INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

EMTRAIC 2024

He discharges with transition on GOLEM - spectroscopic study

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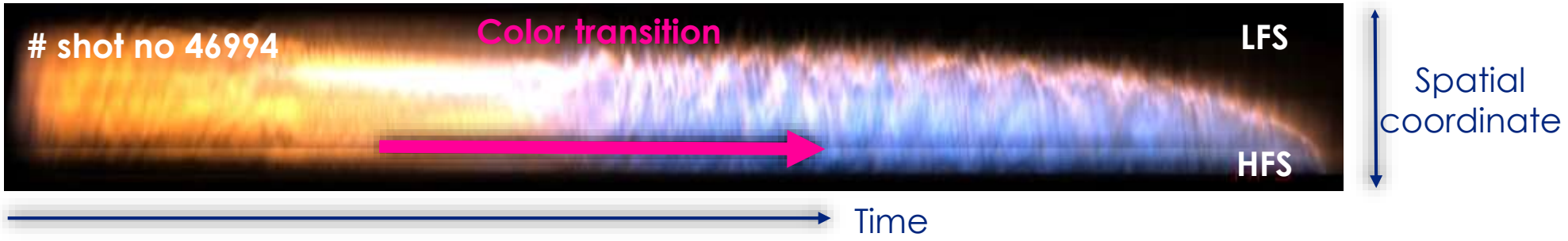
MINISTRY OF EDUCATION
YOUTH AND SPORTS

Motivation

What is behind the transition in He discharges in GOLEM?



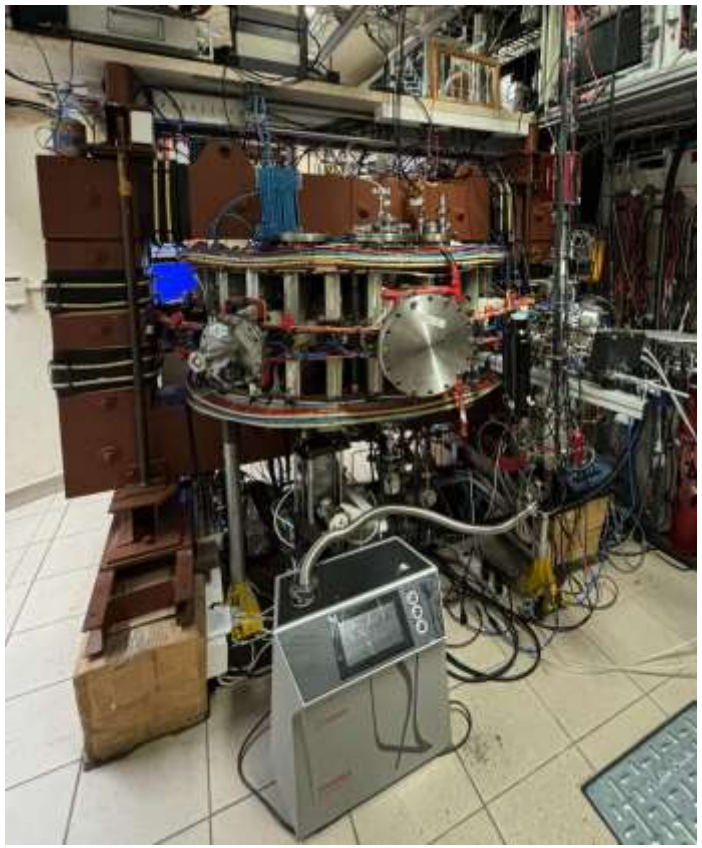
High-speed camera (40 kfps, time evolution of the narrow spatial stripe)

CURRENT TASKS

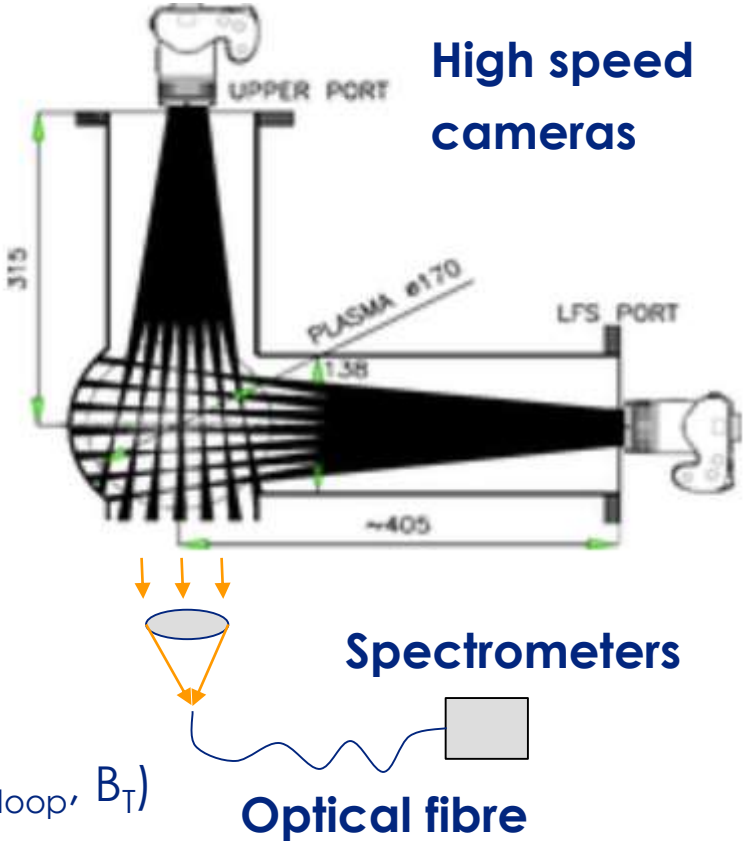
1) **Spectral Calibration**
2) **Critical parameters?** → Ip scan (1-2 kA)
3) **Effect of breakdown and B_T ?** → B_T shift scan
4) **Spectra analysis** → Time evolution of spectra lines, search for impurities.

Set up: GOLEM TOKAMAK

- **Small university tokamak at FNSPE CTU in Prague**



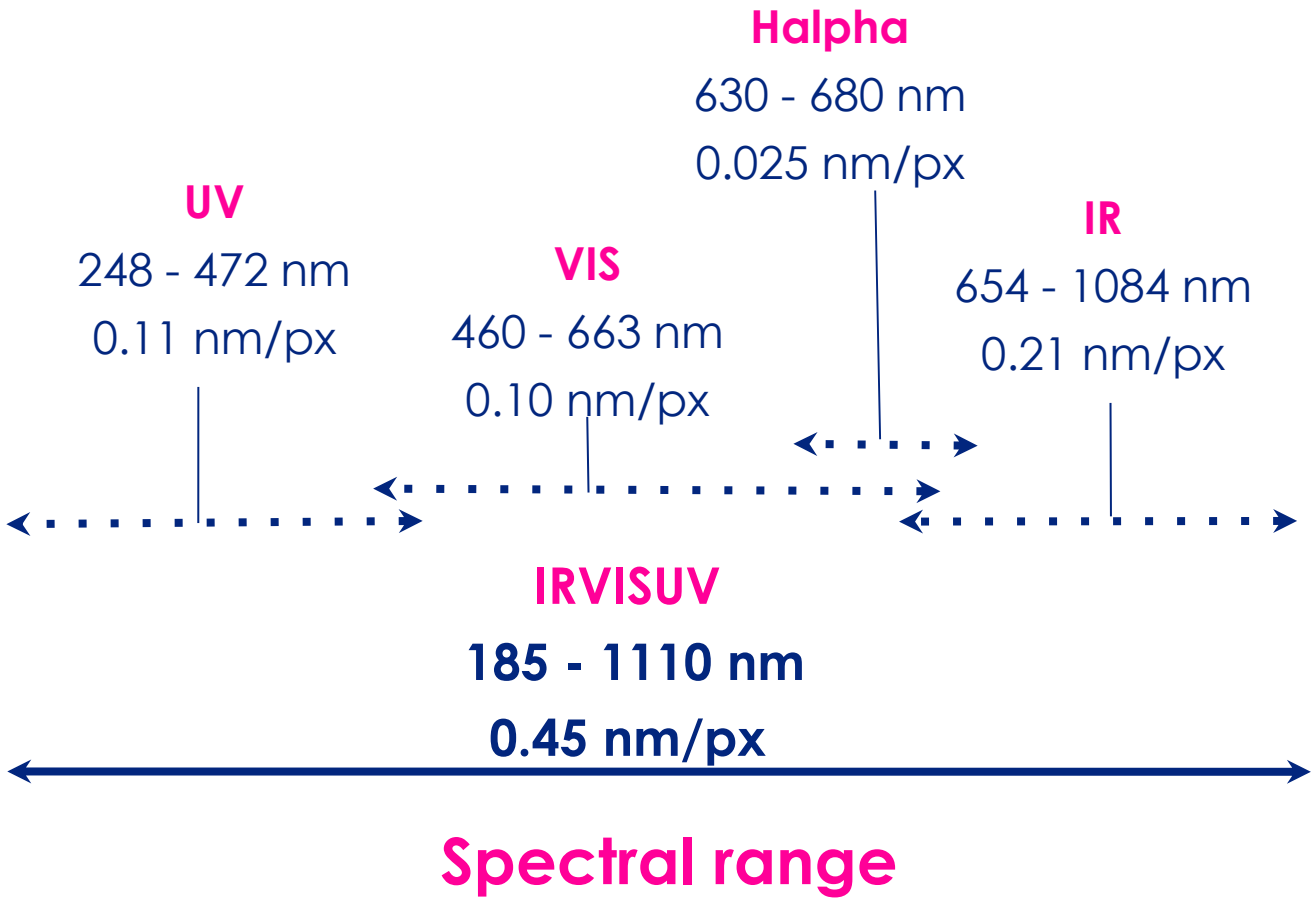
I_p	< 5 kA
B_T	< 0.5 T (sinusoidal)
$\langle n_e \rangle$	< 3×10^{19} m^{-3}
$T_e(0)$	< 100 eV



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)



Spectrometers at GOLEM connected with the tokamak via optical fibers

Spectra Calibration

IRVISUV → Calibrated during SUMTRAIC 2024

$$\lambda[nm] = 186.71 + 0.48\,x - 1.51 \cdot 10^{-5}\,x^2 + 4.01 \cdot 10^{-10}\,x^3$$ ✓

HALPHA

$$\lambda[nm] = 629.78 + 0.03\,x - 4.00 \cdot 10^{-6}\,x^2 + 7.20 \cdot 10^{-11}\,x^3$$ ✓

UV

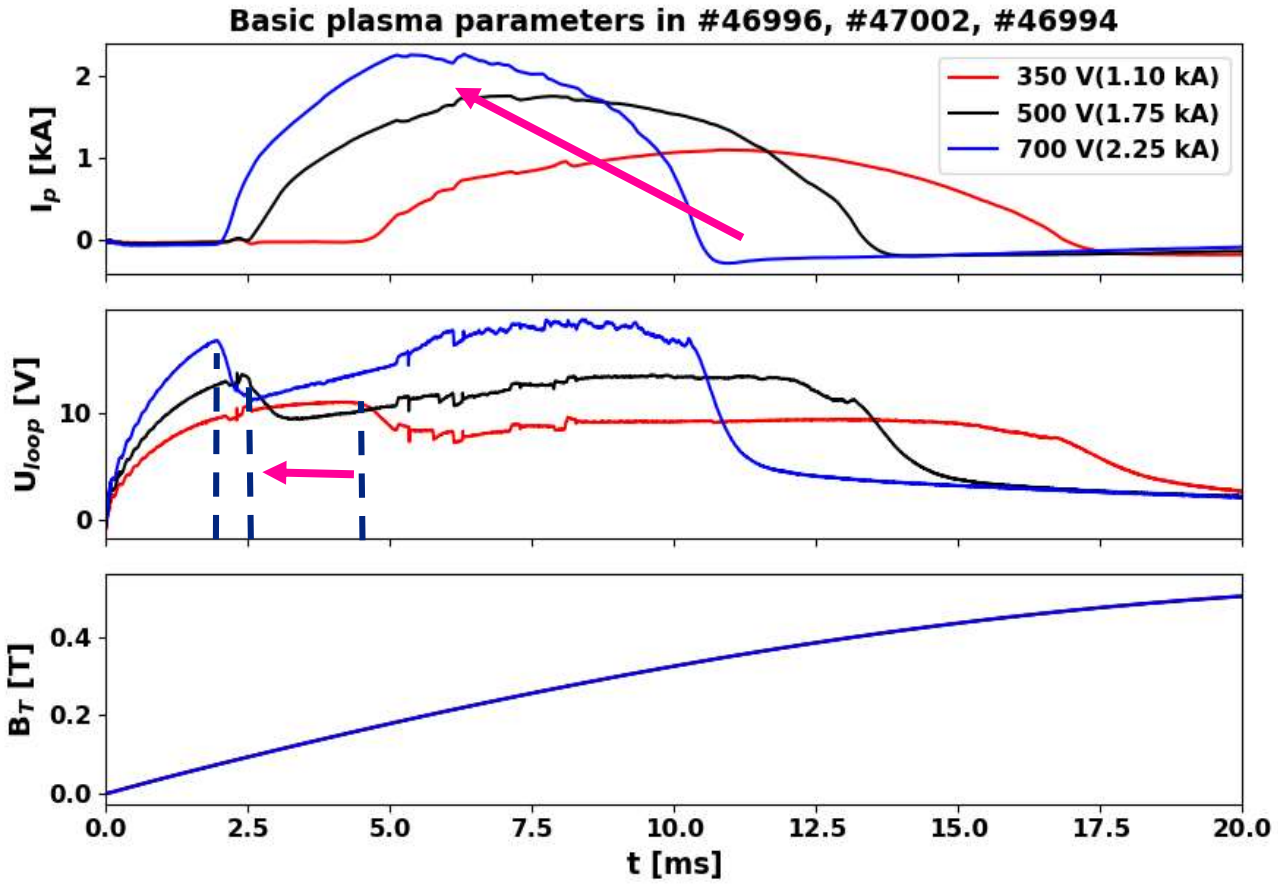
$$\lambda[nm] = 246.87 + 0.12\,x - 3.85 \cdot 10^{-6}\,x^2 + 8.24 \cdot 10^{-11}\,x^3$$ ✓

Extra slides…

I_p scan

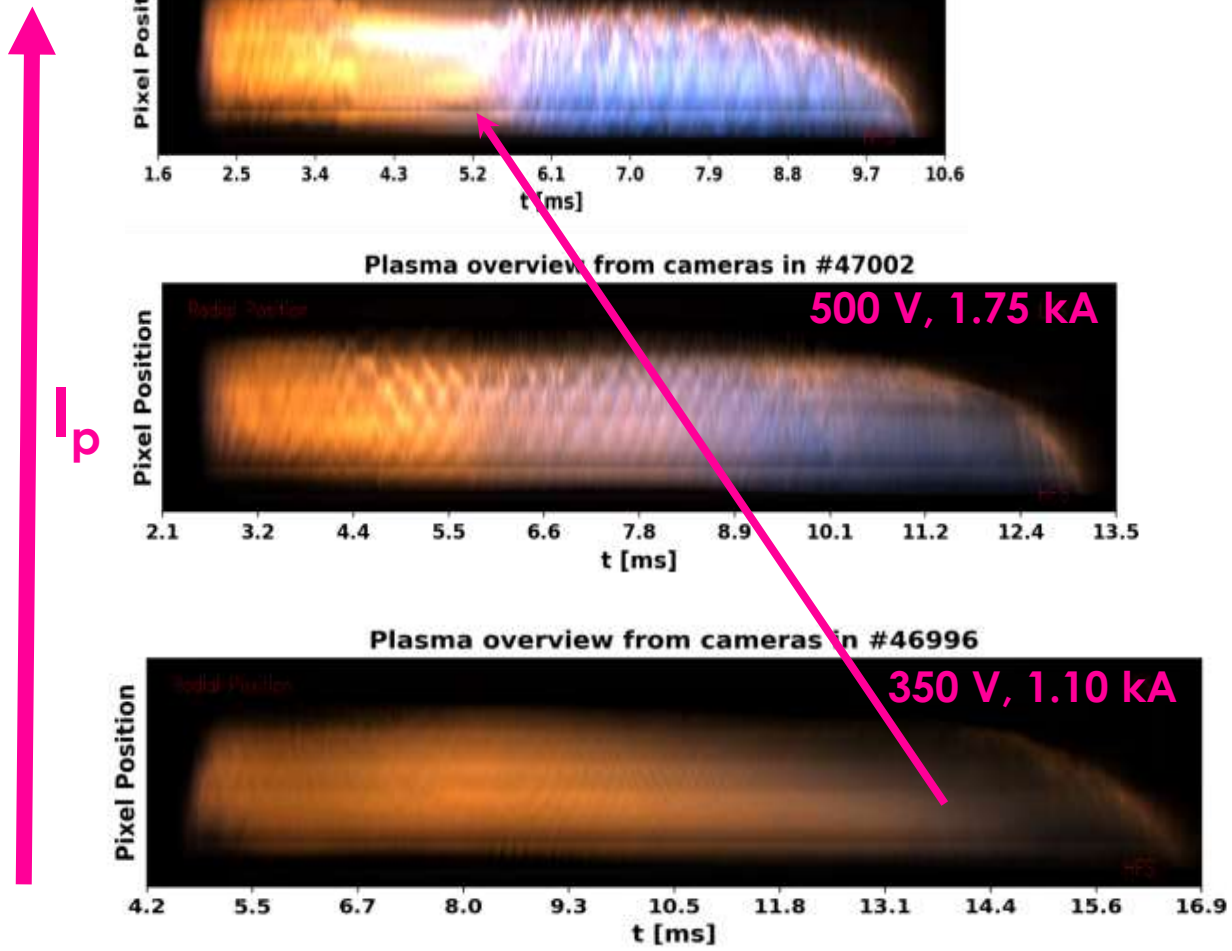
SHOT NUMBER	$U_{CURRENT\ DRIVE}$ [V]	$I_{P,\ MAX}$ [kA]
46993	350	1.10
46996	**350**	**1.10**
46998	400	1.35
47000	450	1.55
47002	**500**	**1.75**
47001	550	1.90
46999	600	2.05
46997	650	2.15
46991	700	2.20
46994	**700**	**2.25**

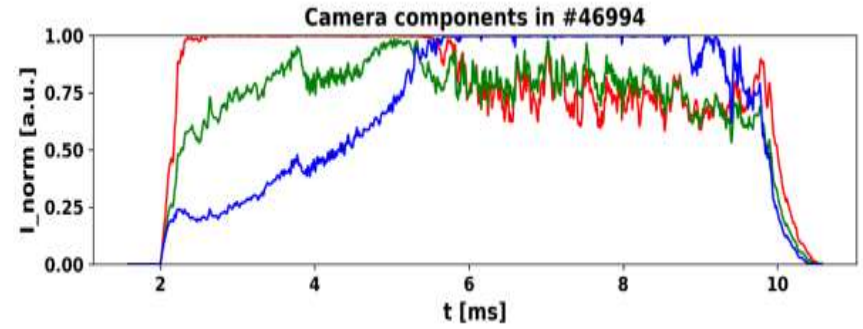
Table of shots with increasing plasma current maximum.

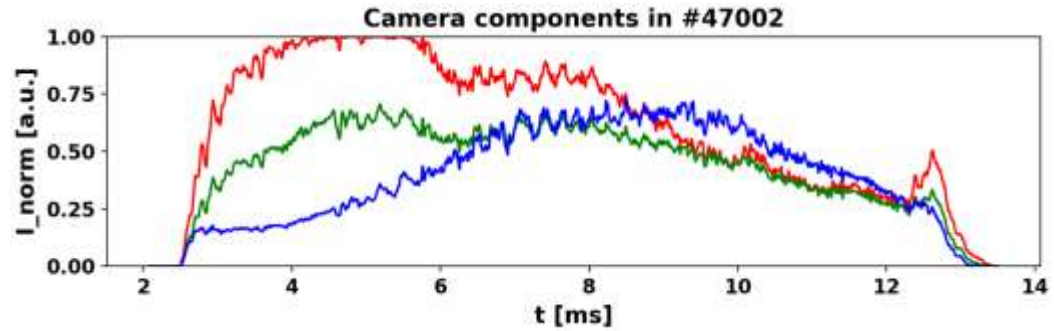


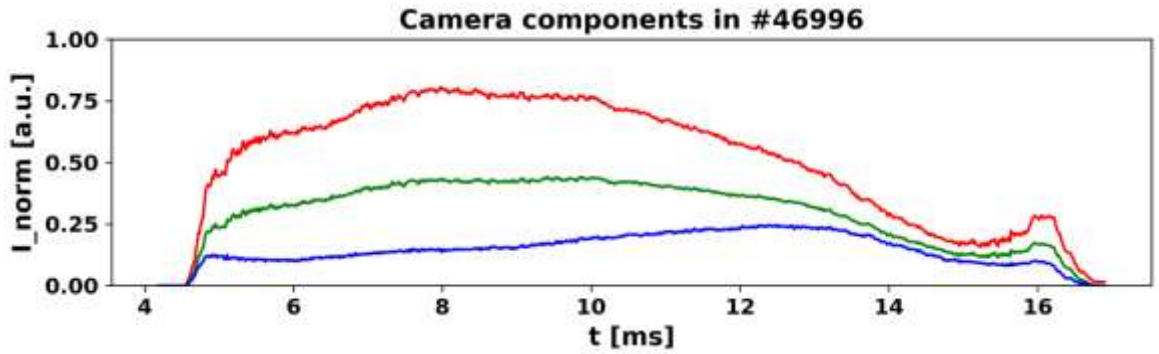
Evolution of plasma parameters for shots with different plasma current.

