

Spectroscopy on magnetically confined plasmas using EBIT spectrometers

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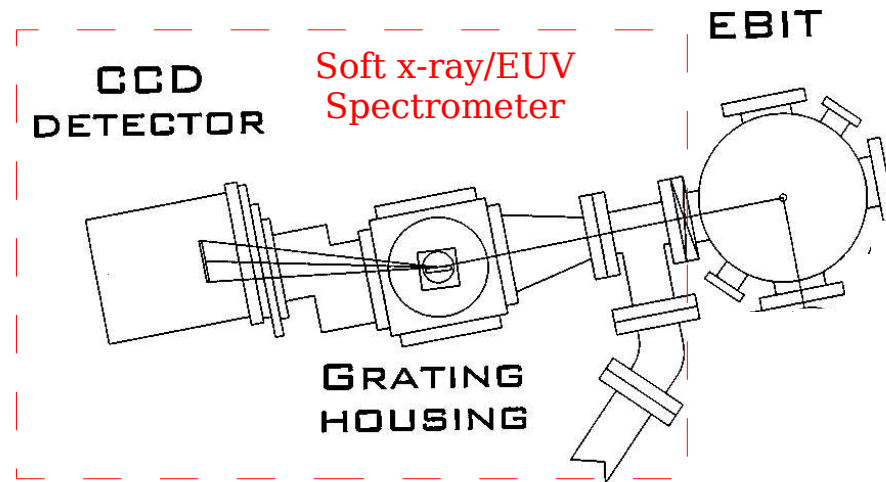
This work was performed under the auspices of the U.S. DOE by UC-LLNL, under contracts W-7405-Eng-48, DE-FGO2-O3ER54732 and DE-FGO3-96ER54373 and by PPPL under contract DE-AC02-76CHO3073.

20 Years of Spectroscopy with the Electron Beam Ion Trap, Berkeley, CA
November 12-16, 2006

Outline

- Soft x-ray/Extreme Ultraviolet (EUV) spectrometer
 - setup and use at the LLNL EBIT
 - setup and use at the National Spherical Torus Experiment (NSTX)
 - setup and use of a similar design at the Sustained Spheromak Plasma Experiment (SSPX)
- Visible range transmission grating spectrometer
 - setup and use at the LLNL EBIT
 - setup and use at the Compact Torus Injection Experiment (CTIX)
 - setup and use at the Alcator C-Mod tokamak

Soft x-ray/EUV spectrometer at the LLNL EBIT



Dispersion element

Reflection grating (2400 or 1200 l/mm) with variable line spacing (i.e. allowing a flat focusing field)

Detector

Photometrics back-illuminated CCD (1024x1024 with 25 μm pixels)

Wavelength range

6-100 \AA (30 mm)

Blazing angle

1.3°

Blazing wavelength

15 \AA

Instrument FWHM

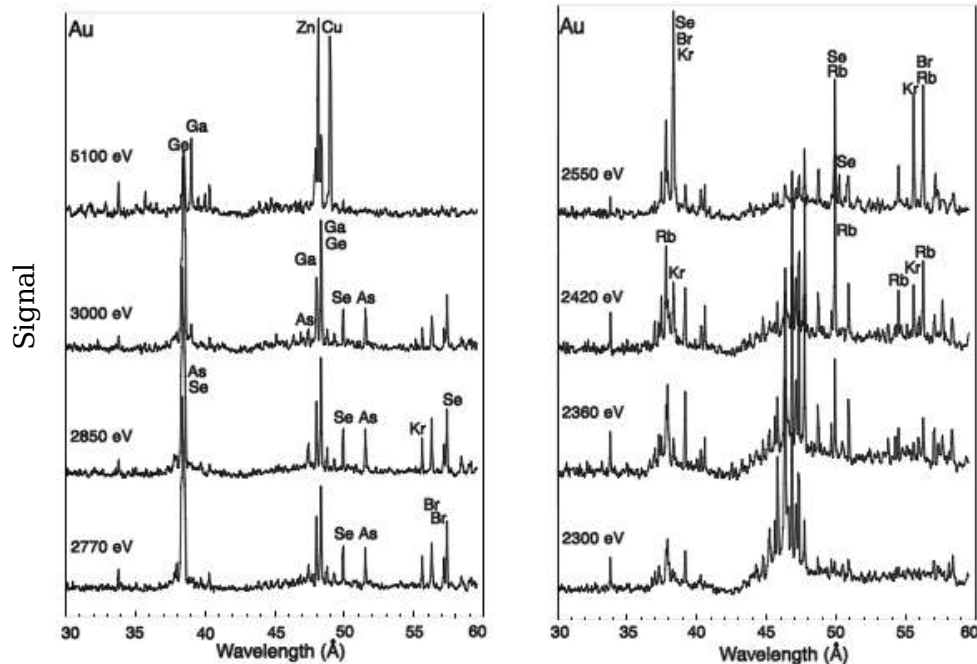
$\sim 0.25 \text{ \AA}$ ($\Delta\lambda/\lambda = 60$ at 15 \AA)

Operating pressure

10^{-6} Torr

Examples of work done at EBIT with the soft x-ray/EUV spectrometer

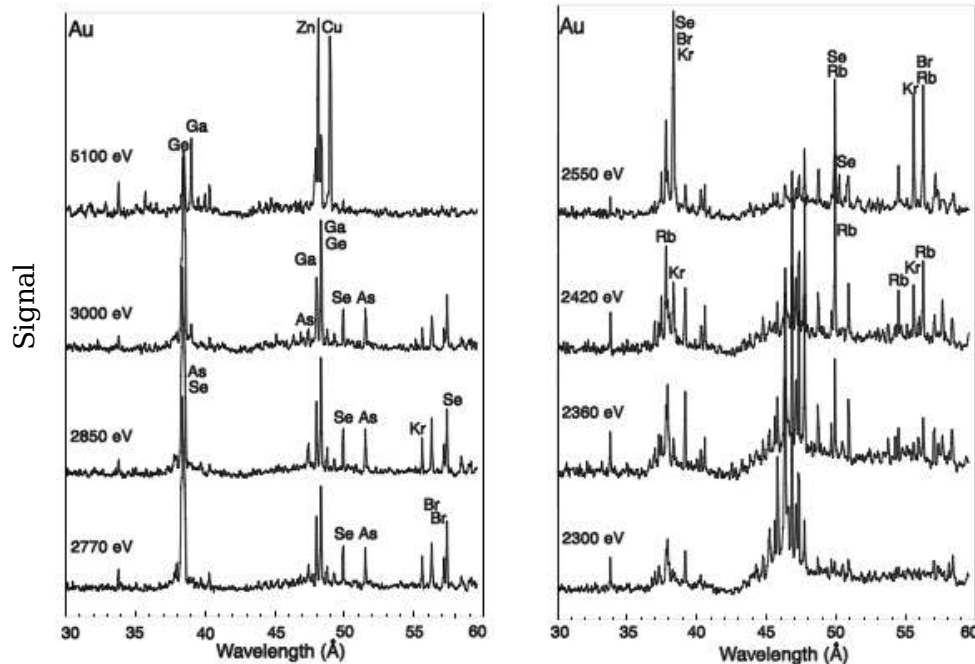
Träbert et al. 2001



- Production of Br-like Au^{44+} to Cu-like Au^{52+} between 20 and 60 Å
- Identification of $\Delta n = 0$ ($n=n'=4$) in Rb-like Au^{42+} to Cu-like Au^{50+}
- Guided by HULLAC

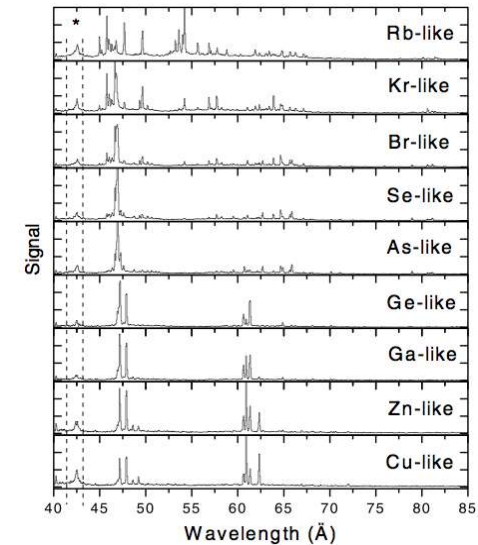
Examples of work done at EBIT with the soft x-ray/EUV spectrometer

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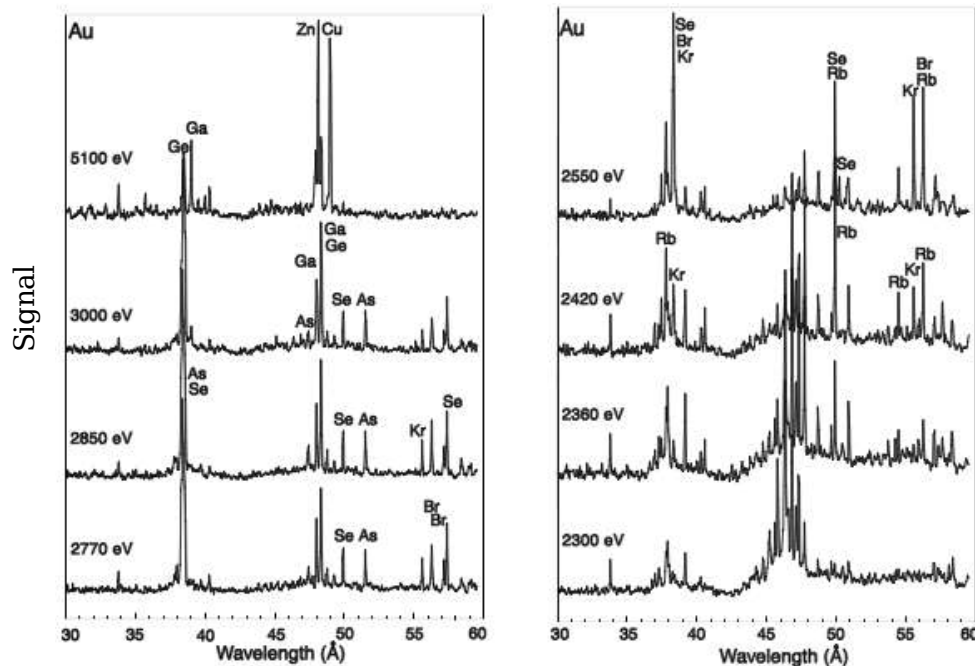
Utter et al. 2002



- Production of Rb-like W^{37+} to Cu-like W^{45+} between 40 and 85 Å
- 60 features identified
- Guided by K. Fournier published calculations using ANGLAR and RELAC

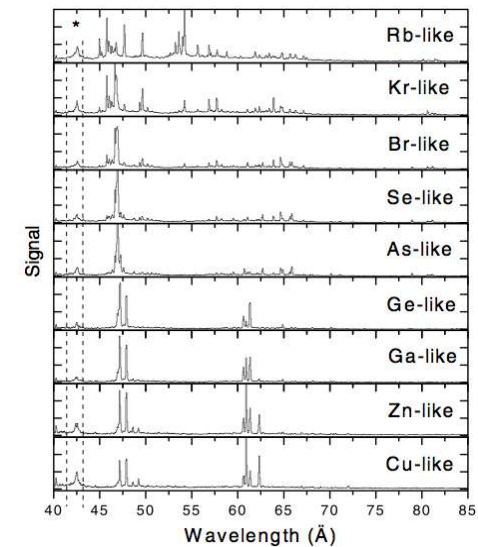
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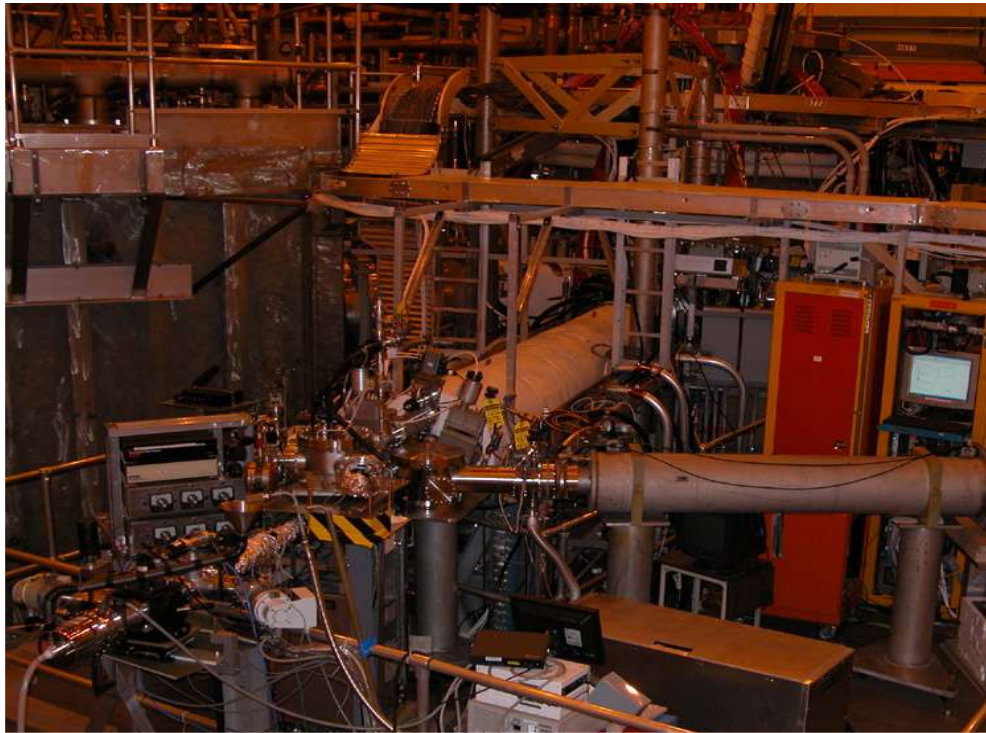
• Utter et al., [Grazing incidence measurements of L-Shell line emission from highly charged Fe in the soft x-ray region](#), Rev. Sci. Instr., **70**; no.1, 284 (1999)

• Träbert et al., [Soft x-ray spectra of highly charged Au ions in an electron beam ion trap](#), Can. J. Phys., **79**; 153-162 (2001)

• Chen et al., [Soft x-ray spectra of highly charged Kr ions in an electron beam ion trap](#), Physical Review E, **65**; 056401 (2002)

• Utter et al., [Electron beam ion trap spectra of tungsten in the EUV](#), Can. J. Phys., **80**; 1503-1515 (2002)

Soft x-ray/EUV Spectrometer at NSTX (XEUS)

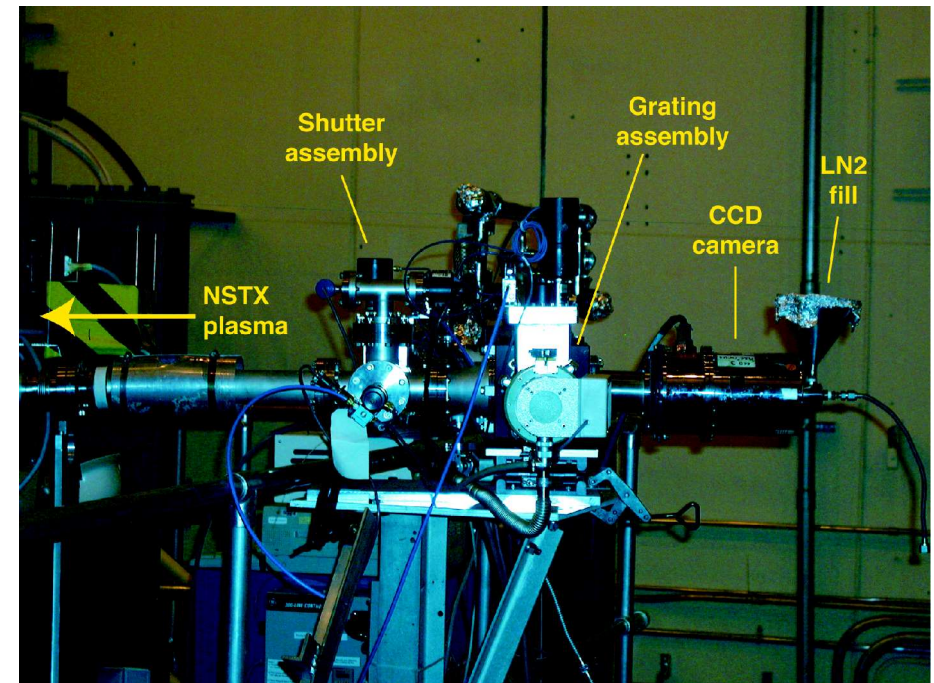


NSTX Characteristics

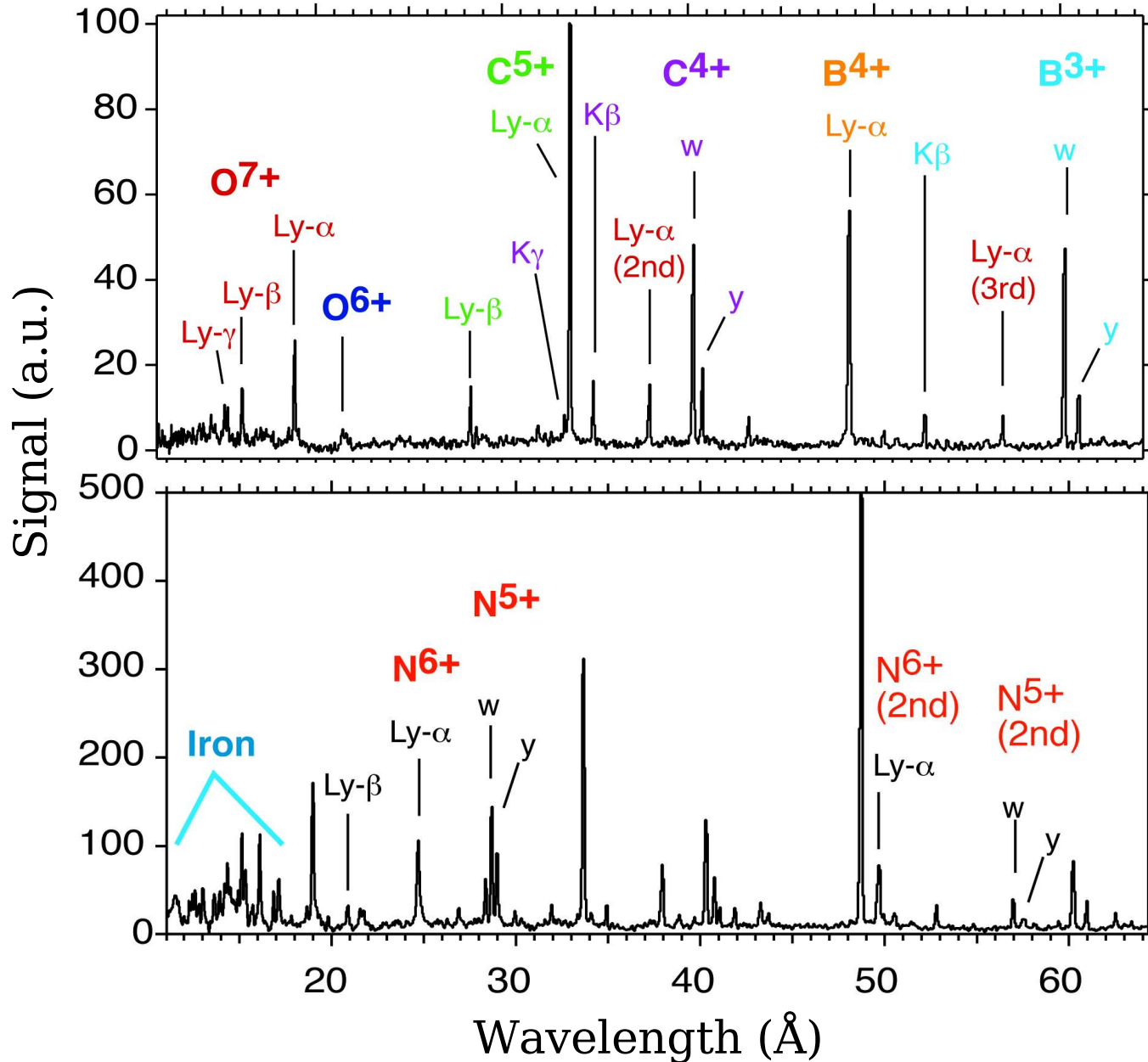
- n_e (peak) $\sim 10^{19}$ particles/m³
- T_e (peak) ~ 1.5 keV
- Aspect ratio (R/a) = 1.26
- Peak toroidal B field ~ 0.25 T
- Pulse length ~ 1.5 s
- Plasma current ~ 1.5 MA

Modifications

- Shutter allowing one 50 ms exposure/discharge
- 30-100 μm entrance slit, giving line width of 0.1 \AA making $\Delta\lambda/\lambda = 400$ for C V at 40 \AA
- Radial view at the plasma midplane (10 m away)



