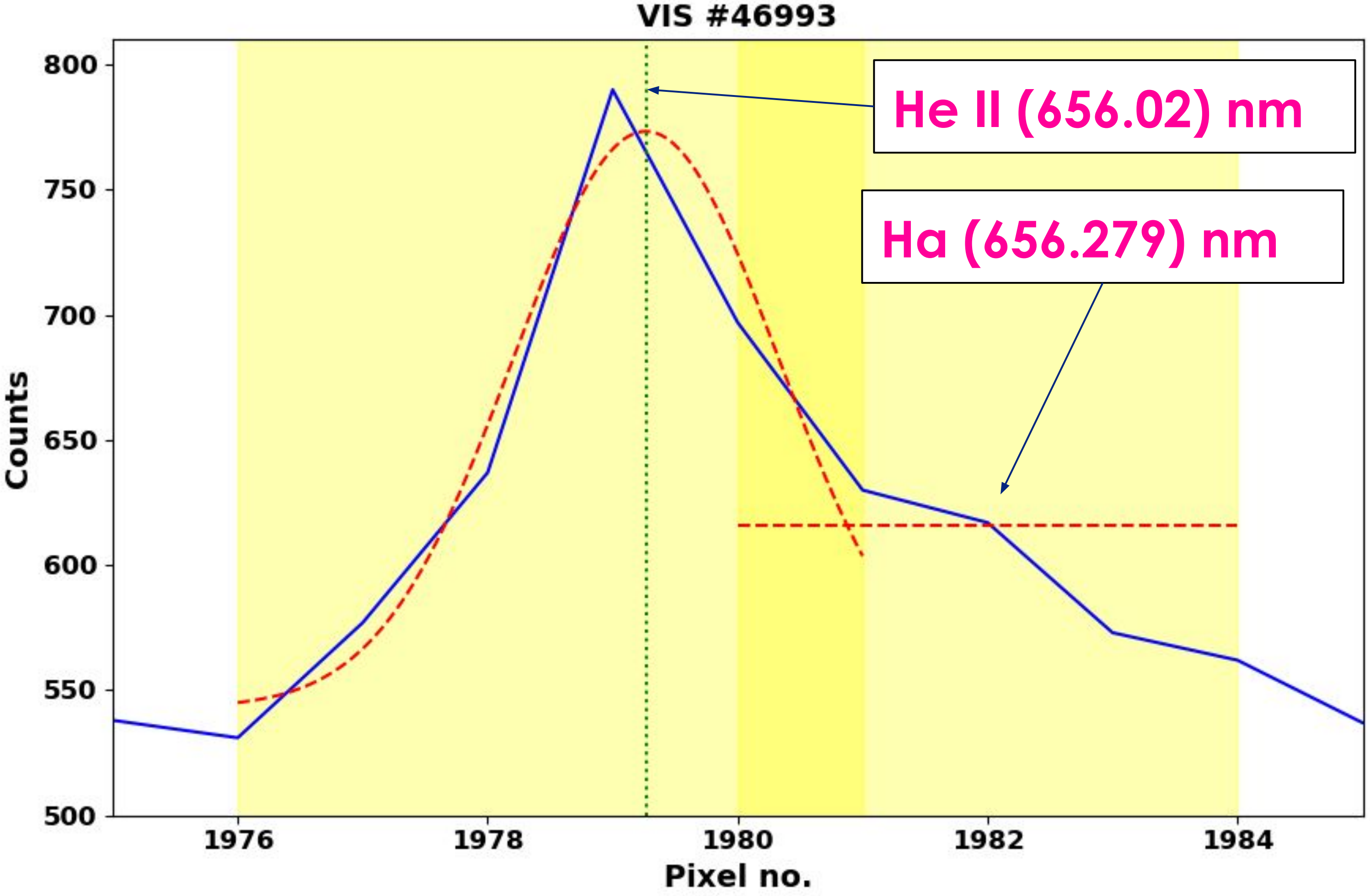
🙁



He II & Ha peak →

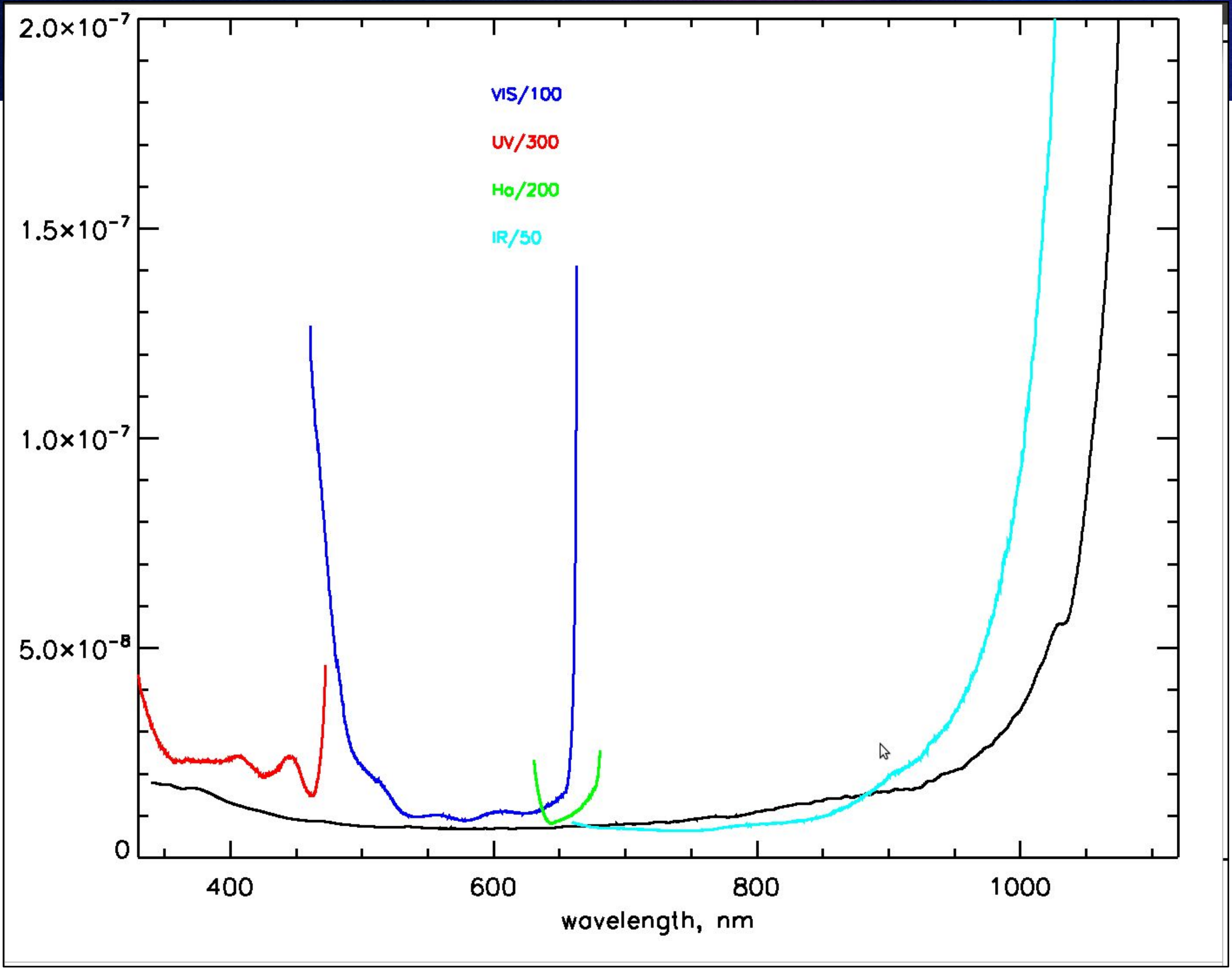
Fit of both peaks not possible

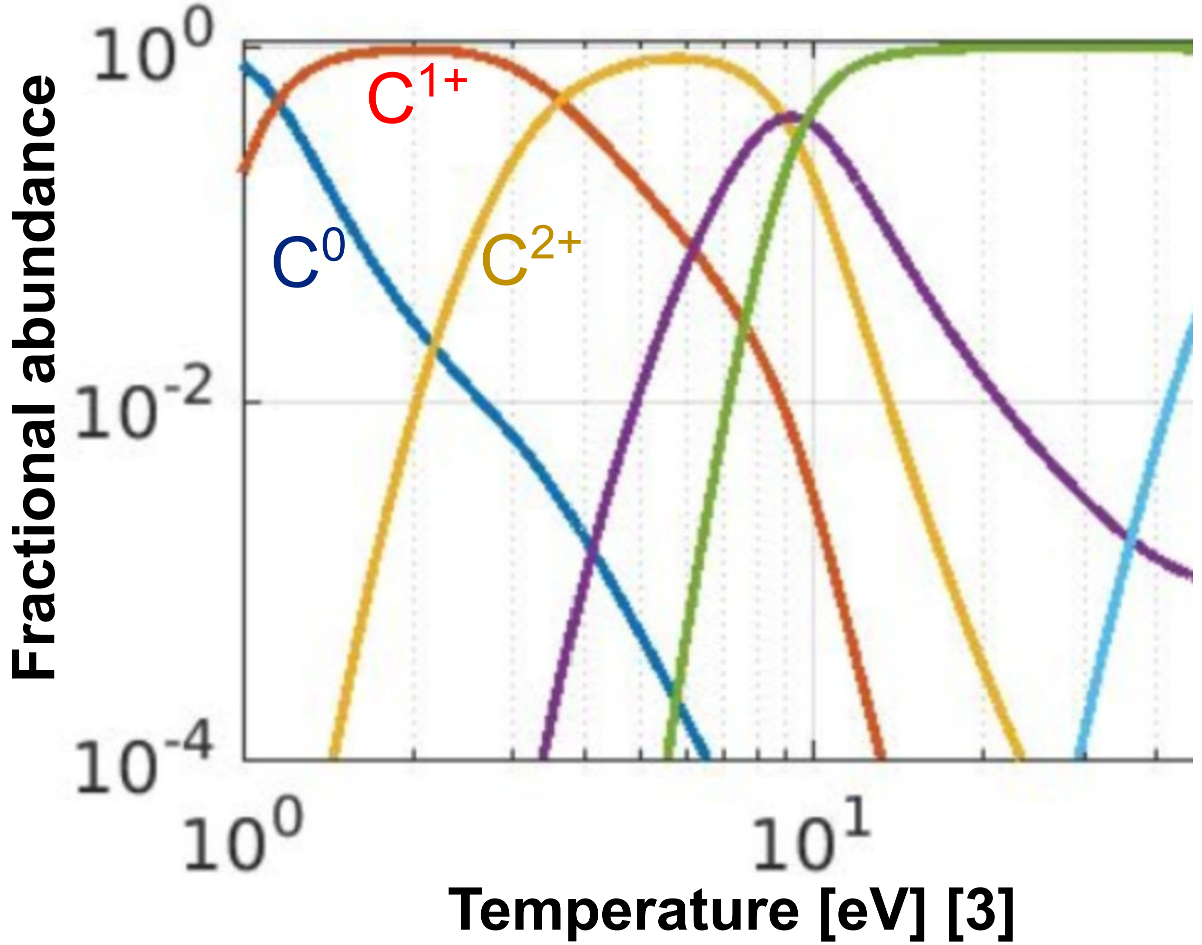
🙁



Absolute Calibration Constant (1/QE)