I_p scan: Color transition



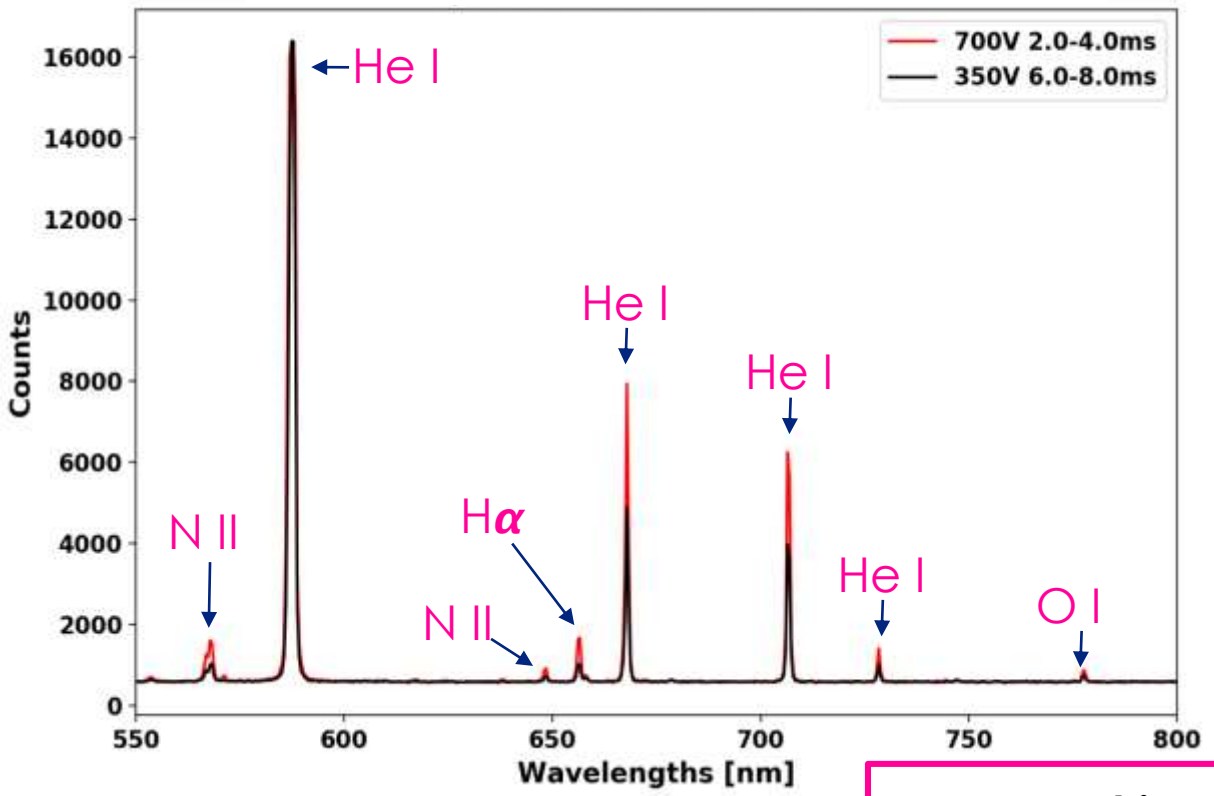




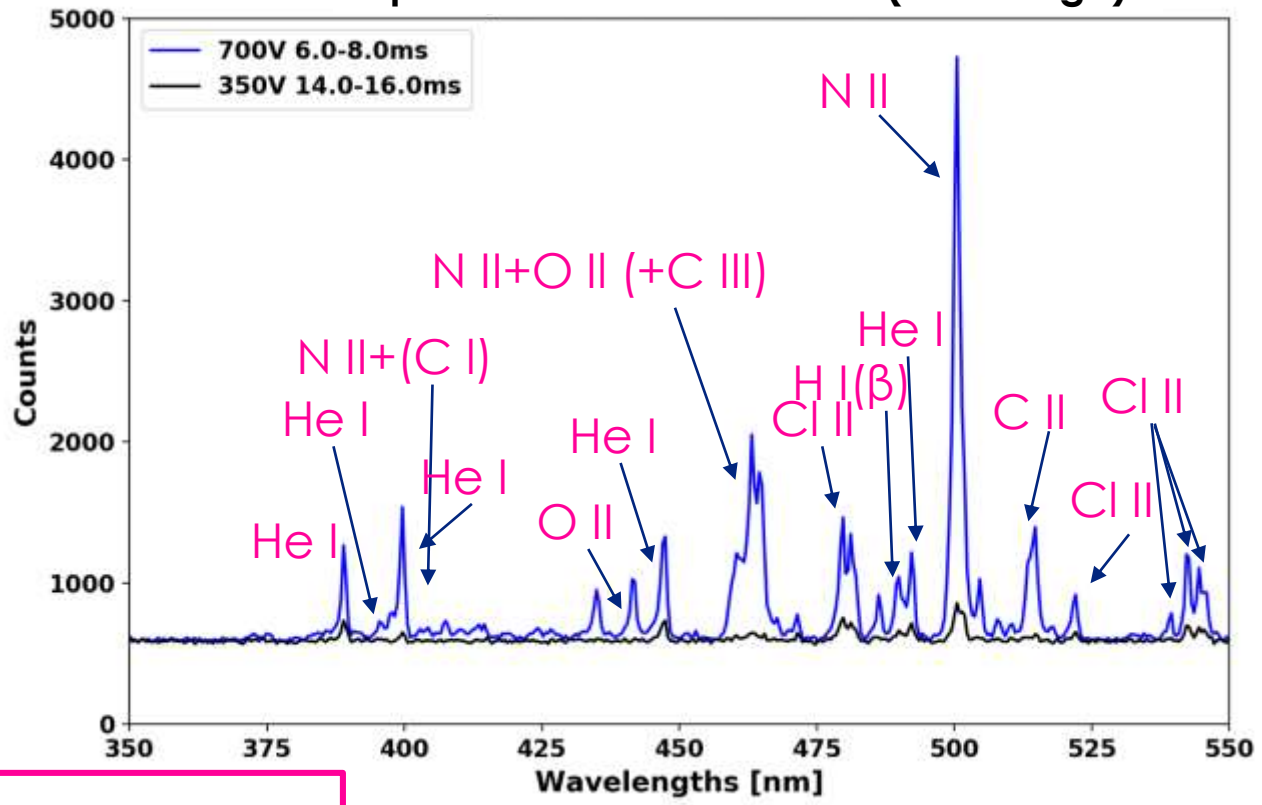


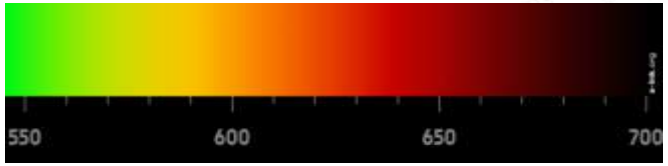
Ip scan: Spectra

Spectra before the transition (Red range)

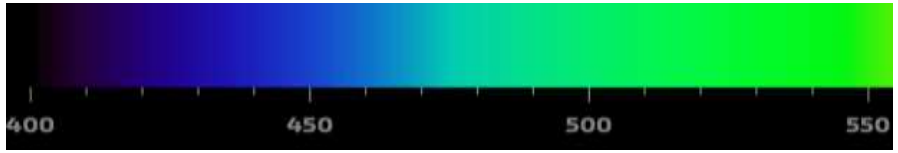


Spectra after the transition (Blue range)





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

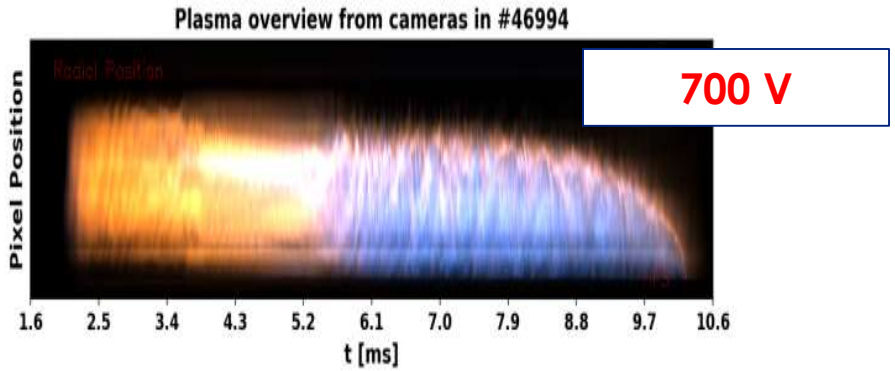


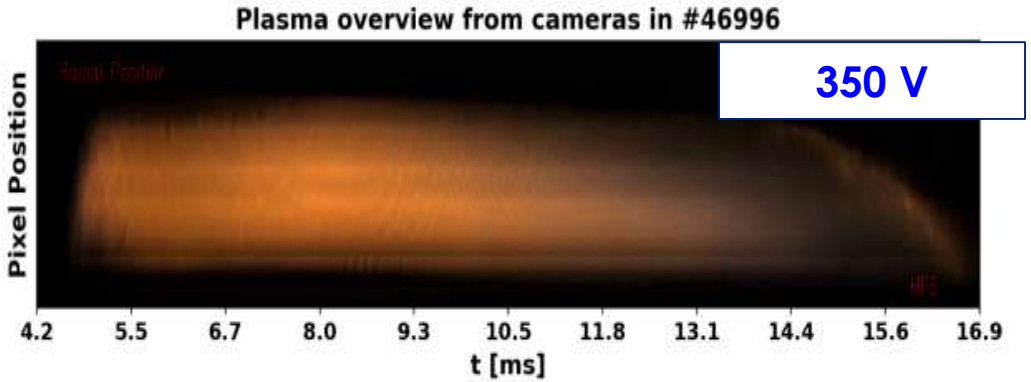
Ip scan: Time evolution of spectra

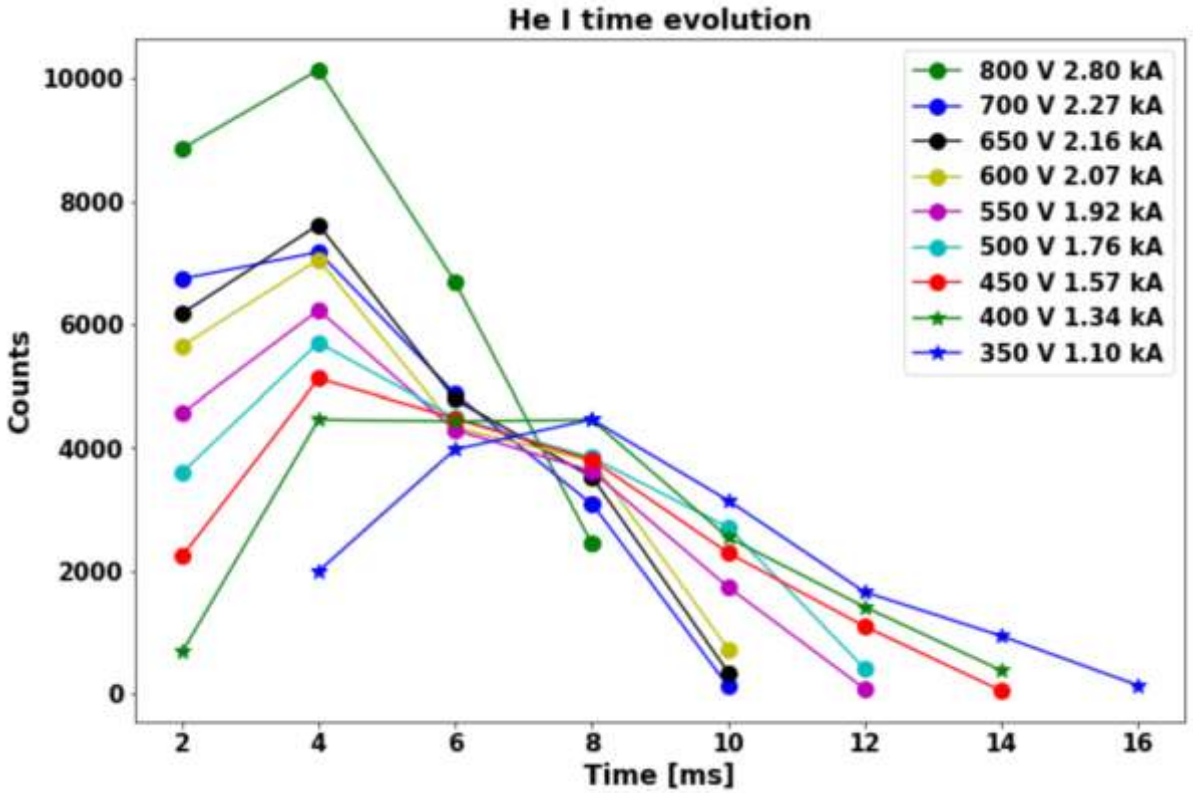
He I (667.8 nm)

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

I_p



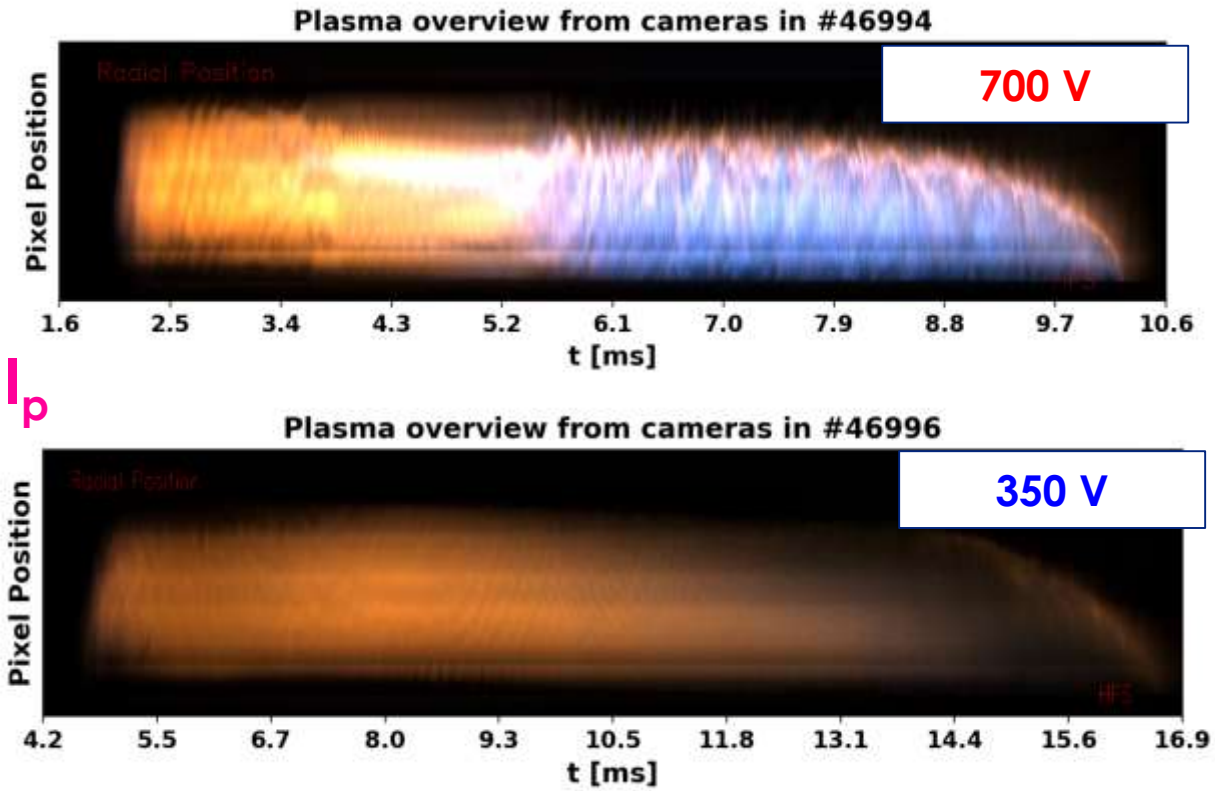


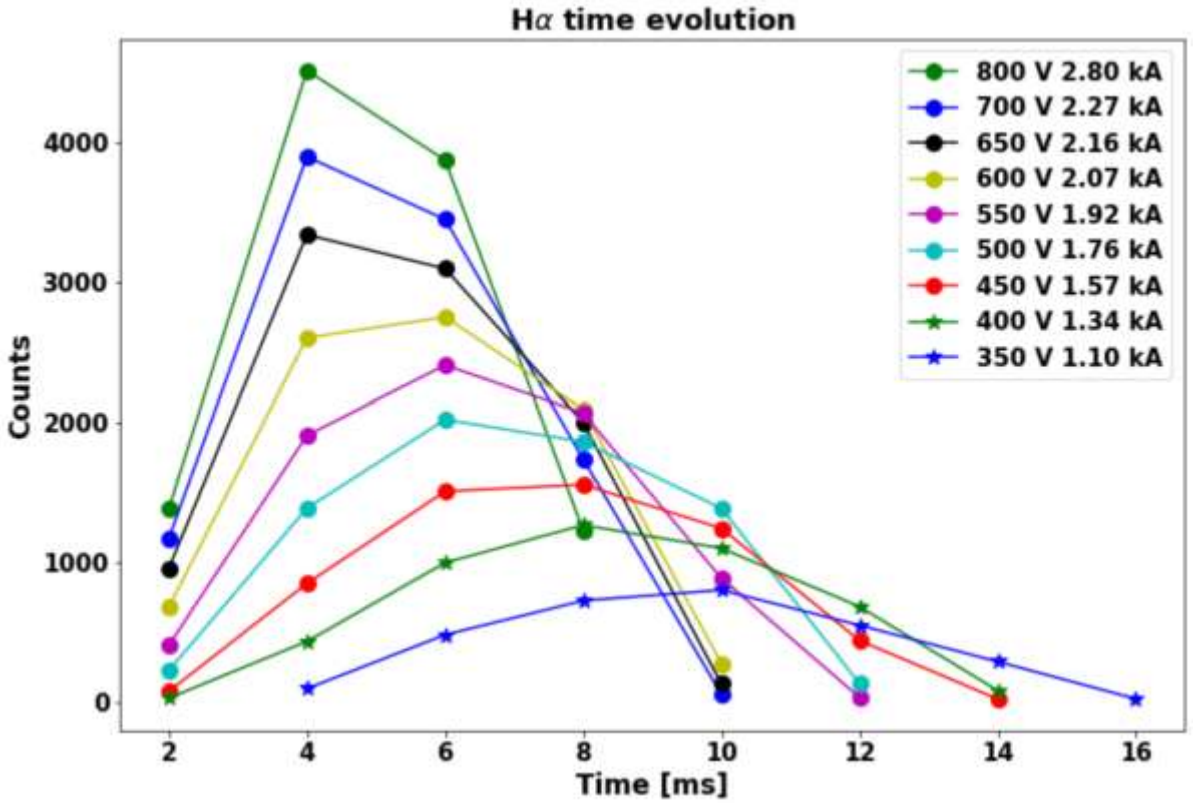


Source: Working gas

Ip scan: Time evolution of spectra

Hα (656.3 nm)

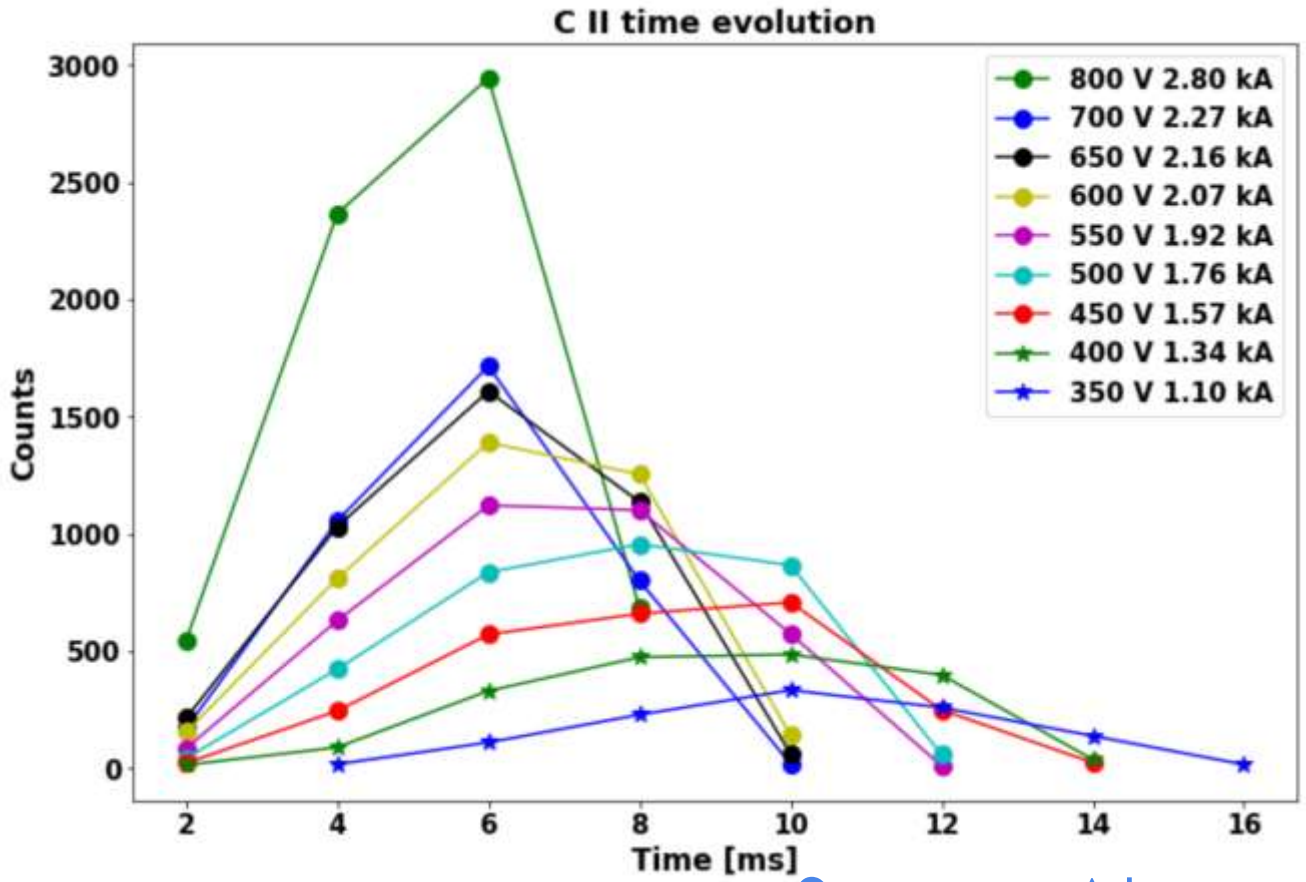




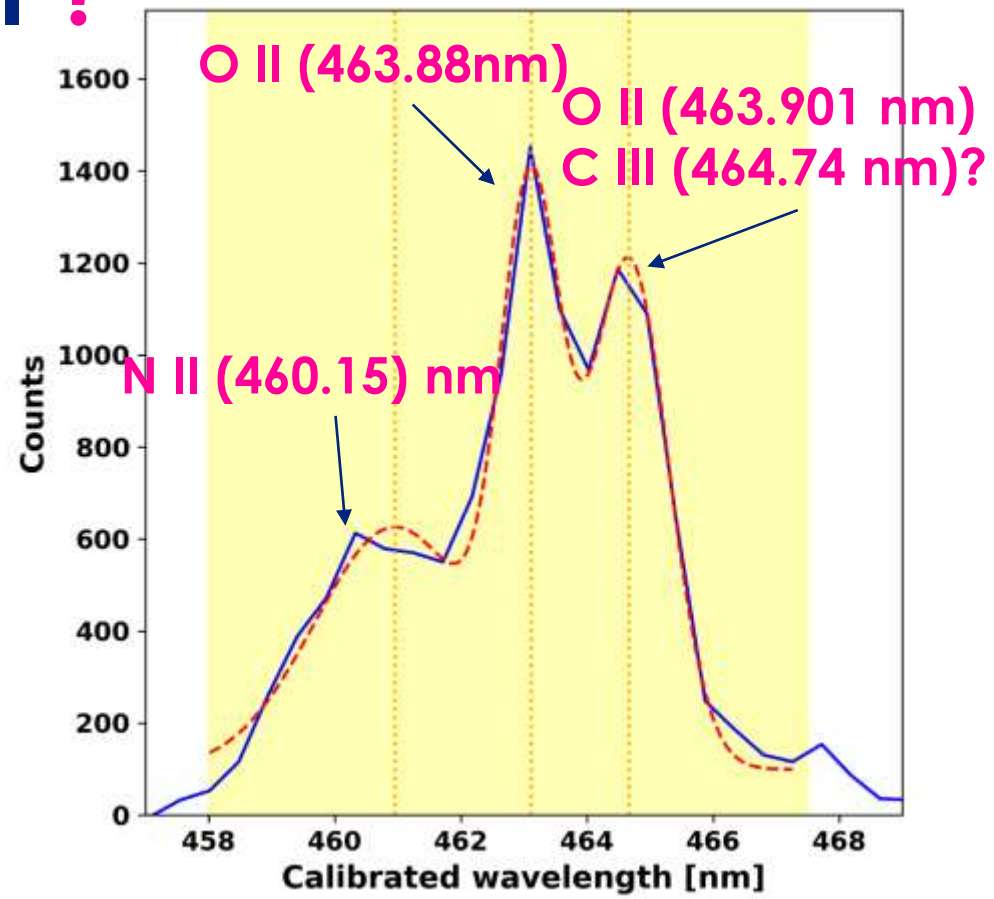
Source: Atmosphere (H_2O), in-vessel materials, previous shots, PVC

Ip scan: Time evolution of spectra

C II (657.80nm)



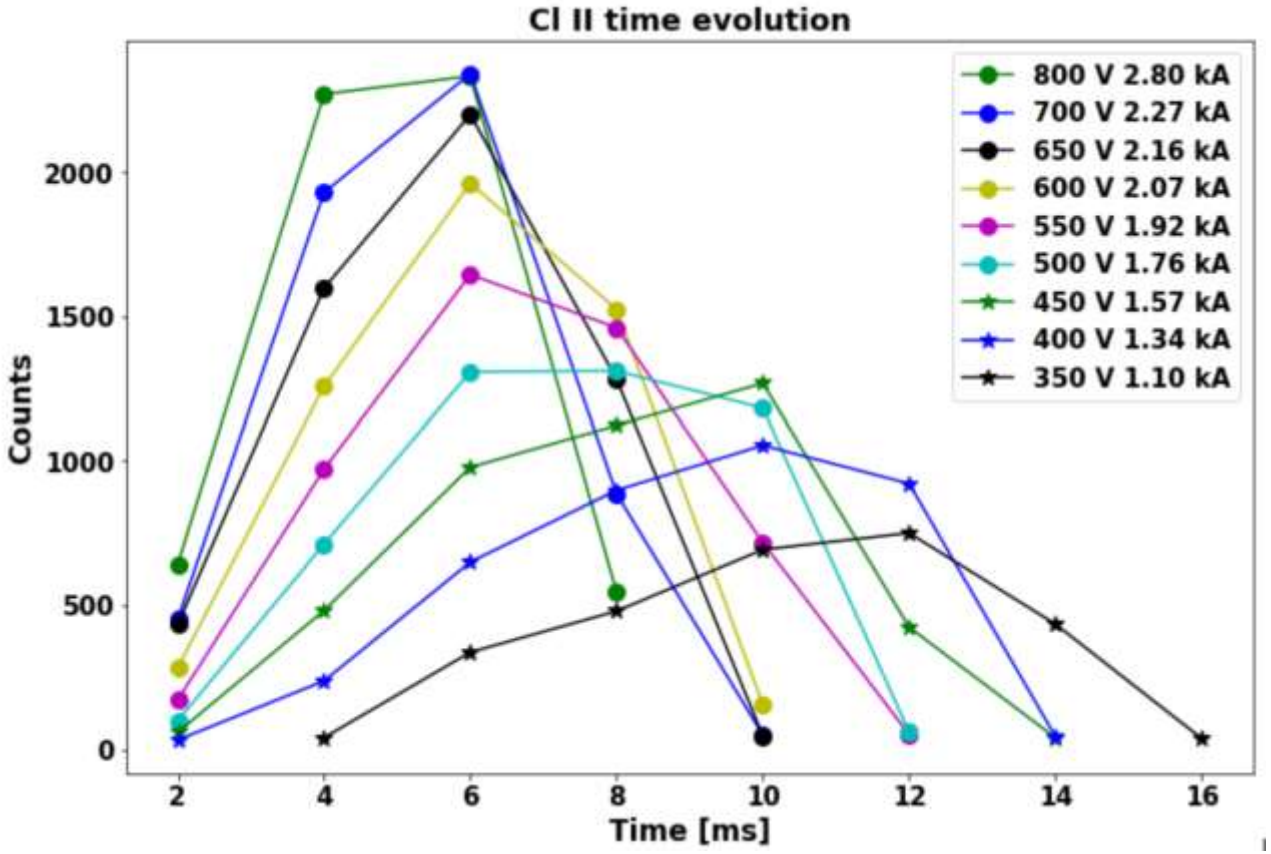
C III ?