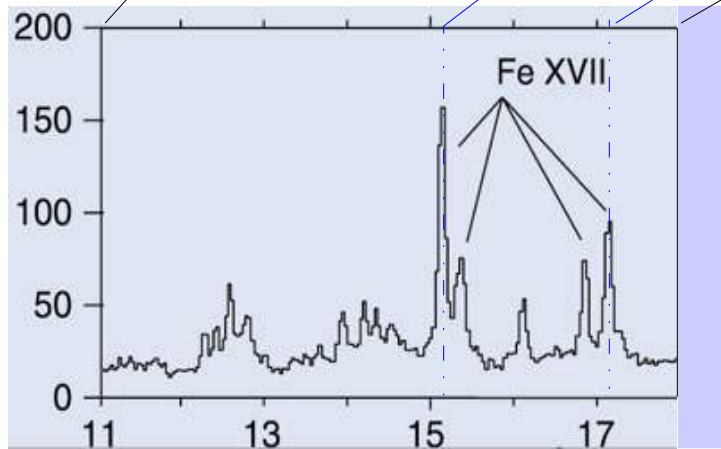
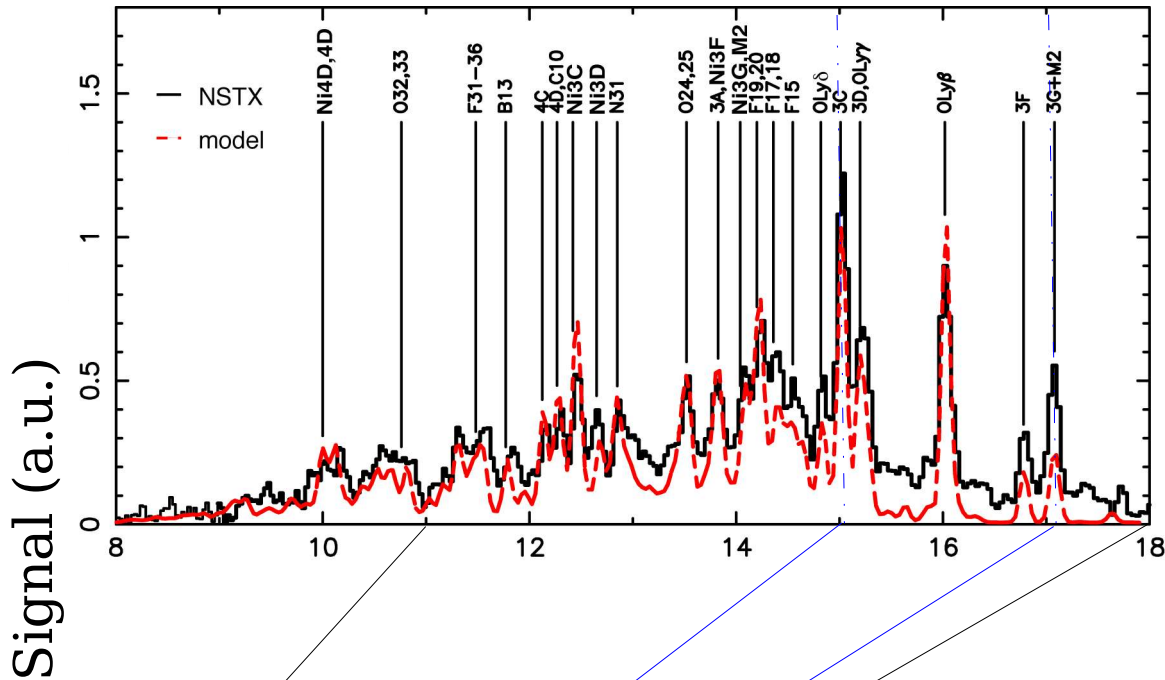
XEUS at NSTX



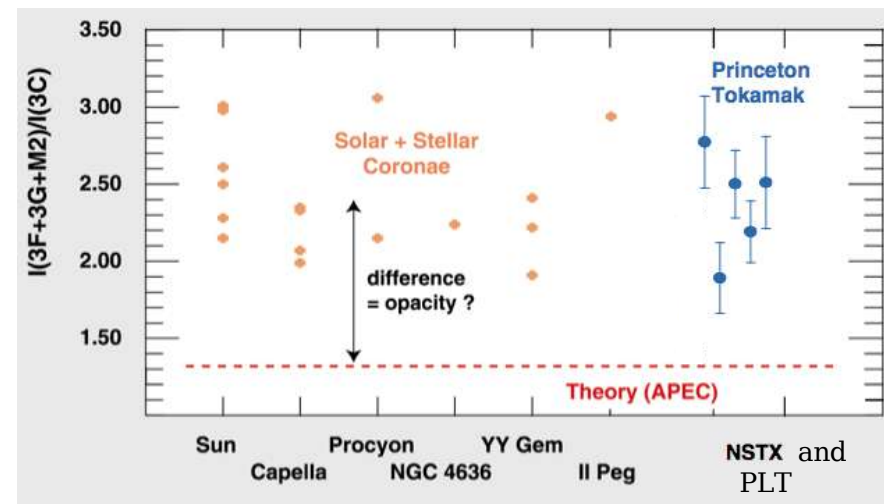
Feature	wavelength (Å)
O ⁷⁺ Ly-γ	15.14
O ⁷⁺ Ly-β	16.11
O ⁷⁺ Ly-α	19.00
C ⁵⁺ Ly-α	33.73
C ⁴⁺ ω	40.31
B ⁴⁺ Ly-α	48.77
O ⁷⁺ Ly-α	56.97
B ³⁺ ω	60.25

XEUS at NSTX

Modeling of L-shell Fe (and Ni)

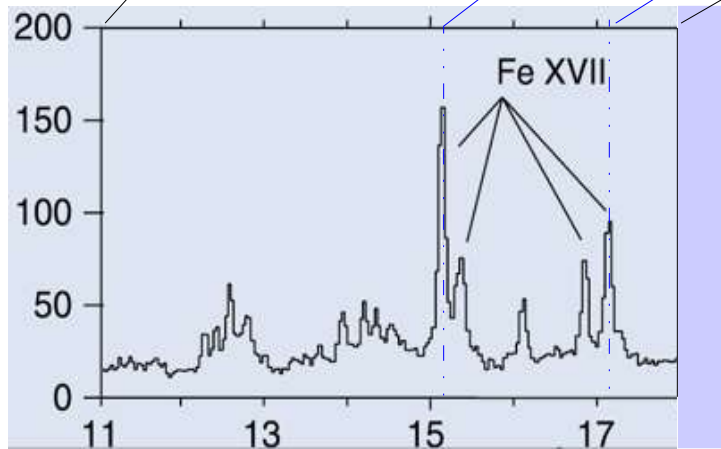
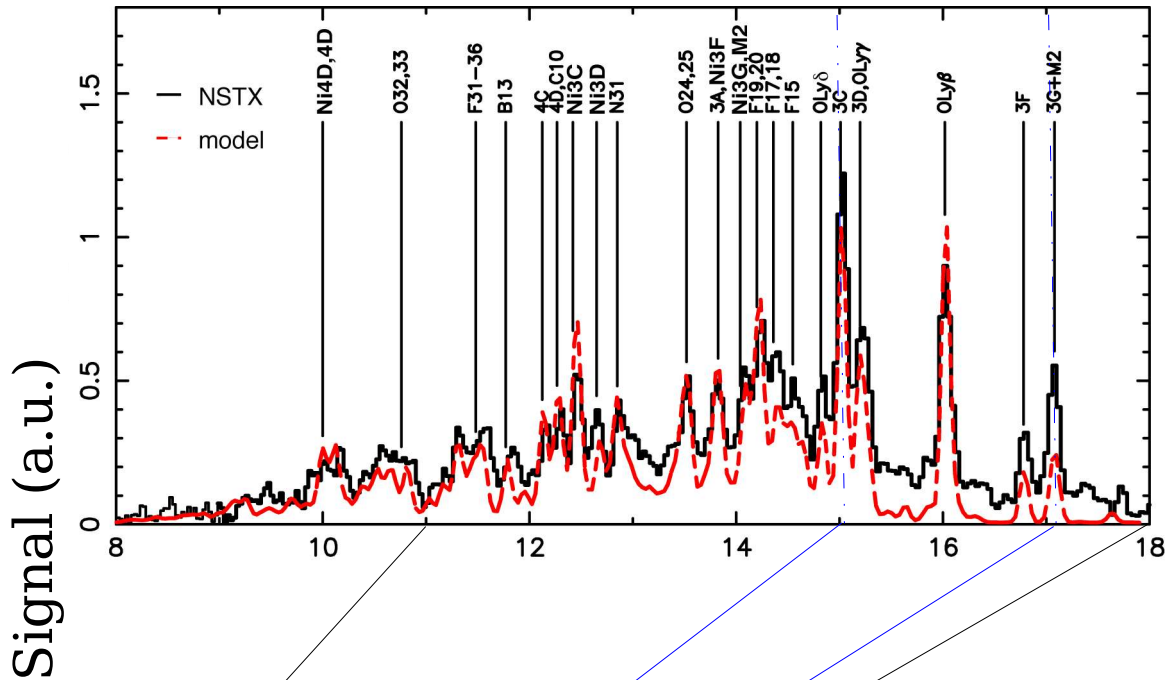


Wavelength (Å)



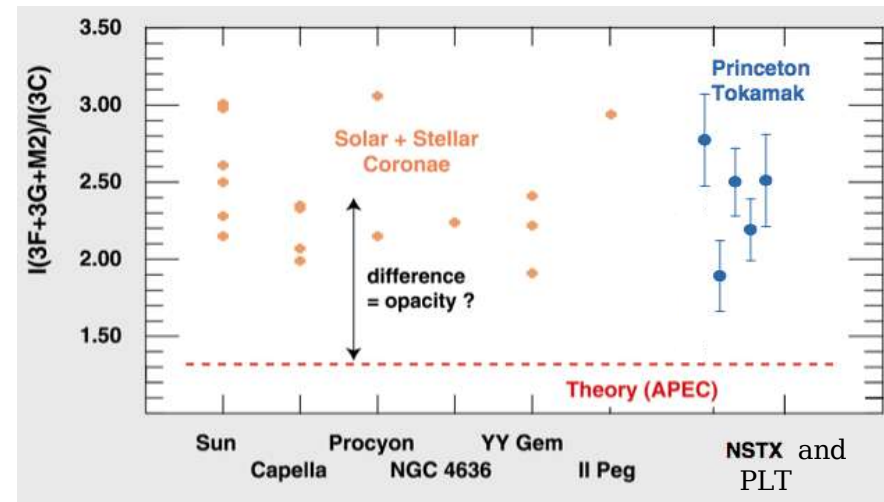
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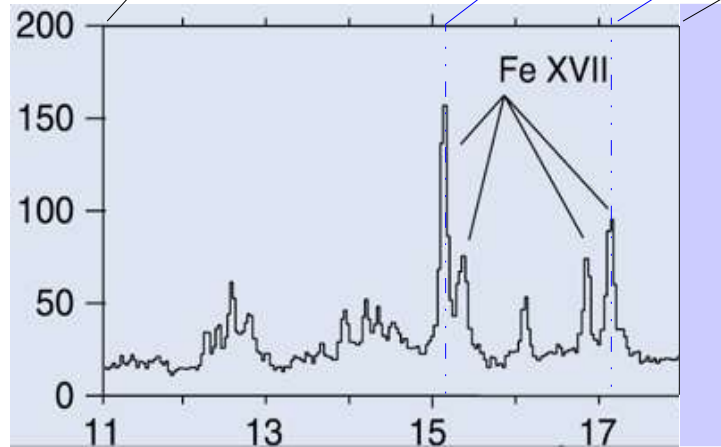
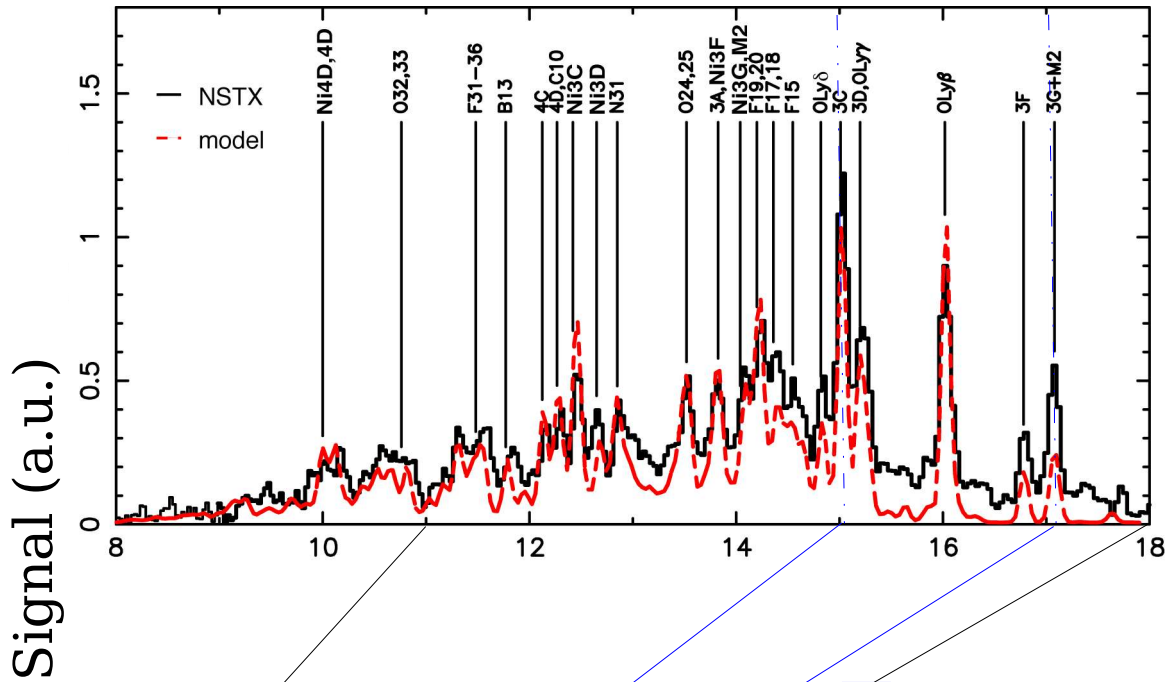
Wavelength (Å)

- APEC under-predicts ratio



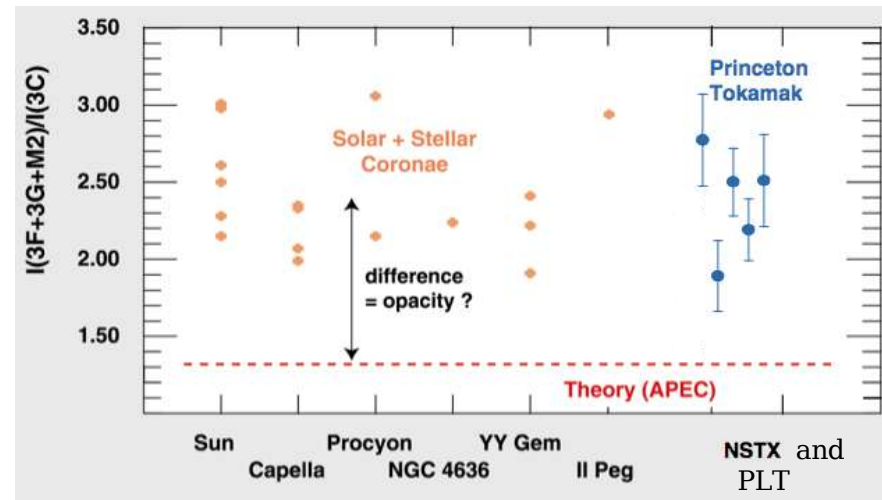
XEUS at NSTX

Modeling of L-shell Fe (and Ni)



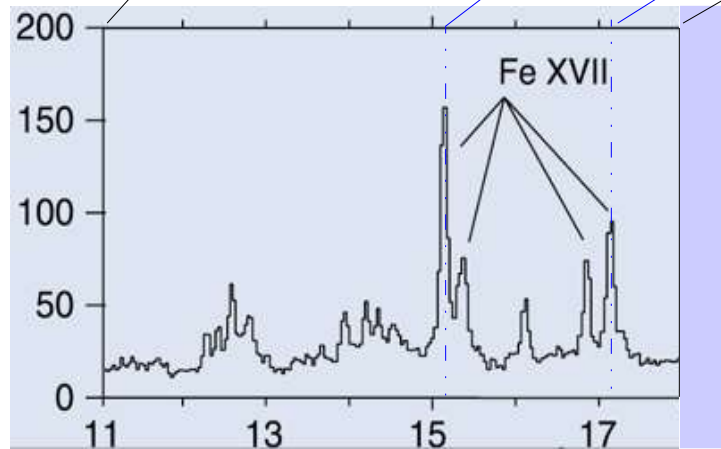
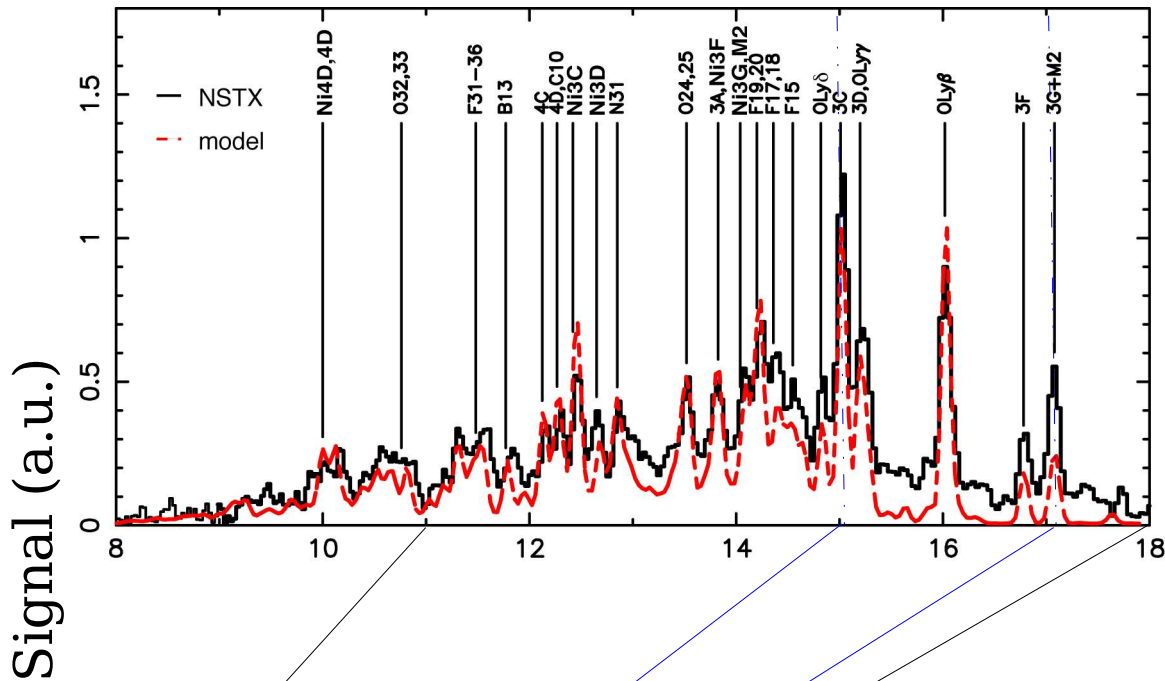
Wavelength (Å)

- APEC under-predicts ratio
- Attributed to preferential resonant scattering of 3C in experiment.



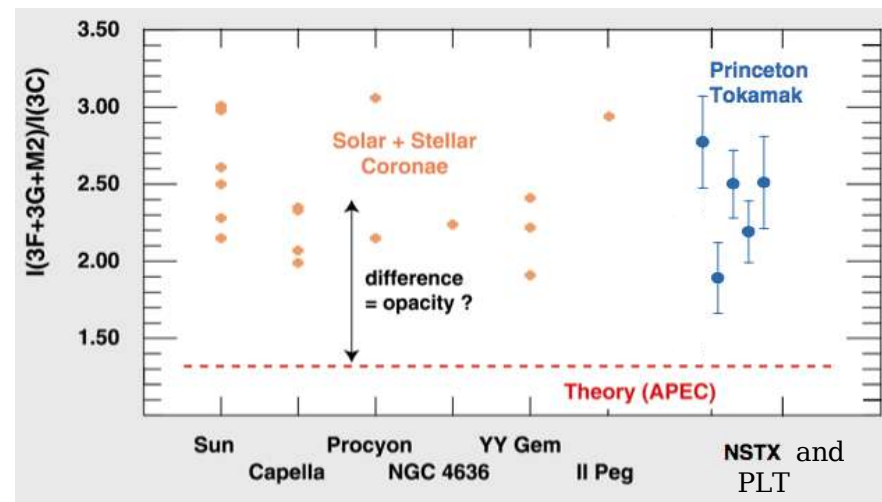
XEUS at NSTX

Modeling of L-shell Fe (and Ni)



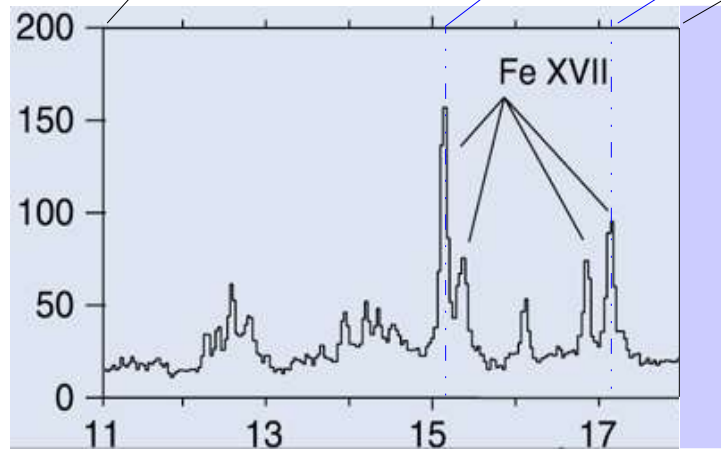
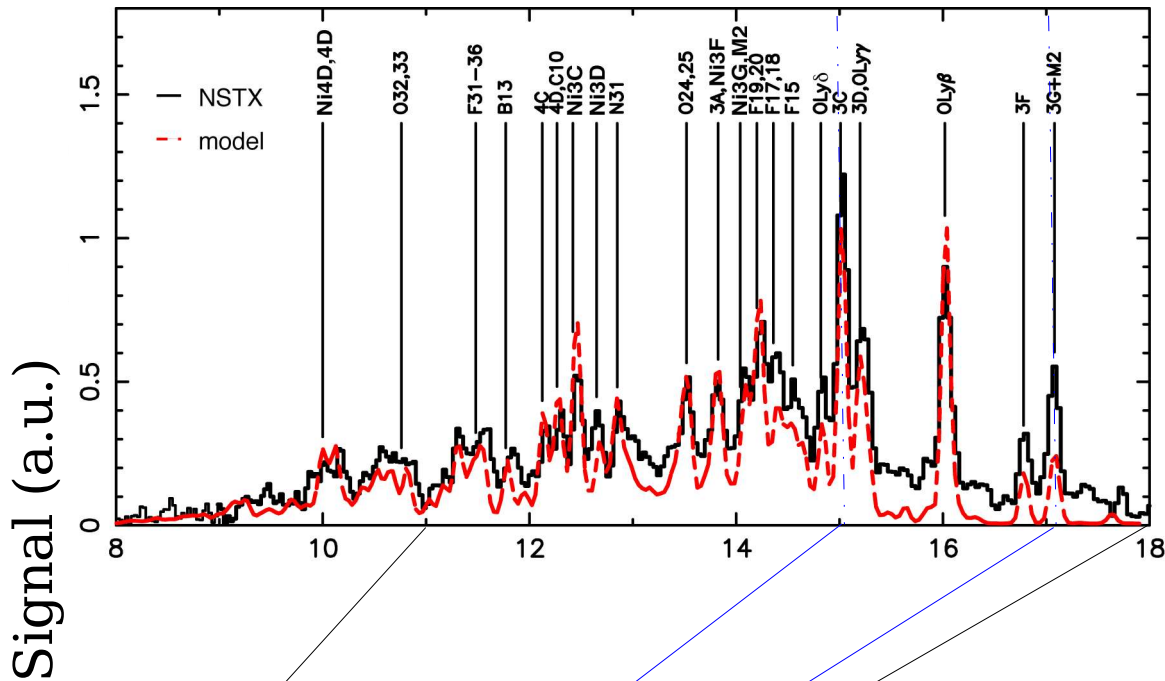
Wavelength (Å)