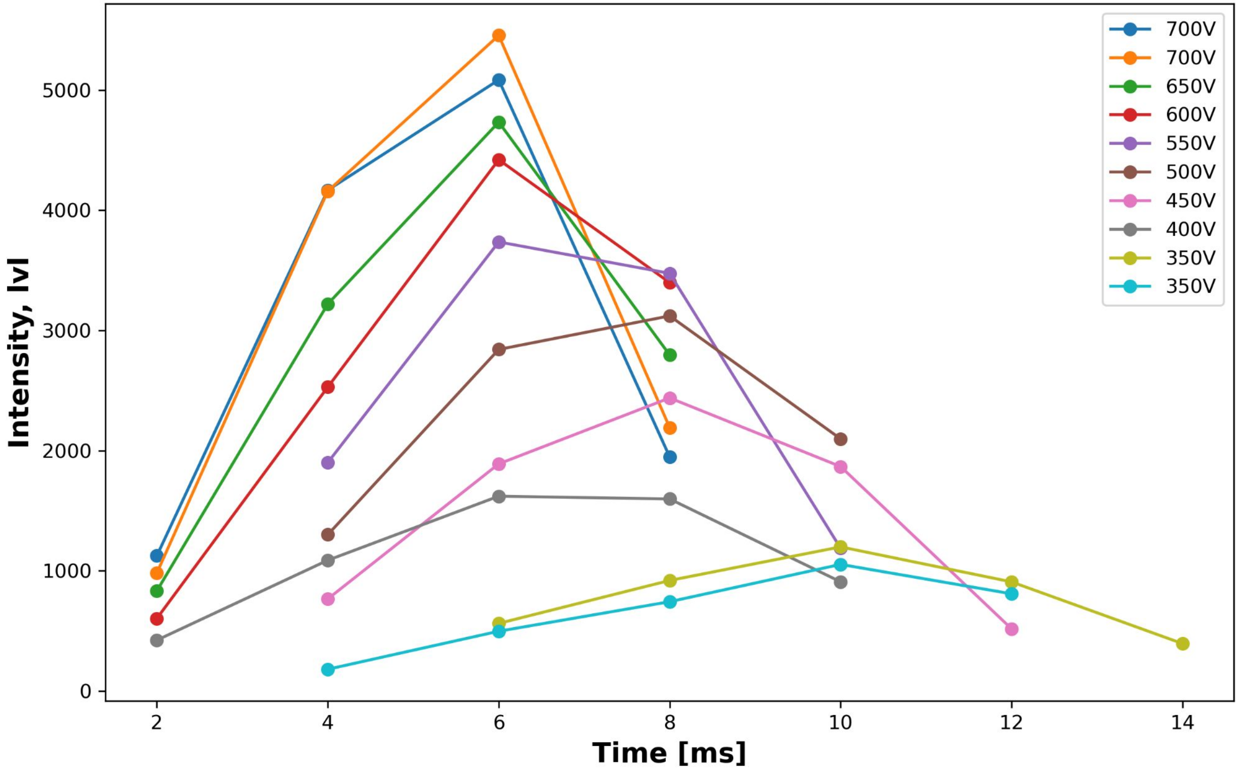
- VIS/100
- UV/300
- Ha/200
- IR/50



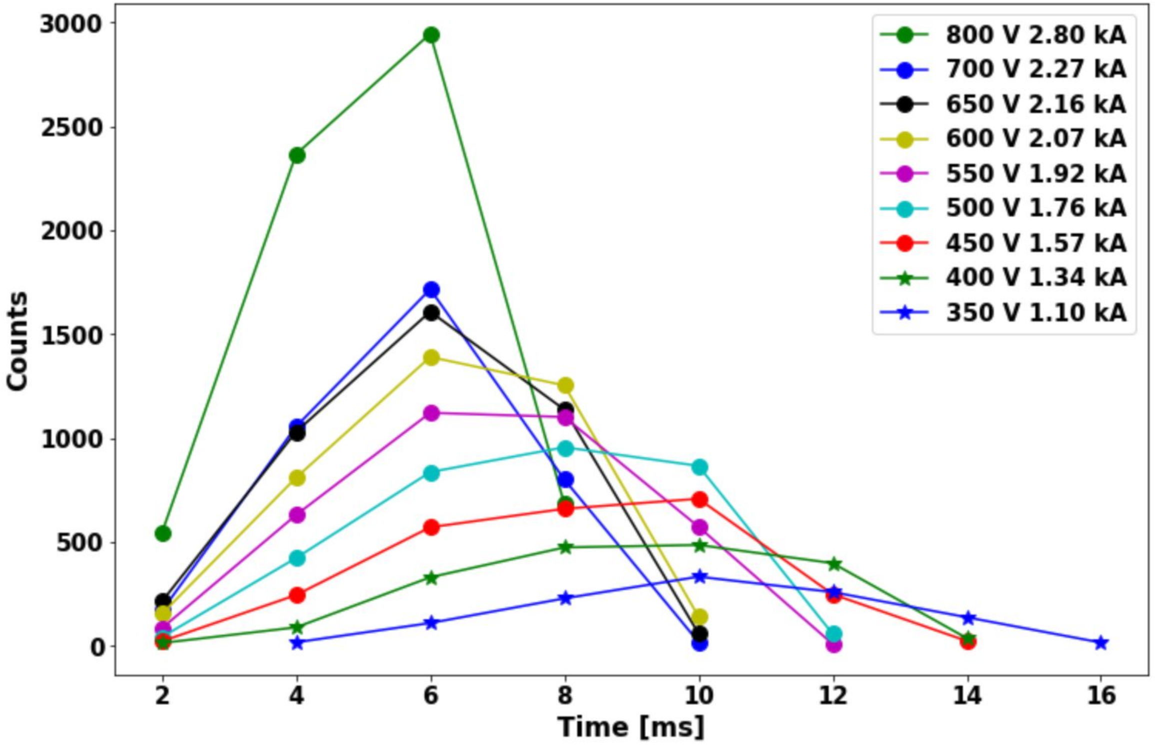

10^0
10^{-2}
10^{-4}
10^0
10^1
Fractional abundance
Temperature [eV] [3]
C^{1+}
C^0
C^{2+}

High Ionized Ions

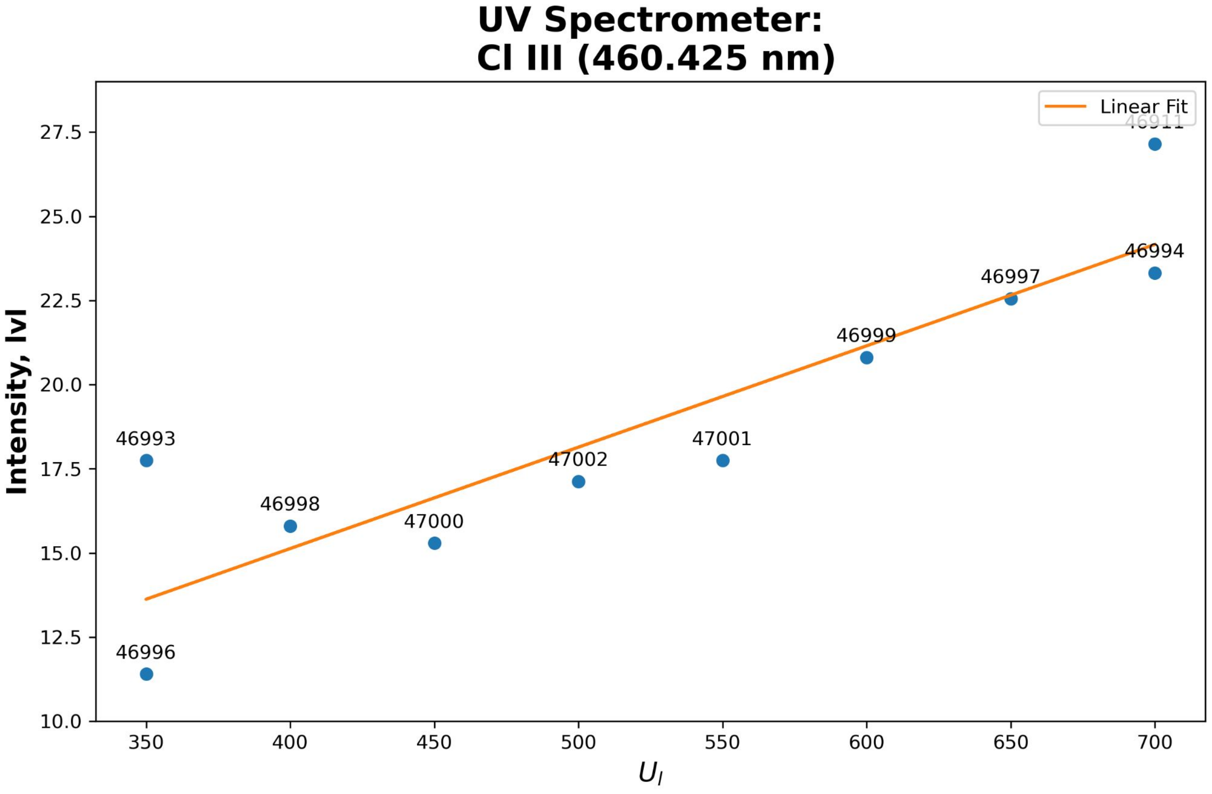
Big Peak Time Evolution (IRVISUV)