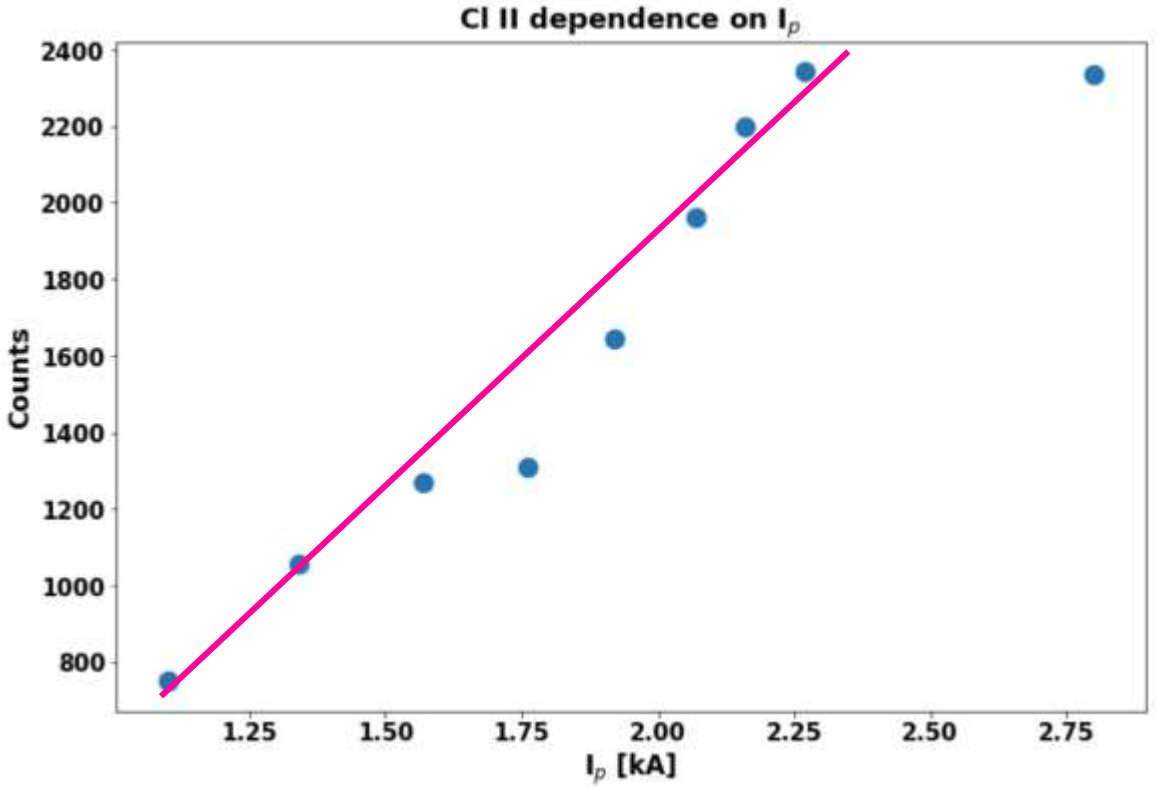


Source: Atmosphere (CO_2), PVC, Steel, pumping

Ip scan: Time evolution of spectra

Cl II (479.46 nm)



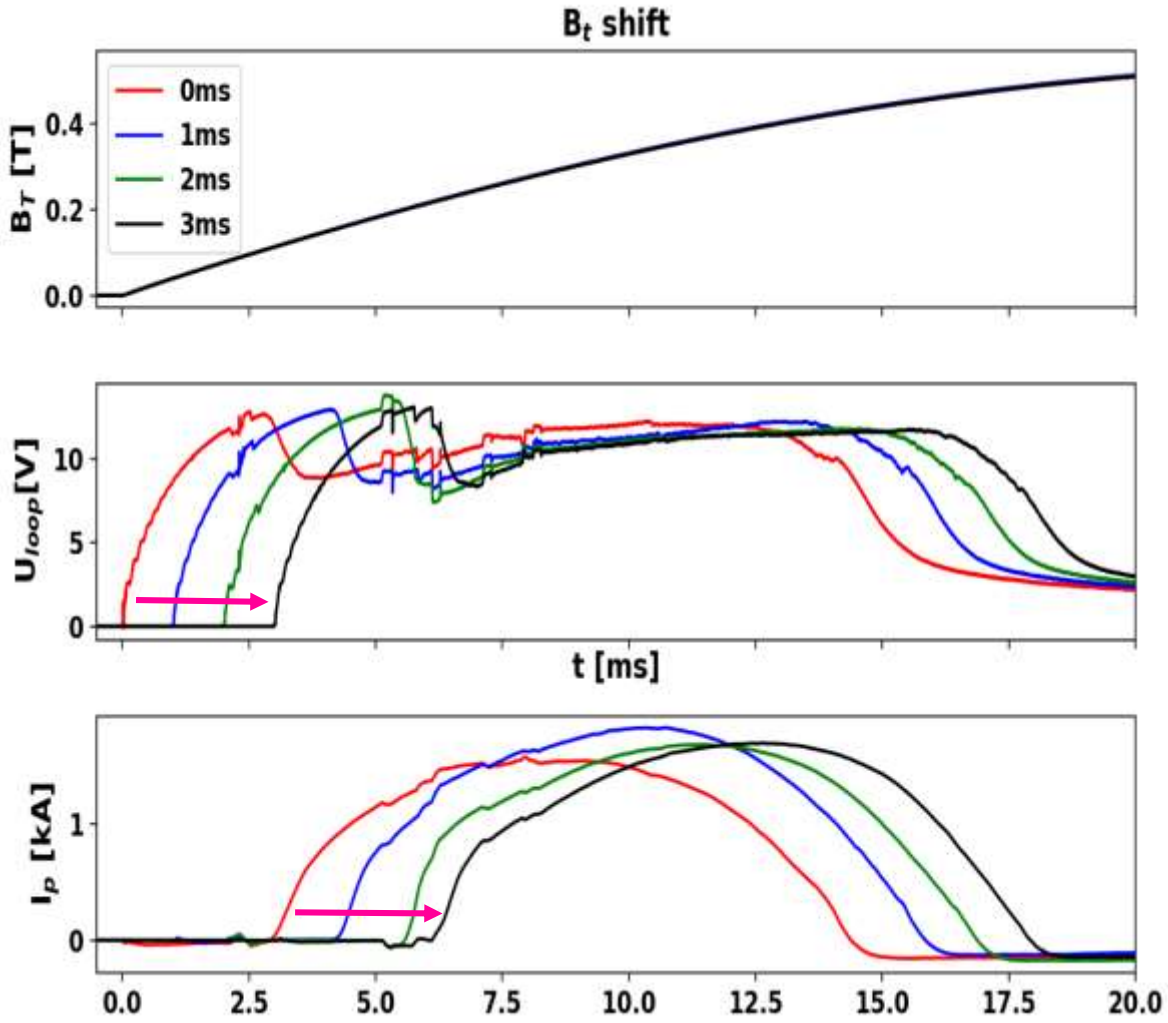


Source: PVC → **cable insulation!**

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

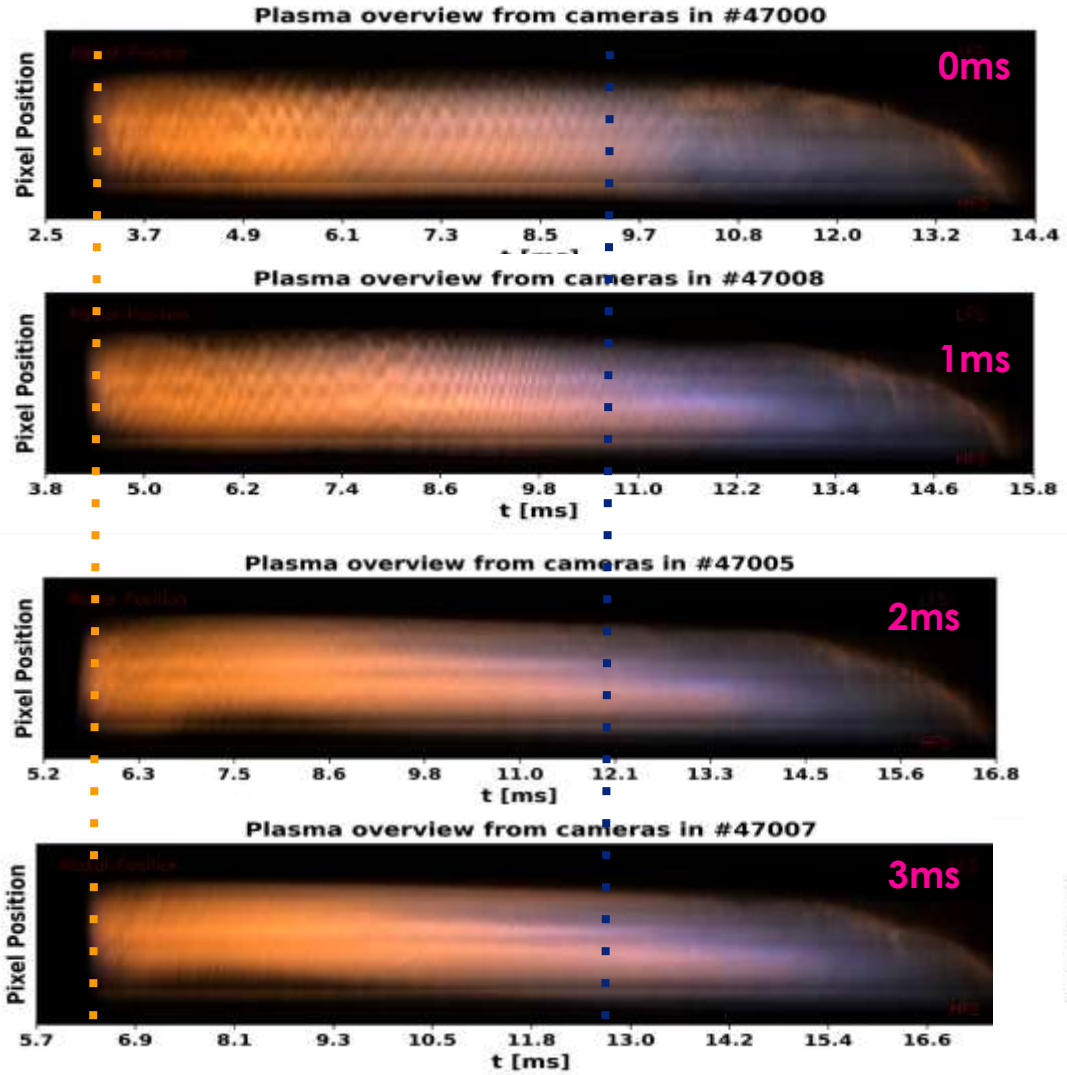
Table of shots with similar current drive values but different toroidal magnetic field shift.

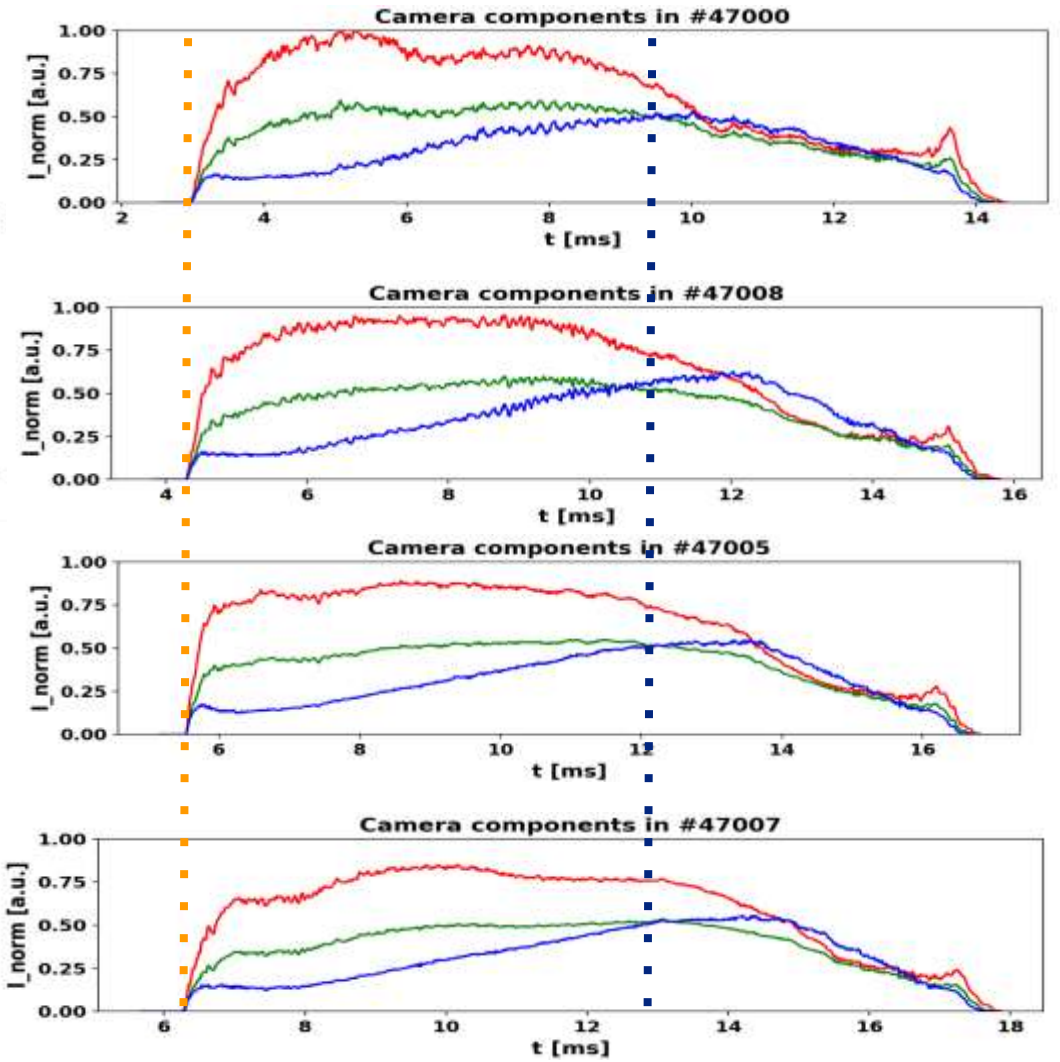


B_T shift scan: Color transition, MHD

B_T

MHD activity

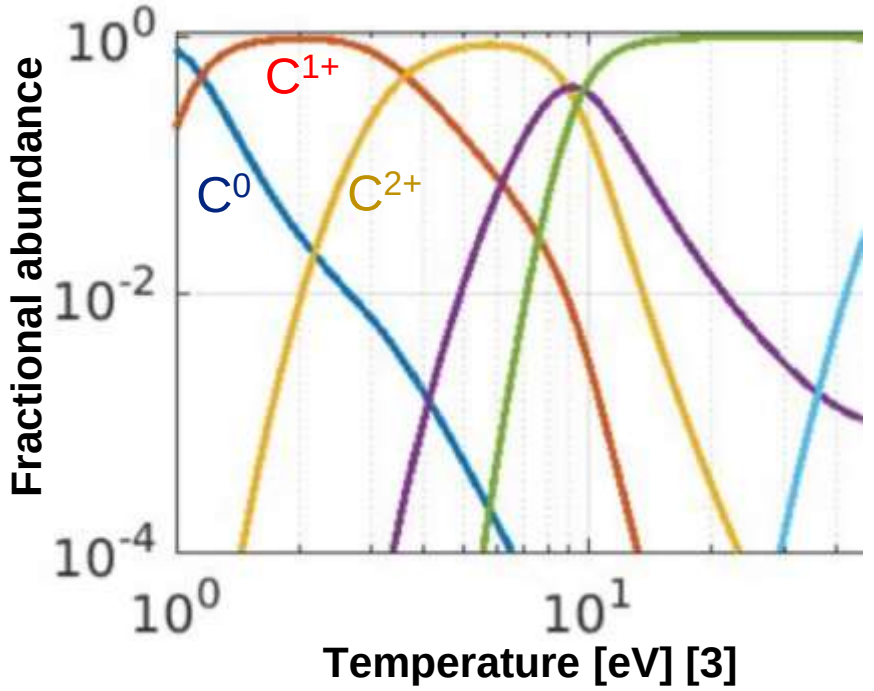




Spectral mystery

- 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+}



Possible reasons:

- Weak lines and noise
- Overlapping lines

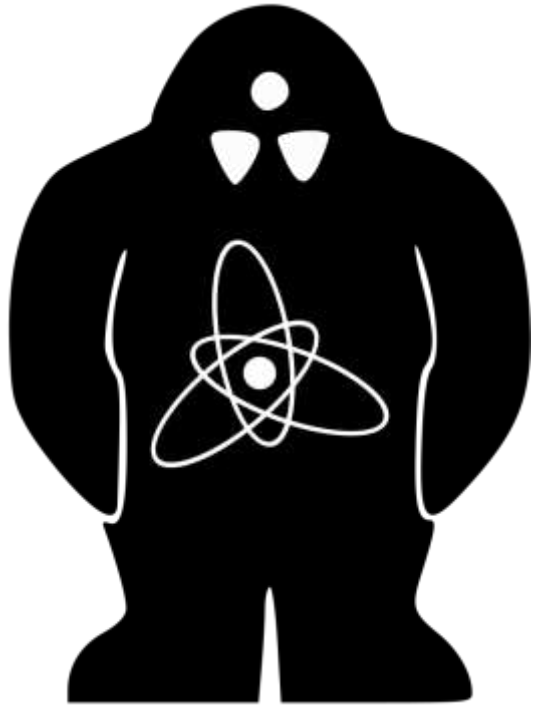
Conclusions

1) **Spectral Calibration** → newly done for Halpha, UV spectrometers 😃

1) **Critical parameters** → smooth behaviour in I_p ($I_{p,crit}$ not found)

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

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



Deep analysis using the measured data possible

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

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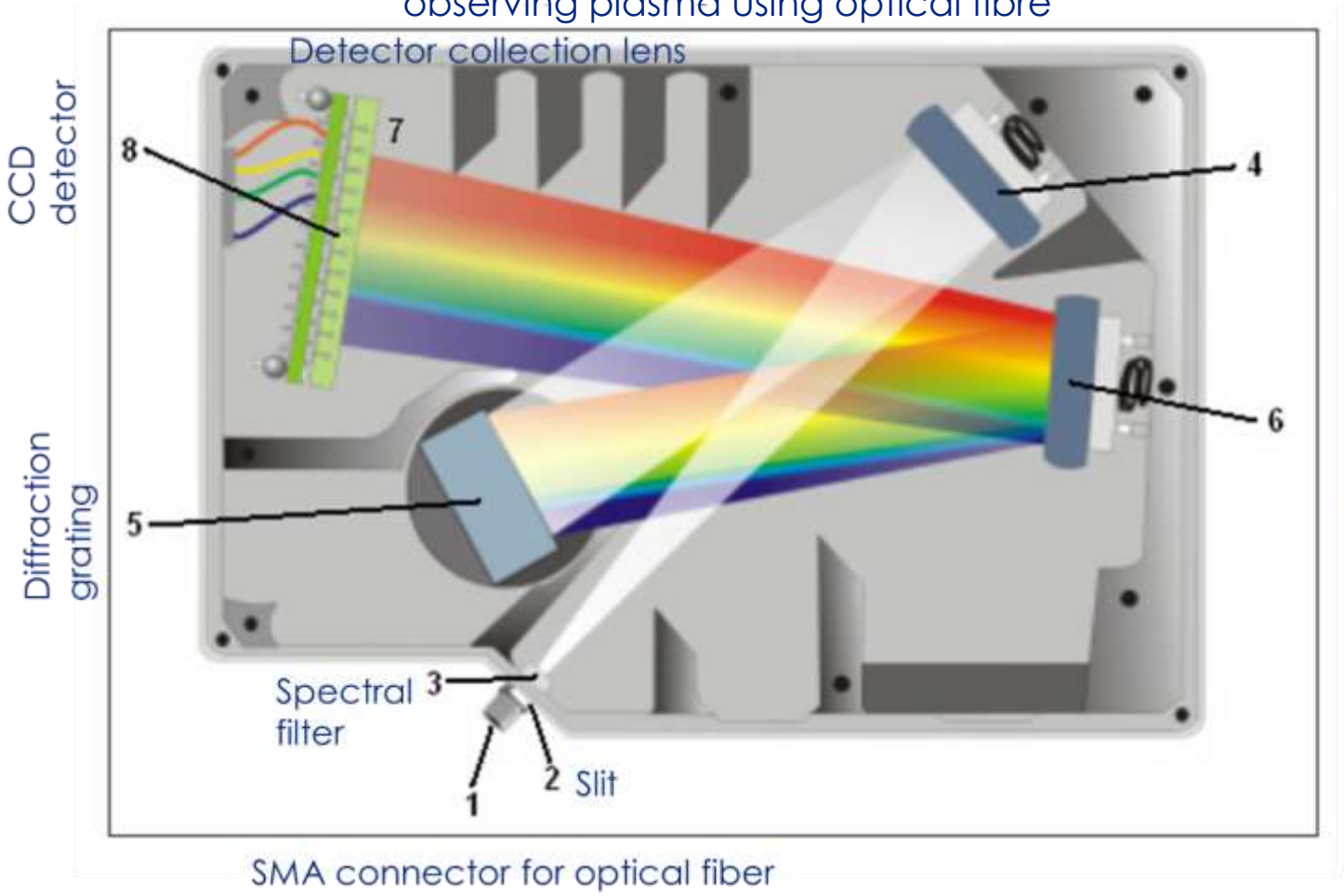
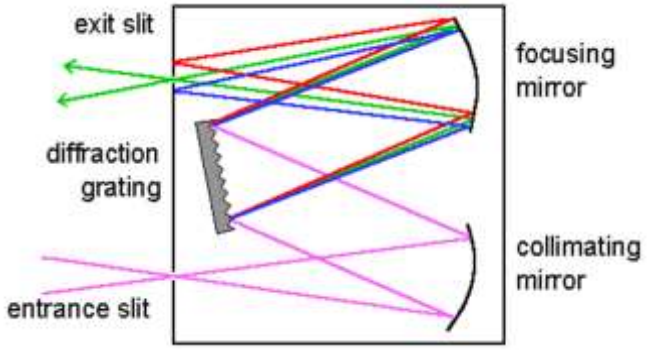
Extra slides