- APEC under-predicts ratio
- Attributed to preferential resonant scattering of 3C in experiment.
- Optically thin tokamak plasmas produce ratios in agreement with astrophysical results



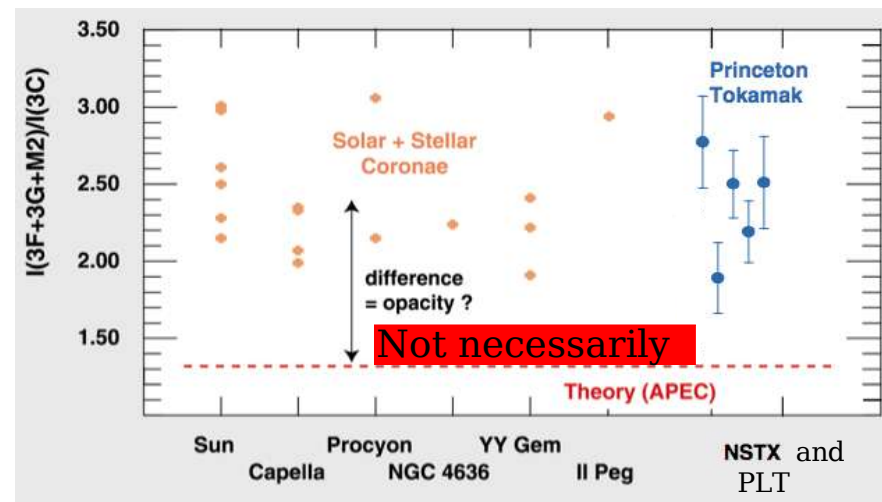
XEUS at NSTX

Modeling of L-shell Fe (and Ni)



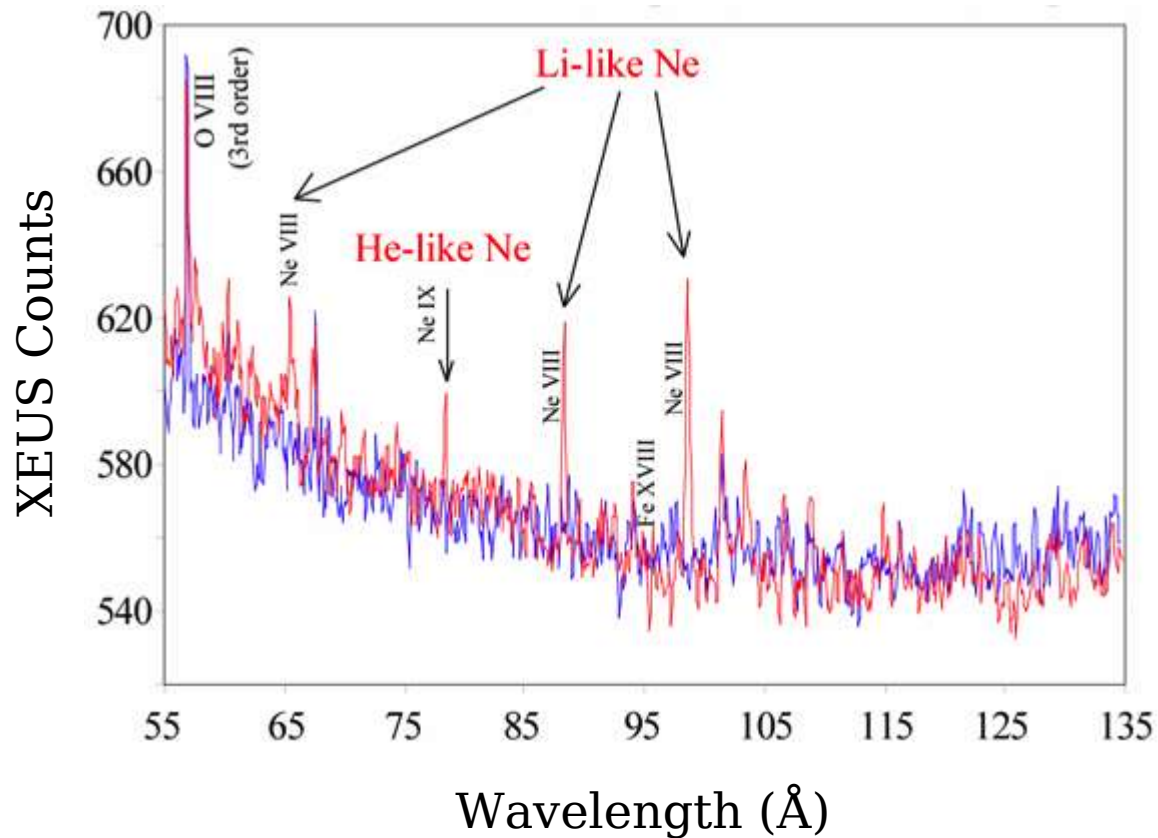
Wavelength (Å)

- APEC under-predicts ratio
- Attributed to preferential resonant scattering of 3C in experiment.
- Optically thin tokamak plasmas produce ratios in agreement with astrophysical results
- Invoking resonant scattering of 3C isn't necessary and theory needs to be adjusted



XEUS at NSTX

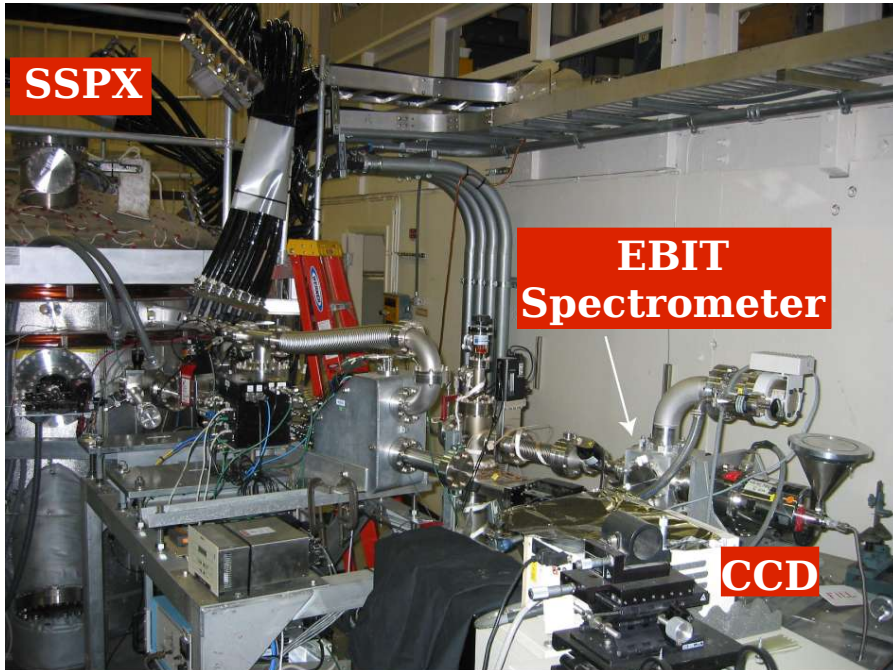
Impurity transport monitoring from Ne gas puffing



Thanks to Luis Delgado for the data evaluation

Soft x-ray/EUV spectrometer at SSPX

Work performed by P. Beiersdorfer and J. Clementson



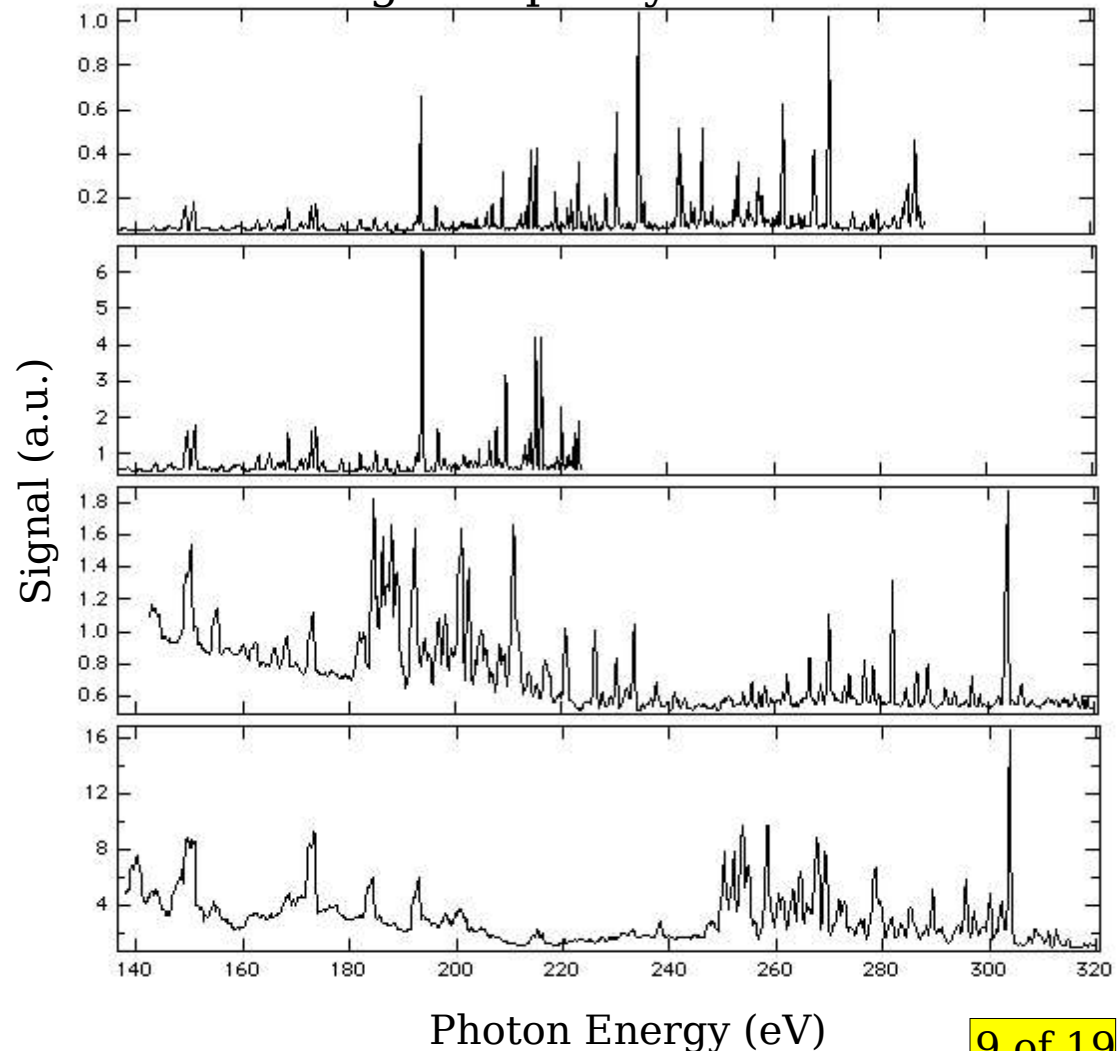
SSPX characteristics

- n_e (peak) $\sim 10^{20}$ particles/m³
- T_e (peak) ~ 350 eV
- Plasma volume = 0.4 m³
- Peak toroidal B field ~ 0.35 T
- Pulse length (max) ~ 4 ms
- Injector current ~ 200 kA

Spectrometer changes

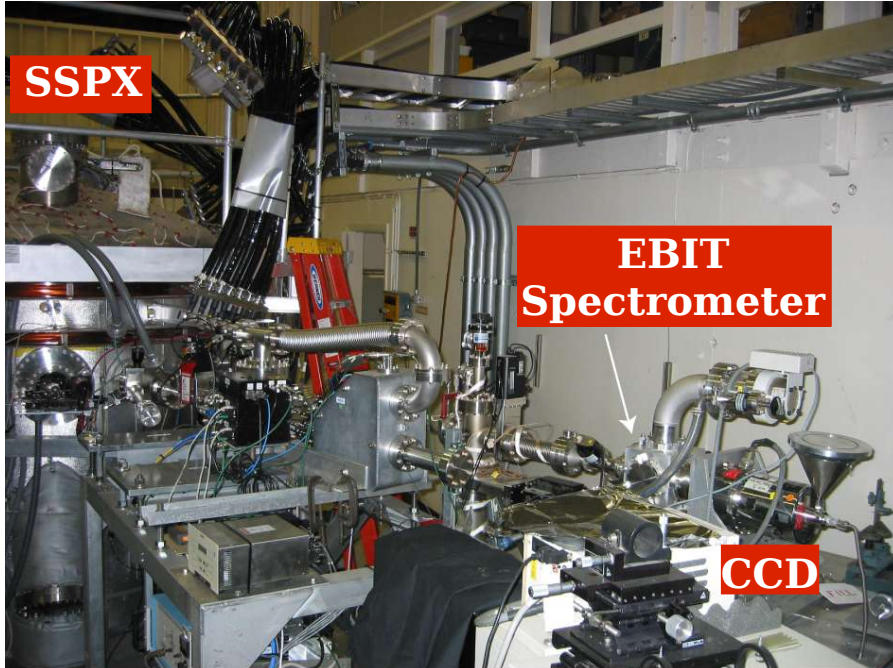
- No-shutter (time integrated)
- 1200 /mm grating
- Midplane Toroidal view ~ 1 m away

First light impurity identification



Soft x-ray/EUV spectrometer at SSPX

Work performed by P. Beiersdorfer and J. Clementson



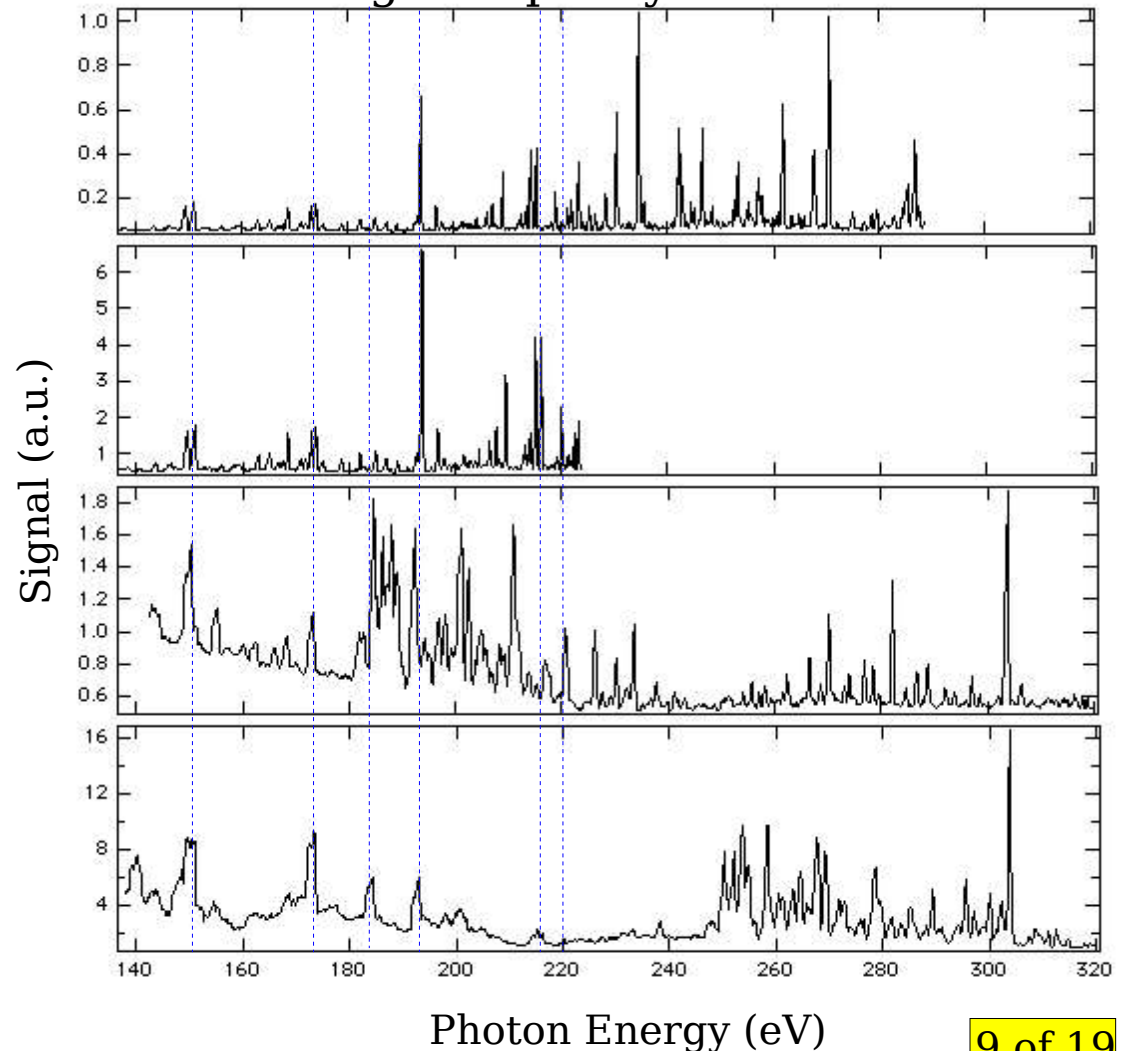
Possible impurities

- O V -VI

Spectrometer changes

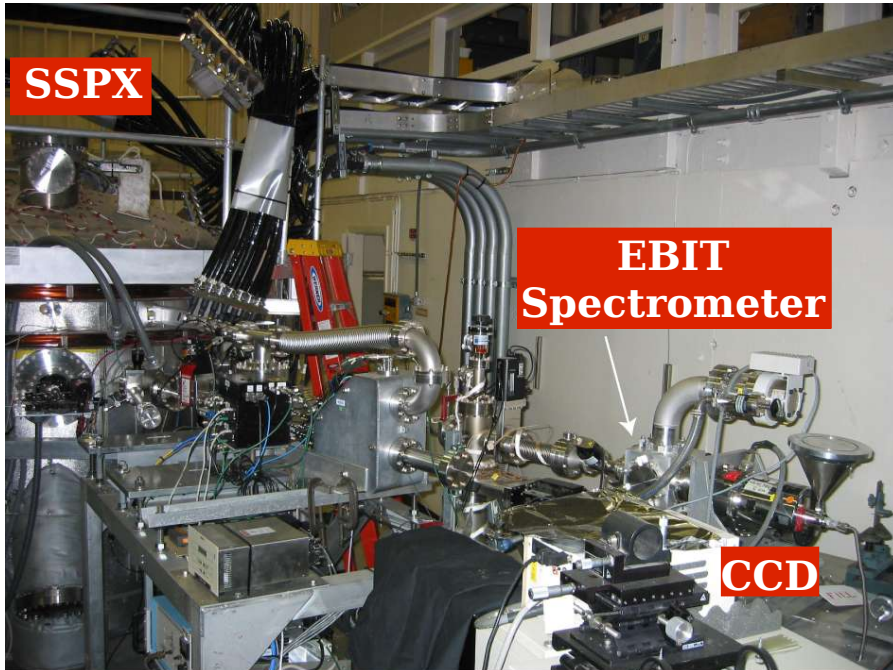
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- Midplane Toroidal view ~1 m away

First light impurity identification



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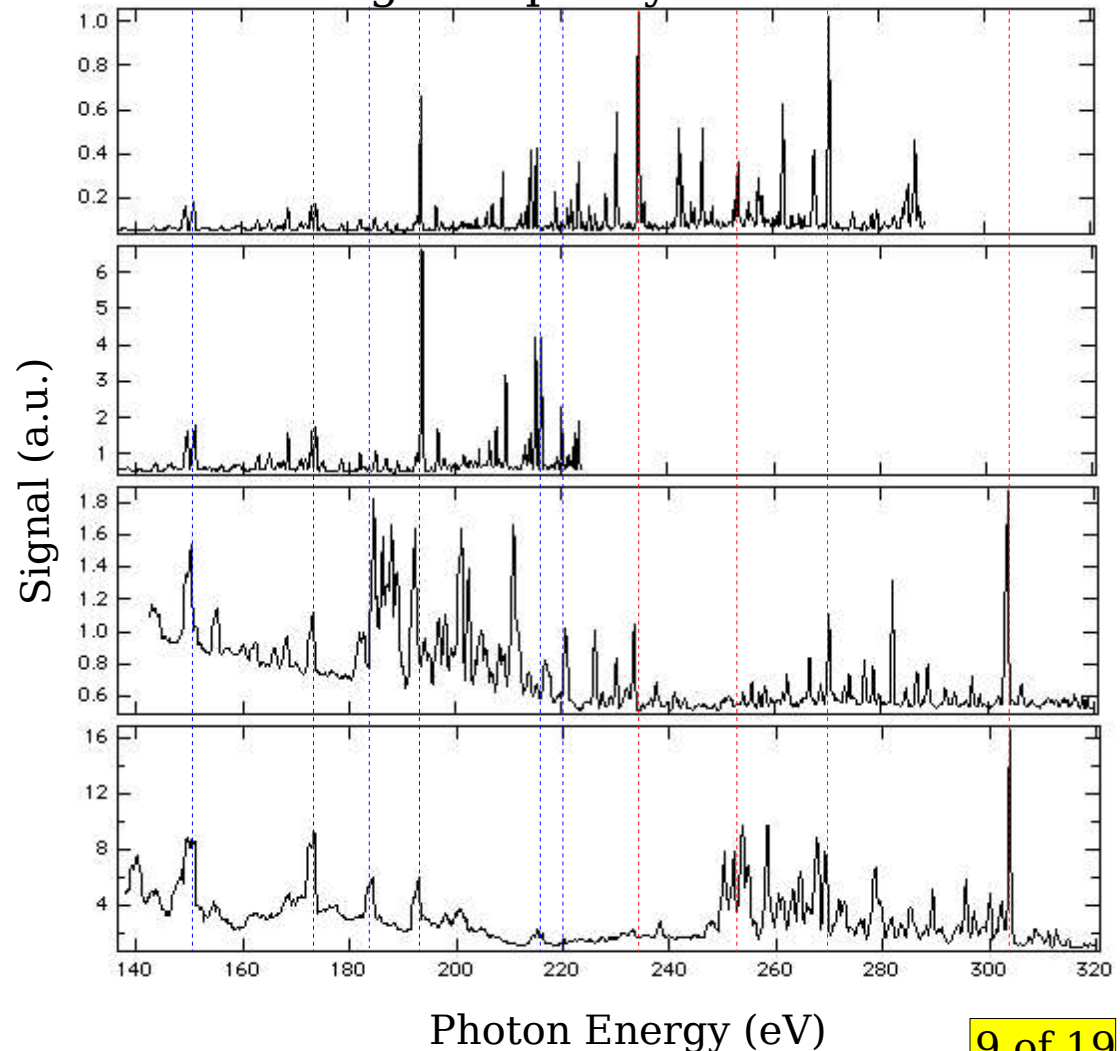
Possible impurities