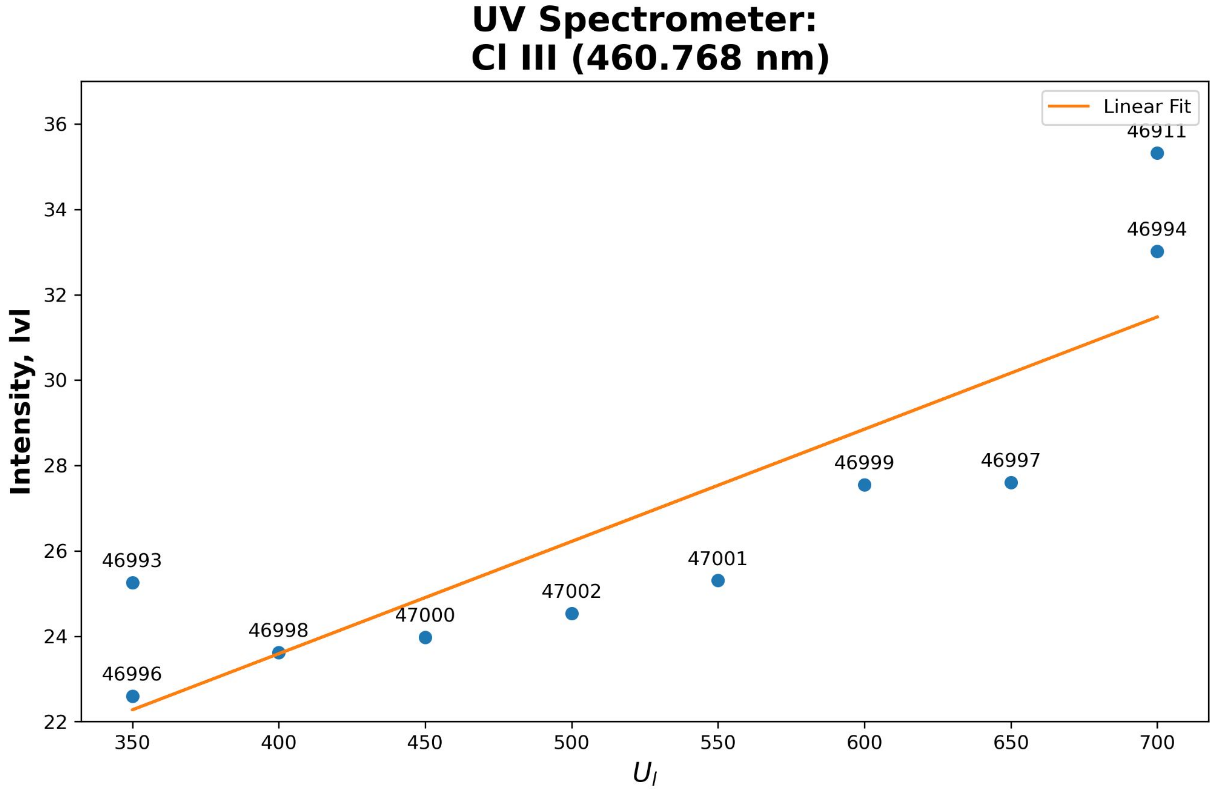


C II Time Evolution (IRVISUV)