SPECTROSCOPY / SPECTROMETER SET-UP

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



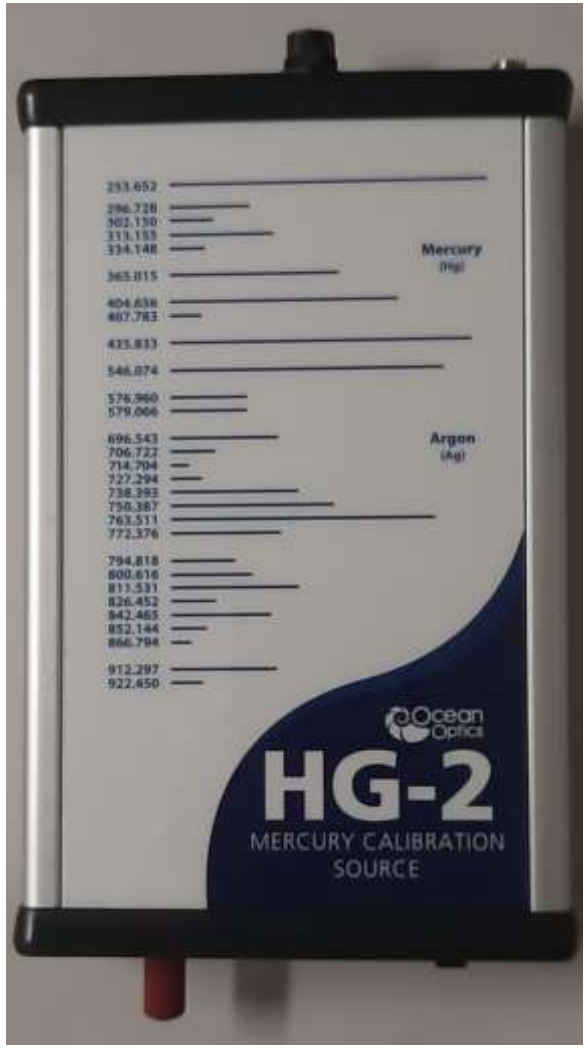
Czerny-Turner set-up



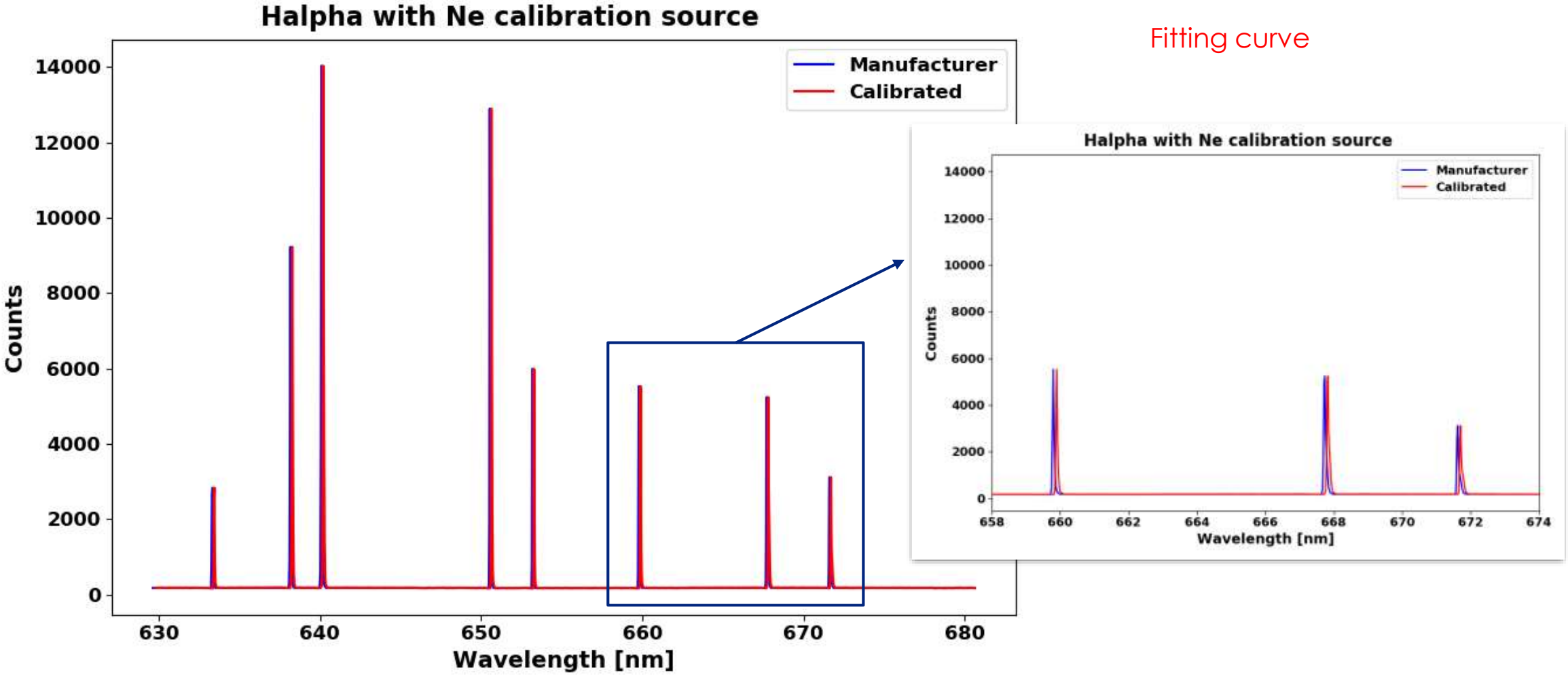
Spectral Calibration

allows precise wavelength assignment

- **Hg-2 (Hg+Ar) spectral calibration source:** UV-IPP spectrometer calibrated (60 ms); usable for VIS-TG (done within SUMTRAIC 2024), IR-IPP and VIS-IPP
- **Ne-2 spectral calibration source:** Halpha-IPP spectrometer calibrated (1.6 ms, partly removed fibre); usable for VIS-IPP

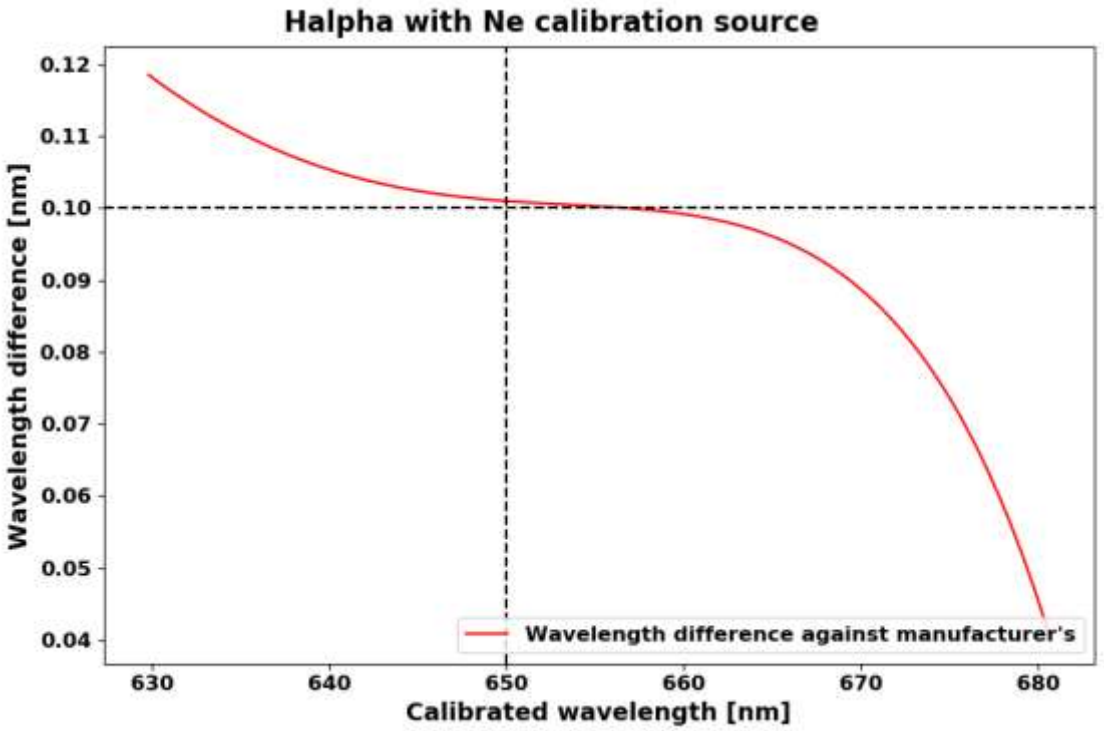


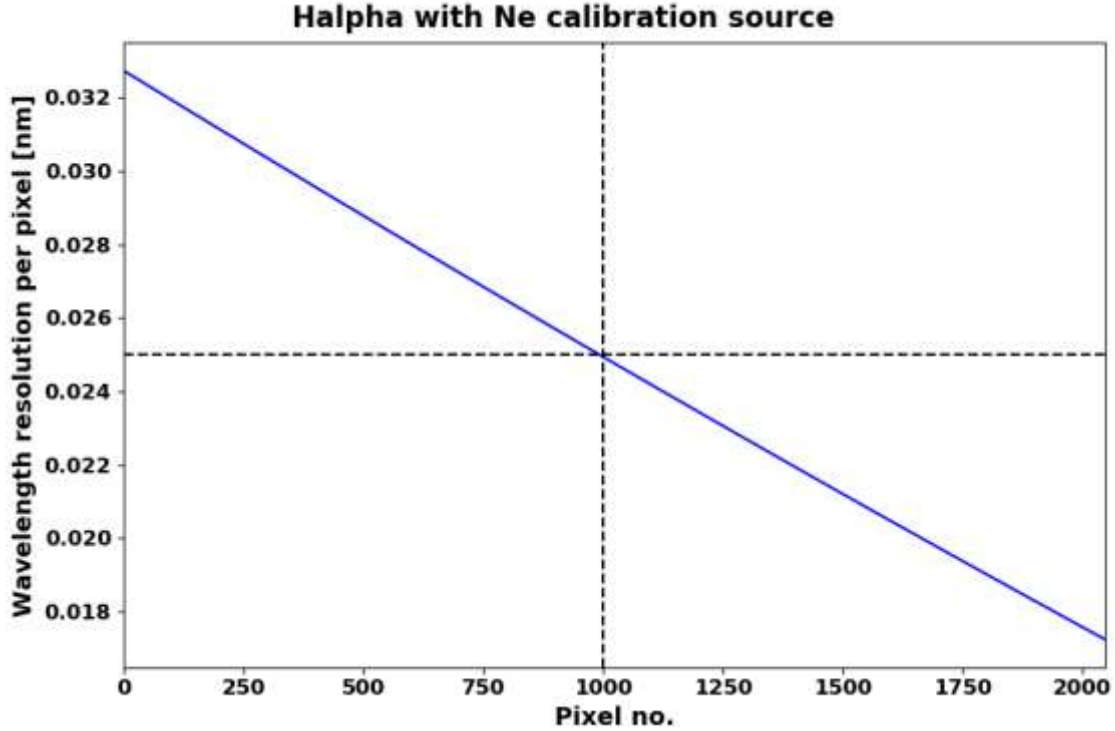
Spectral calibration of Halpha-IPP



Fitting curve

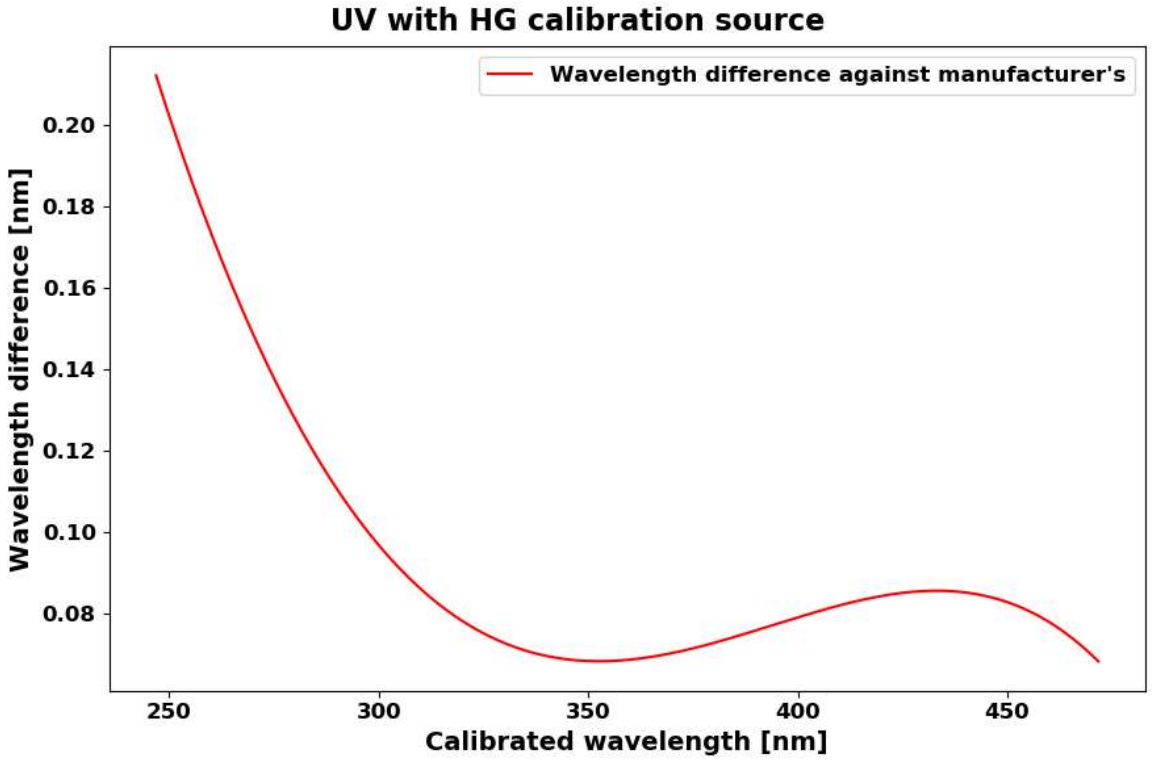
Spectral calibration of Halpha-IPP

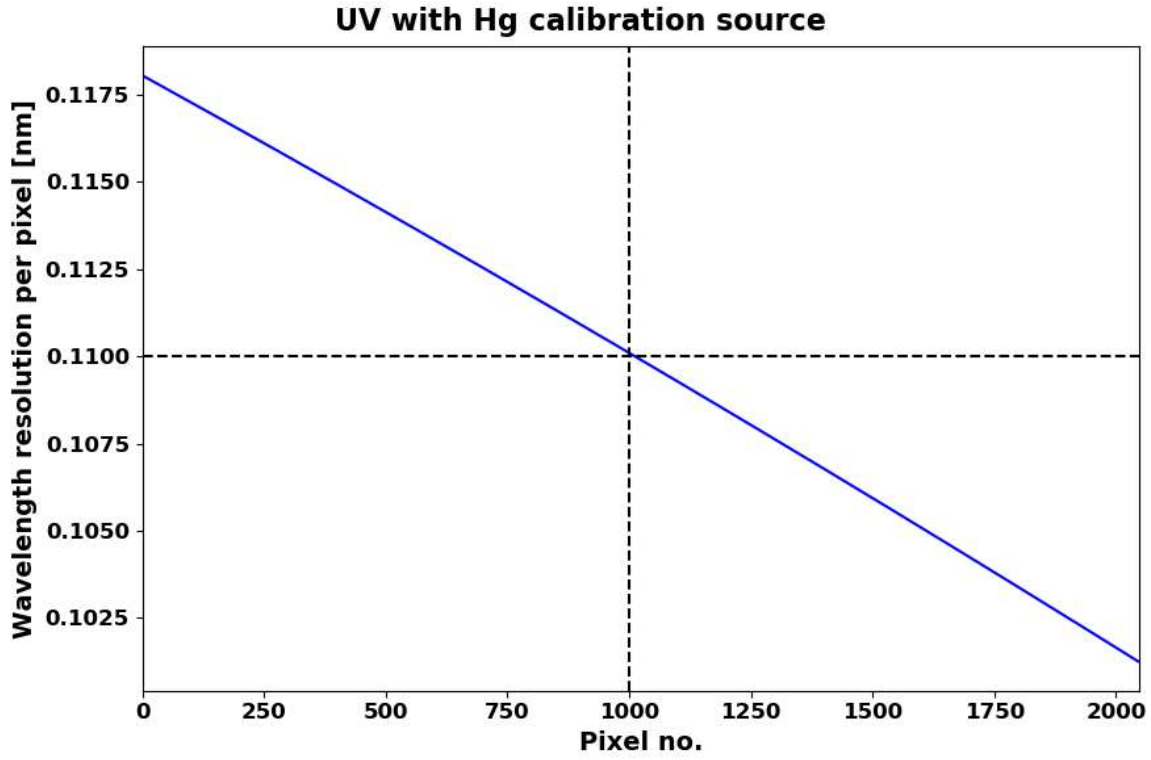




- **Wavelength difference Δλ ~ 0.1nm** against the manufacturer's calibration
- Resolution per pixel ~ 0.025 nm/pixel → ~ 4 pixels systematic shift, if not included
- FWHM ~ 0.055 nm

UV Spectral Calibration



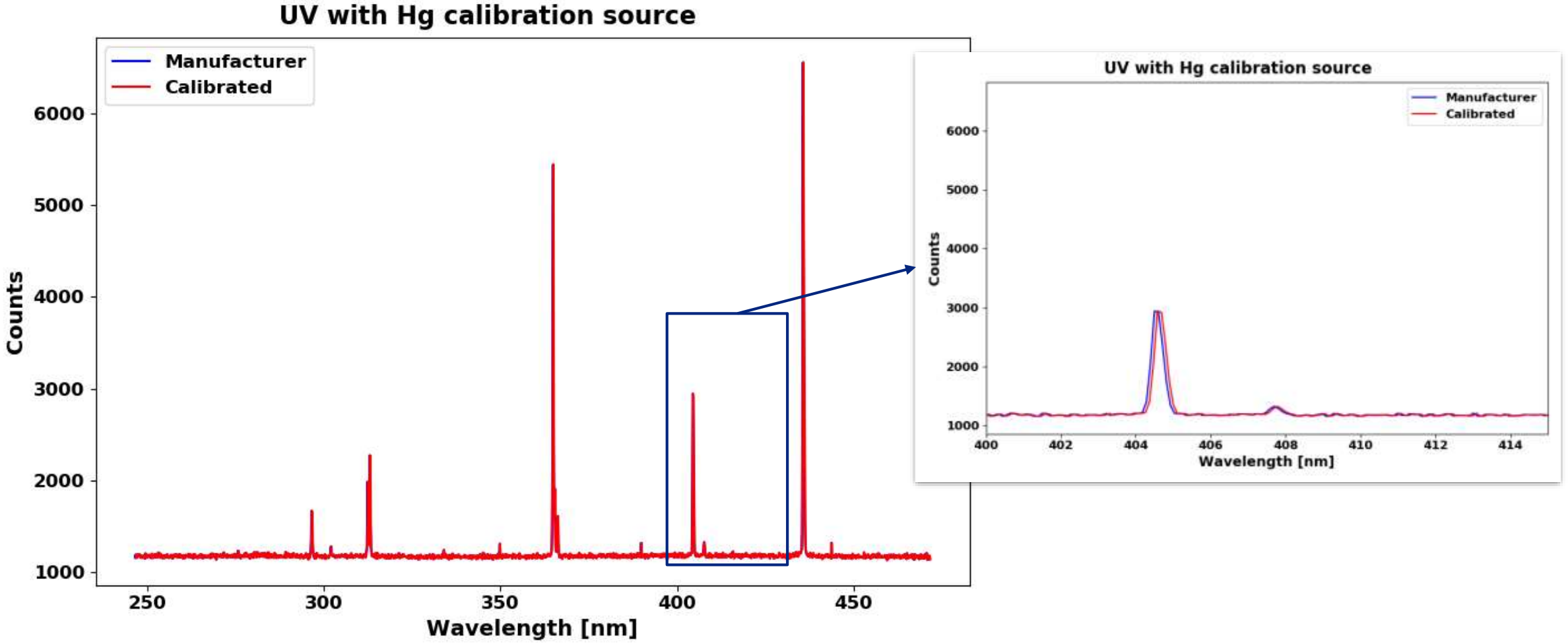


- Around the center λ difference ~ 0.07nm
- Blue region λ difference ~ 0.09nm

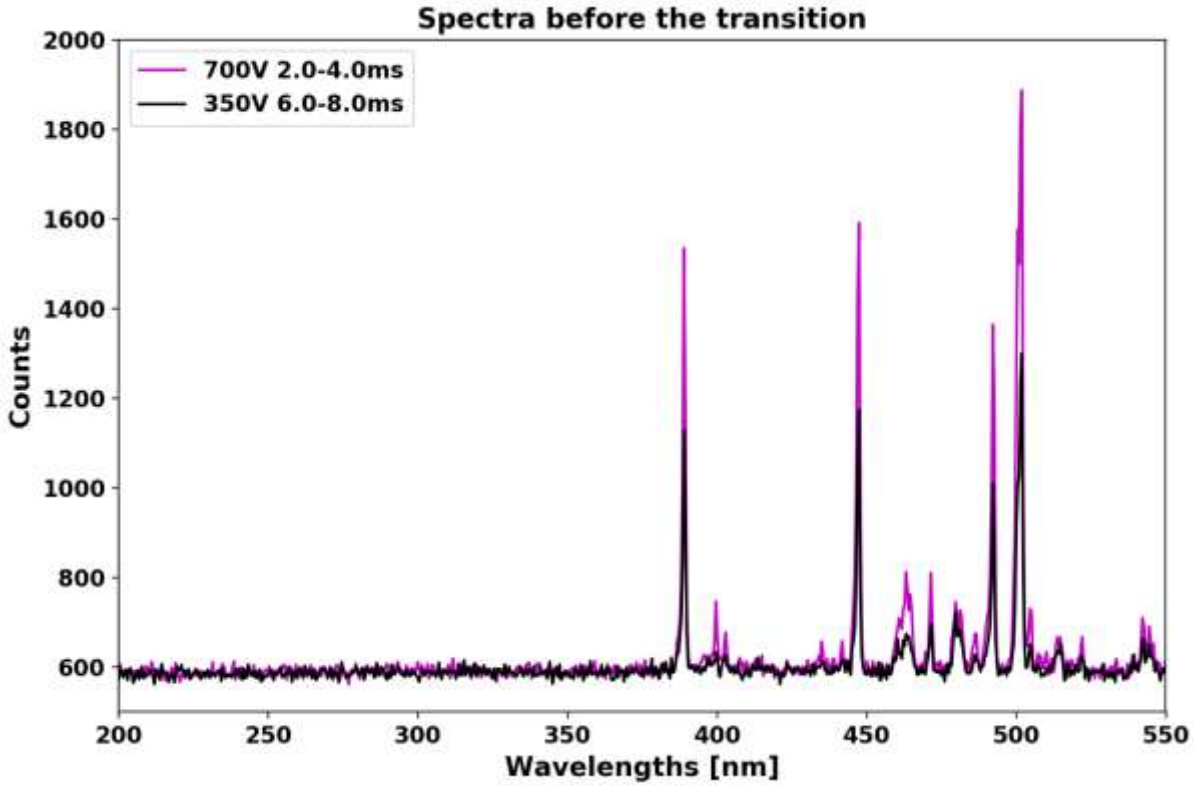
  → Small difference

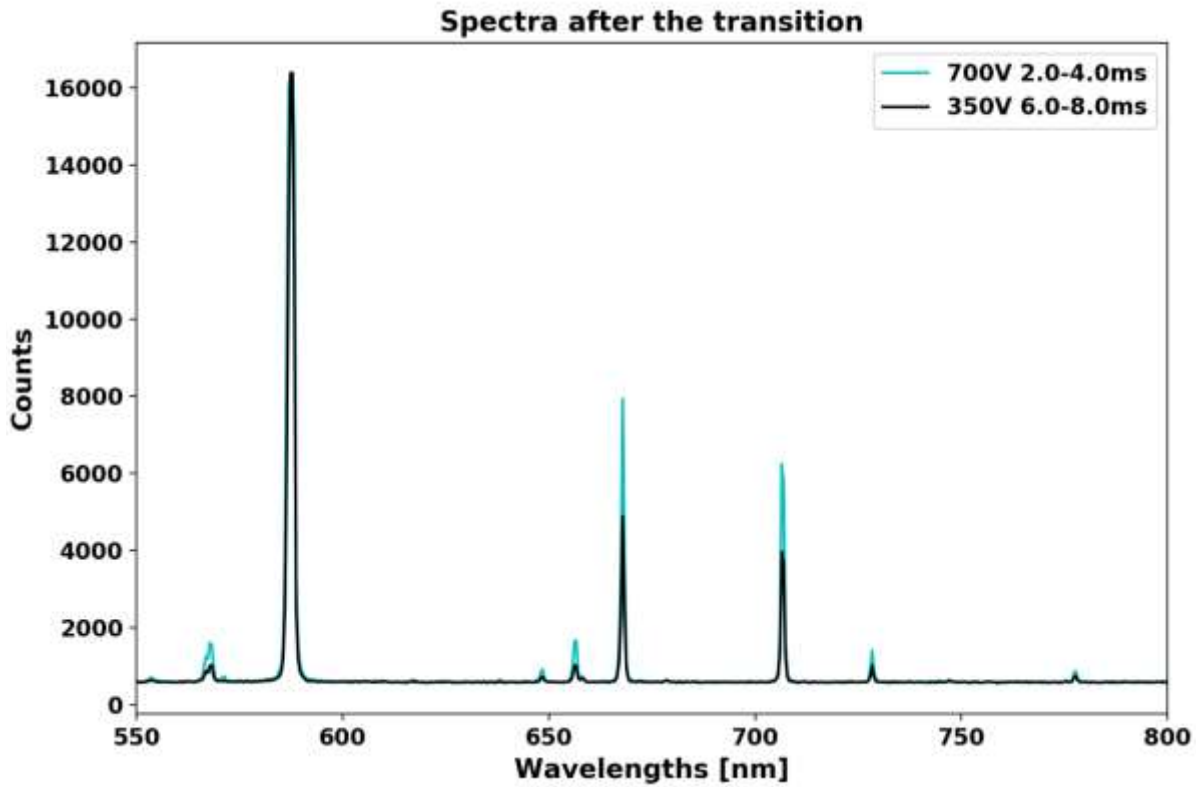
- Around the center λ resolution per pixel ~ 0.11 nm/pixel
- Blue region λ resolution per pixel ~ 0.106 nm/pixel