- O V -VI
- He II

Spectrometer changes

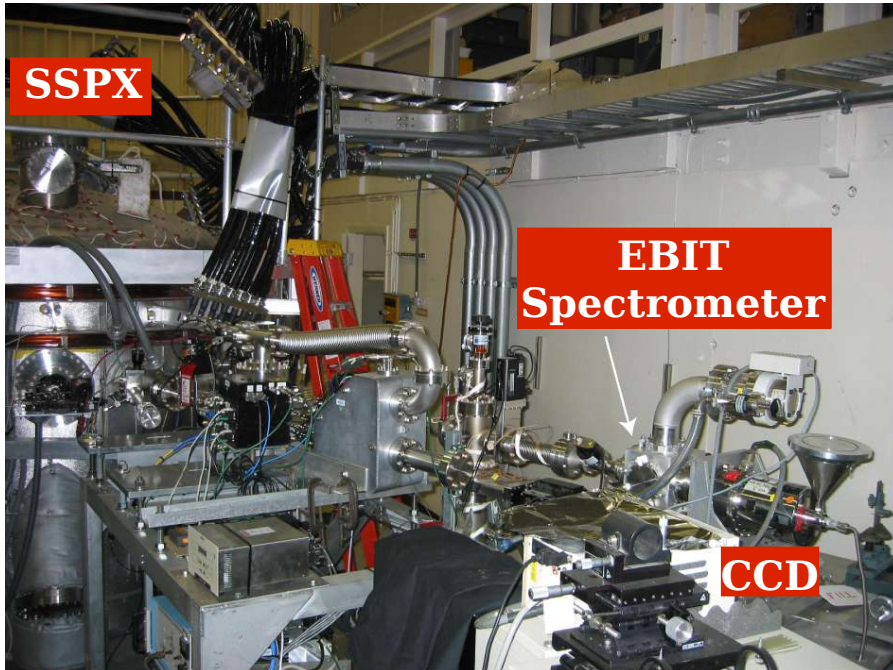
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- 1200 /mm grating
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First light impurity identification



Soft x-ray/EUV spectrometer at SSPX

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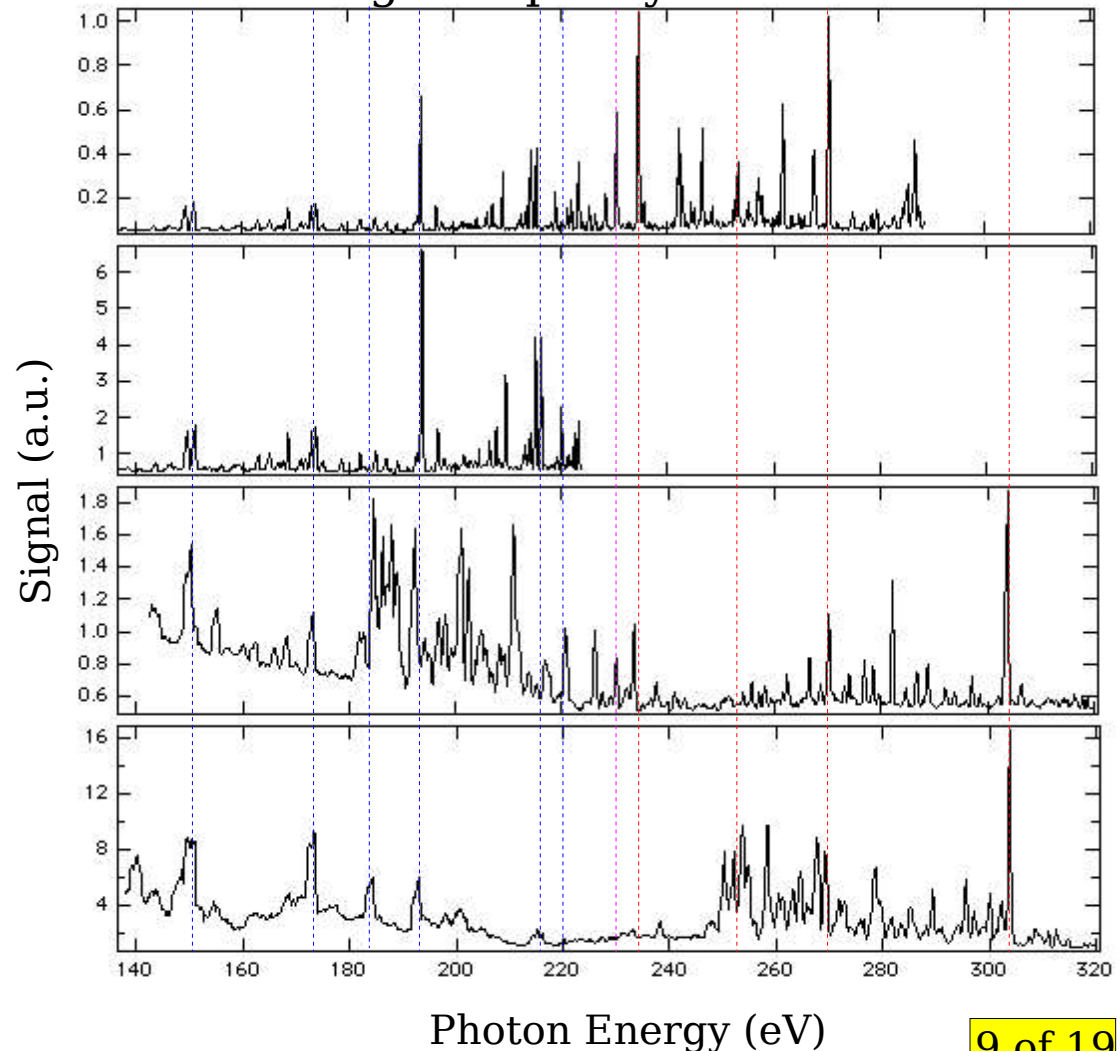
Possible impurities

- O V -VI
- He II
- Fe VII

Spectrometer changes

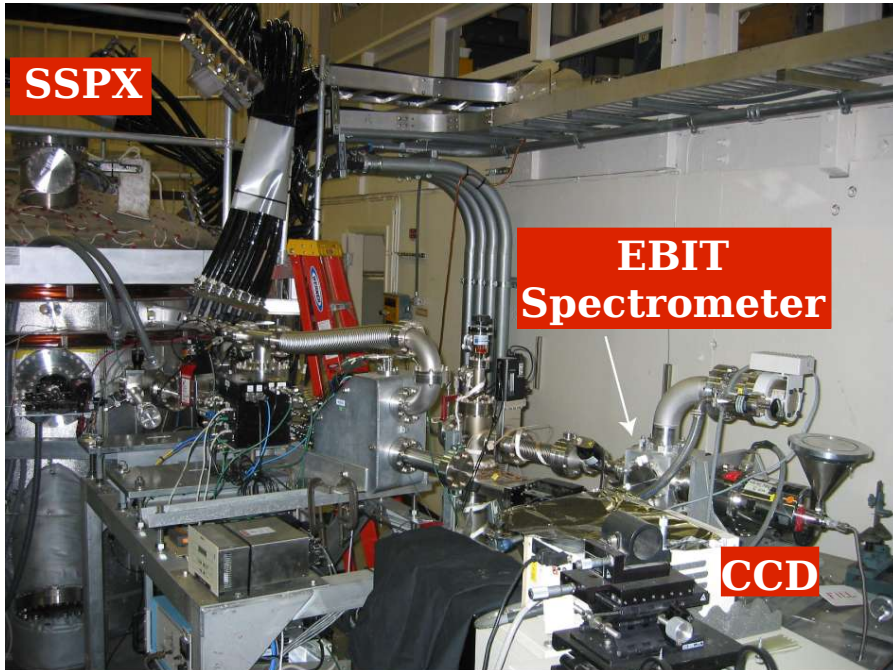
- No-shutter (time integrated)
- 1200 /mm grating
- Midplane Toroidal view ~1 m away

First light impurity identification



Soft x-ray/EUV spectrometer at SSPX

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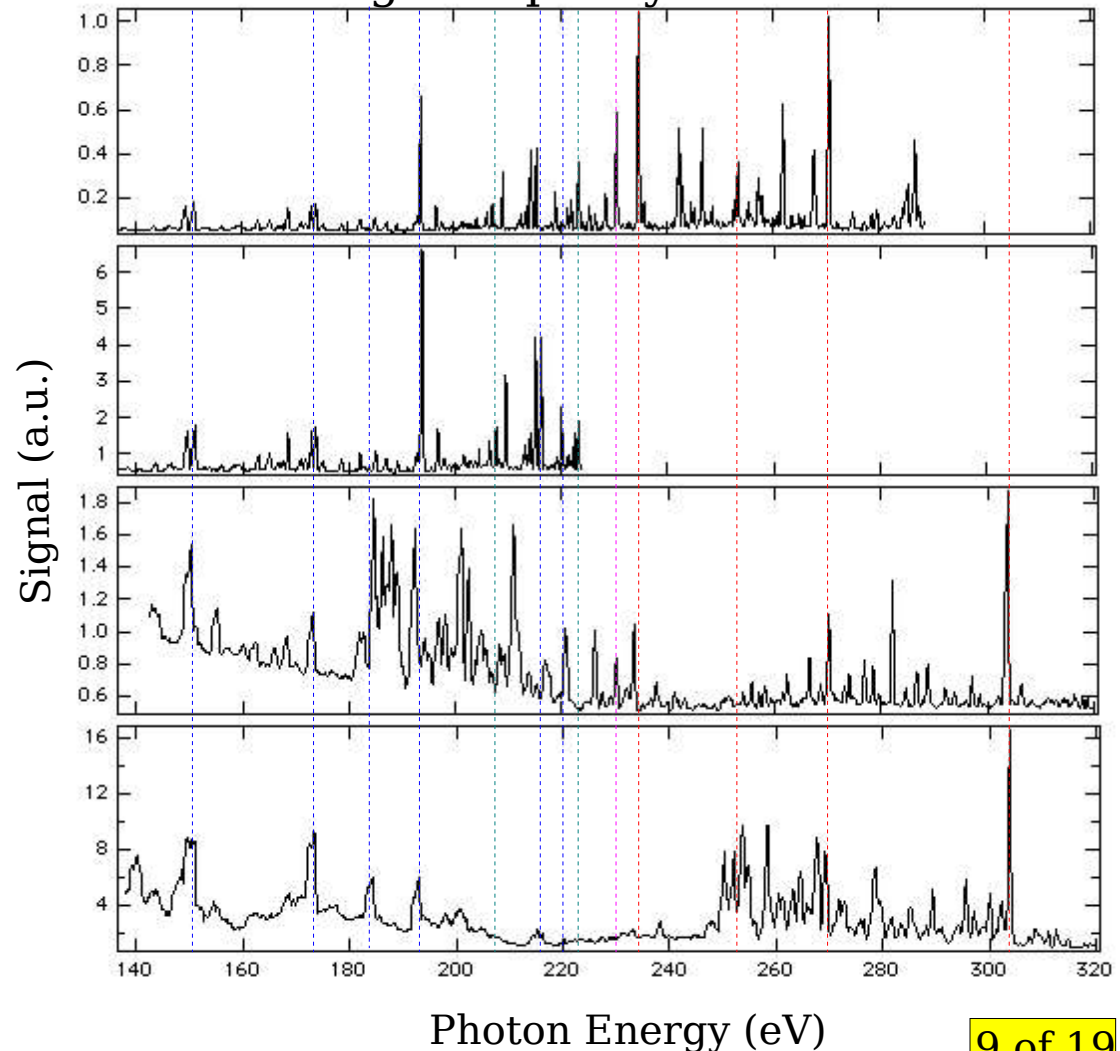
Possible impurities

- O V -VI
- He II
- Fe VII
- C IV

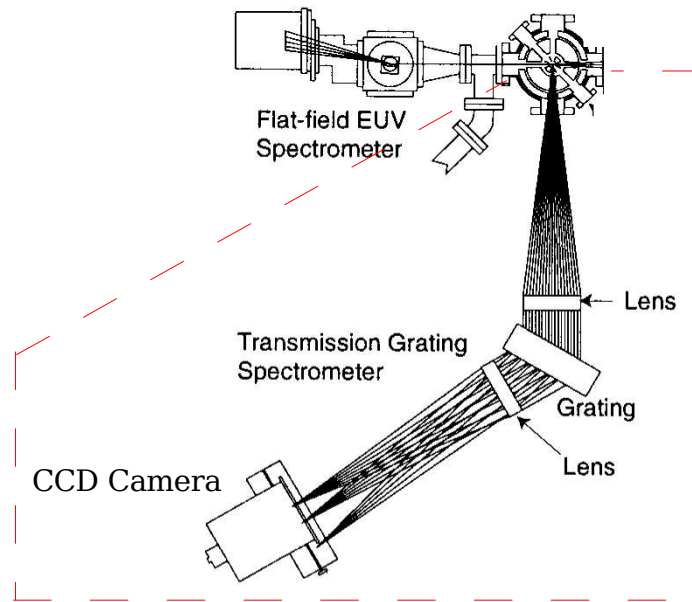
Spectrometer changes

- No-shutter (time integrated)
- 1200 /mm grating
- Midplane Toroidal view ~1 m away

First light impurity identification



Transmission grating spectrometer at EBIT



Dispersion element

6" diameter transmission grating
(2857 l/mm)

Collimating Achromats
 $f/\#$

5" diameter, 16-24" focal length
3.1- 4.6

Detector

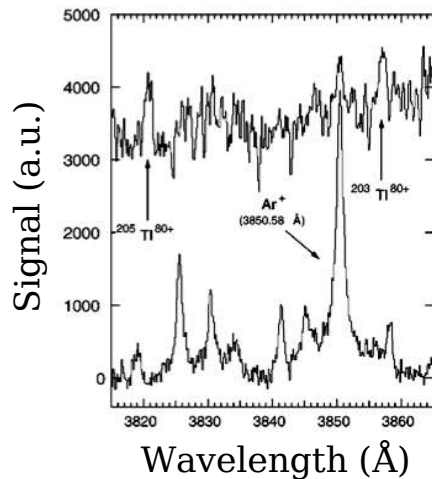
Photometrics Back-illuminated
LN2 cooled CCD
(1300x1300 with 20 μm pixels)

Wavelength range
Instrument FWHM

3600-6700 \AA ~ 130 $\text{\AA}/\text{spectrum}$
0.4 \AA

Examples of work done at EBIT with the transmission grating visible spectrometer

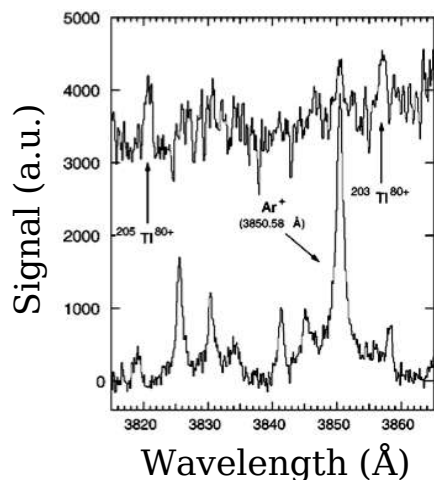
Beiersdorfer et al. 2001



- Hyperfine splitting of the 1s ground state of the two isotopes H-like $^{205}\text{Tl}^{80+}$ (3858.22 Å) and $^{203}\text{Tl}^{80+}$ (3821.84 Å)
- 30.6 meV splitting
- Determination of nuclear magnetization radii 5.83 fm ($^{203}\text{Tl}^{80+}$) and 5.89 fm ($^{205}\text{Tl}^{80+}$)

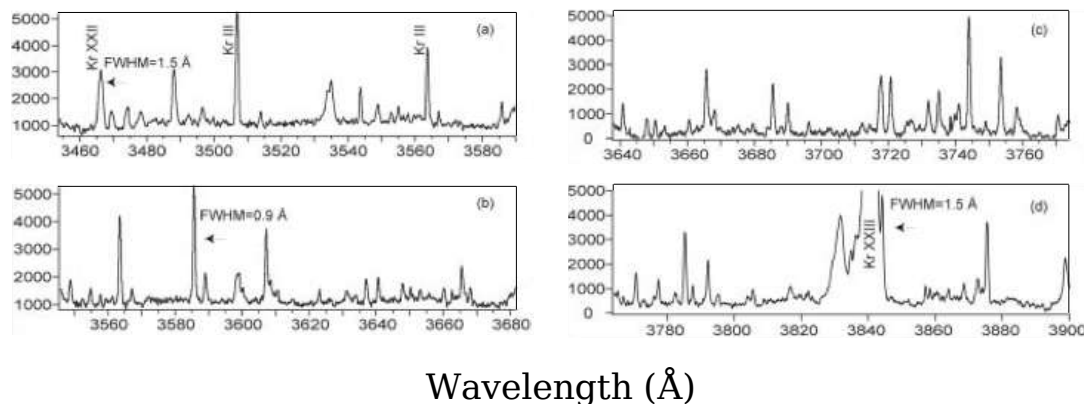
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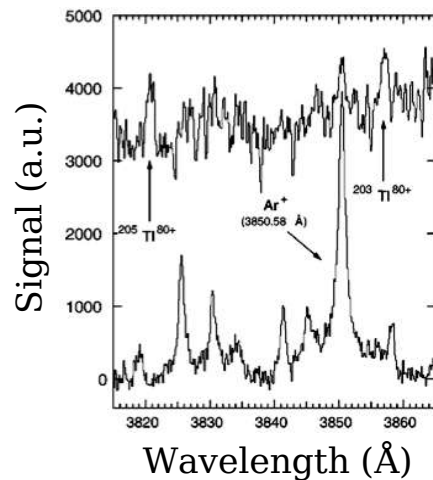
Chen et al. 2002



- Krypton for radiative cooling and transport studies in magnetic confinement devices
- 3450 – 3900 Å, 78 line features identified only 20 of which were known previously. From neutral to He-like Kr^{34+}
- Accuracy to within 0.2-0.5 Å
- Si-like Kr^{22+} (M1) $3s^23p^2\ ^3P_1$ - 3P_2 at 3841.1 Å

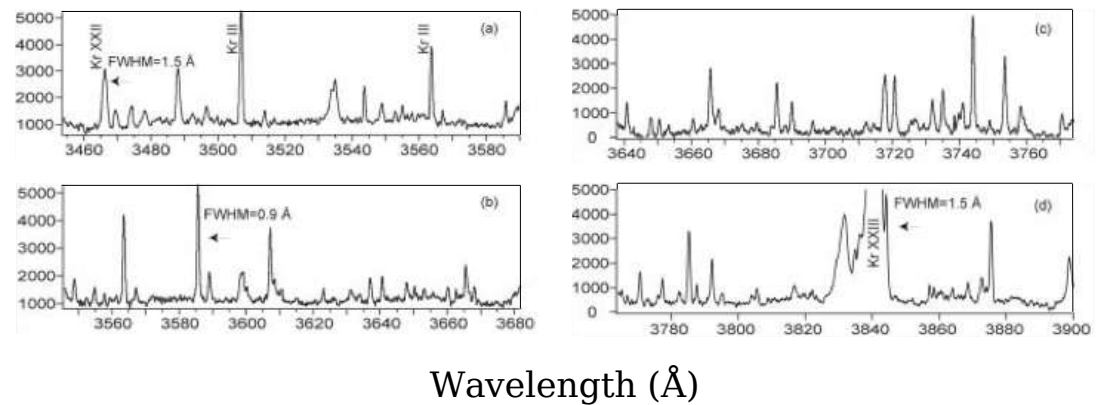
Examples of work done at EBIT with the transmission grating visible spectrometer

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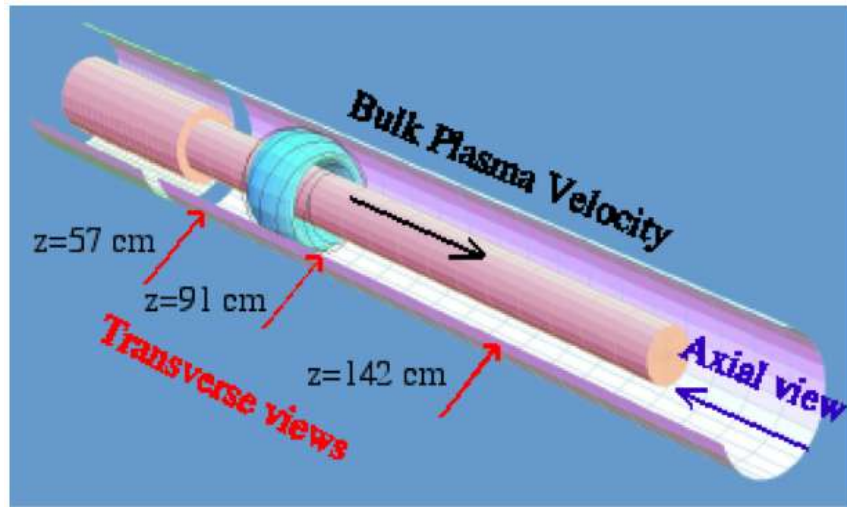
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- Träbert et al., [Visible range spectroscopy and lifetime measurement on Kr22+ in an electron beam ion trap](#), Physics Letters A, **272**; 86-92 (2000)
- Beiersdorfer et al., [Hyperfine structure of hydrogenlike thallium isotopes](#), Physical Review A, **64**; 032506 (2001)
- Chen et al., [Spectral catalog of Kr optical lines for the development of diagnostics for fusion plasmas](#), Rev. Sci. Instr., **72**; no 1, 983 (2001)
- Chen et al., [Krypton spectrum in the wavelength range 3450 – 3900 Å](#), Physica Scripta, **66**; 133-139 (2002)
- Utter et al., [Wavelength measurement of the prominent M1 transition in the ground state of Ti-like Pt, Au, and Tl ions](#), Physical Review A, **67**; 012508 (2003)

Transmission grating spectrometer at CTIX



CTIX parameters

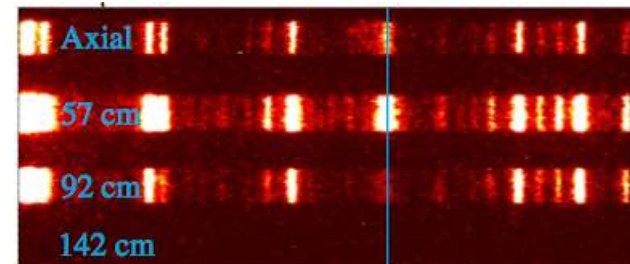
- | | |
|------------------------------|------------------------------------|
| • Shot length | ~60 μ s |
| • Velocity (magnetic probes) | ~200 km/s |
| • Te and Ti | <100 eV |
| • ne | >10 ¹⁴ cm ⁻³ |
| • Mass of Compact Torus | 10's of μ g |
| • B (peak) | 0.6 T |
| • Repetition rate | 0.2 Hz |