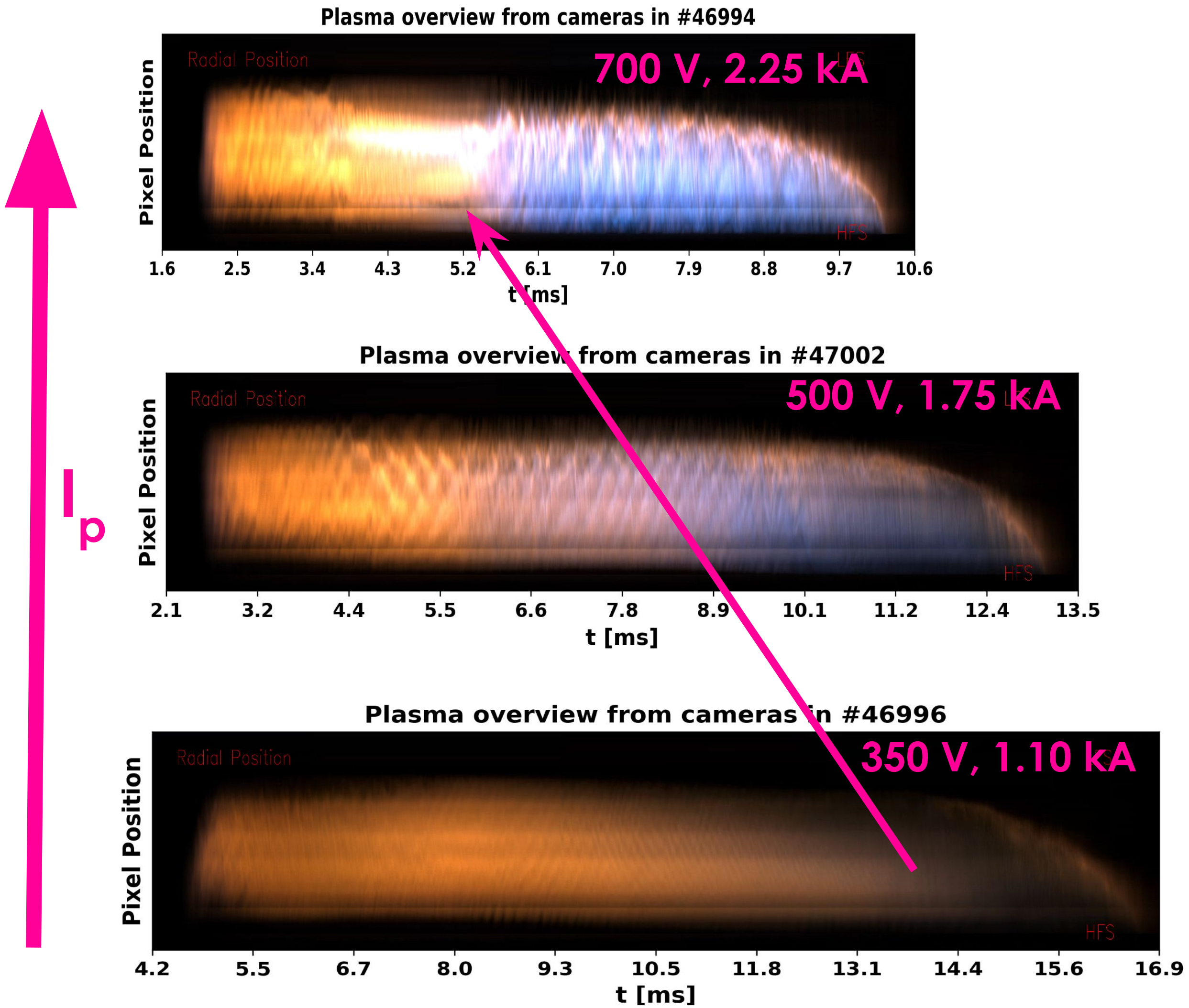


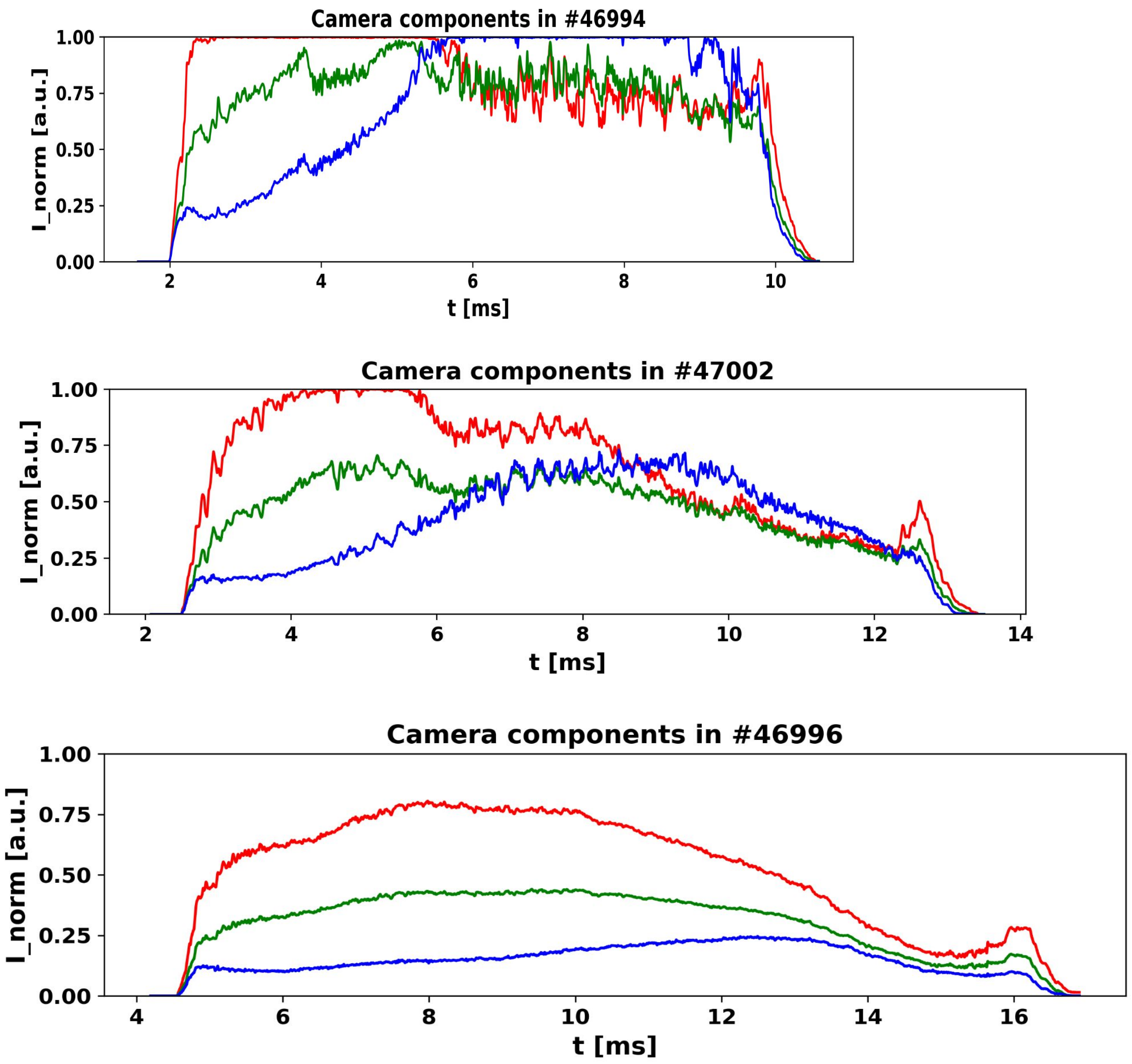
Cl III doublet: 460.425, 460.768 nm





I_p scan: Color transition

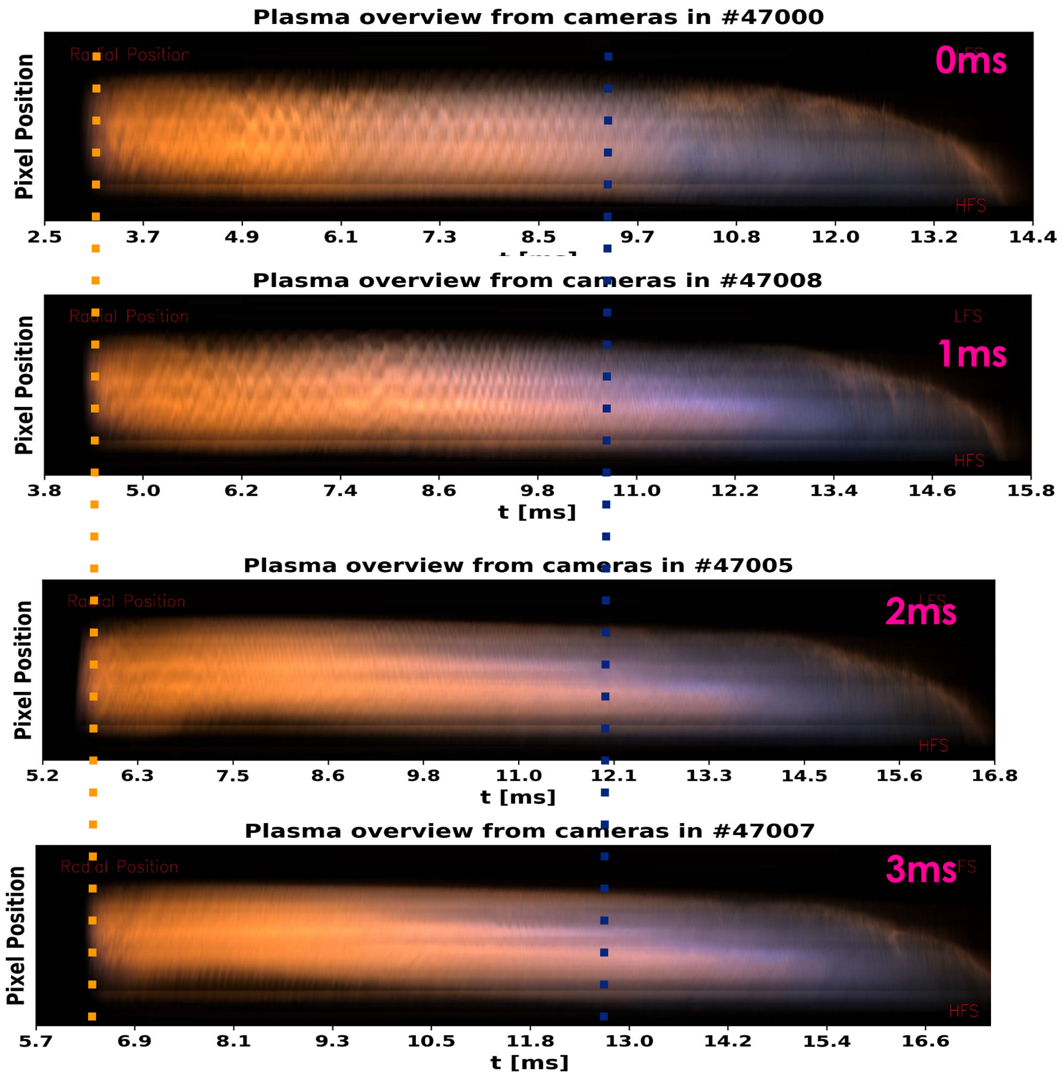


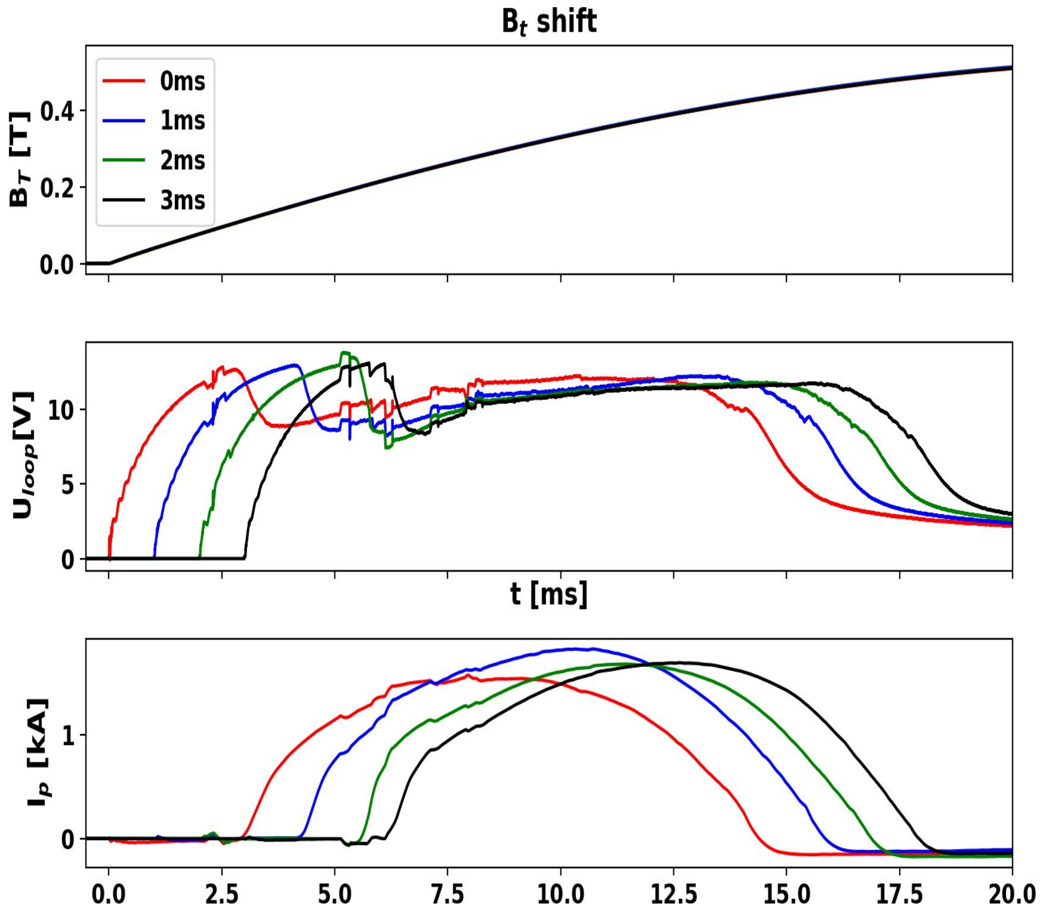


B_T shift scan: Color transition, MHD

B_T

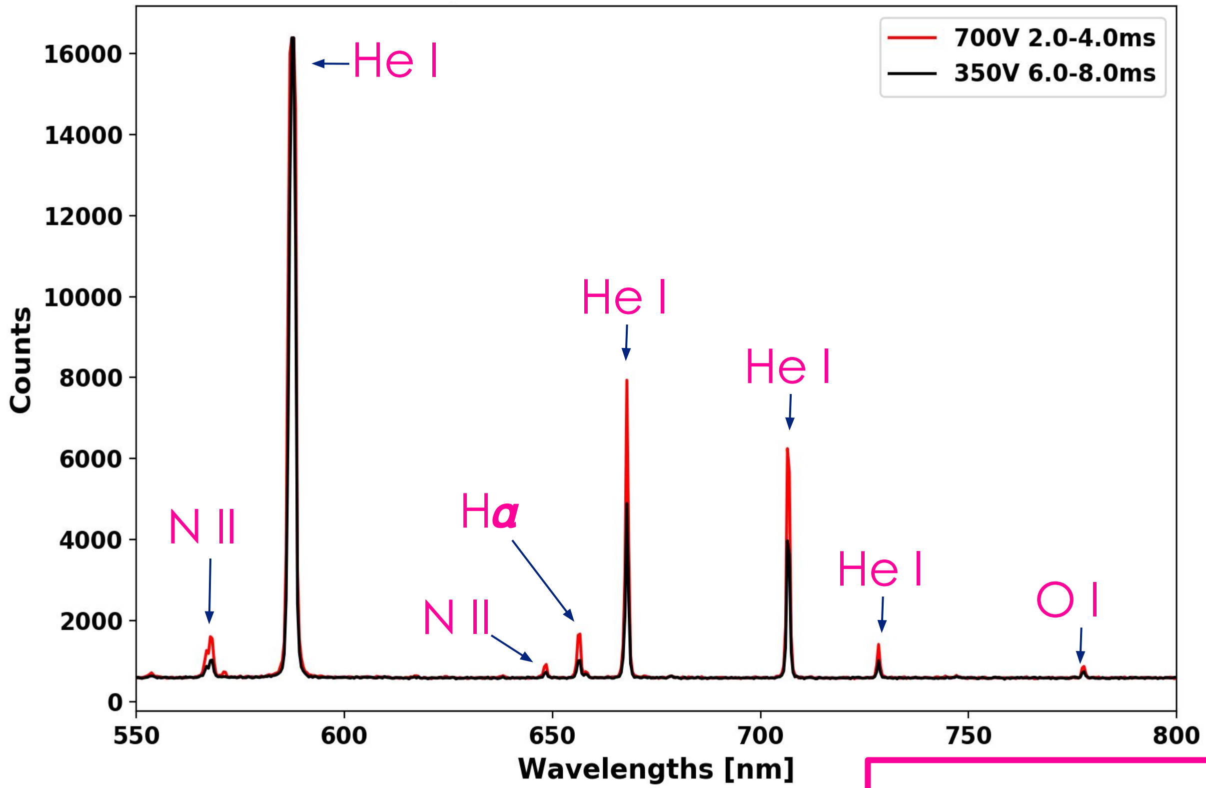
MHD activity

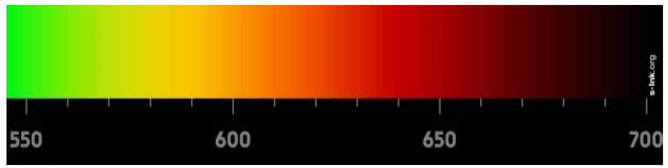




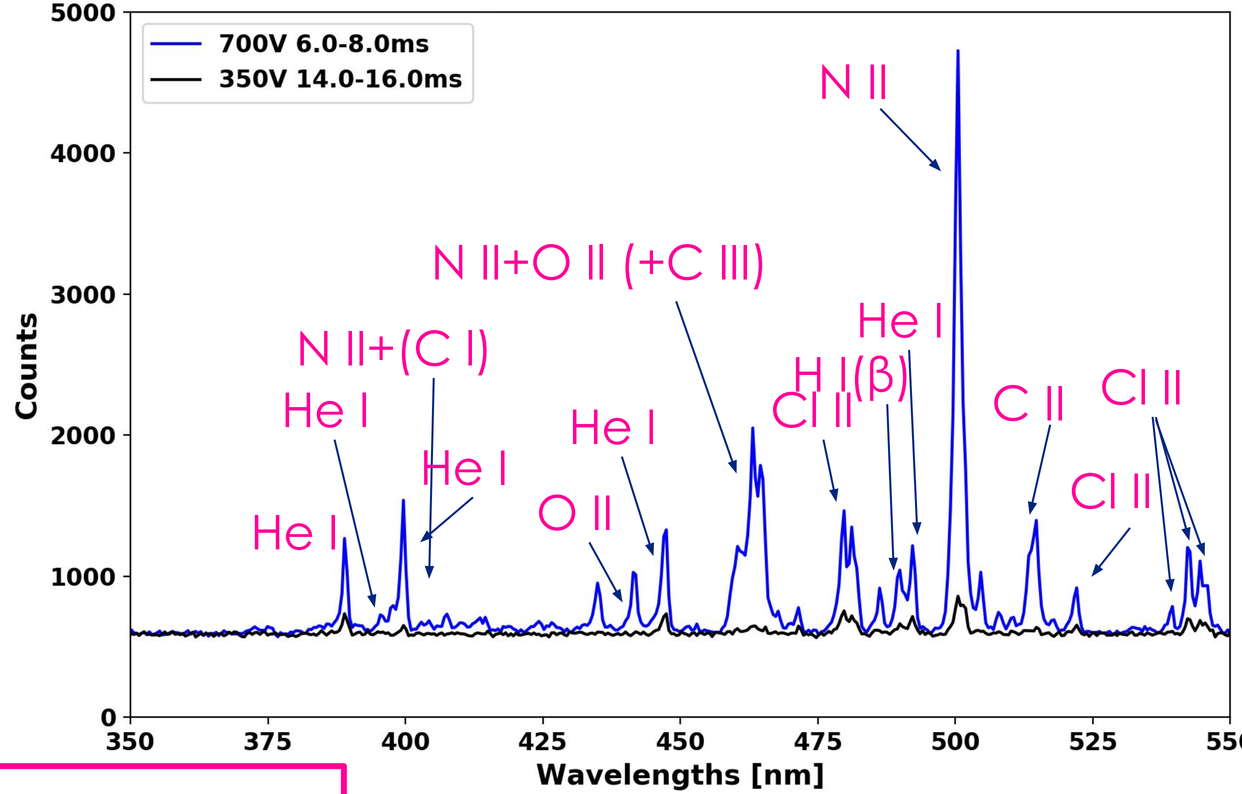