UV Spectral Calibration



Ip scan: Spectra

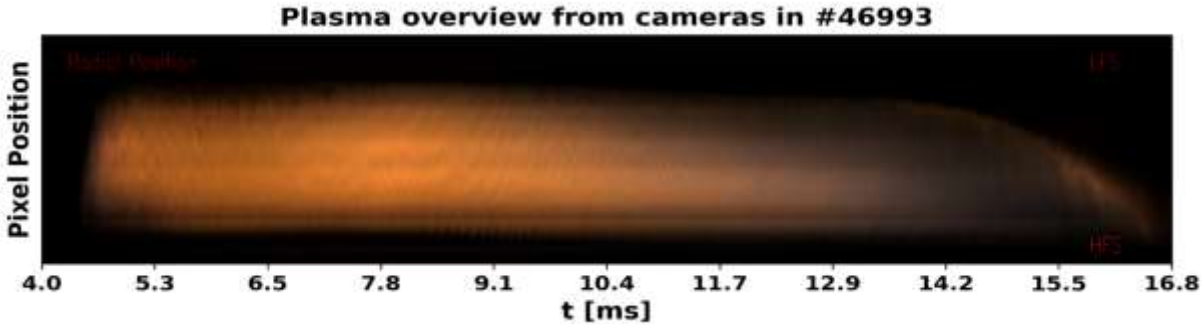


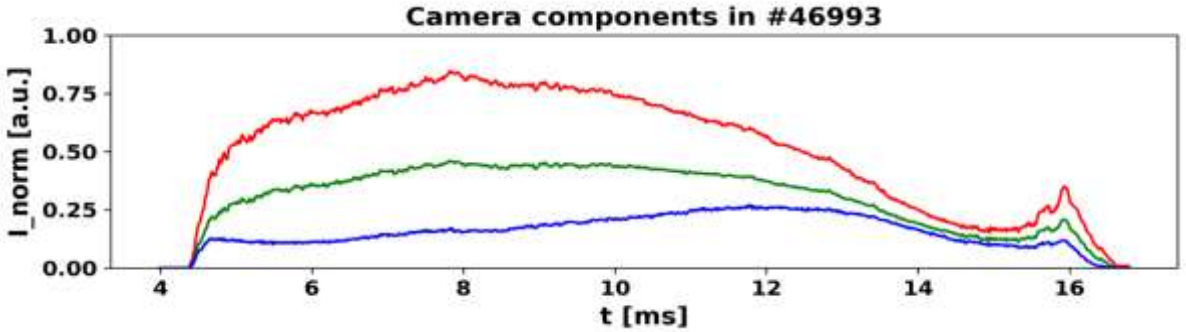


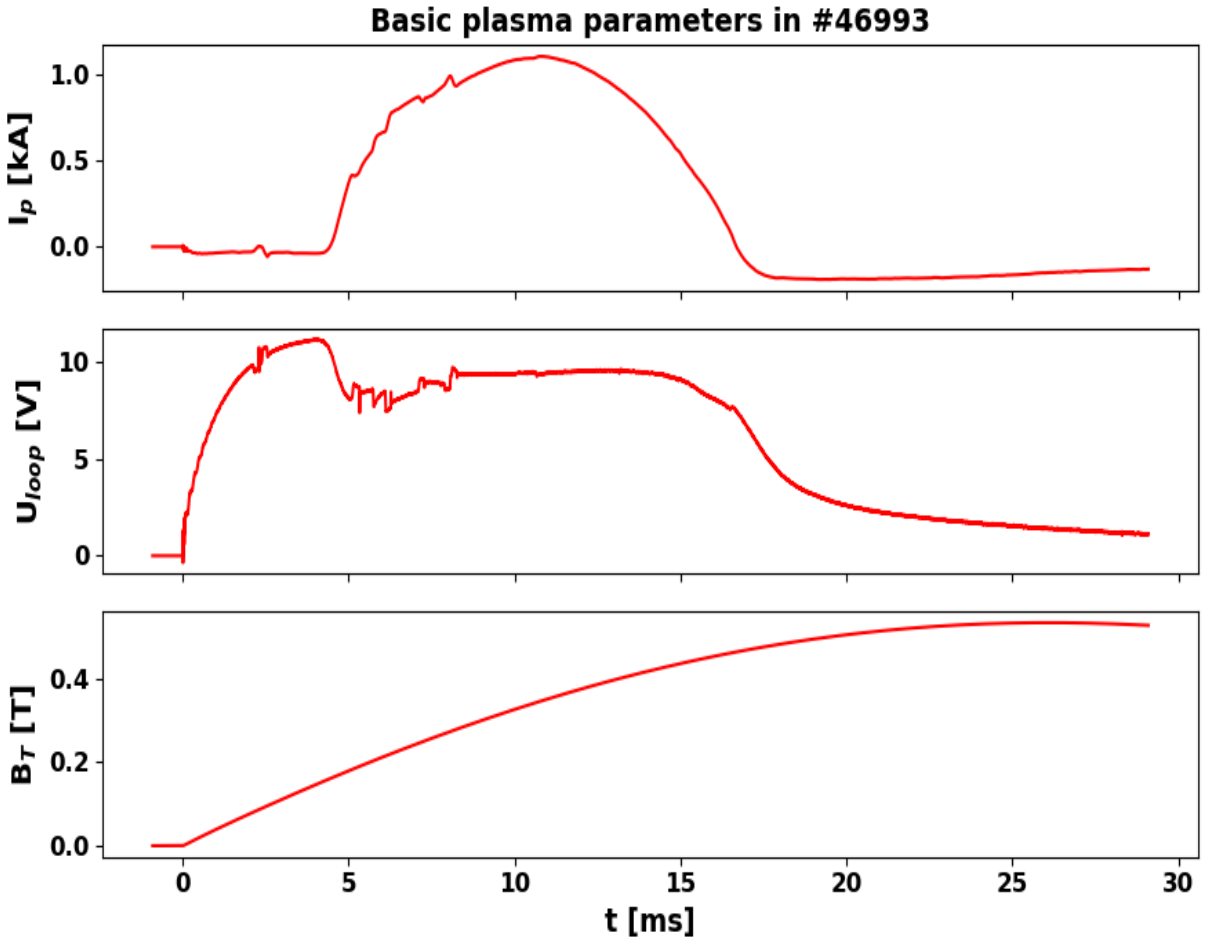
Ip scan

Shot 46993

U_{CD}: 350 V
t_{Start} : 3.99 ms
t_{End} : 16.79 ms
Δt : 12.80 ms
$I_{p,max}$: 1.1 kA

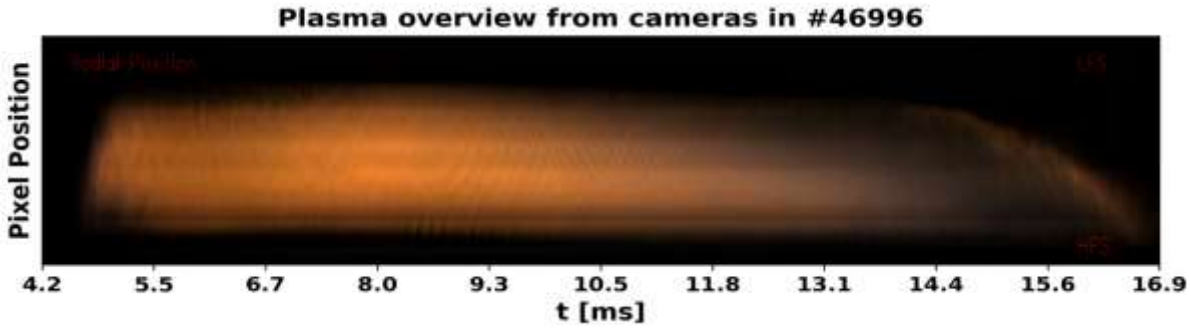


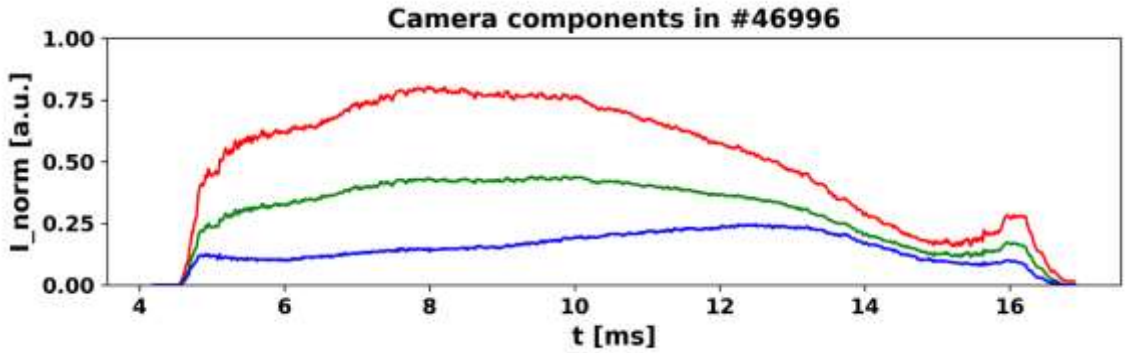


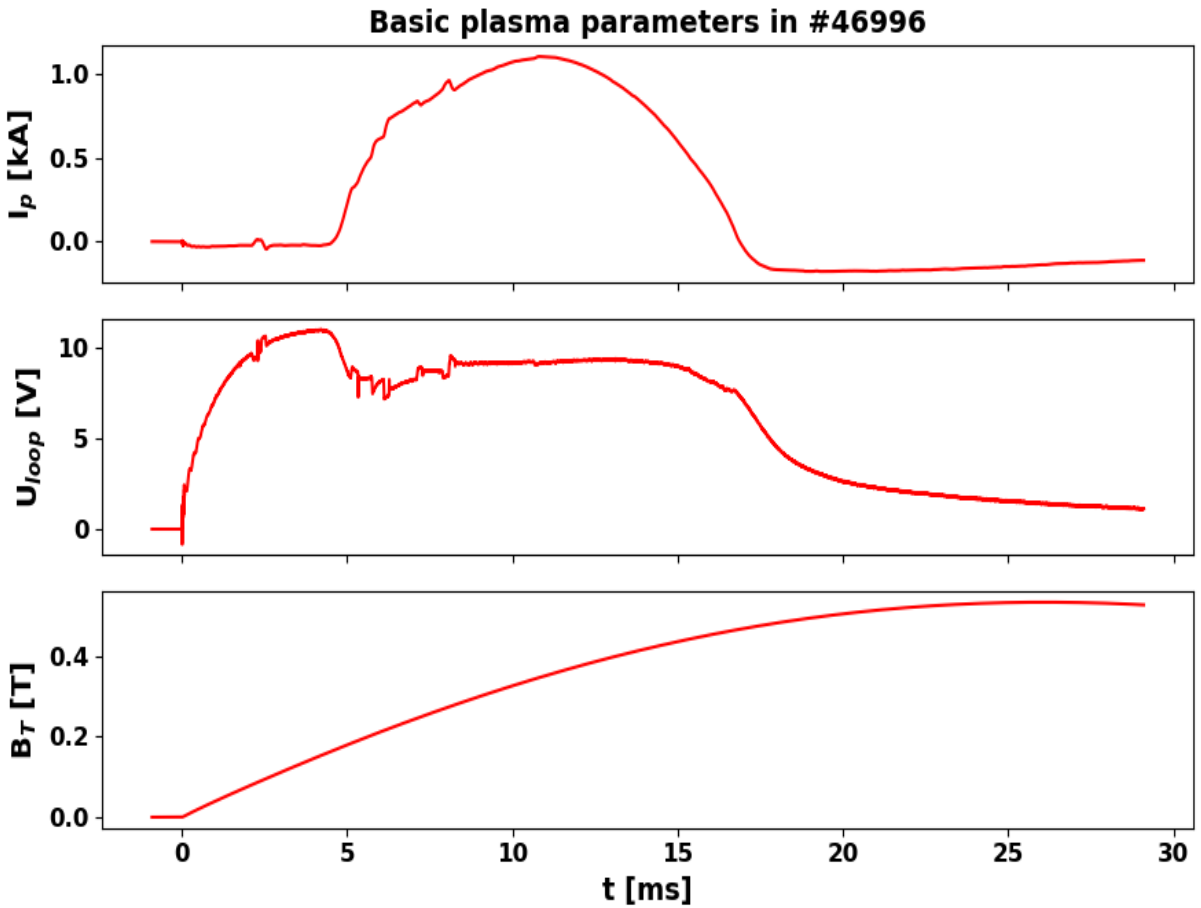


Shot 46996

U_{CD}: 350 V
t_{Start} : 4.19 ms
t_{End} : 16.90 ms
Δt : 12.70 ms
$I_{p,max}$: 1.1 kA

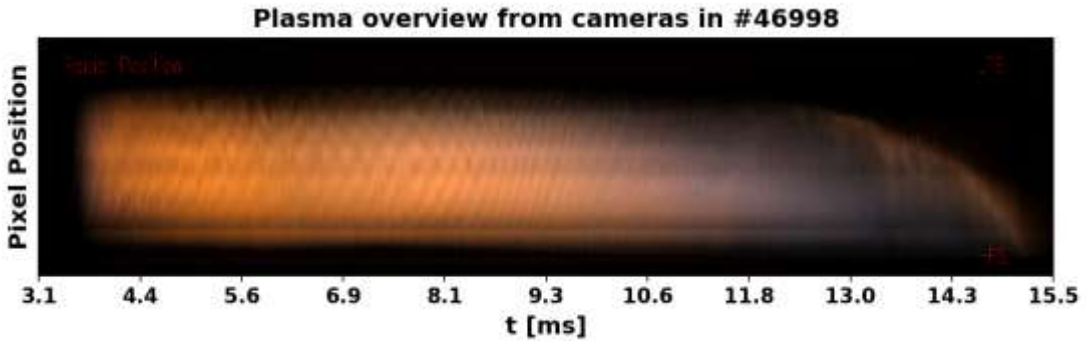


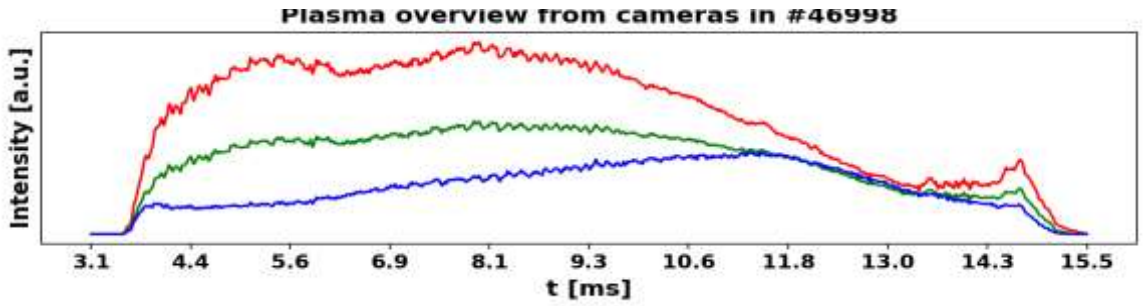


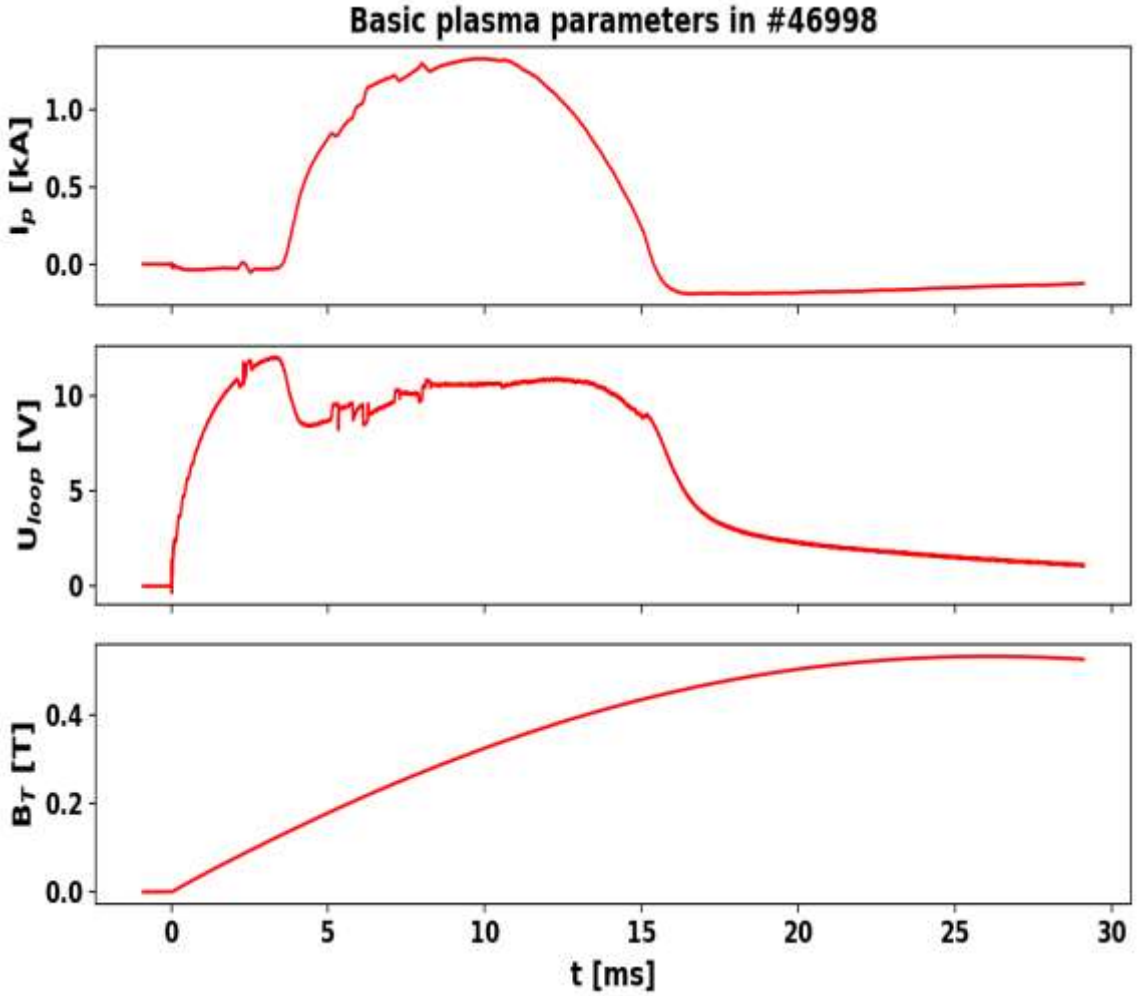


Shot 46998

U_{CD} : 400V
t_{Start} : 3.13 ms
t_{End} : 15.52 ms
Δt : 12.39 ms
Ip_max : 1.3 kA