Spectrometer changes

- Gated and intensified DiCam Pro CCD by Cooke Camera
- 1 μ s exposure, 1 pe/shot
- 4 fiber optically connected spatial points

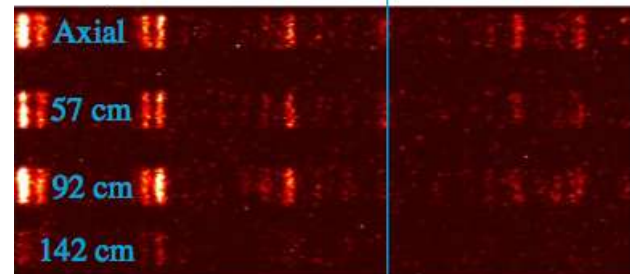
Multiple spatial channels

t = 2 μ s



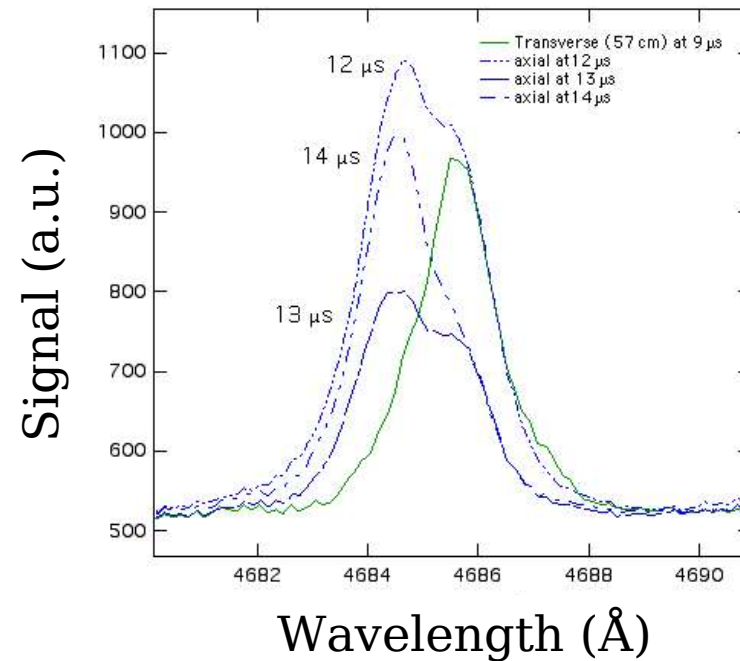
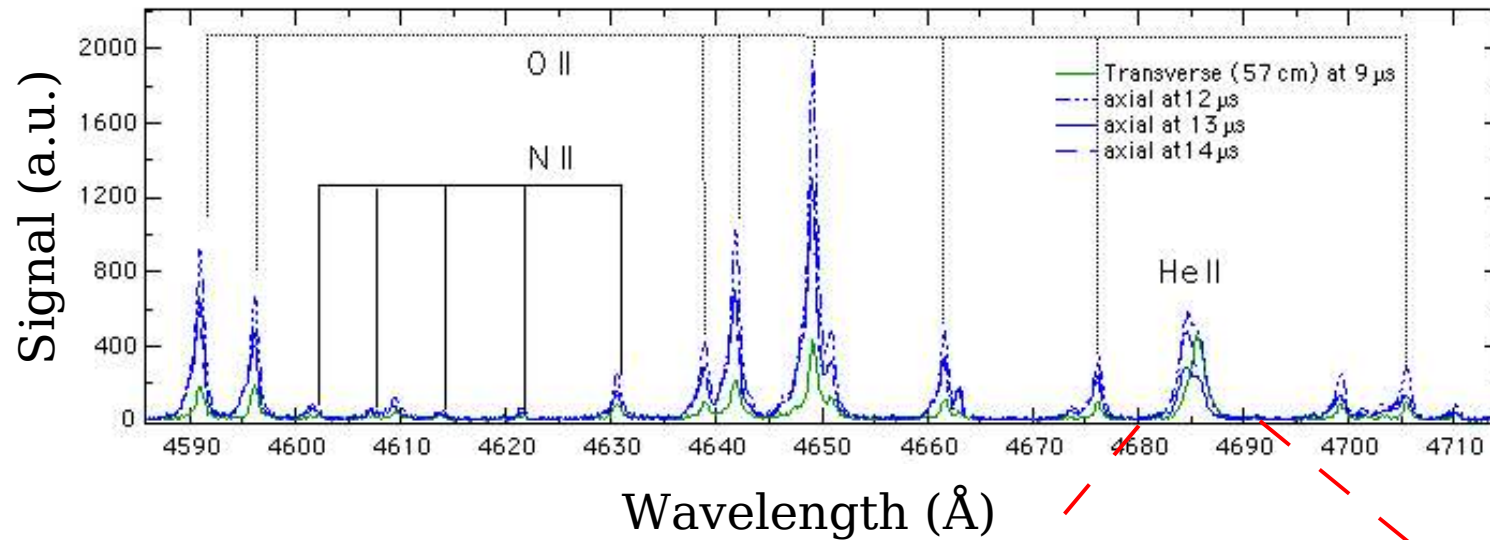
He II 4686 Å

t = 20 μ s

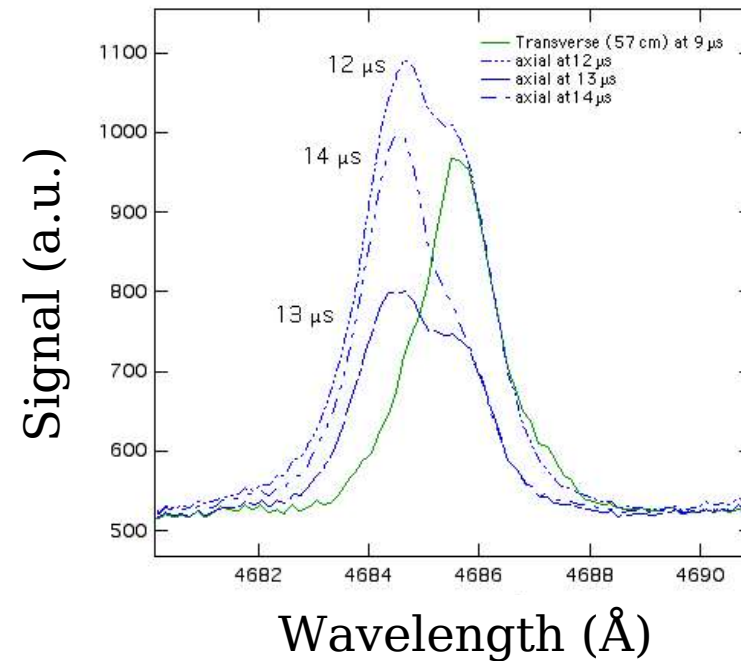
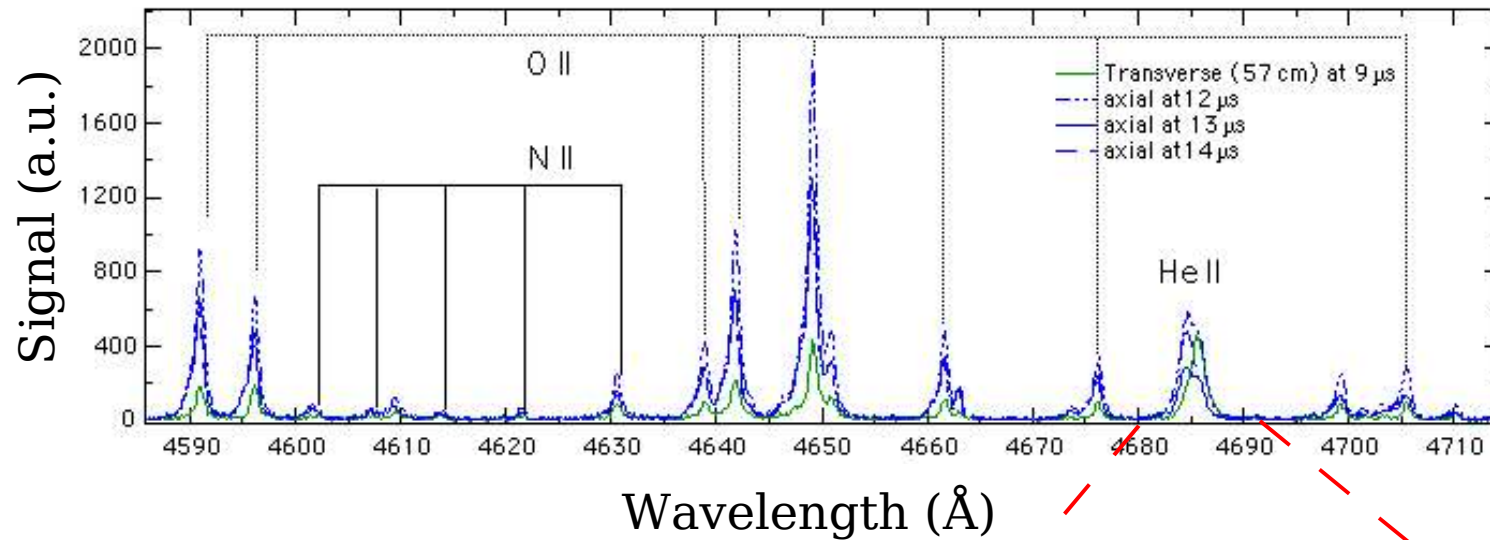


Wavelength

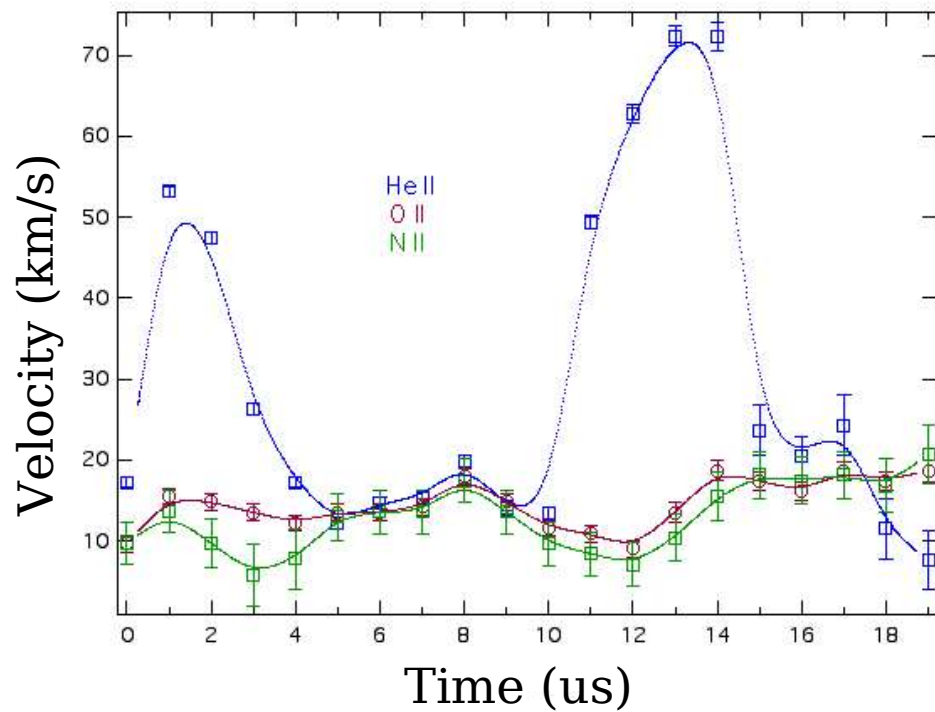
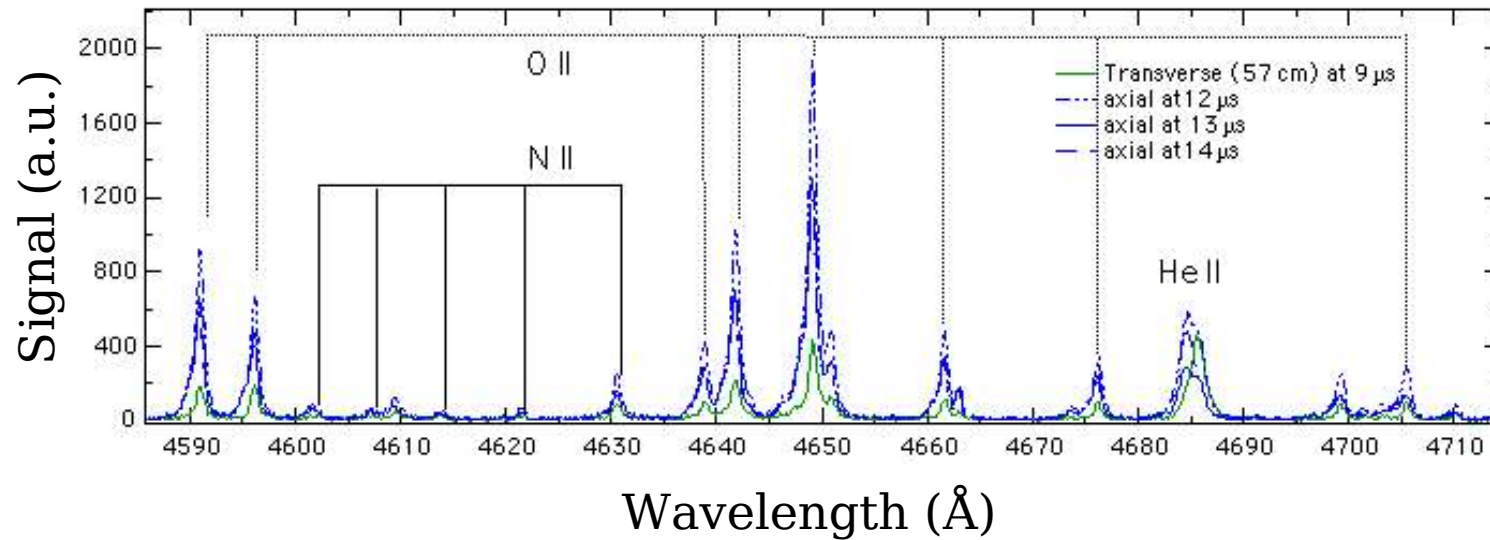
Transmission grating spectrometer at CTIX



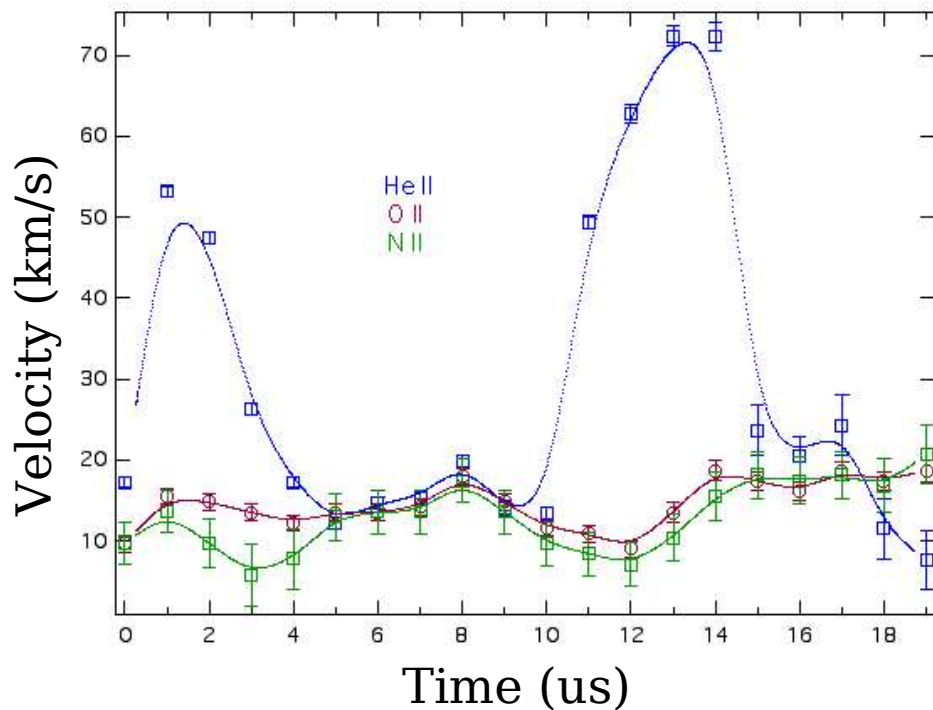
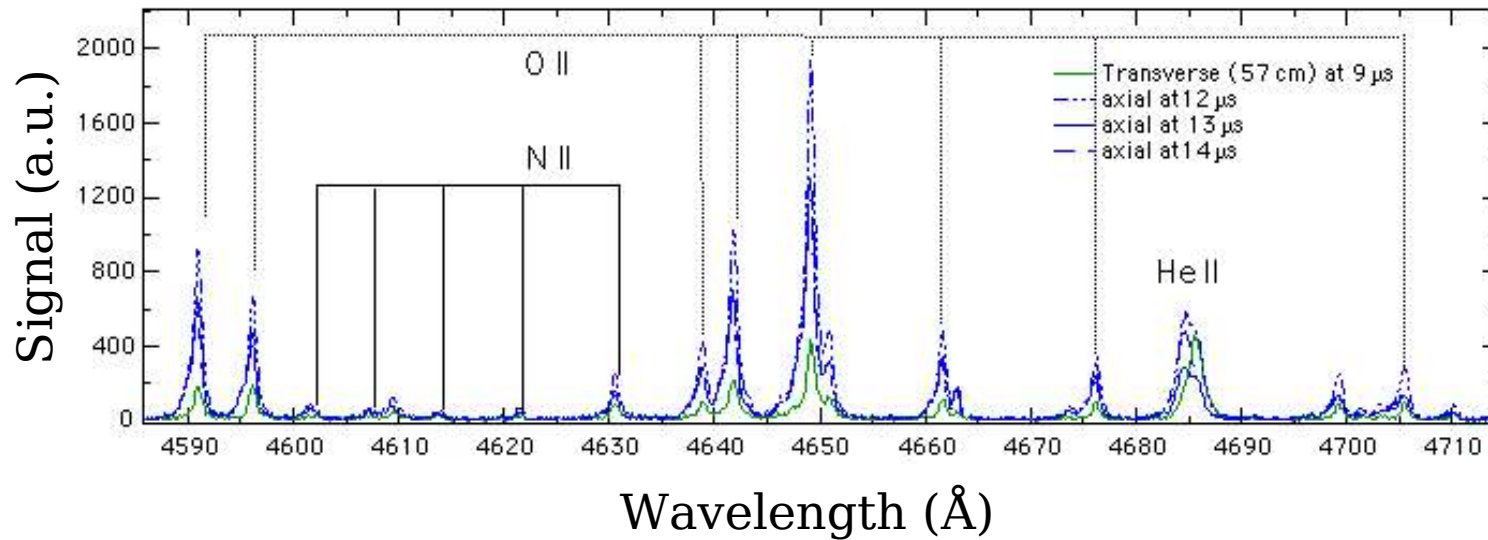
Transmission grating spectrometer at CTIX



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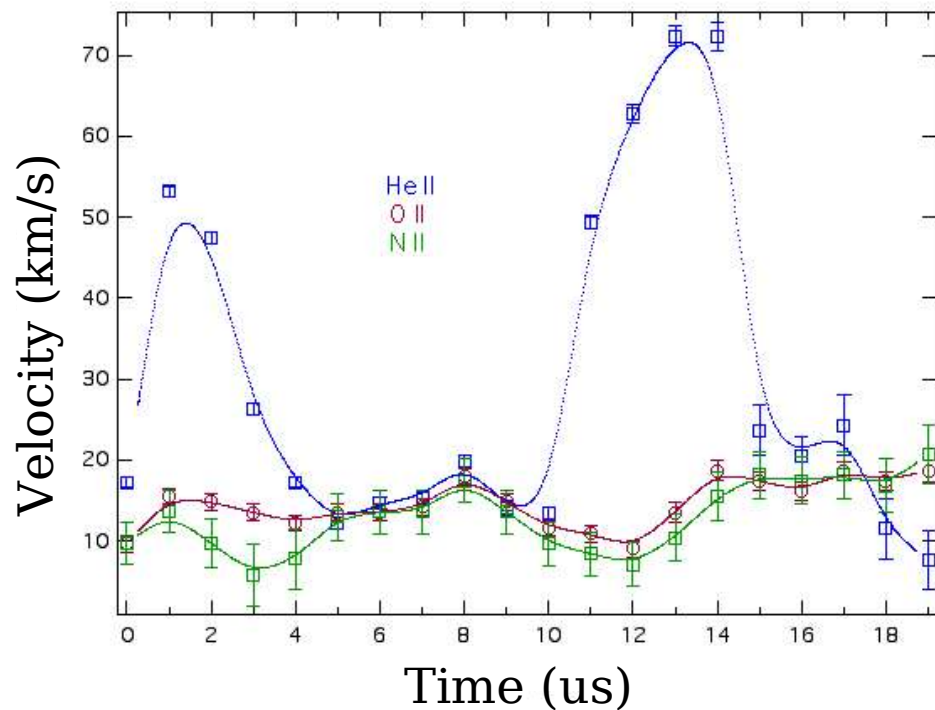
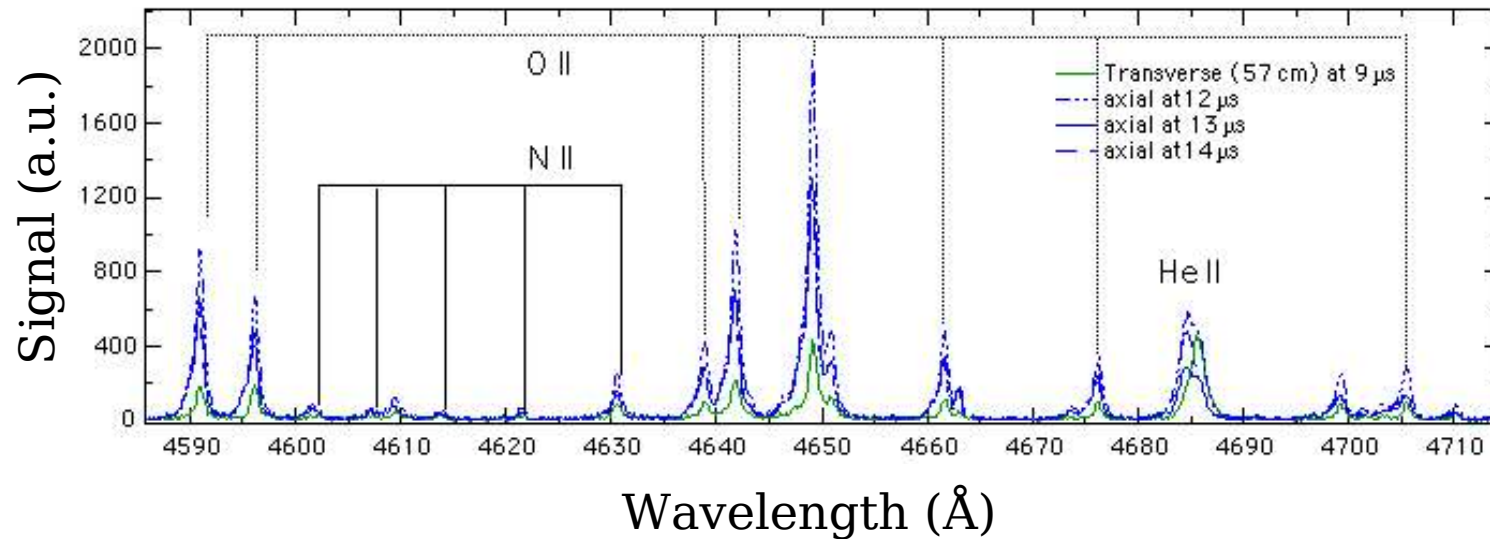