IRVISUV Spectra

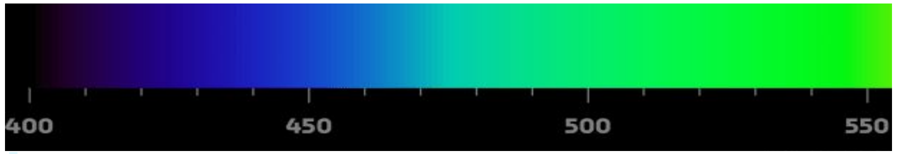
Spectra before the transition (Red range)





Spectra after the transition (Blue range)





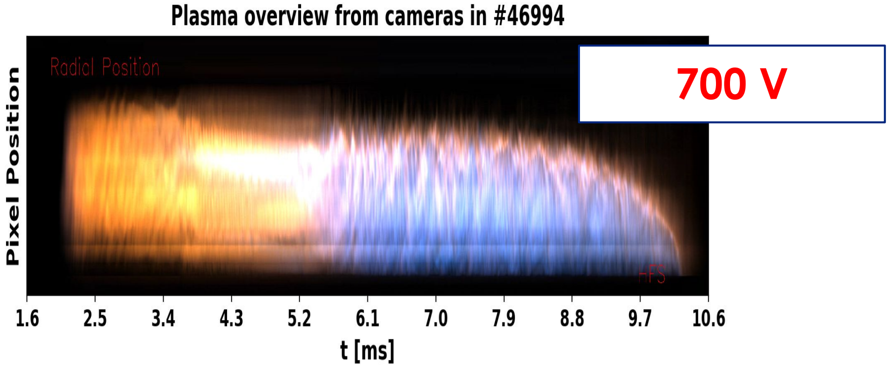
Working gas: He I
Impurities:
H I, N II, C II, Cl II,O I, O II
59 lines, 2ms exposure time

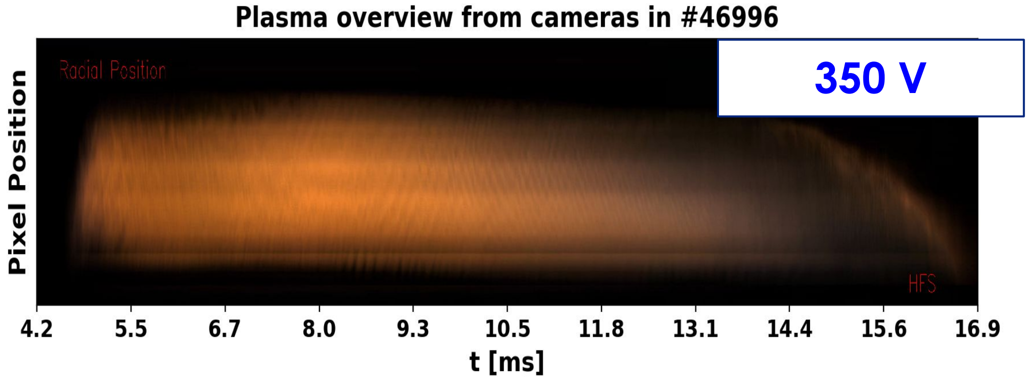
Ip scan: Time evolution of spectra

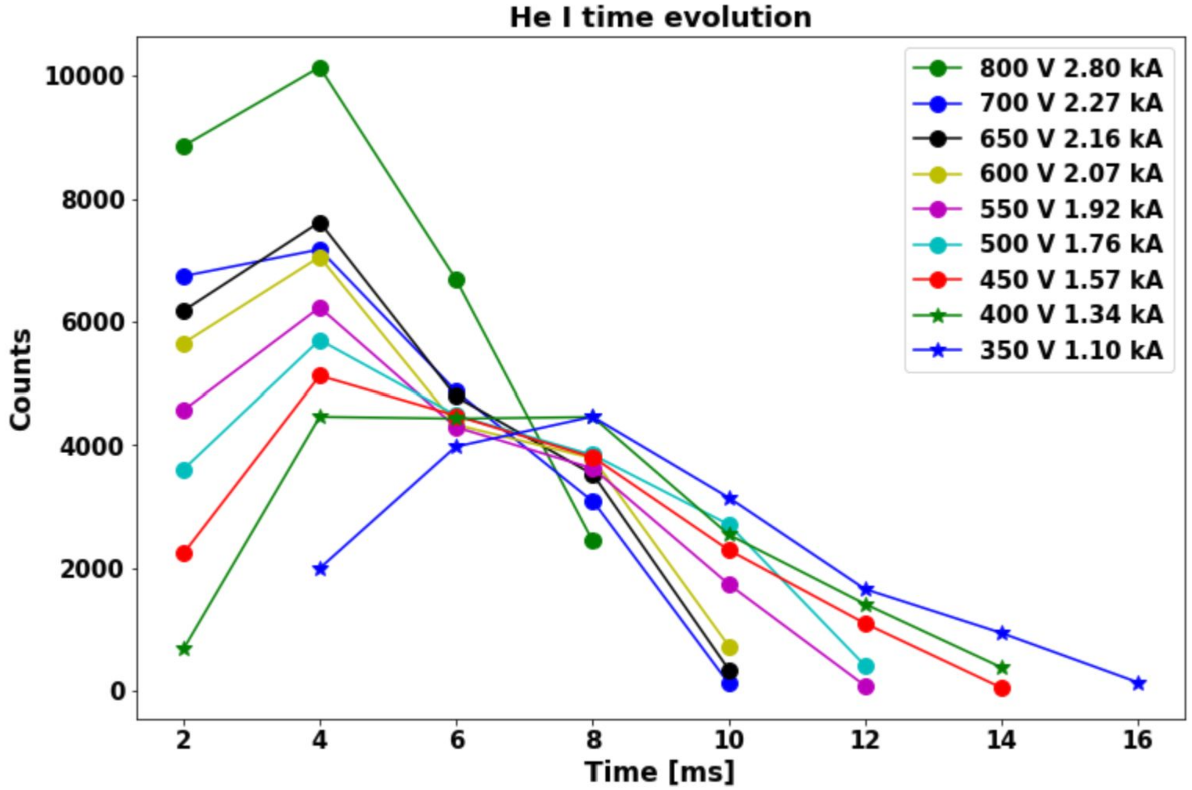
He I (667.8 nm)