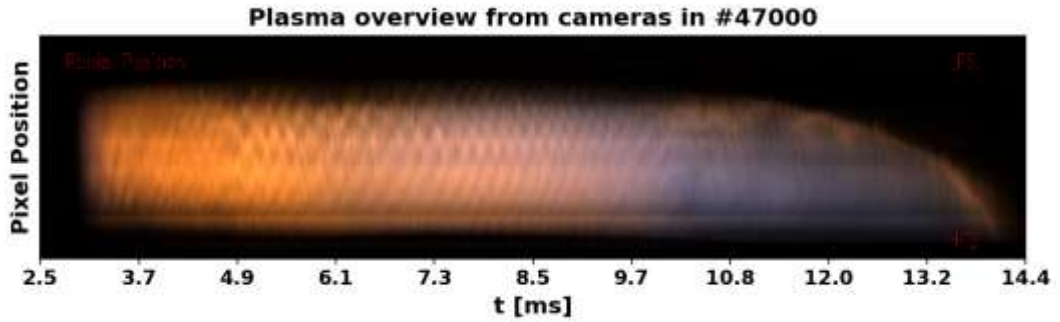


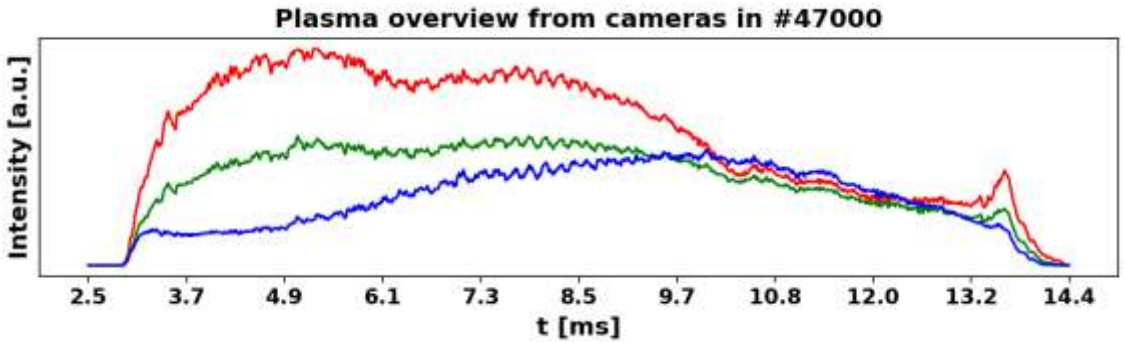


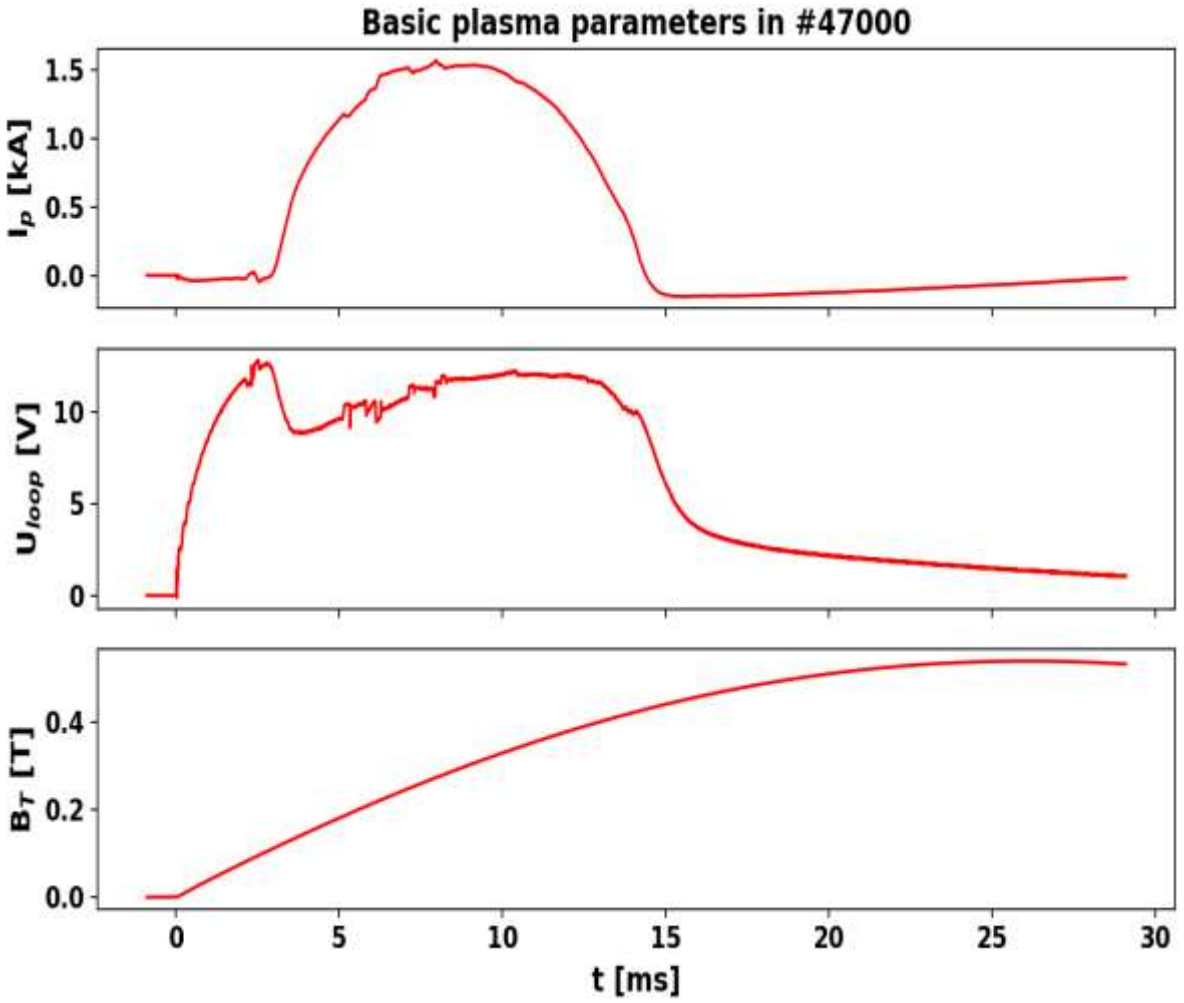
Ip scan

Shot 47000

U_cd : 450V
t_start : 2.53
t_end : 14.41 ms
Δt : 11.87 ms
Ip_max : 1.6 kA



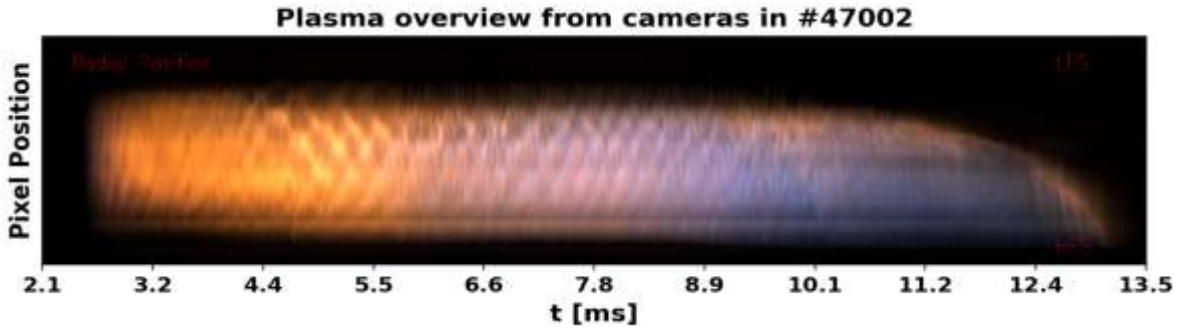


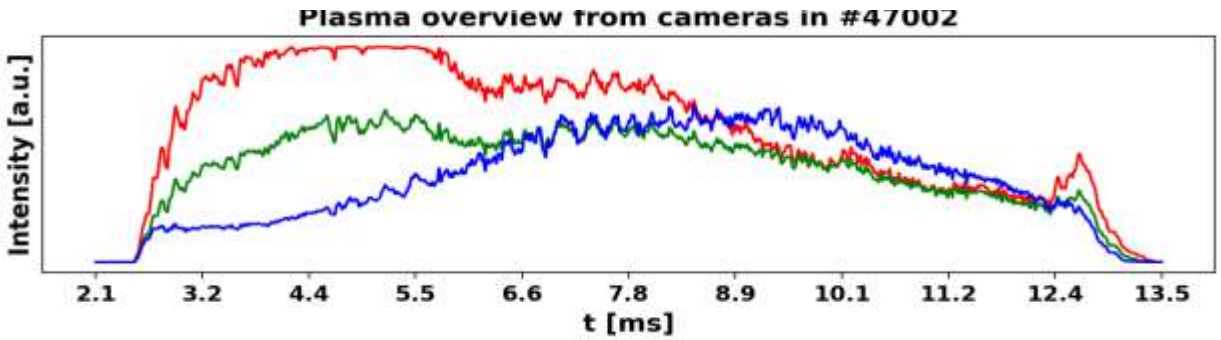


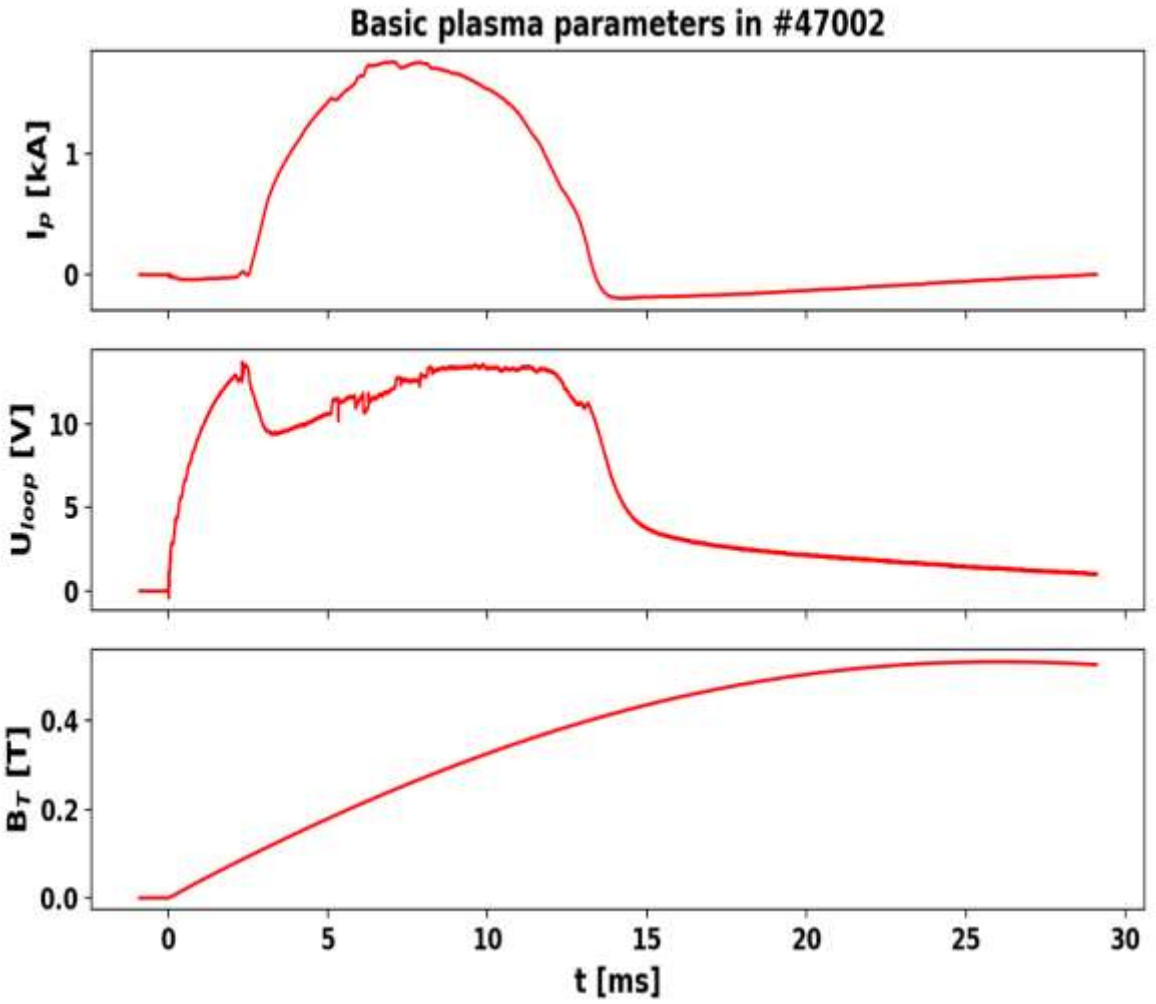
Ip scan

Shot 47002

U_cd : 500 V
t_start : 2.08 ms
t_end : 13.50 ms
Δt : 11.42 ms
Ip_max : 1.8 kA

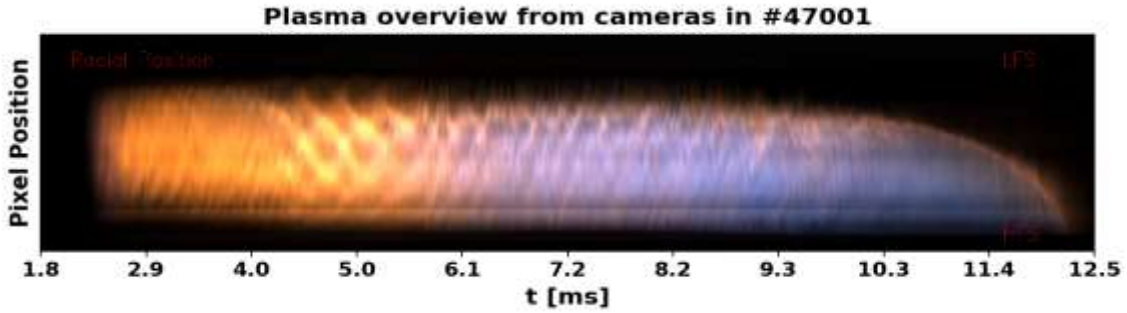


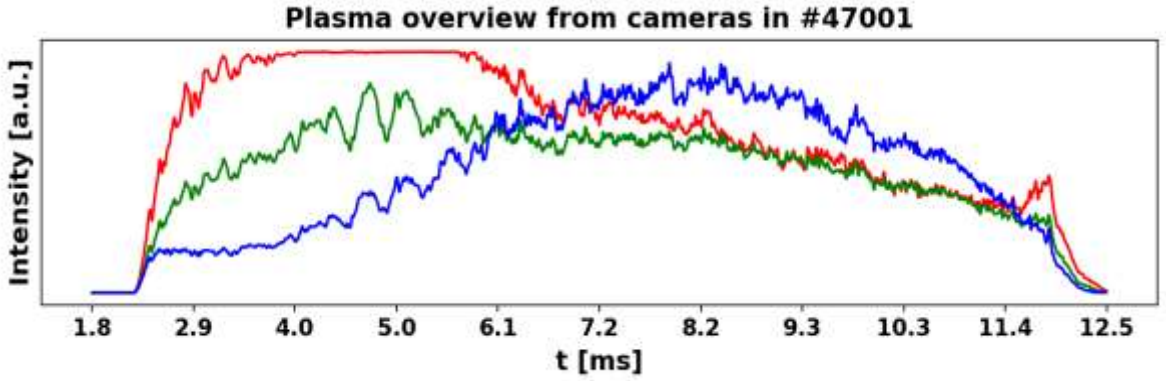


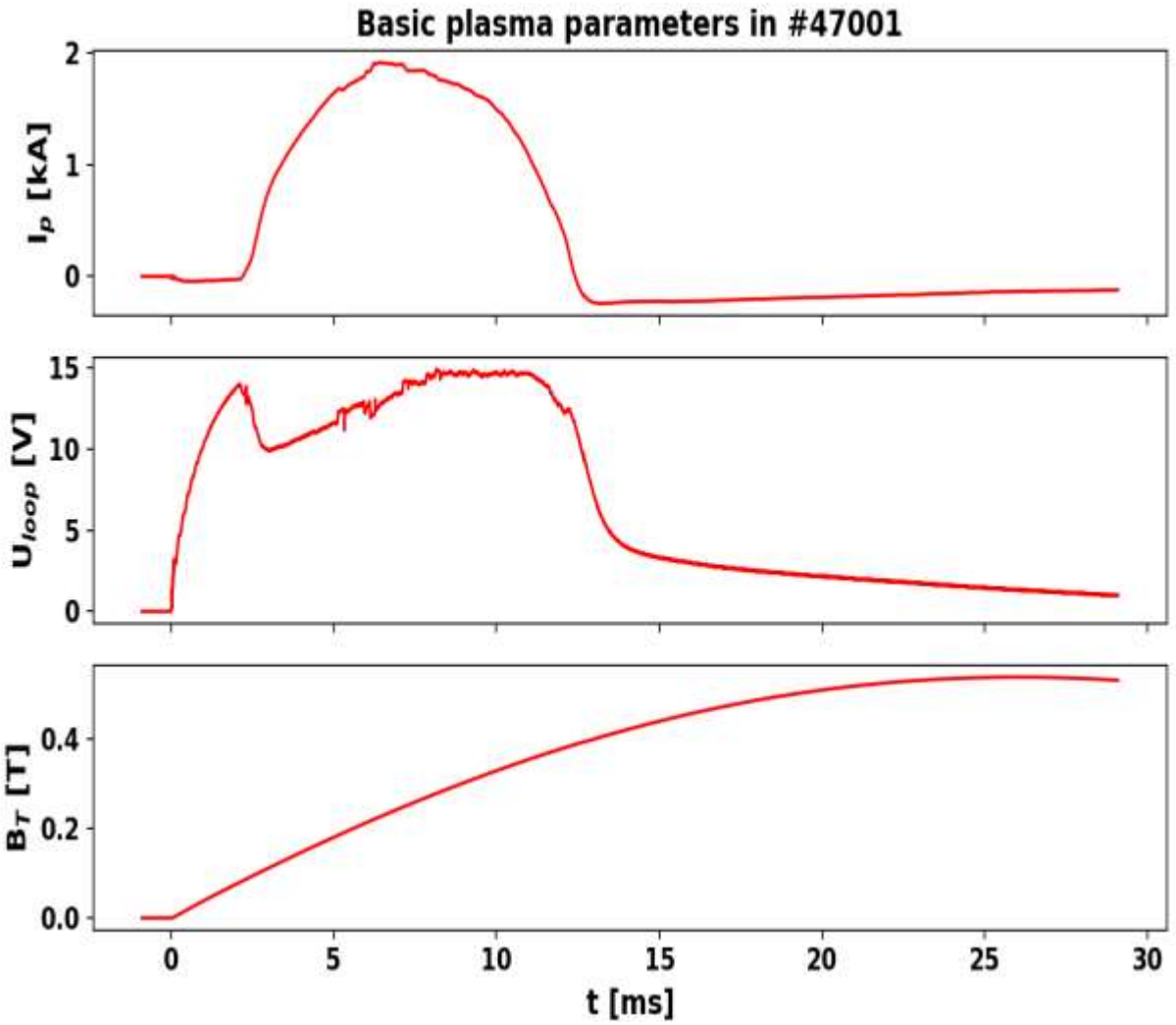


Shot 47001

U_cd : 550 V
t_start : 1.83 ms
t_end : 12.48 ms
Δt : 10.65 ms
Ip_max : 1.9 kA



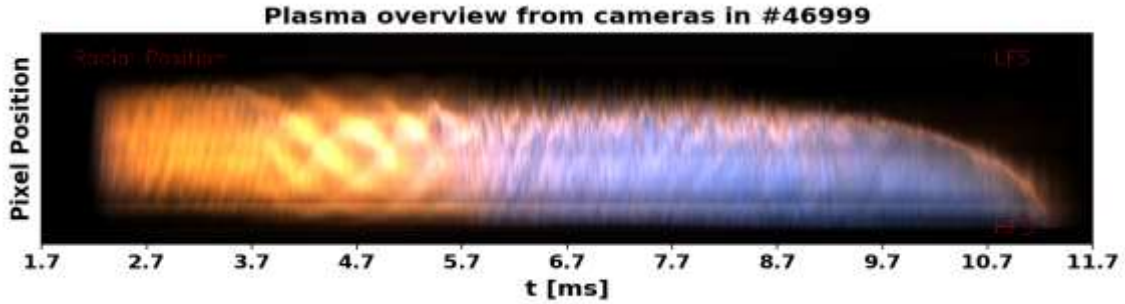


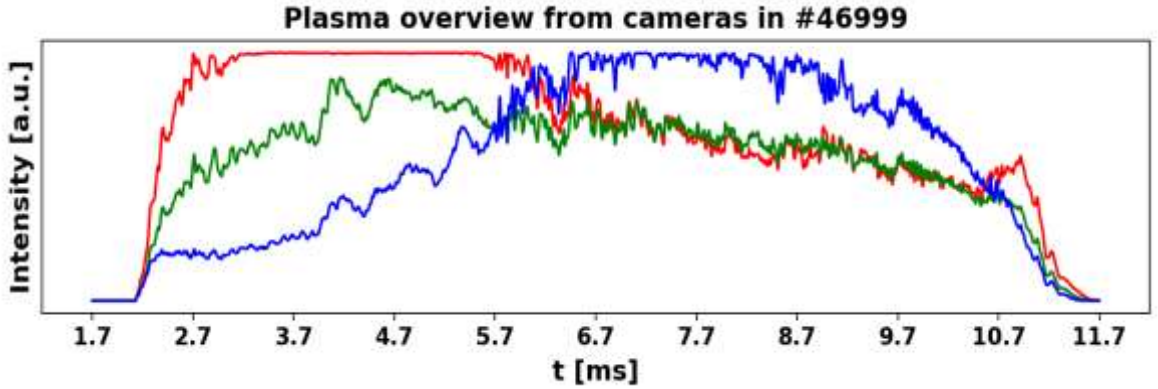


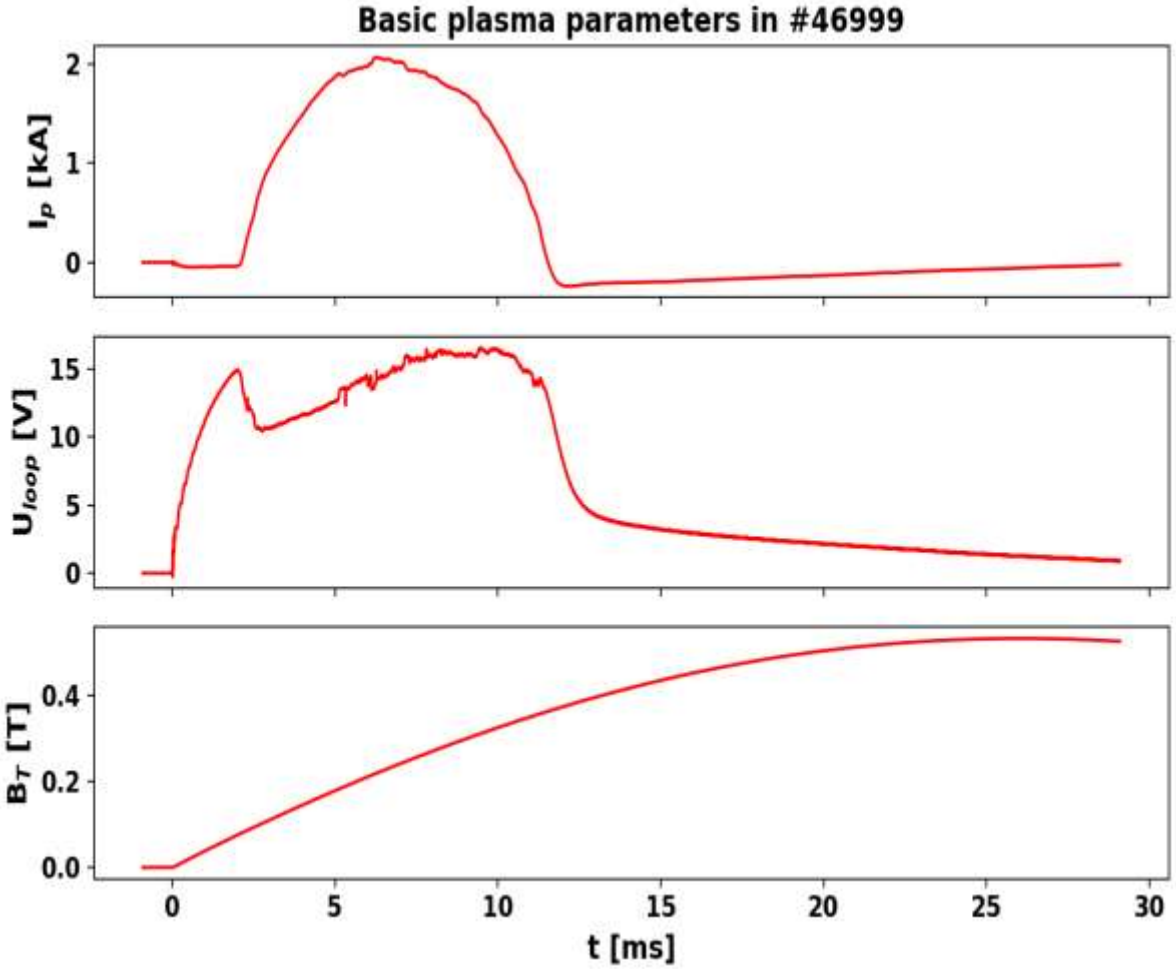
Ip scan