Transmission grating spectrometer at CTIX



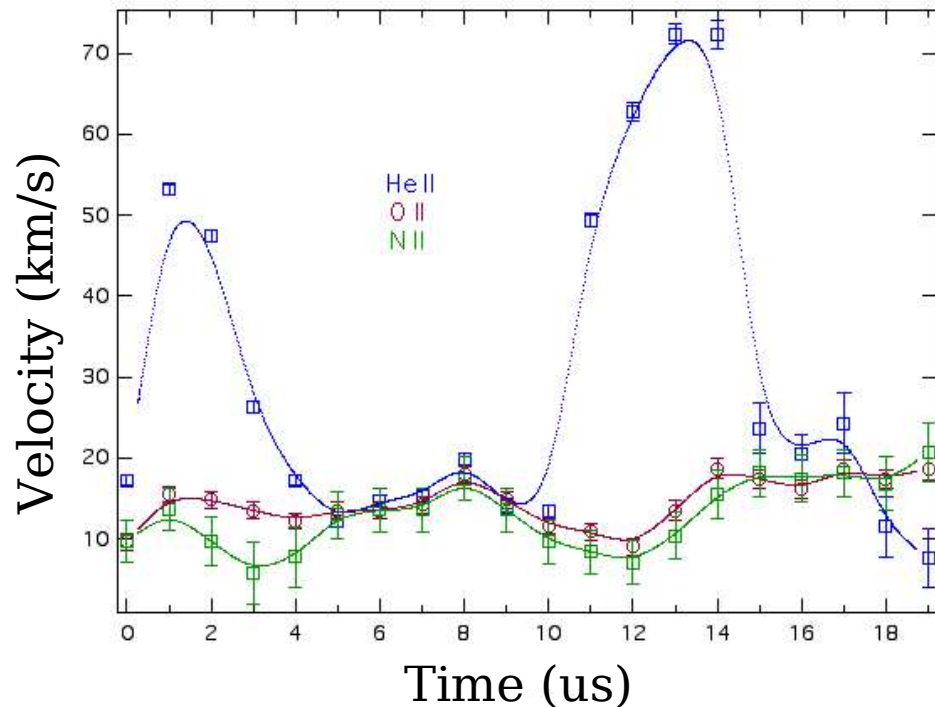
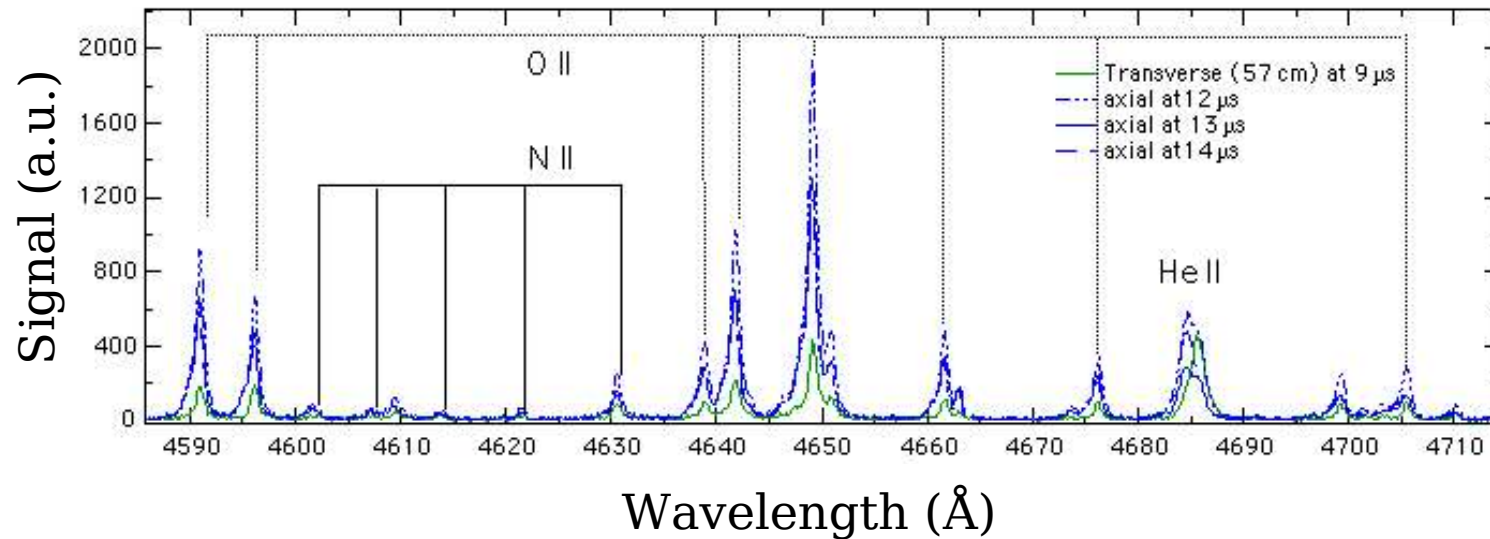
- Early peaking of He II to a maximum velocity of 50 km/s

Transmission grating spectrometer at CTIX



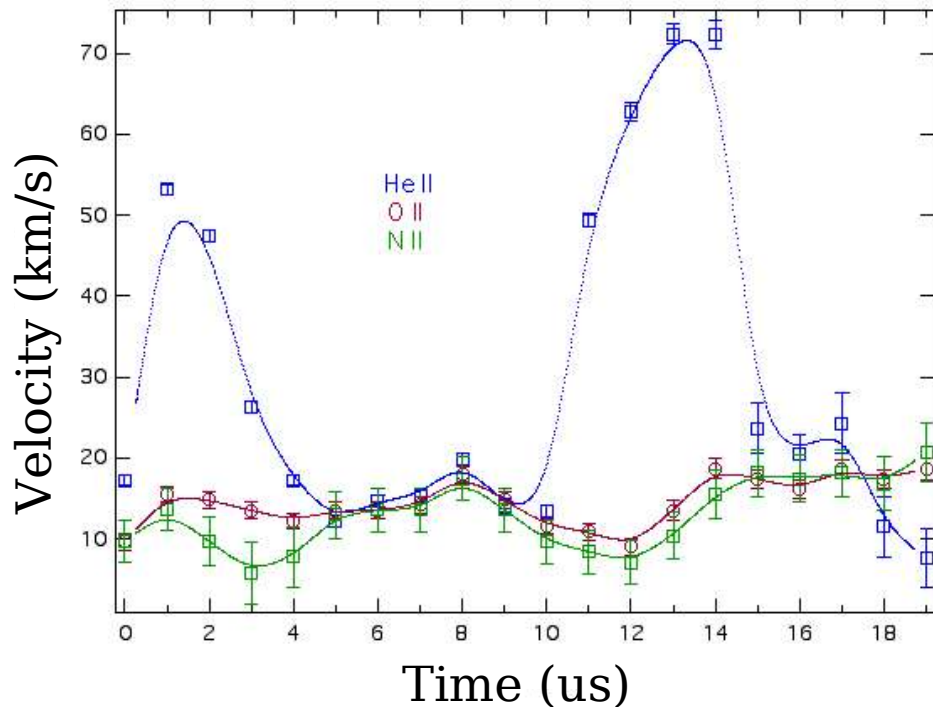
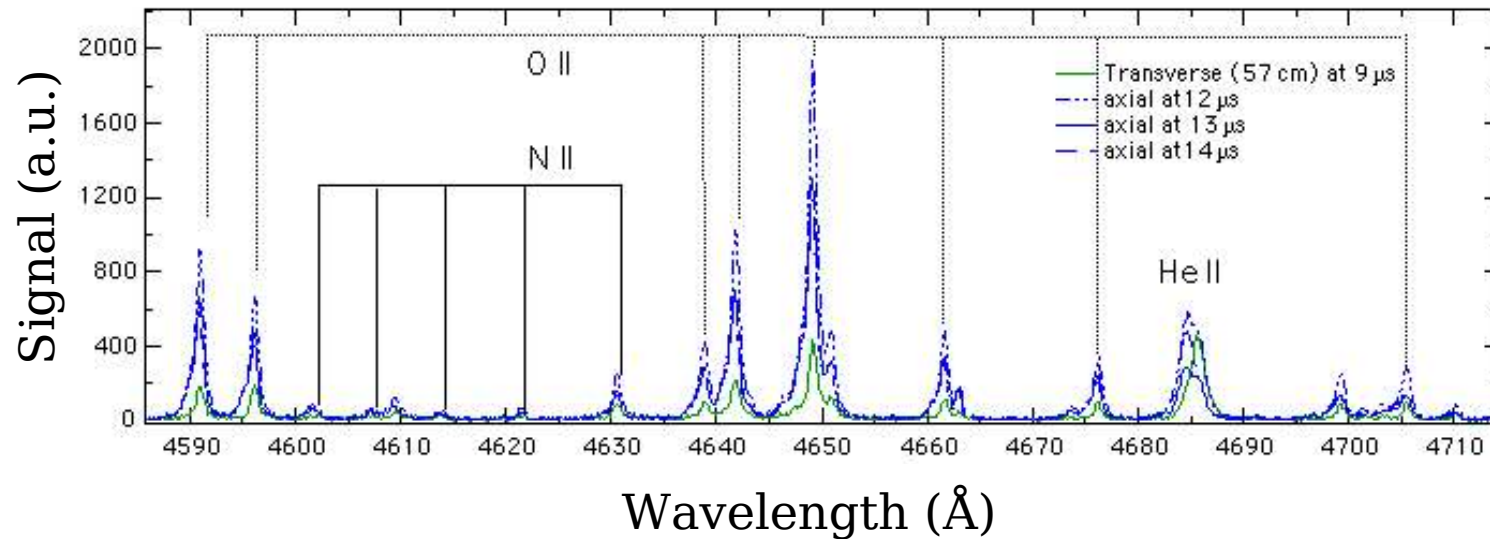
- Early peaking of He II to a maximum velocity of 50 km/s
- Second peaking to 70 km/s coincident with plasma leaving accelerator section

Transmission grating spectrometer at CTIX



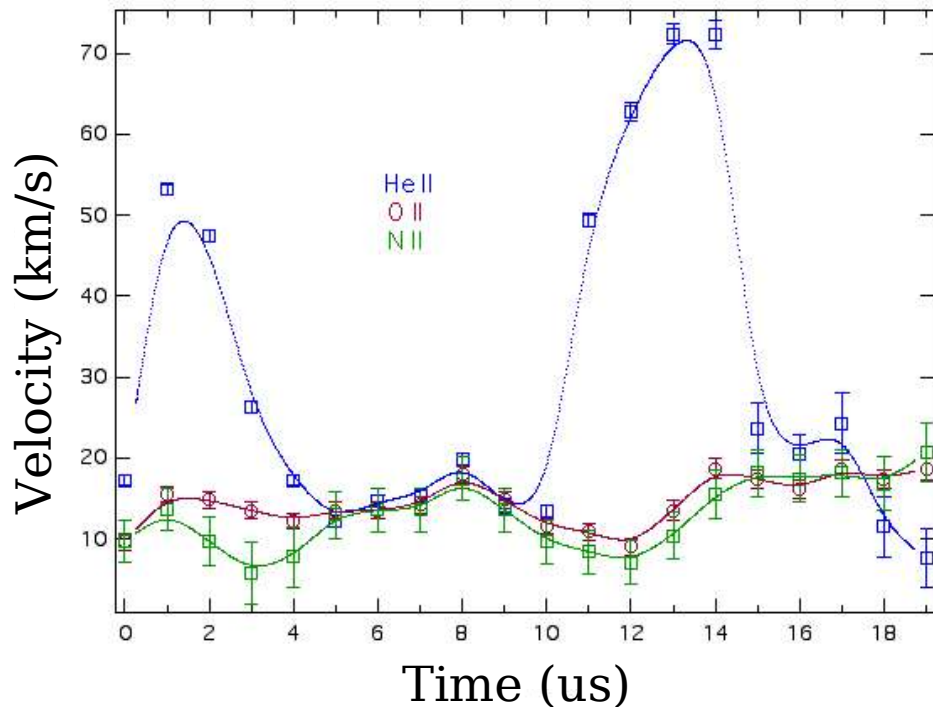
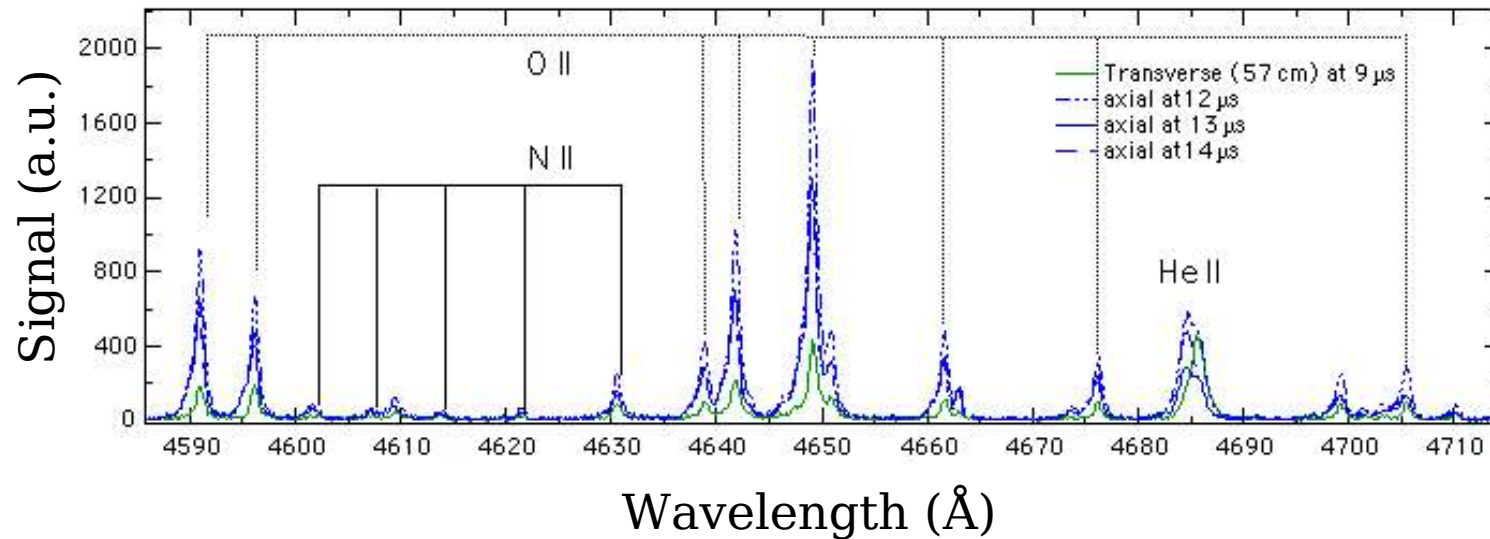
- Early peaking of He II to a maximum velocity of 50 km/s
- Second peaking to 70 km/s coincident with plasma leaving accelerator section
- 70 km/s less than the maximum velocity determined by magnetic probes (i.e. 200 km/s)

Transmission grating spectrometer at CTIX



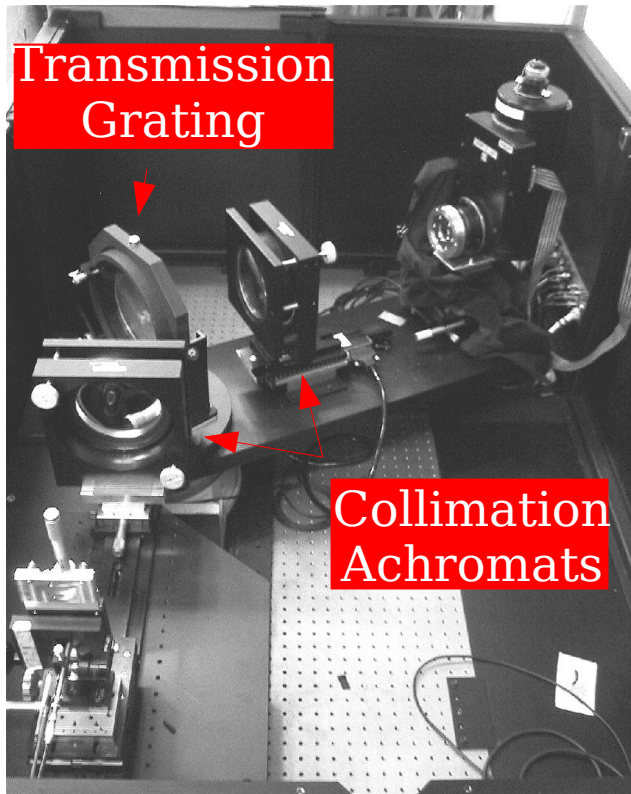
- Early peaking of He II to a maximum velocity of 50 km/s
- Second peaking to 70 km/s coincident with plasma leaving accelerator section
- 70 km/s less than the maximum velocity determined by magnetic probes (i.e. 200 km/s)
- He II is shown to burn out as the plasma travels down the tube and as the Te increases to ~55 eV

Transmission grating spectrometer at CTIX



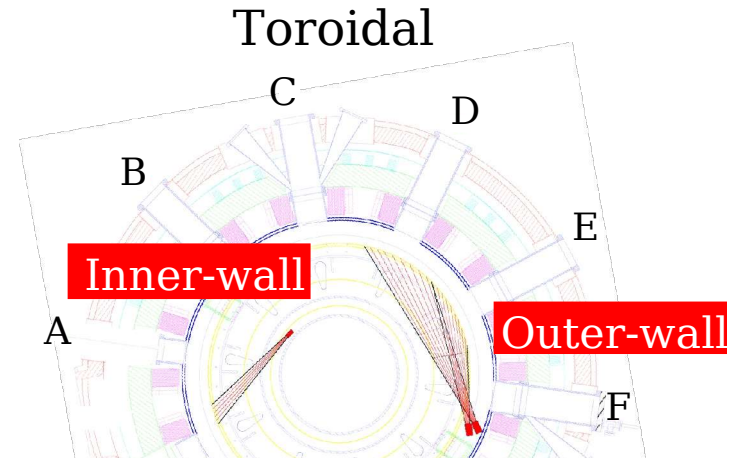
- Early peaking of He II to a maximum velocity of 50 km/s
- Second peaking to 70 km/s coincident with plasma leaving accelerator section
- 70 km/s less than the maximum velocity determined by magnetic probes (i.e. 200 km/s)
- He II is shown to burn out as the plasma travels down the tube and as the Te increases to ~55 eV
- Heavier impurities are left trailing the compact torus plasma

Transmission grating spectrometer at the Alcator C-Mod tokamak



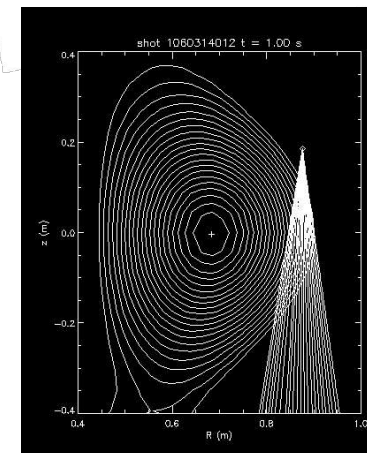
Alcator C-Mod parameters

- n_e (peak) $\sim 10^{21}$ particles/m³
- T_e (peak) $\sim 2-3$ keV
- Plasma volume = 1 m³
- Peak toroidal B field $\sim 6-8$ T
- Pulse length (max) ~ 4 s
- $I_p \sim 1.5$ MA



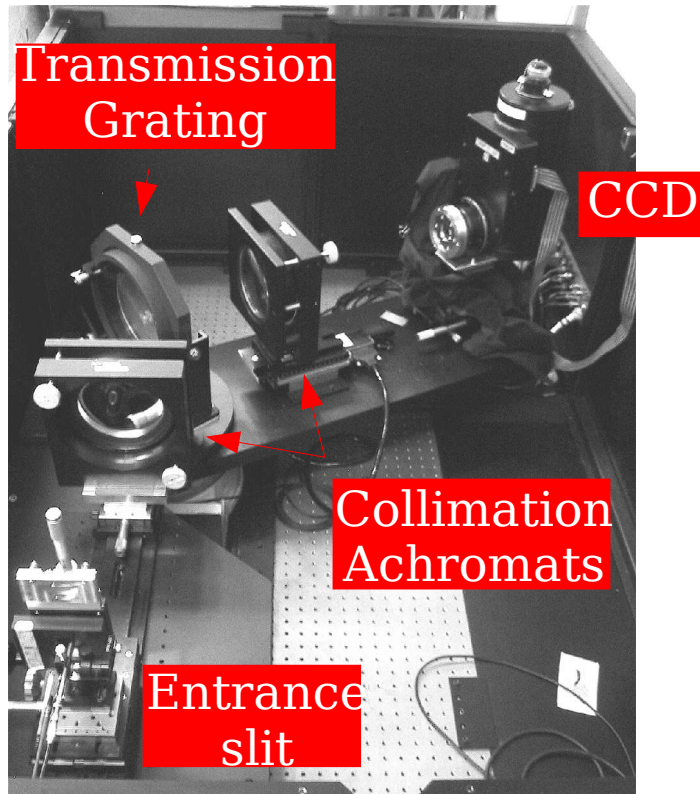
Both sets are on the midplane
 Outer-wall $78 < R < 88$ cm
 Inner-wall - more of a radial view