$$\text{Intensity} \sim n_e * n_{ion} * C_{ex}(n_e, T_e)$$

I_p

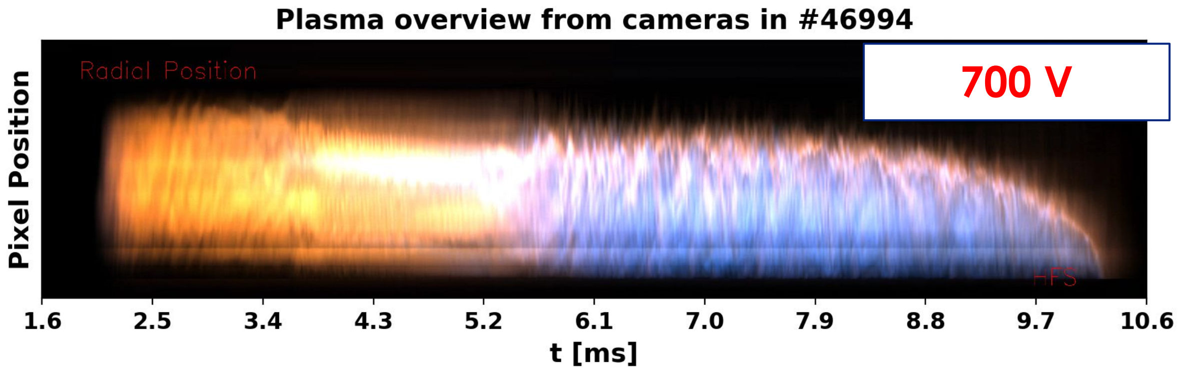




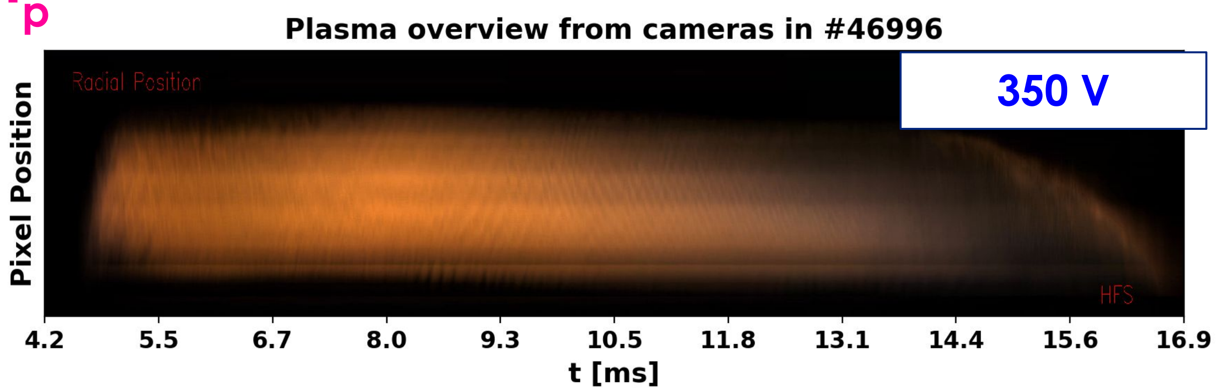


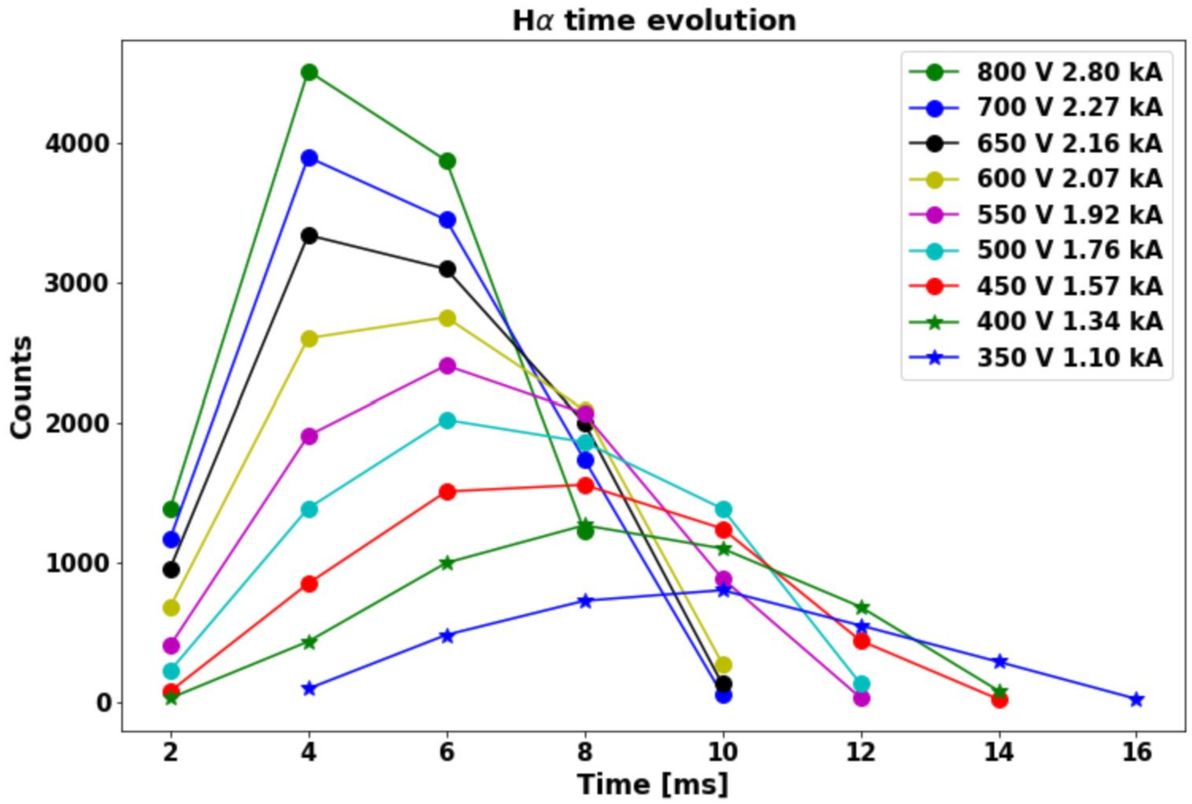
Source: Working gas

Hα (656.3 nm)



I_p

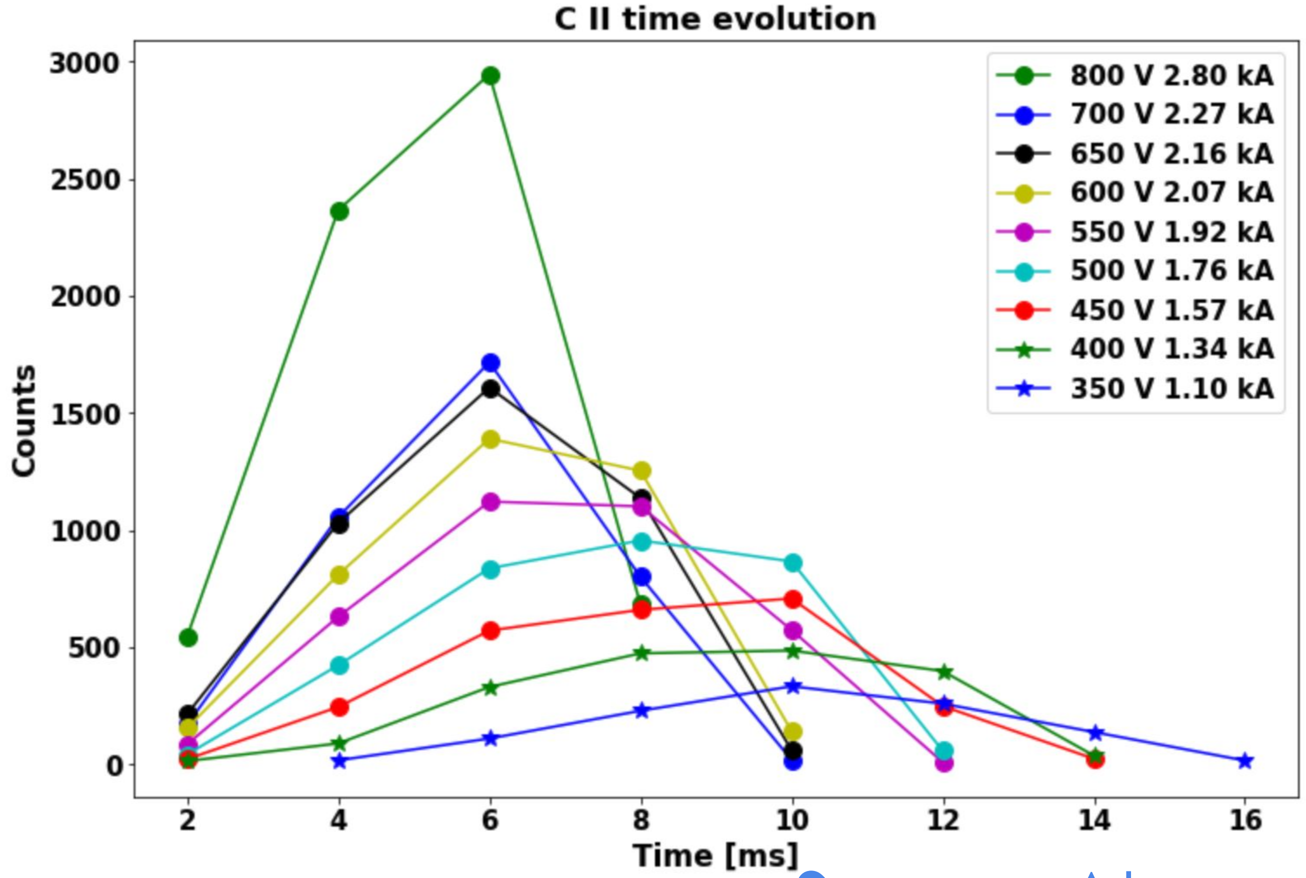




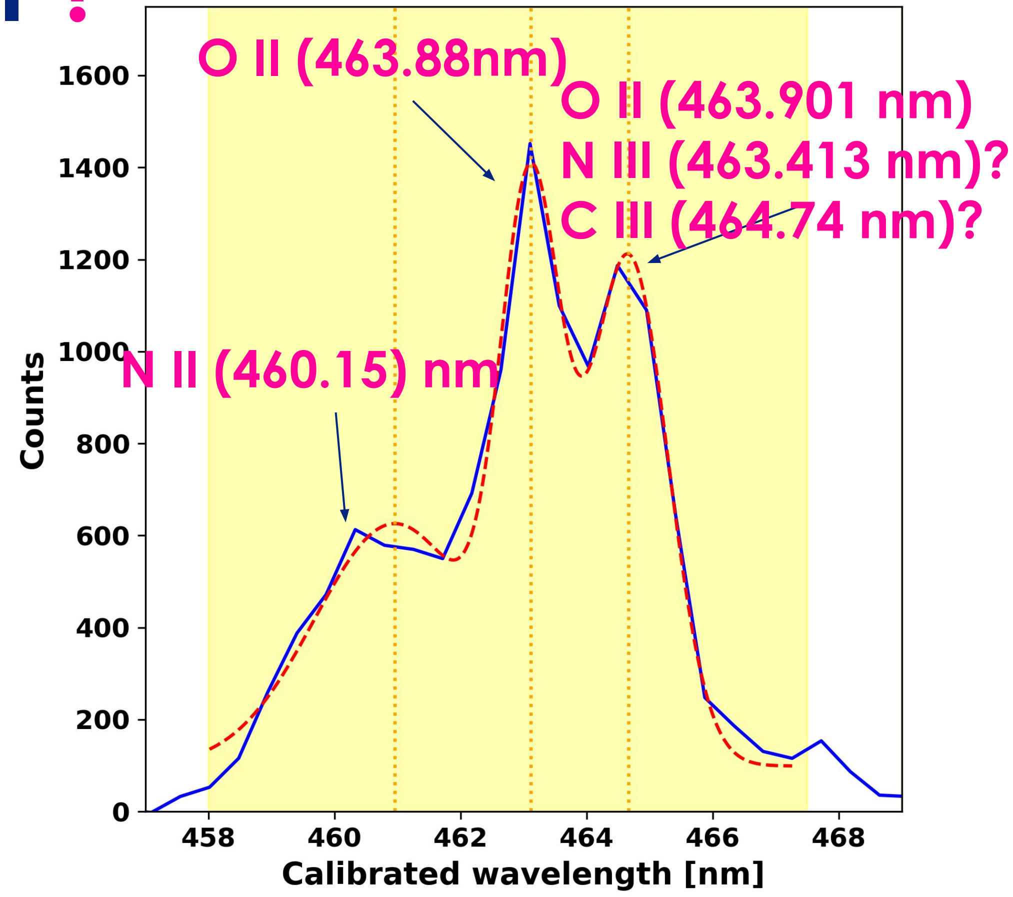
Source: Atmosphere (H_2O), in-vessel materials, previous shots, PVC