Shot 46999

U_cd : 600 V
t_start : 1.65 ms
t_end : 11.69 ms
Δt : 10.04 ms
Ip_max : 2.1 kA

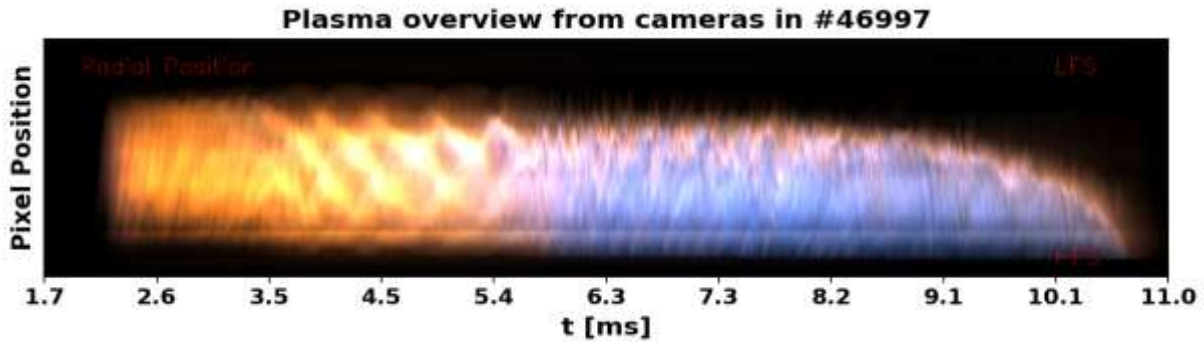


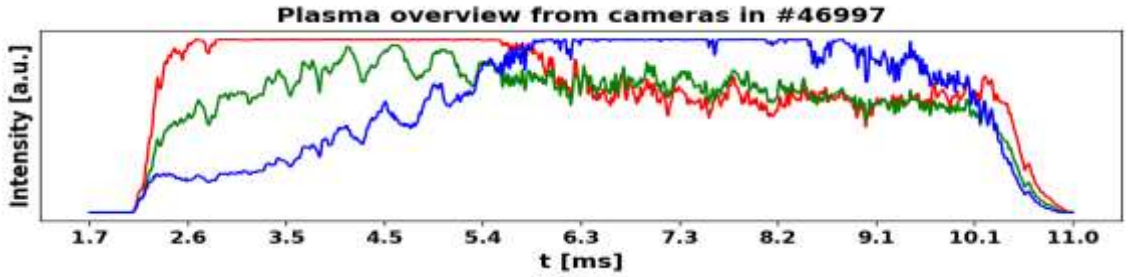


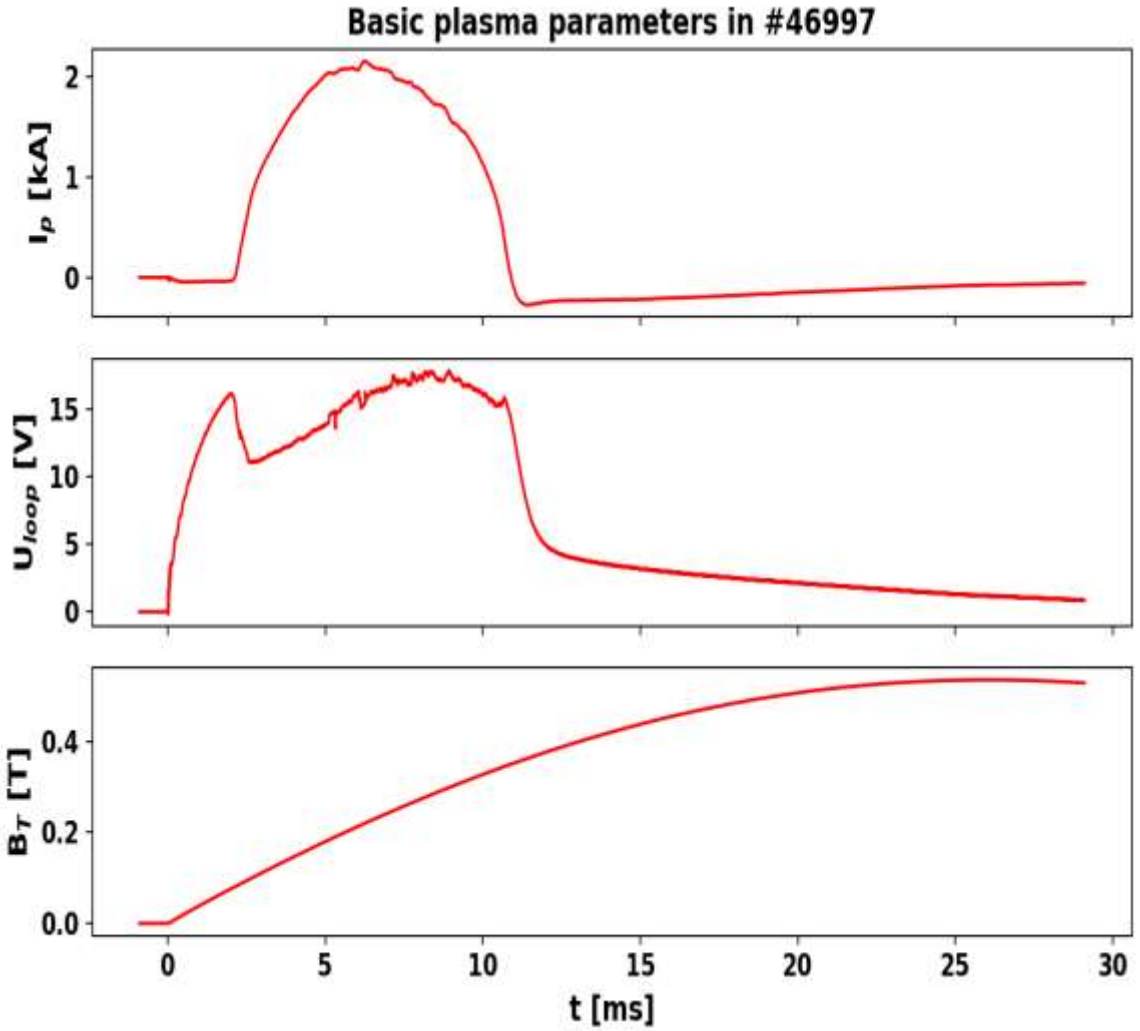


Shot 46997

U_{CD} : 650V
t_{Start} : 1.66 ms
t_{End} : 10.99 ms
Δt : 9.33 ms
$I_{p,max}$: 2.2 kA

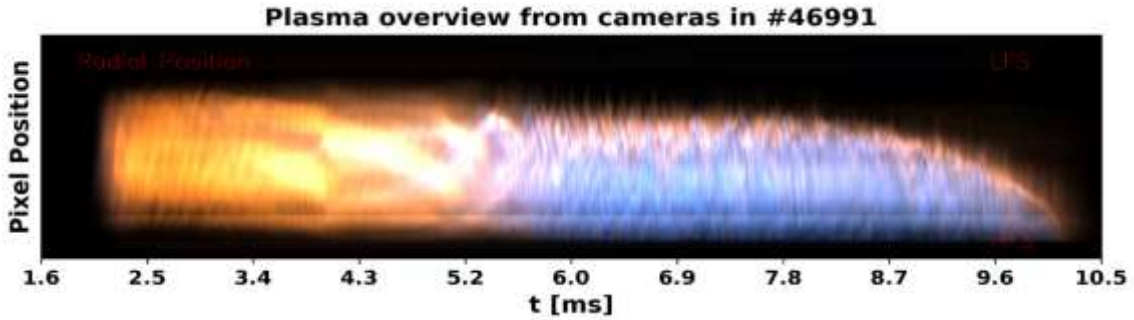


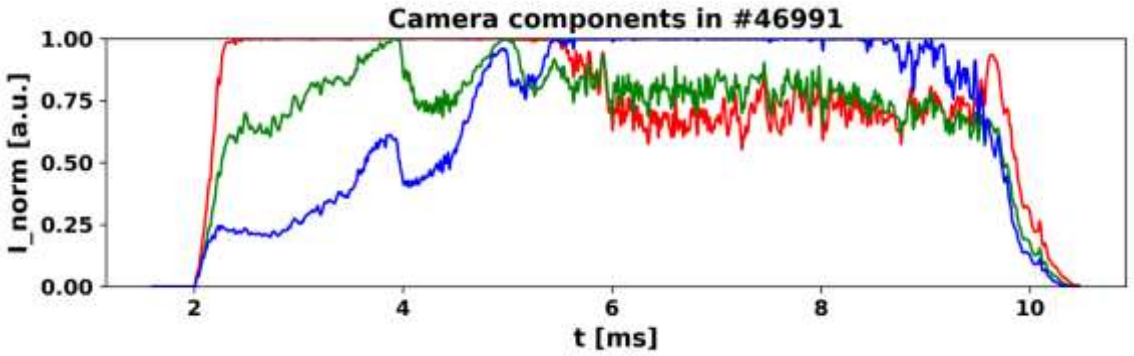


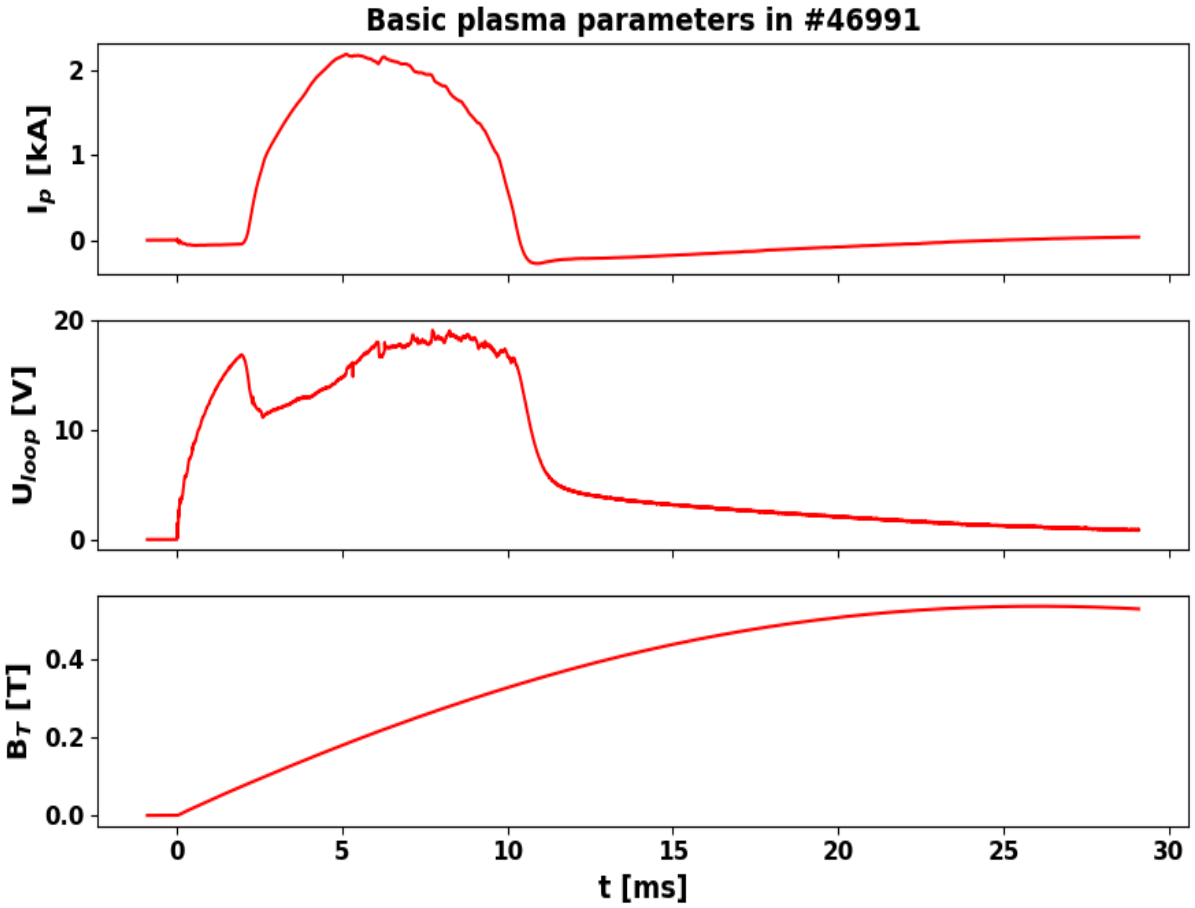


Shot 46991

U_{CD}: 700 V
t_{Start} : 1.60 ms
t_{End} : 10.47 ms
Δt : 8.87 ms
$I_{p,max}$: 2.2 kA

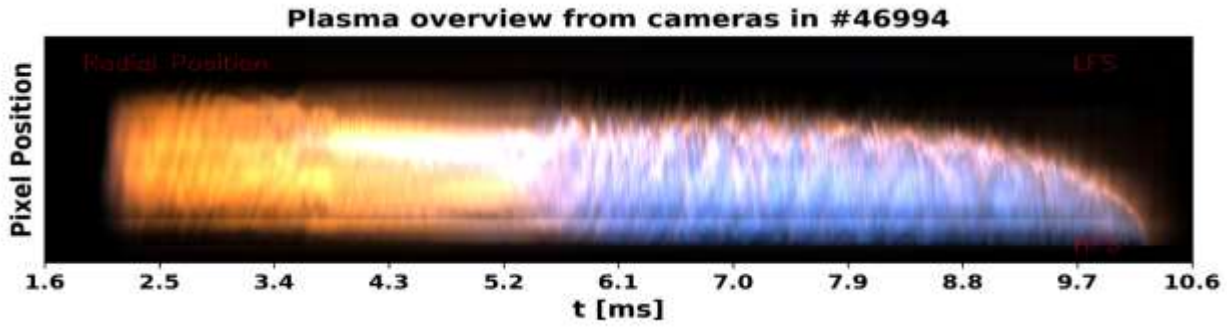


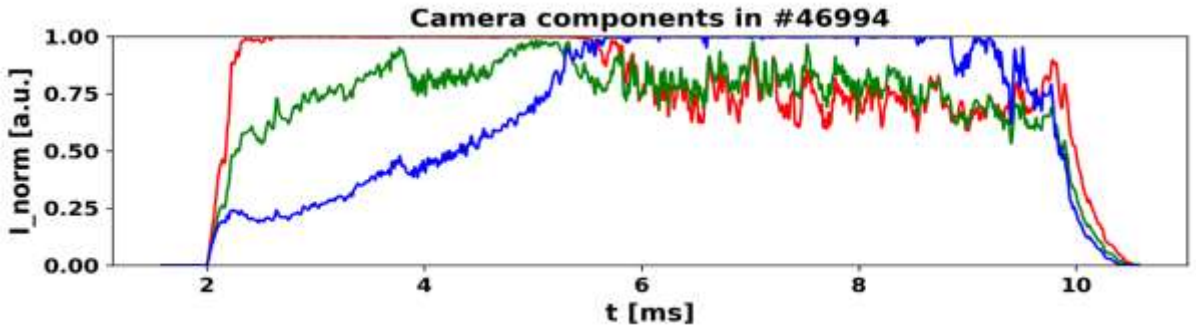


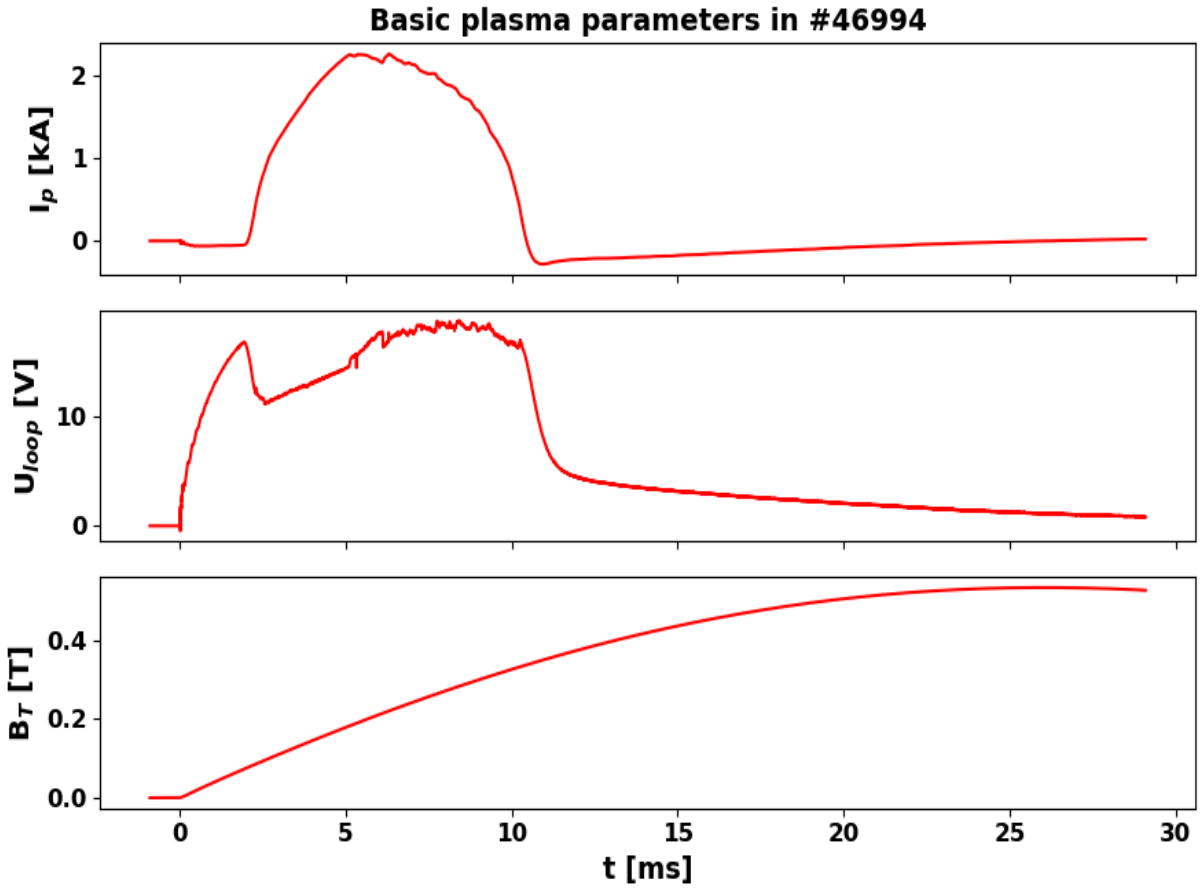


Shot 46994

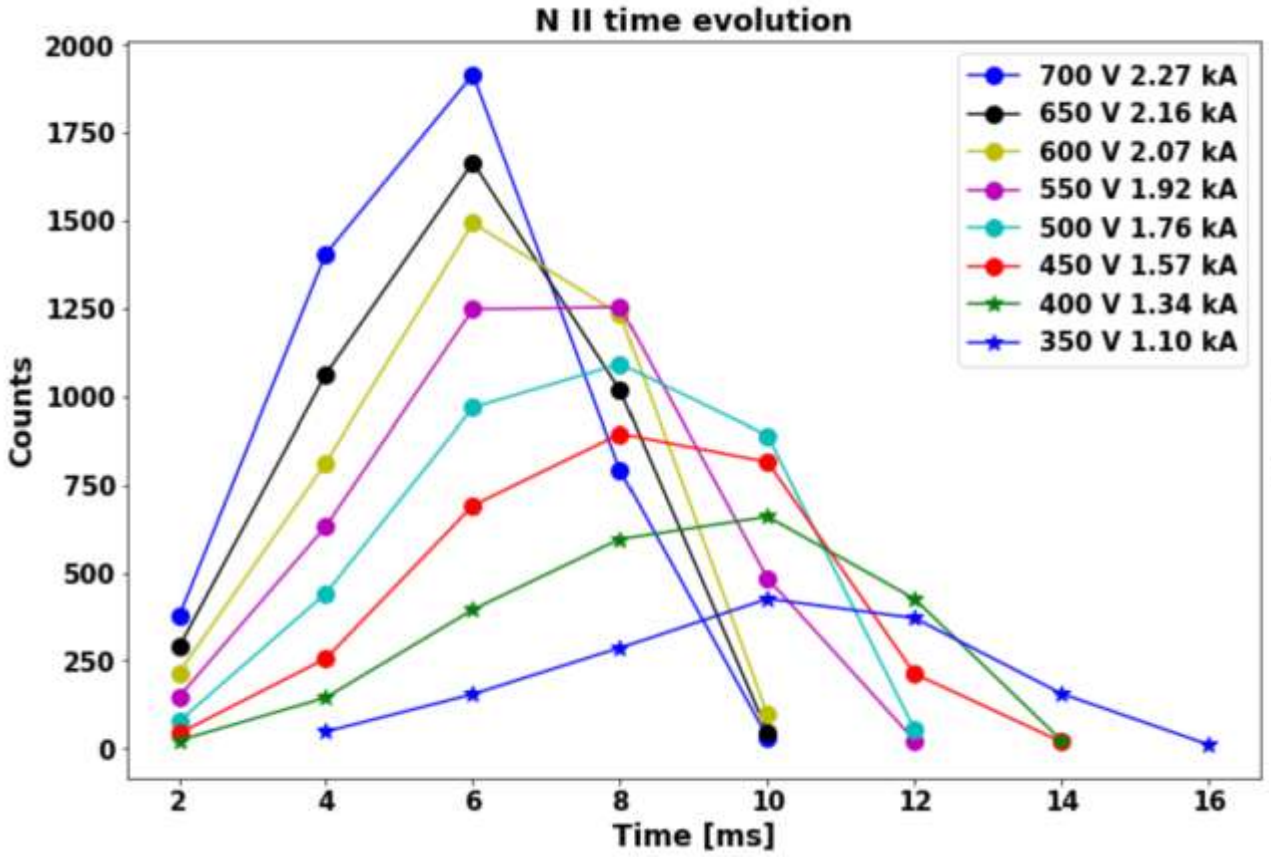
U_{CD}: 700 V
t_{Start} : 1.58 ms
t_{End} : 10.57 ms
Δt : 8.99 ms
I_{max} : 2.3 kA