Poloidal



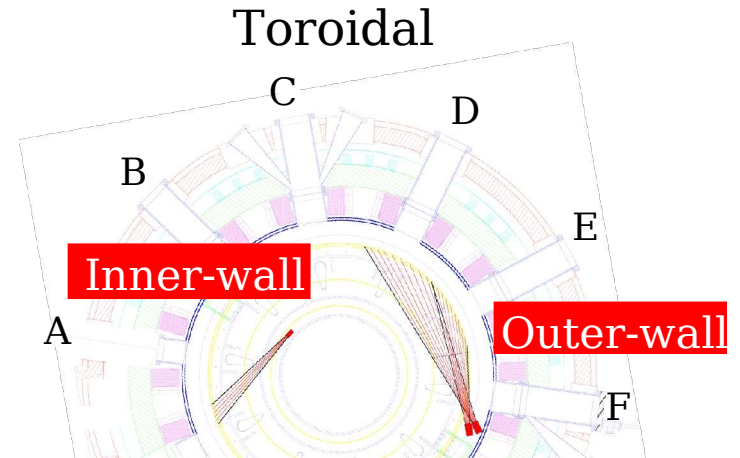
$84 < R < 90$ cm

Transmission grating spectrometer at the Alcator C-Mod tokamak



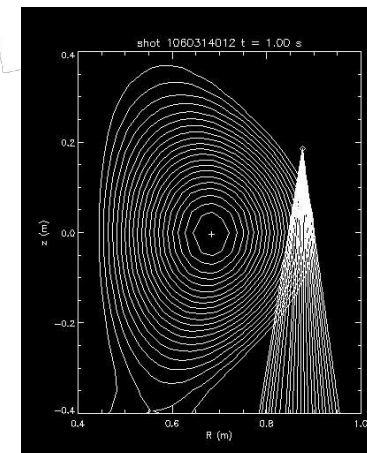
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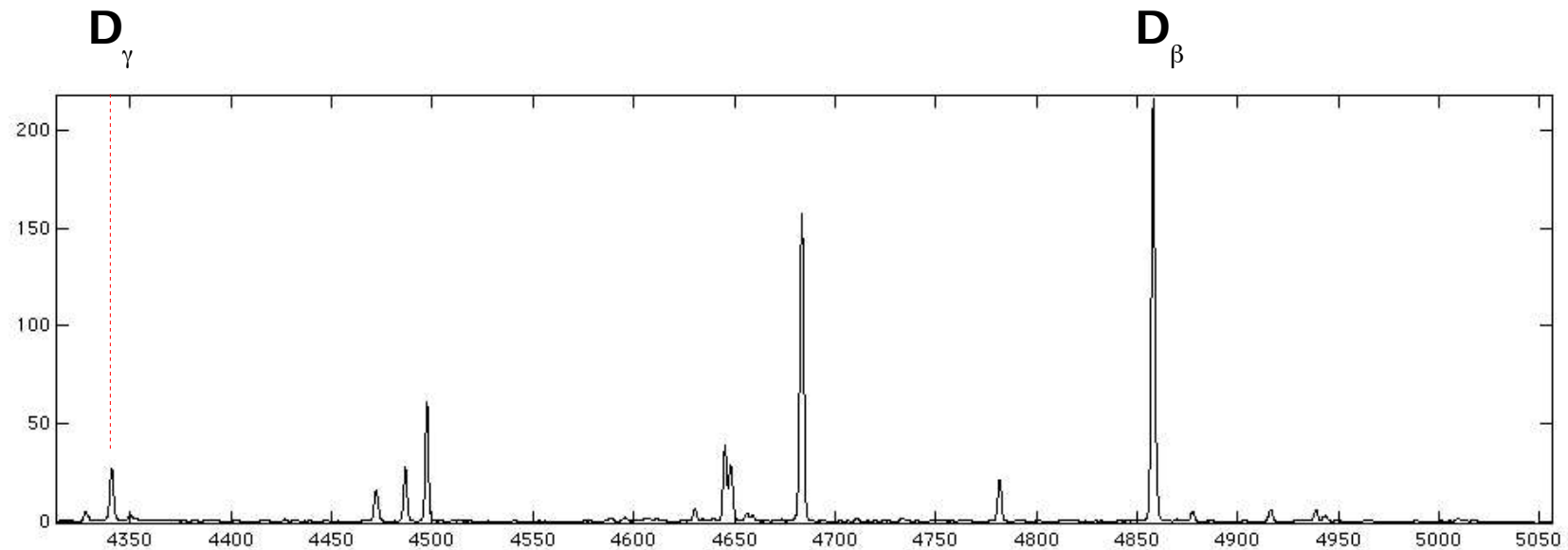
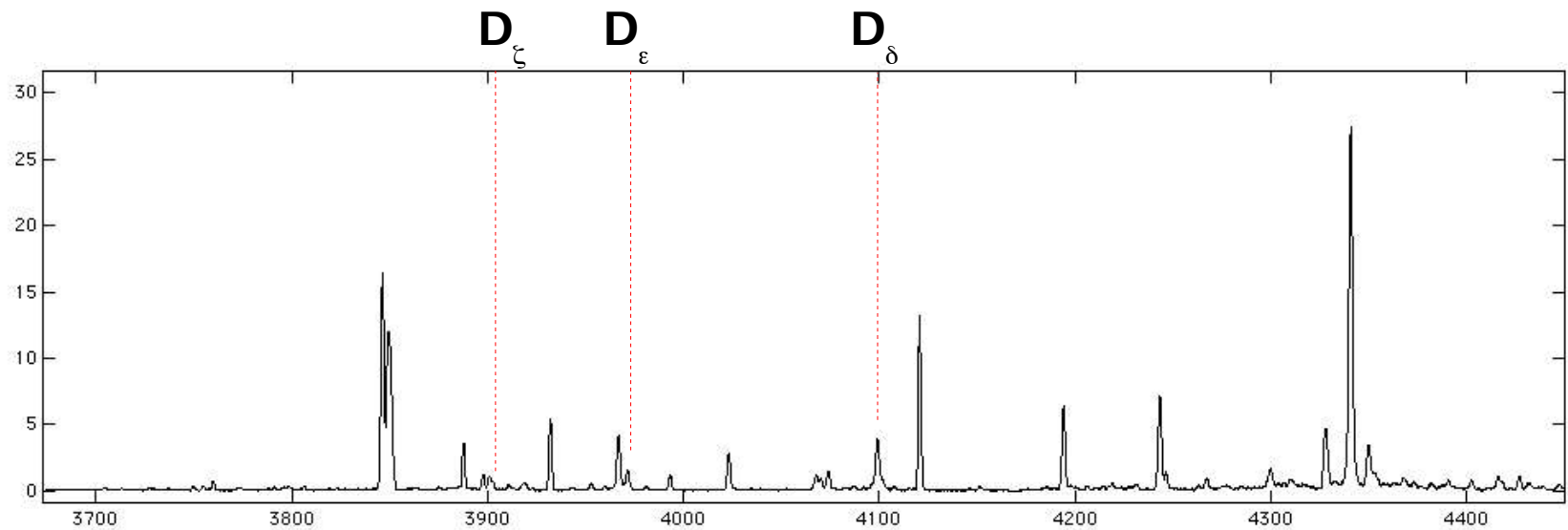
Poloidal



$84 < R < 90$ cm

Partial visible survey at Alcator C-Mod

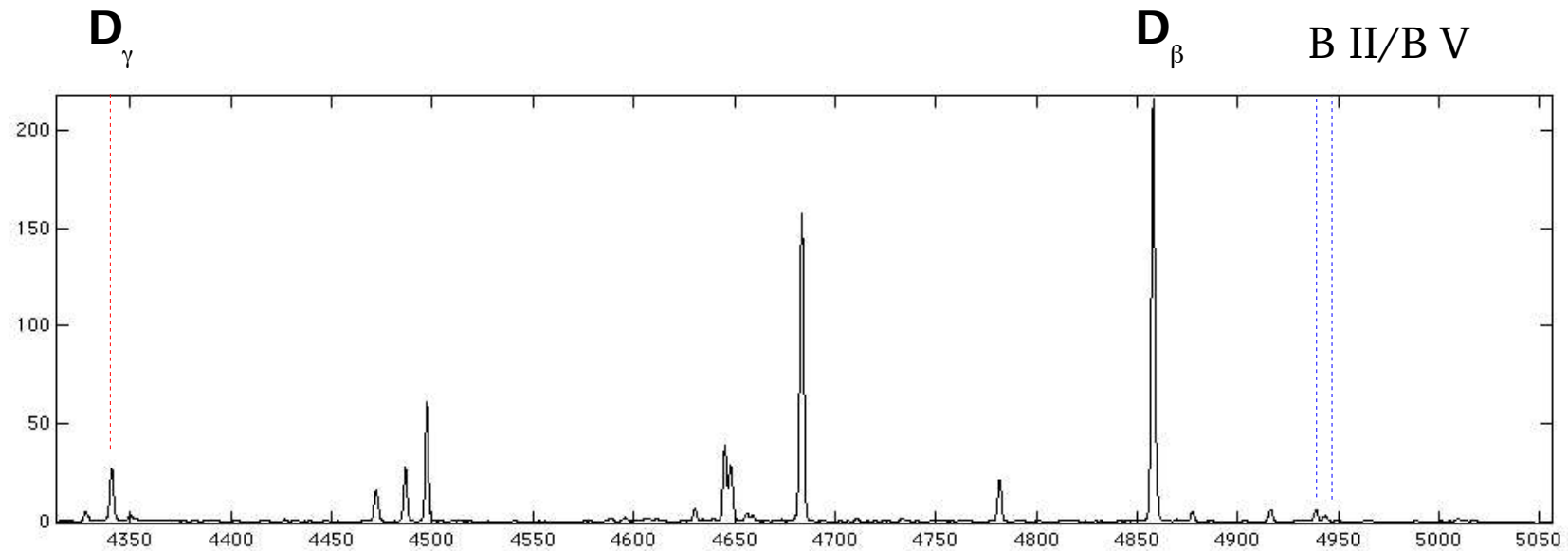
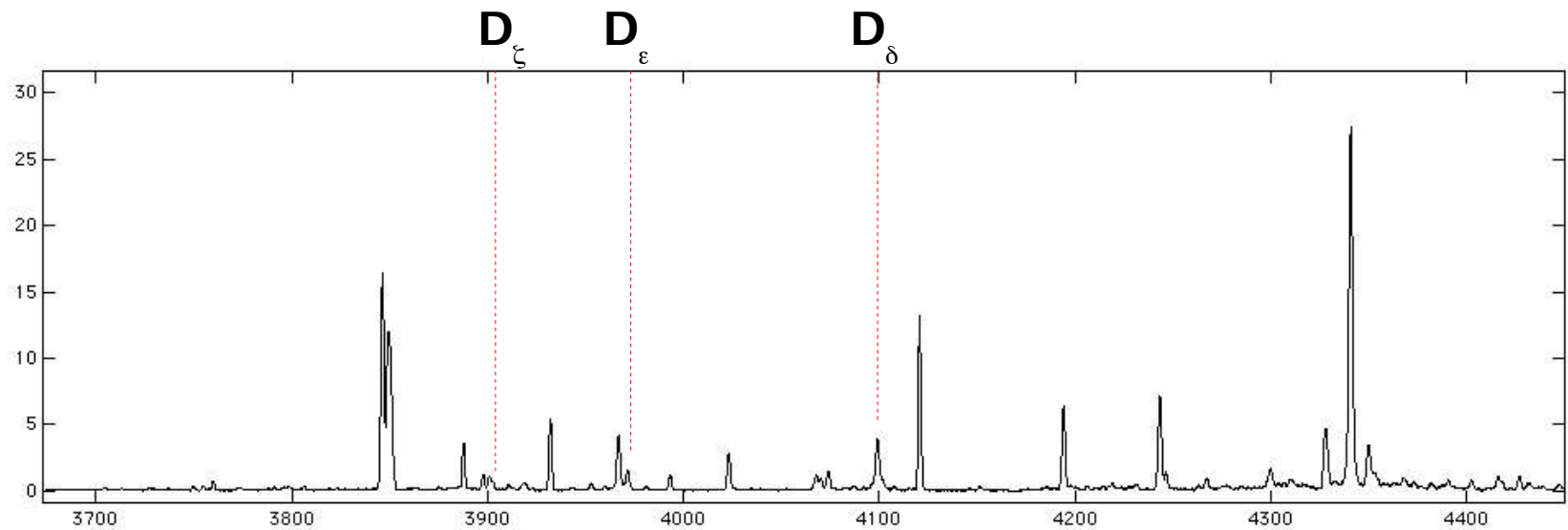
Inner-wall toroidal view at R=45 cm



Wavelength (Å)

Partial visible survey at Alcator C-Mod

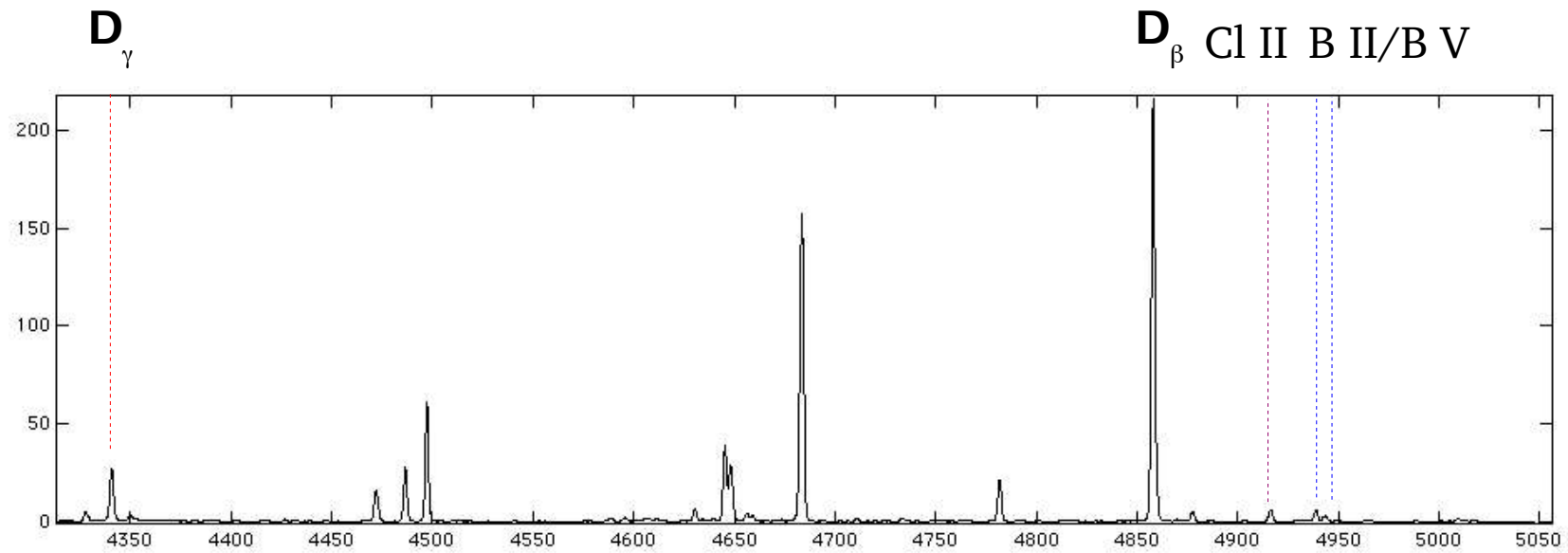
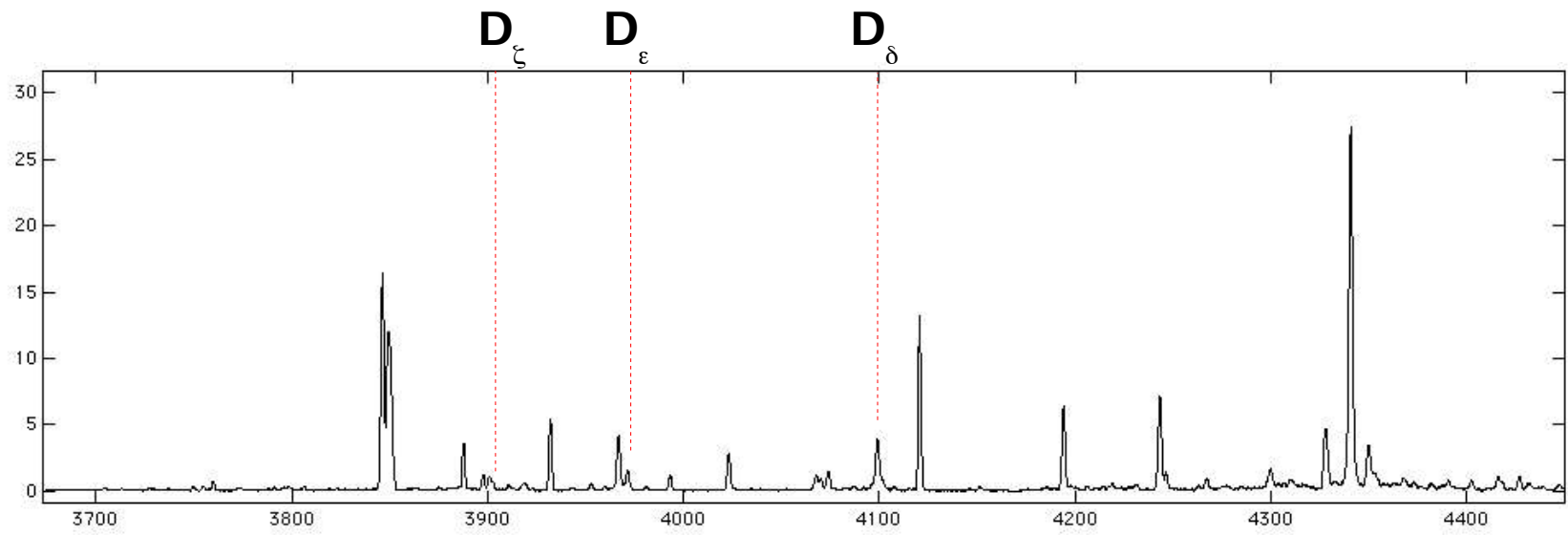
Inner-wall toroidal view at R=45 cm



Wavelength (Å)

Partial visible survey at Alcator C-Mod

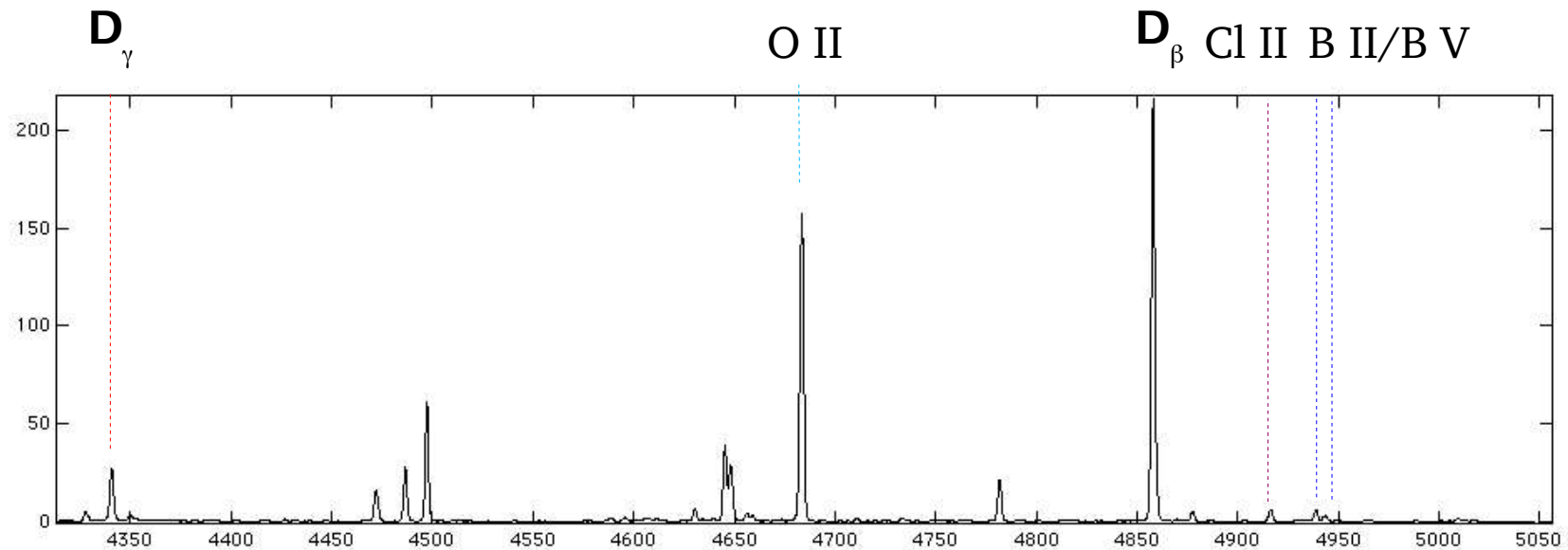
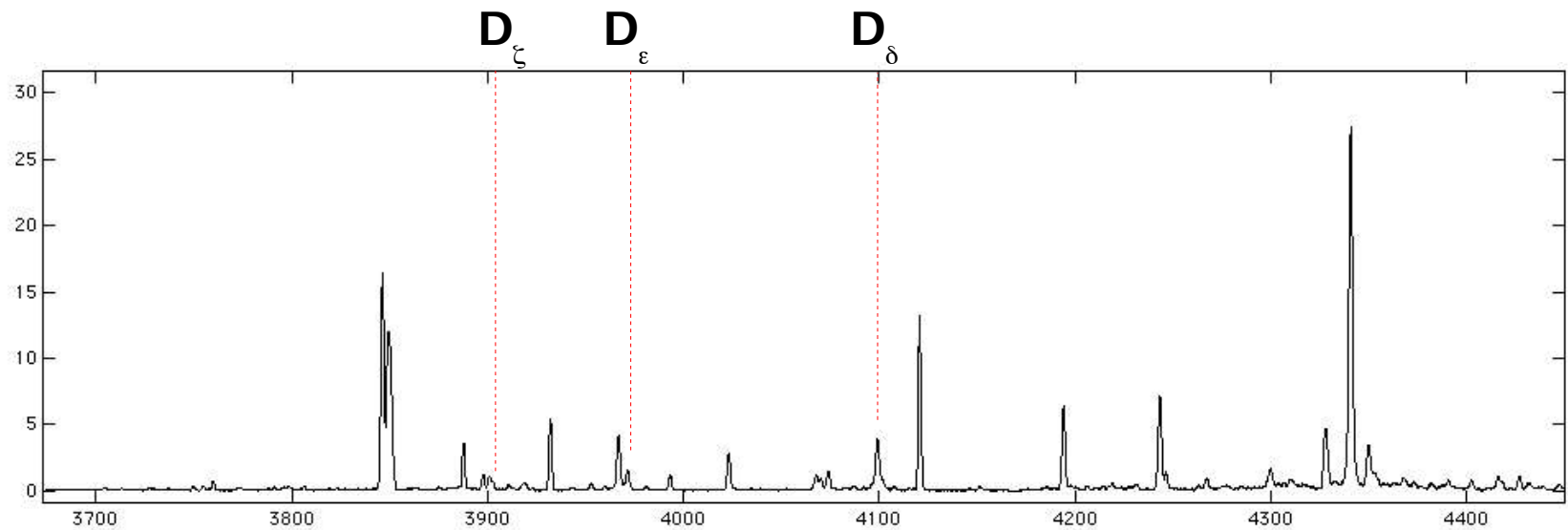
Inner-wall toroidal view at R=45 cm