Ip scan: Time evolution of spectra

C II (657.80nm)

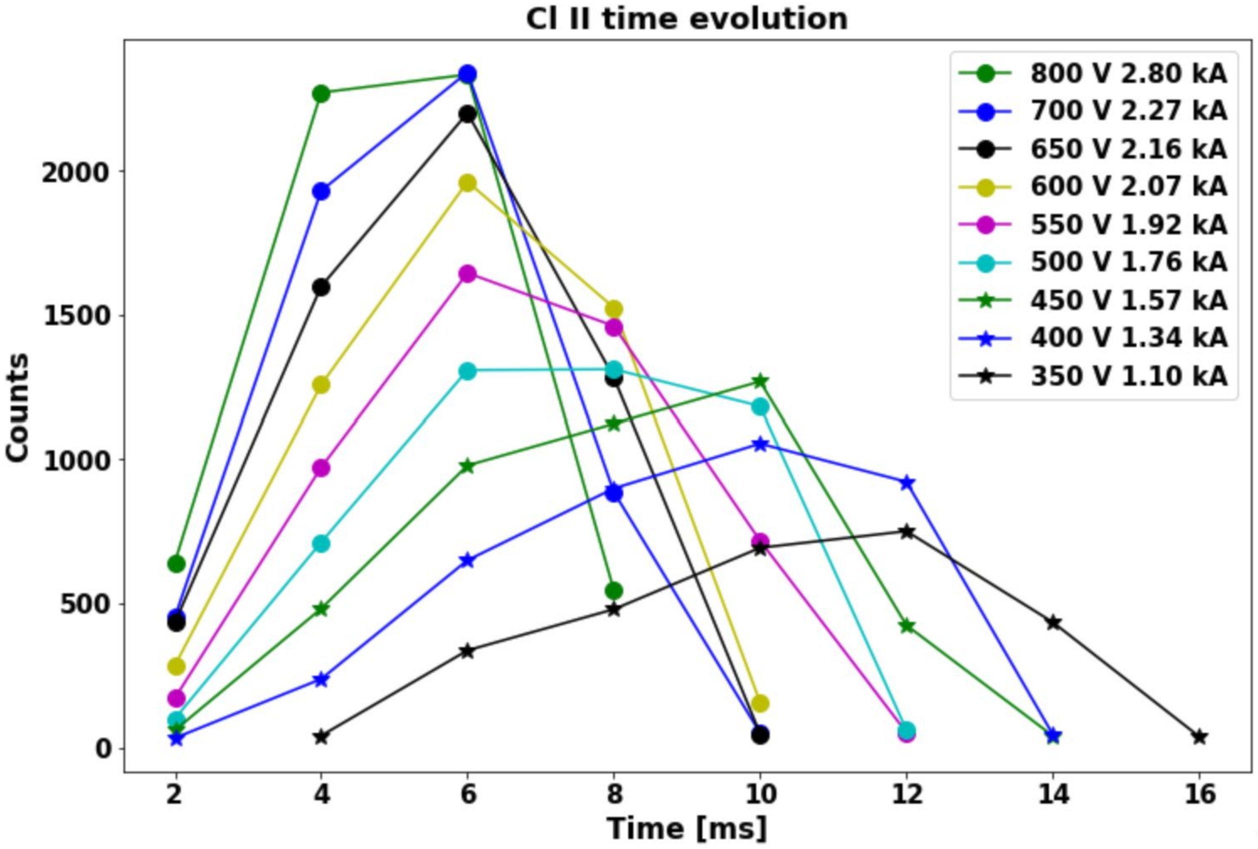


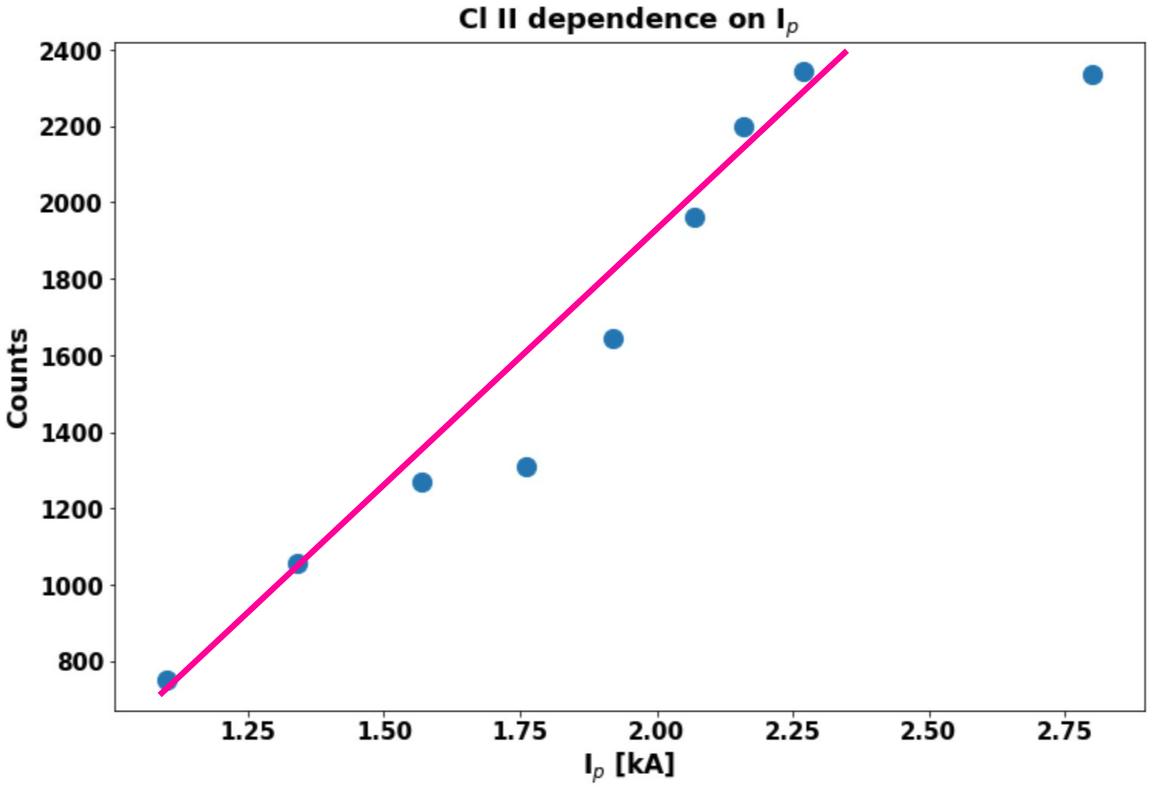
C III ?



Source: Atmosphere (CO_2), PVC, Steel, pumping

Cl II (479.46 nm)