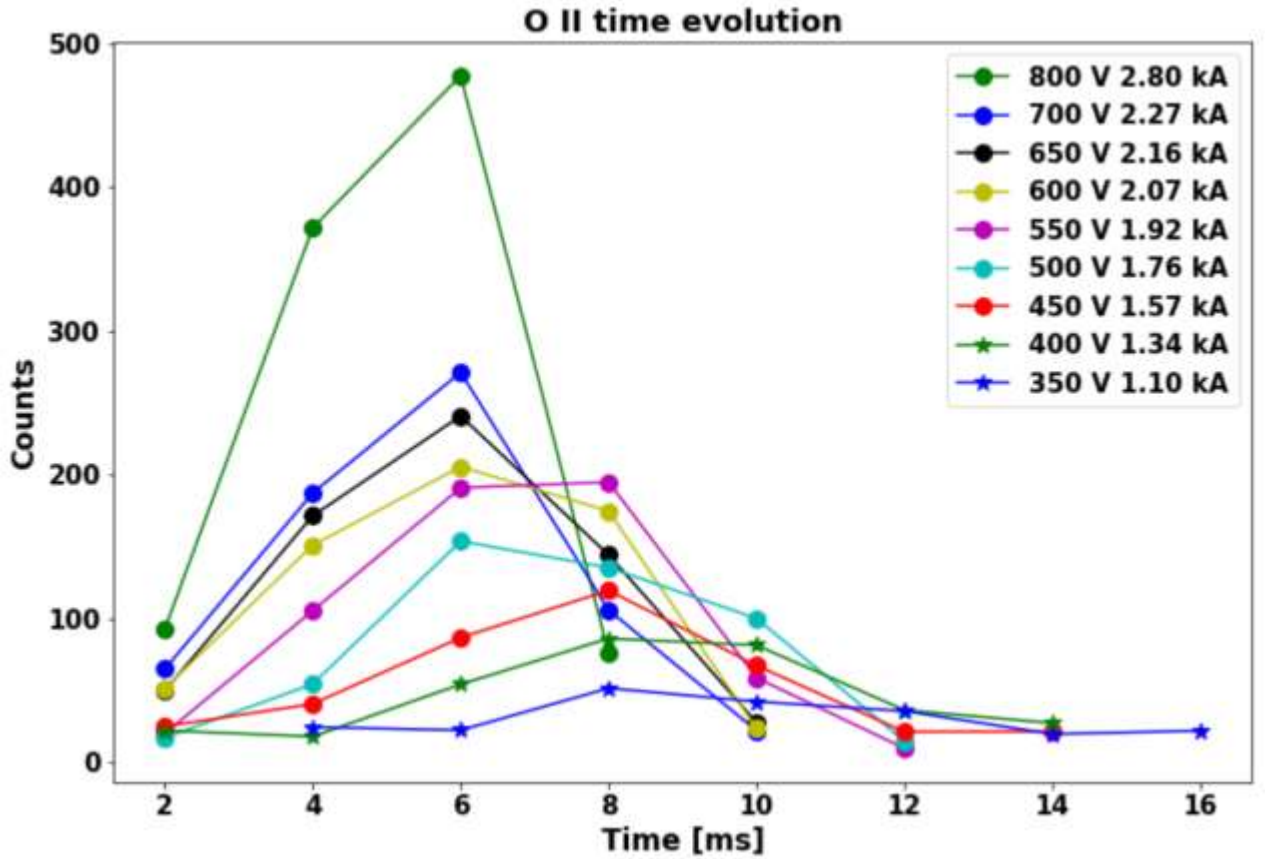


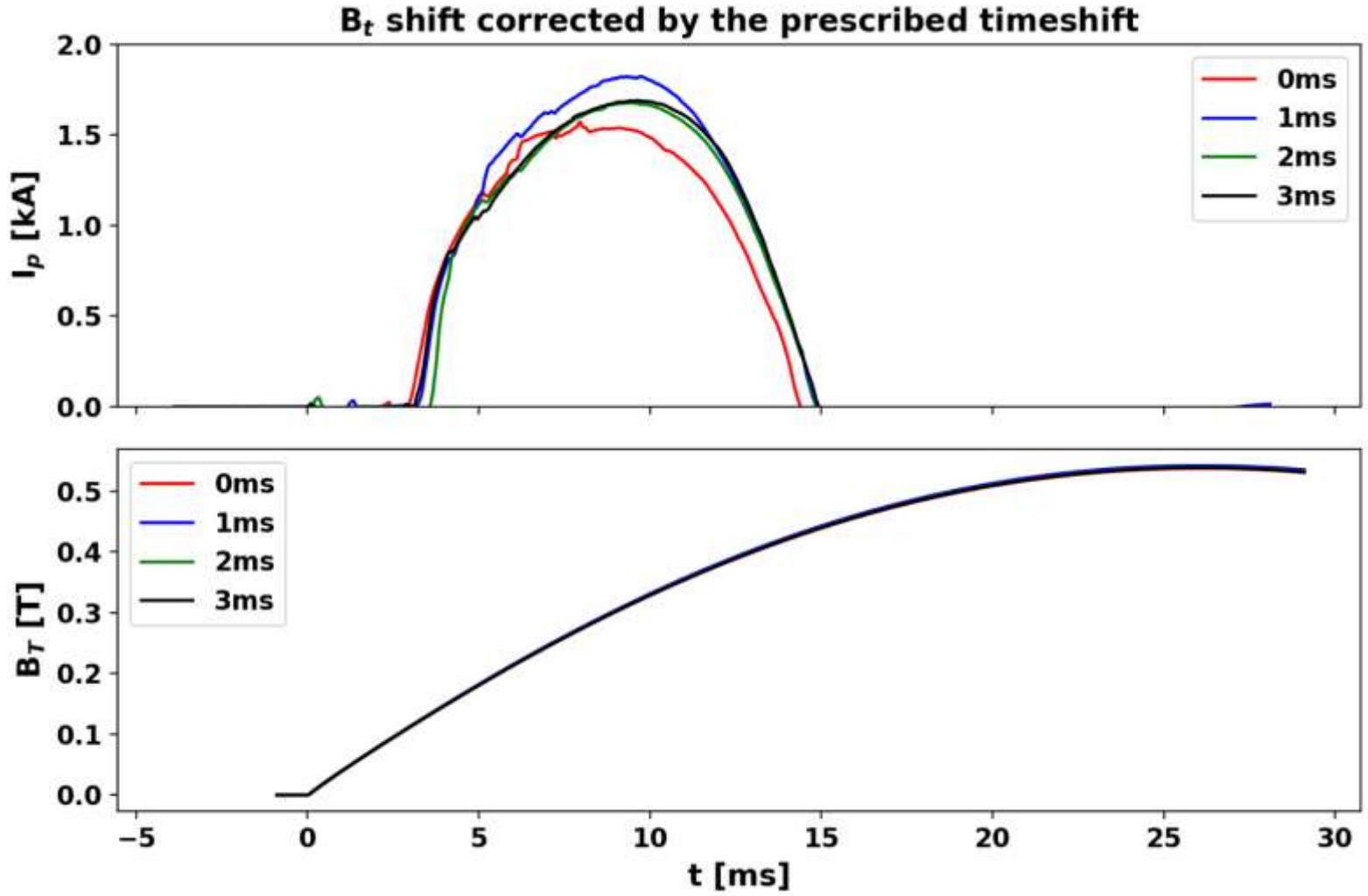


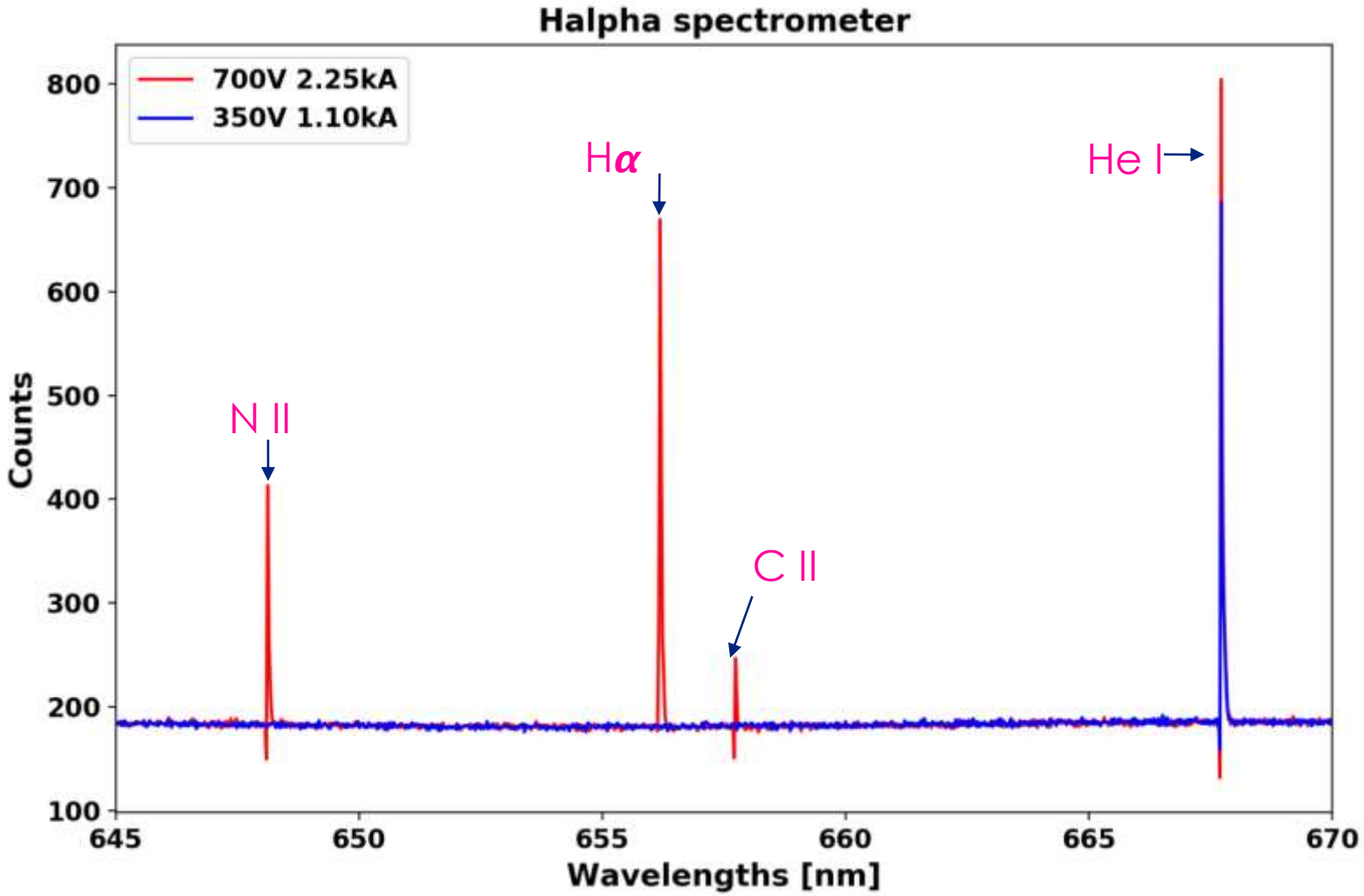


Ip scan: Time evolution

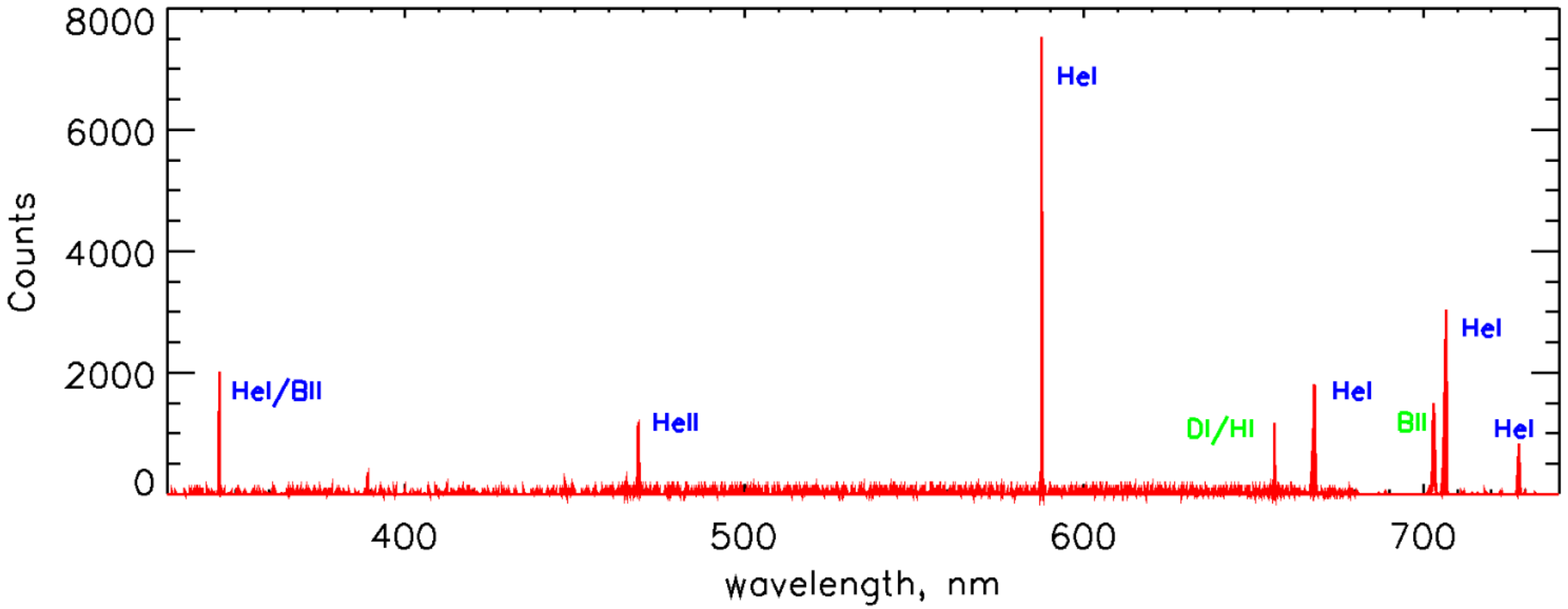





B_t shift corrected by the prescribed timeshift
I_p [kA]
2.0
1.5
1.0
0.5
0.0
0ms
1ms
2ms
3ms
B_T [T]
0.5
0.4
0.3
0.2
0.1
0.0
−5
0
5
10
15
20
25
30
t [ms]


Halpha spectrometer
700V 2.25kA
350V 1.10kA
Hα
He I
N II
C II
Counts
Wavelengths [nm]
100
200
300
400
500
600
700
800
645
650
655
660
665
670

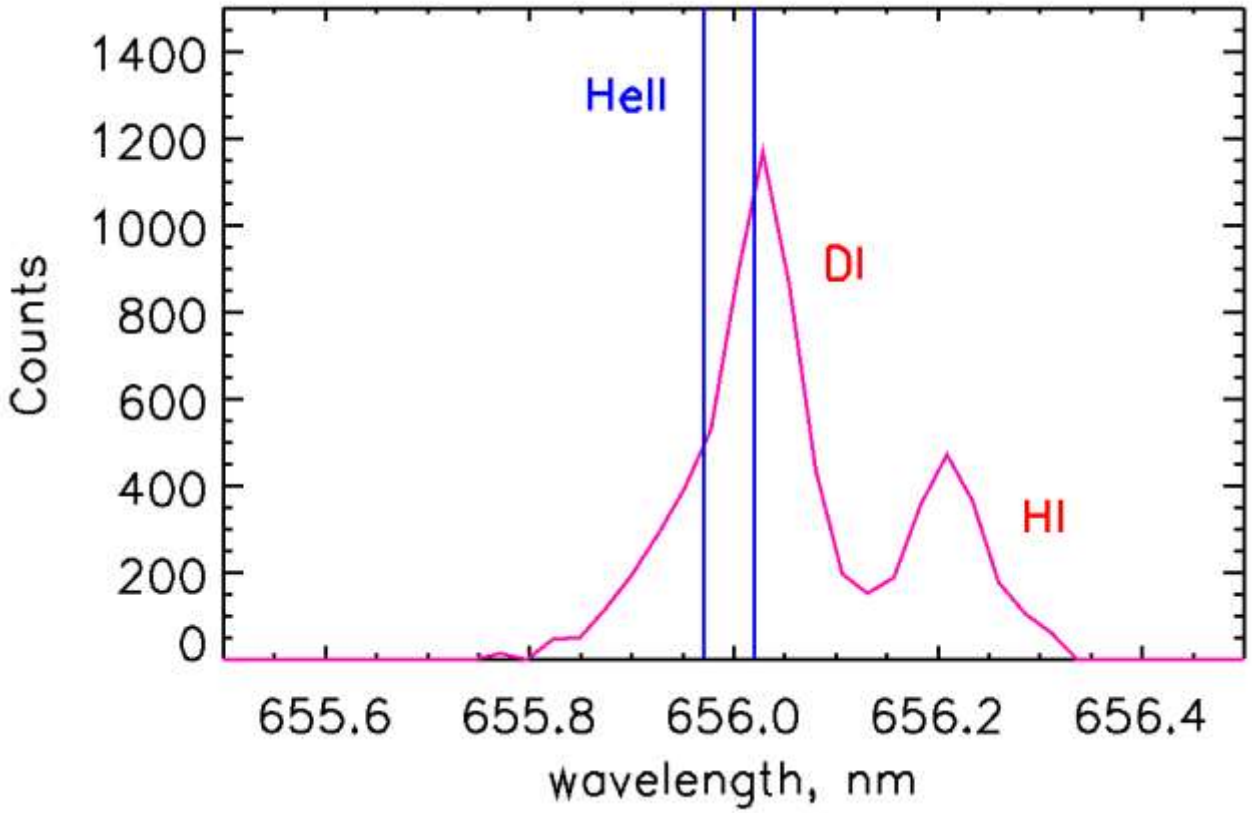
Spectrum of He discharge on COMPASS

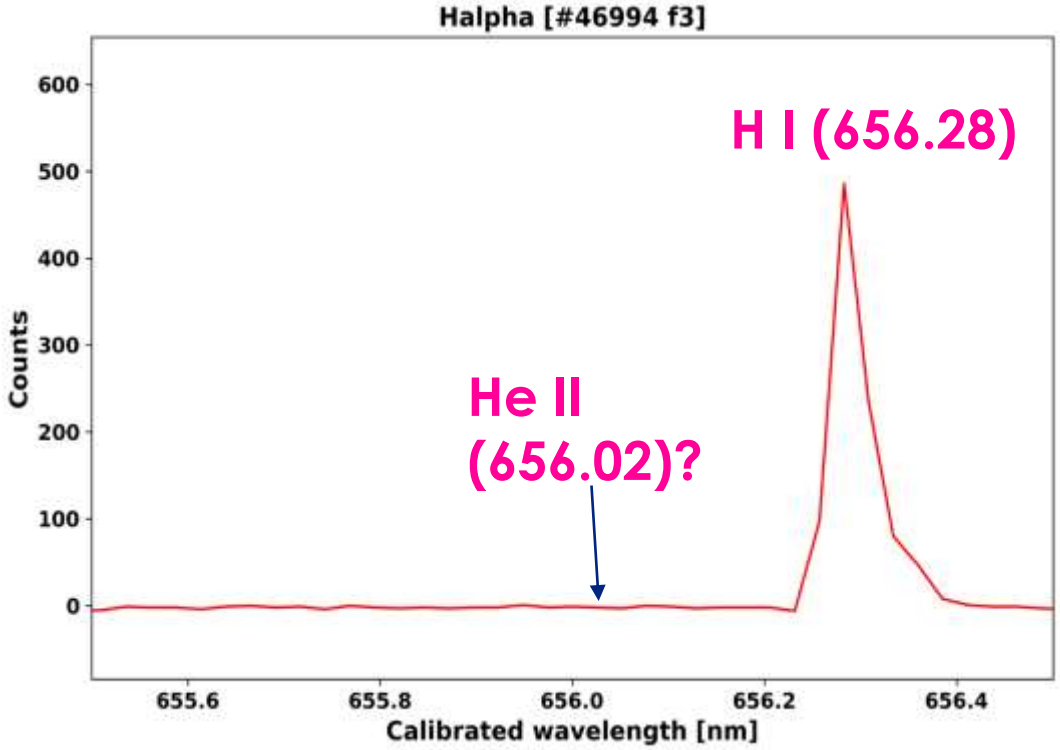


IR 20 µs, VIS 3µs, UV 50 µs, Halpha 20 µs

He II (656.02 nm)

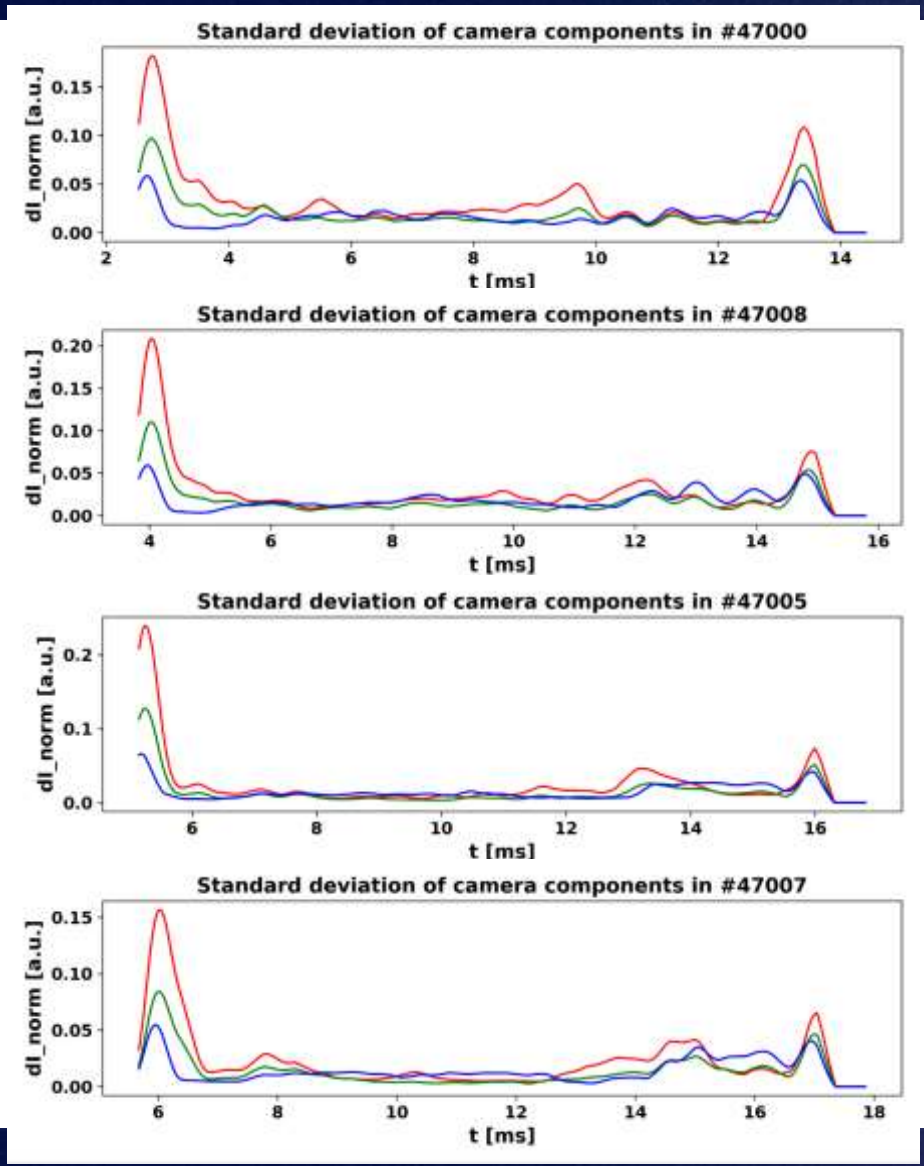
COMPASS discharge





0.025 nm/px

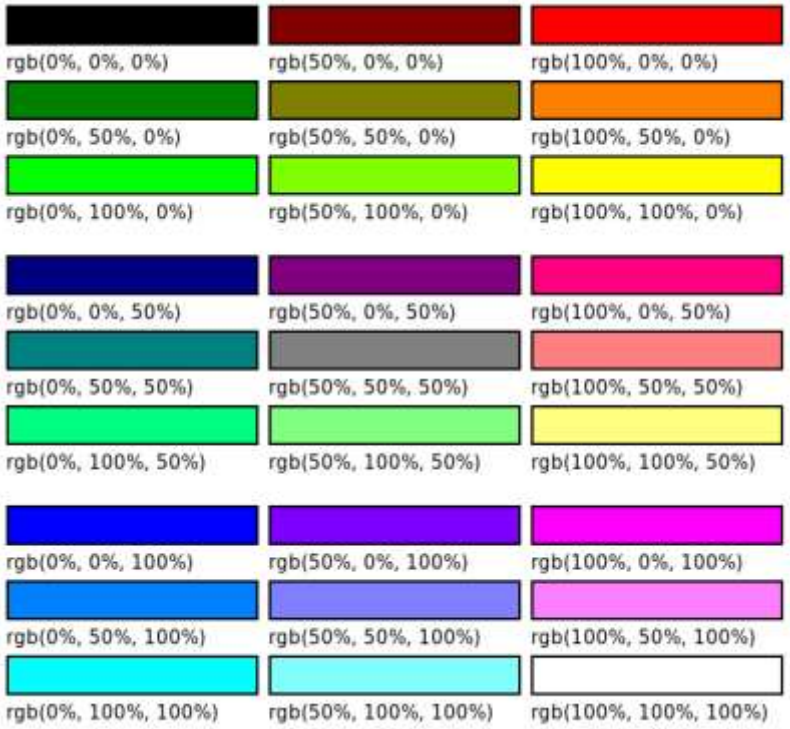
Standard deviation

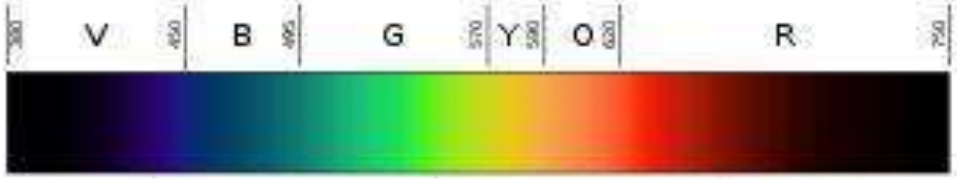


wavelength - color

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

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





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