Wavelength (Å)

Partial visible survey at Alcator C-Mod

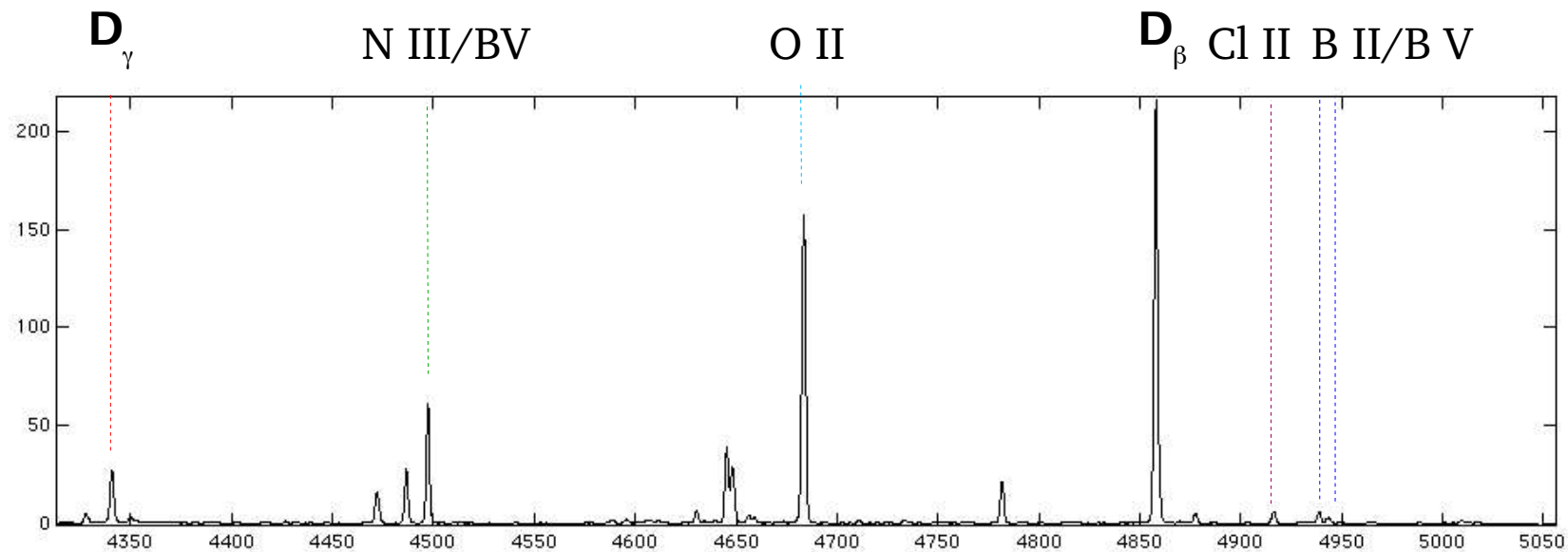
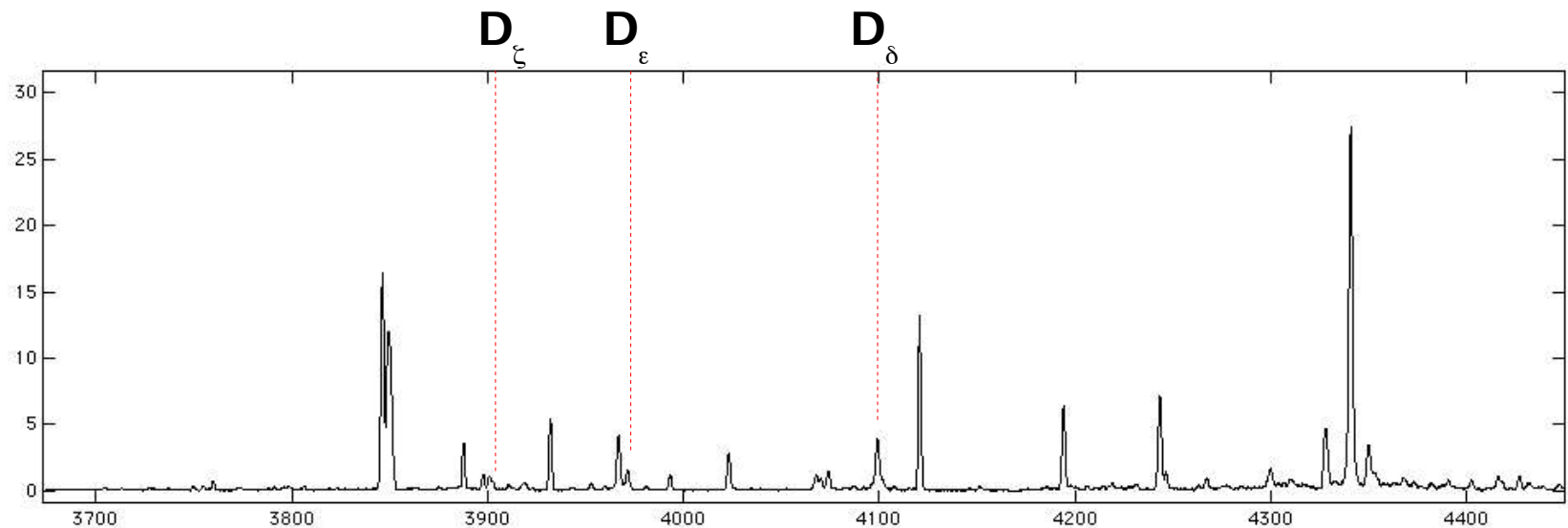
Inner-wall toroidal view at R=45 cm



Wavelength (Å)

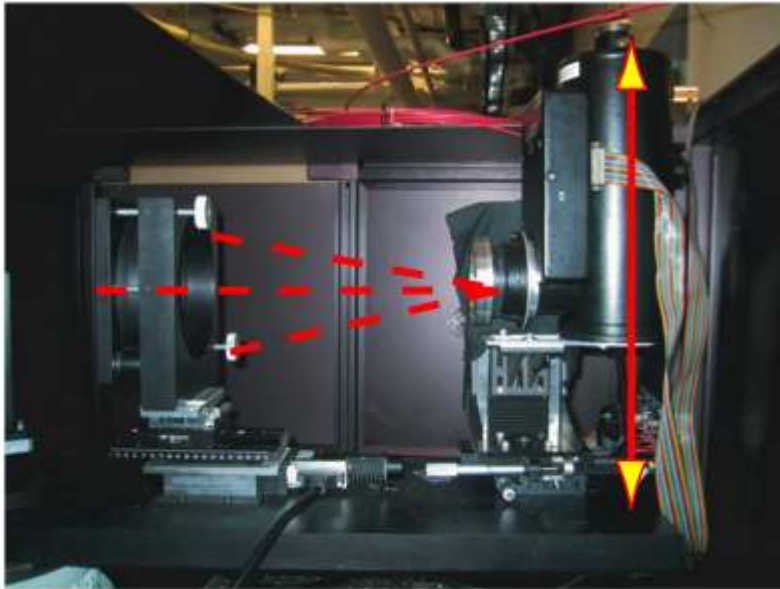
Partial visible survey at Alcator C-Mod

Inner-wall toroidal view at R=45 cm

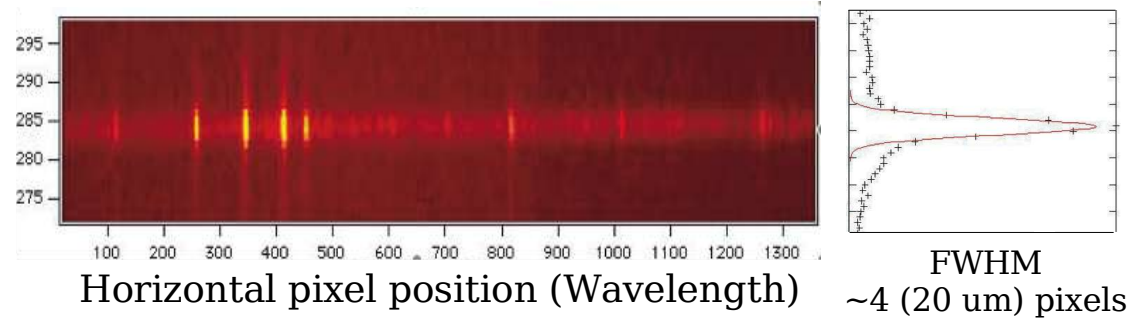


Wavelength (Å)

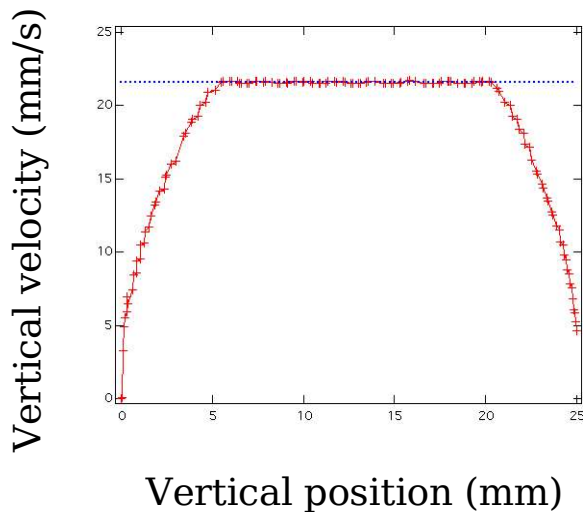
Preservation of time resolved spectra



Static image of dispersion plane



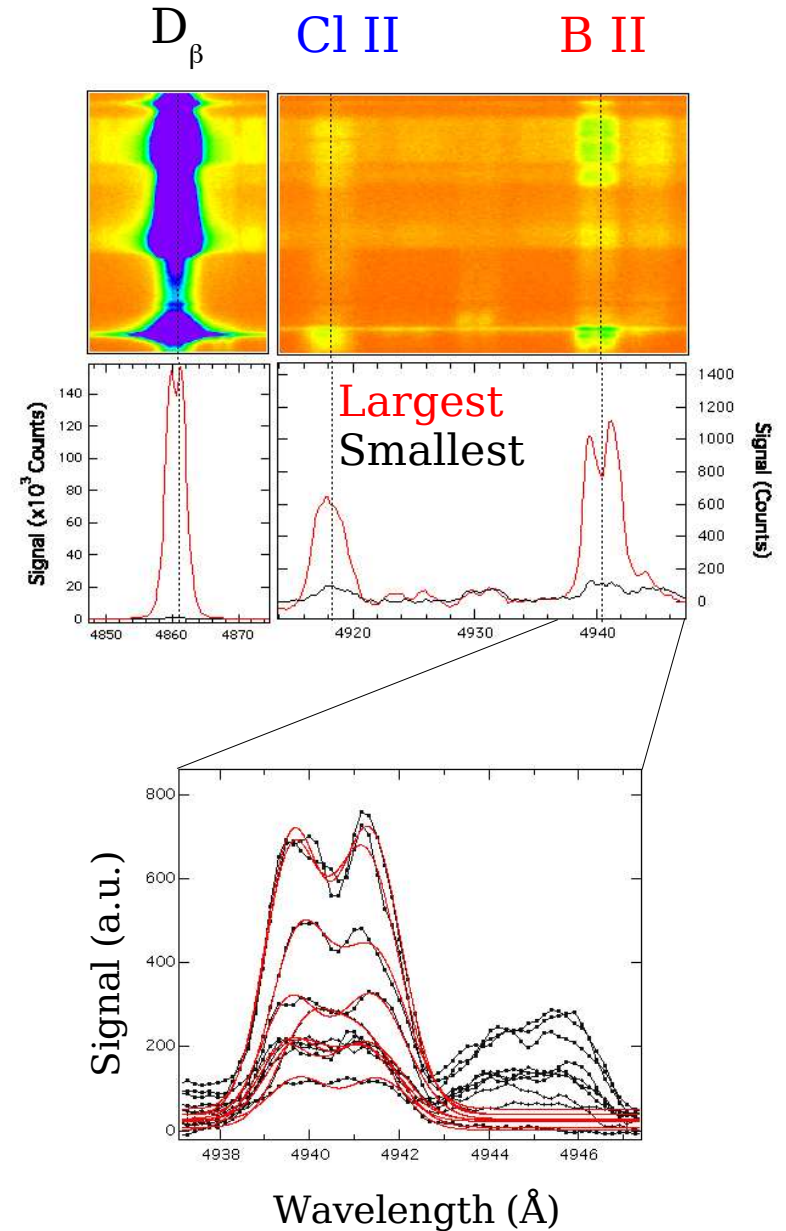
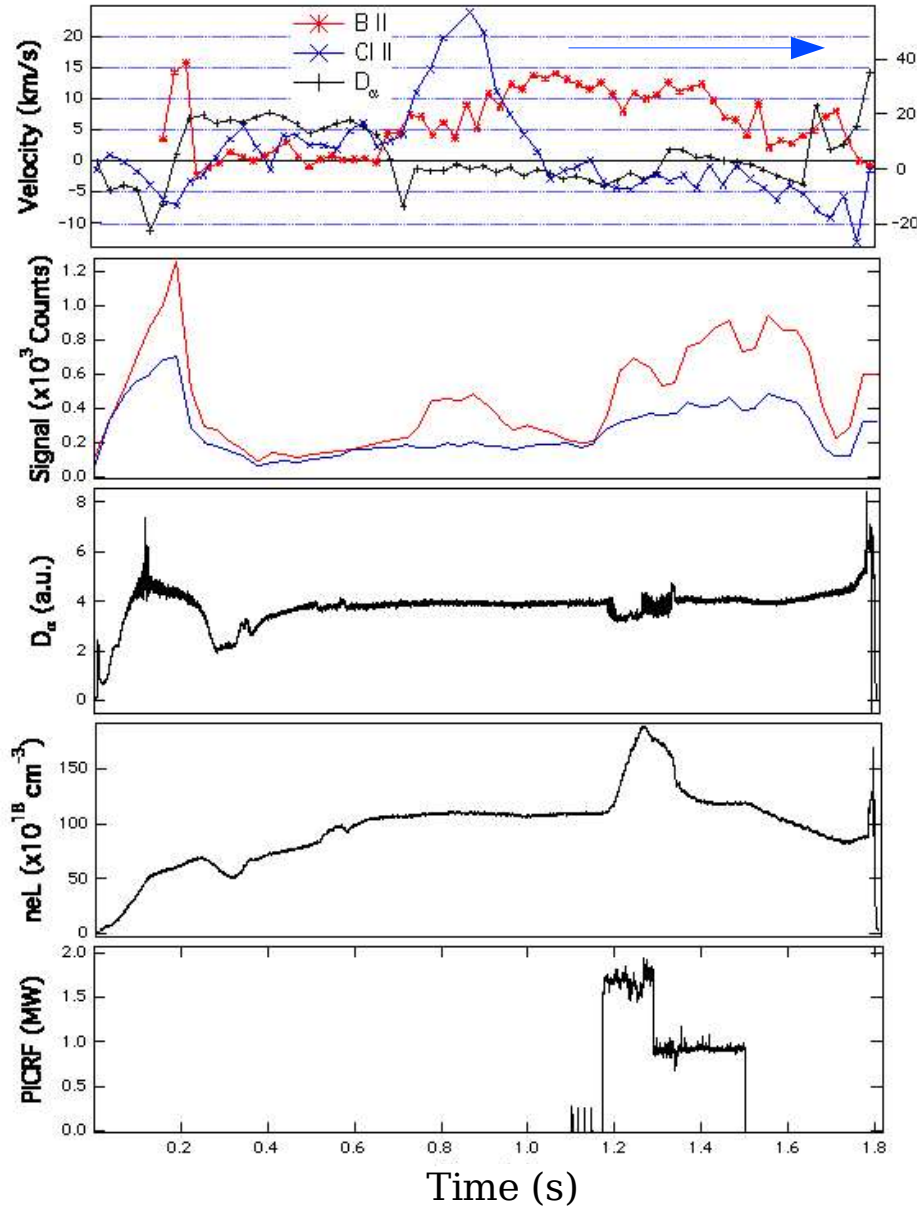
Vertical velocity of camera



$$\text{Time Resolution} = \frac{\text{Vertical width of dispersion plane}}{\text{Vertical velocity of camera face}}$$

Transmission grating spectrometer at the Alcator C-Mod tokamak

Shot #1060314012
Inner-wall toroidal at R ~ 45 cm

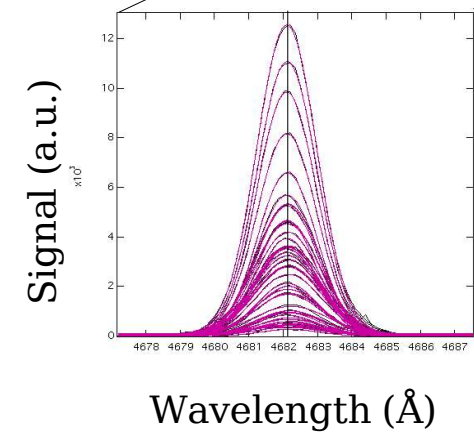
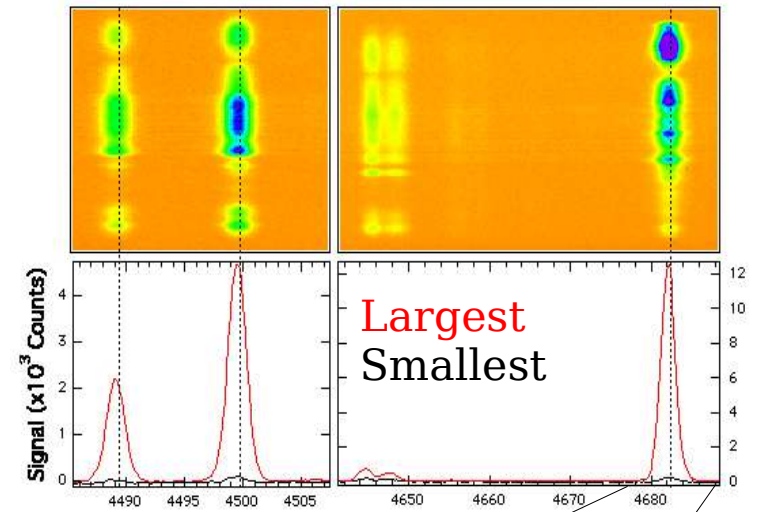
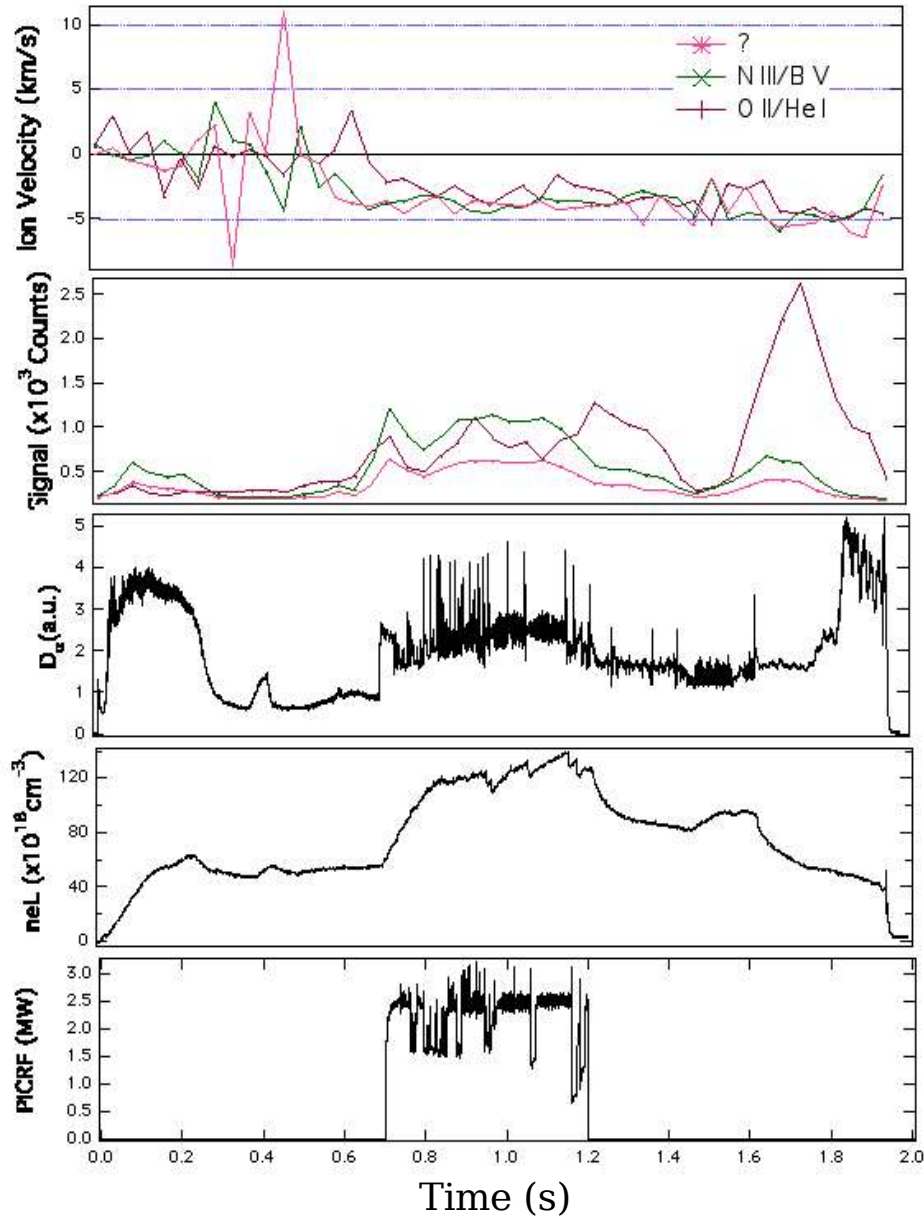


Transmission grating spectrometer at the Alcator C-Mod tokamak

Shot #1060616006
Poloidal at R ~ 87 cm

? N III/B V

O II



Summary

- Soft x-ray/EUV spectrometer (XEUS) successful at NSTX
 - for impurity identification
 - Fe in a an optically thin environment for comparison to astrophysical results
 - impurity transport
- Similar soft x-ray/EUV spectrometer successful at SSPX
 - 2 days of running have provided a good start at impurity identification
- Visible range transmission grating successful at CTIX and the Alcator C-Mod tokamak
 - for high resolution impurity identification
 - ion velocity diagnosis of various impurities