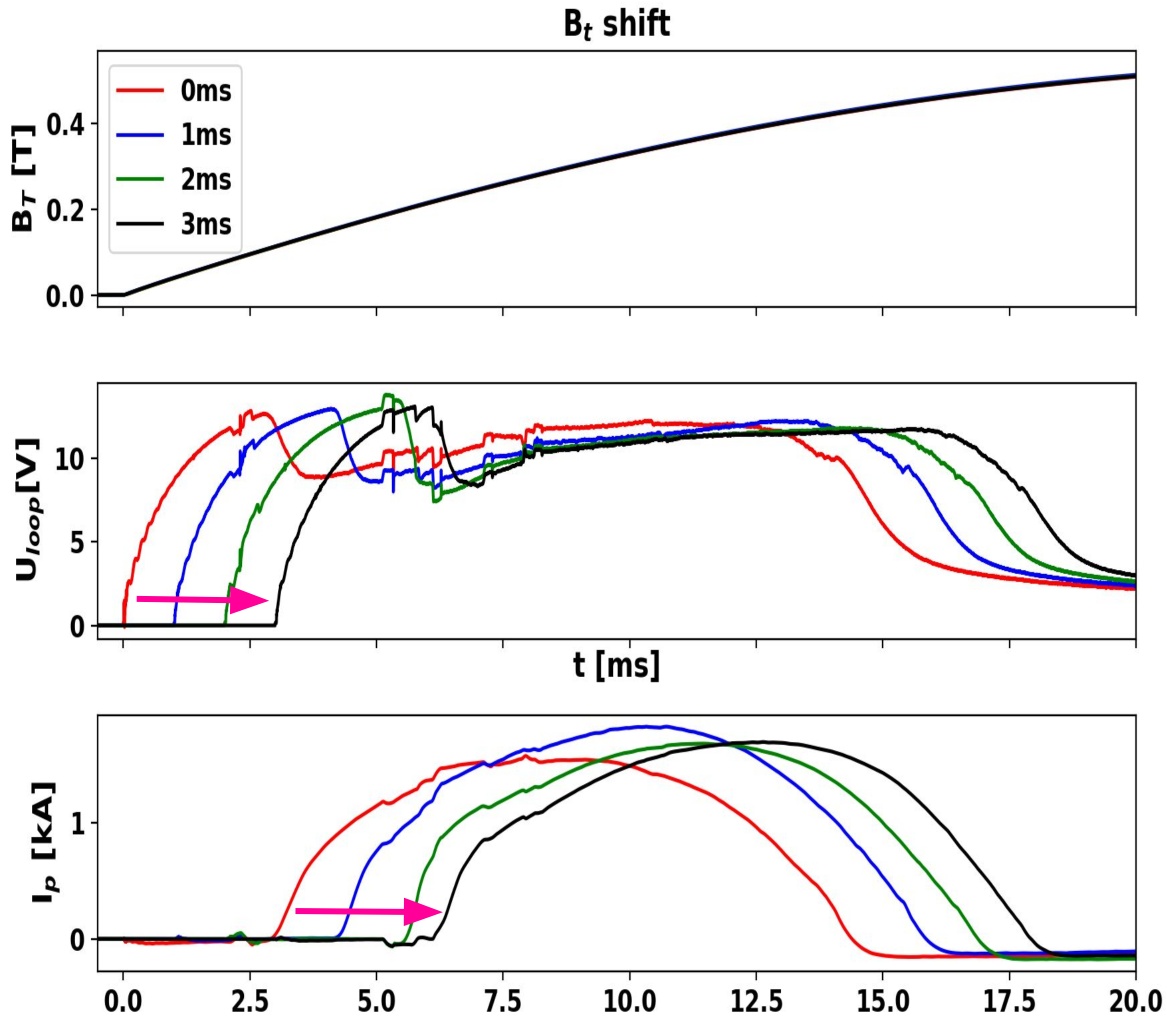


Source: PVC → **cable insulation!**

B_T shift scan: Breakdown conditions, effect of B_T

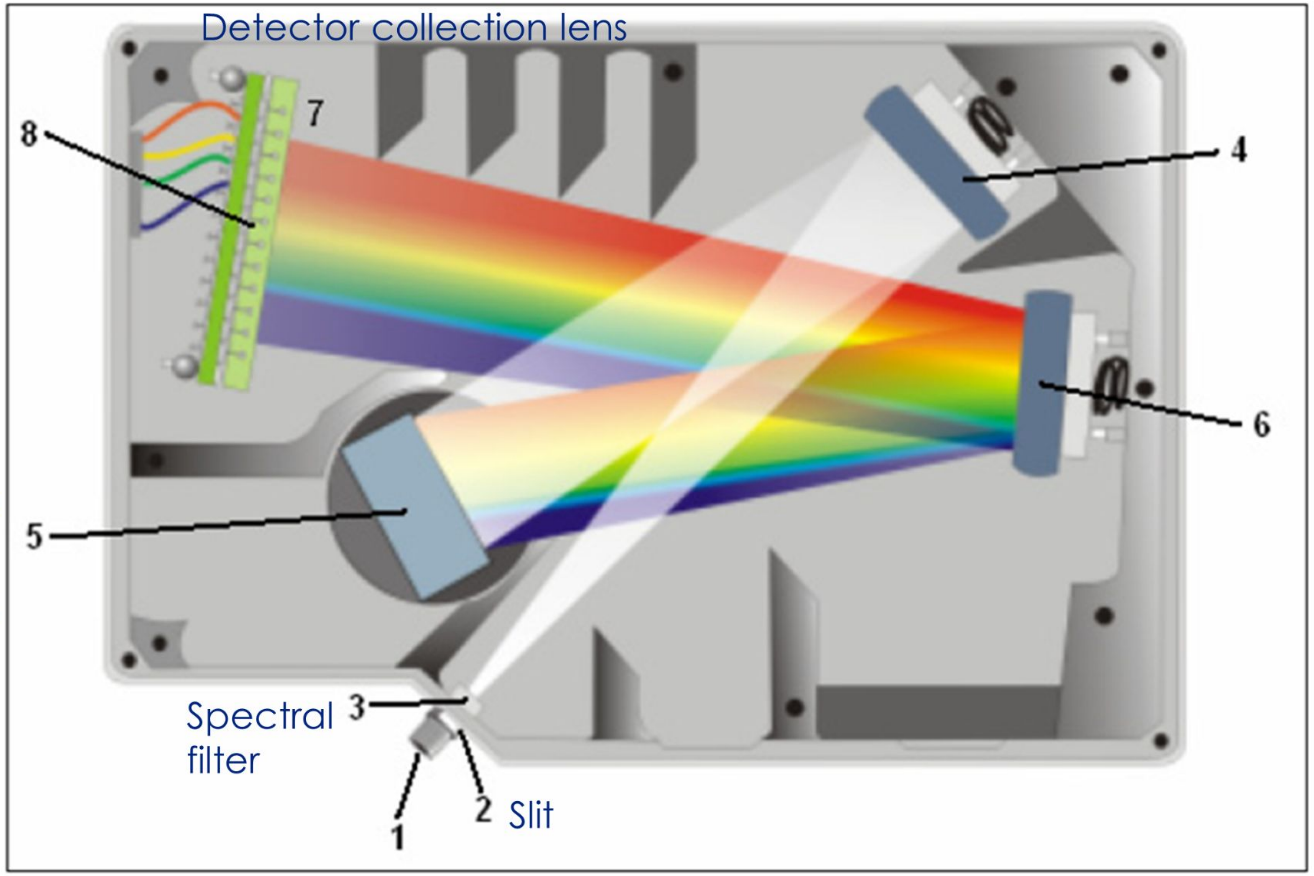
SHOT NUMBER	time delay [ms]	U (Current drive) [V]	$I_{P,\,MAX}$ [kA]	B_t(at $I_{P,\,MAX}$) [T]
47000	0	450	1.6	0.27
47008	1	450	1.8	0.35
47005	2	450	1.7	0.37
47007	3	450	1.7	0.39

Table of shots with similar current drive values but different toroidal magnetic field shift.



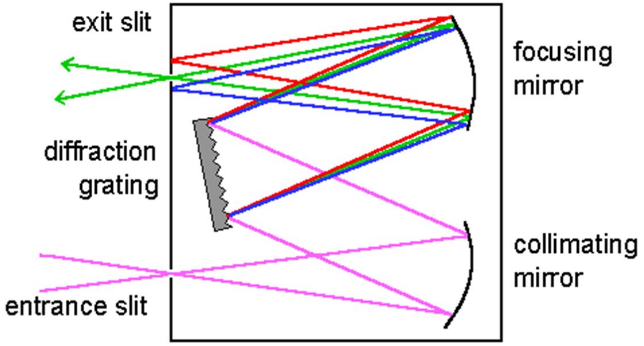
SPECTROSCOPY / SPECTROMETER SET-UP

HR2000+: crossed **Czerny-Turner spectrometer** observing plasma using optical fibre

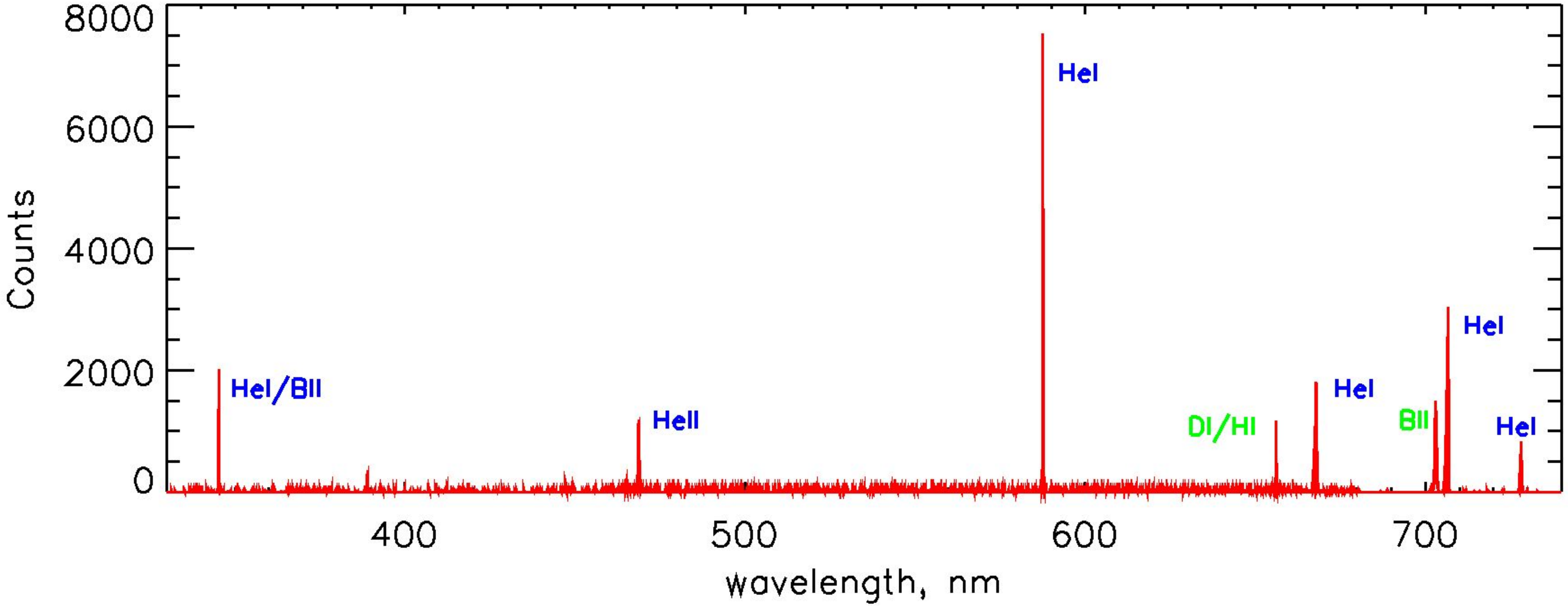


SMA connector for optical fiber

Czerny-Turner set-up



Spectrum of He discharge on COMPASS



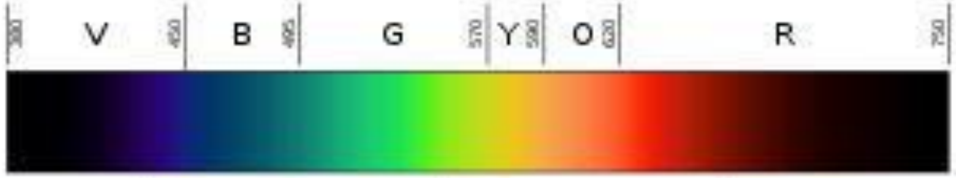
IR 20 µs, VIS 3µs, UV 50 µs, Halpha 20 µs

wavelength - color

https://www.agcled.com/blog/basic-information-of-the-visible-light.html

https://www.pythoninformer.com/computer-science/colour/rgb-colour/

rgb(0%, 0%, 0%)	rgb(50%, 0%, 0%)	rgb(100%, 0%, 0%)
rgb(0%, 50%, 0%)	rgb(50%, 50%, 0%)	rgb(100%, 50%, 0%)
rgb(0%, 100%, 0%)	rgb(50%, 100%, 0%)	rgb(100%, 100%, 0%)
rgb(0%, 0%, 50%)	rgb(50%, 0%, 50%)	rgb(100%, 0%, 50%)
rgb(0%, 50%, 50%)	rgb(50%, 50%, 50%)	rgb(100%, 50%, 50%)
rgb(0%, 100%, 50%)	rgb(50%, 100%, 50%)	rgb(100%, 100%, 50%)
rgb(0%, 0%, 100%)	rgb(50%, 0%, 100%)	rgb(100%, 0%, 100%)
rgb(0%, 50%, 100%)	rgb(50%, 50%, 100%)	rgb(100%, 50%, 100%)
rgb(0%, 100%, 100%)	rgb(50%, 100%, 100%)	rgb(100%, 100%, 100%)



Color	Wavelength (nm)	Frequency (THz)	Photon energy (eV)
violet	380–450	670–790	2.75–3.26
blue	450–485	620–670	2.56–2.75
cyan	485–500	600–620	2.48–2.56
green	500–565	530–600	2.19–2.48
yellow	565–590	510–530	2.10–2.19
orange	590–625	480–510	1.98–2.10
red	625–750	400–480	1.65–1.98