

# A Spatially Imaging High Resolution X-ray Spectrometer System for the Alcator C-Mod Tokamak

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with thanks to

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# Tokamak Parameter Ranges and Diagnostic Requirements

## Currently Operating Devices

a (m)	R (m)	B (T)	I <sub>p</sub> (MA)	n (m <sup>-3</sup> )	T (keV)	P (MPa)
0.2-1.2	0.6-3.4	1-8	0.5-5.0	$10^{18}$ - $10^{21}$	1-45	0.01-0.4
<b>ITER</b> (International Thermonuclear Experimental Reactor)						
2.0	6.2	5.3	15	$8 \times 10^{19}$	18	

X-ray spectroscopy provides measurements of: (J.E.Rice et al., Fusion Eng Des. 34 (1997) 159.)

electron, impurity and neutral hydrogen densities, electron temperature      **Line intensity**  
impurity rotation velocity      **Doppler shift**  
ion temperature      **Doppler width**  
also fluctuations, polarization, bonus atomic physics

## Outline

- Spectrometer design/construction
- X-ray measurements and interpretation
- Examples of diagnostic capabilities
- Future considerations

# Alcator C-Mod Tokamak



$R = 0.67 \text{ m}$     $r \sim 0.21 \text{ m}$     $\kappa < 1.8$

Molybdenum plasma facing components

$B_T = 2\text{-}8 \text{ T}$     $I_P = 0.3\text{-}2.0 \text{ MA}$

Discharge length < 5 sec

$n_e = 0.1\text{-}10 \times 10^{20}/\text{m}^3$     $T_e \sim T_i = 1\text{-}6 \text{ keV}$

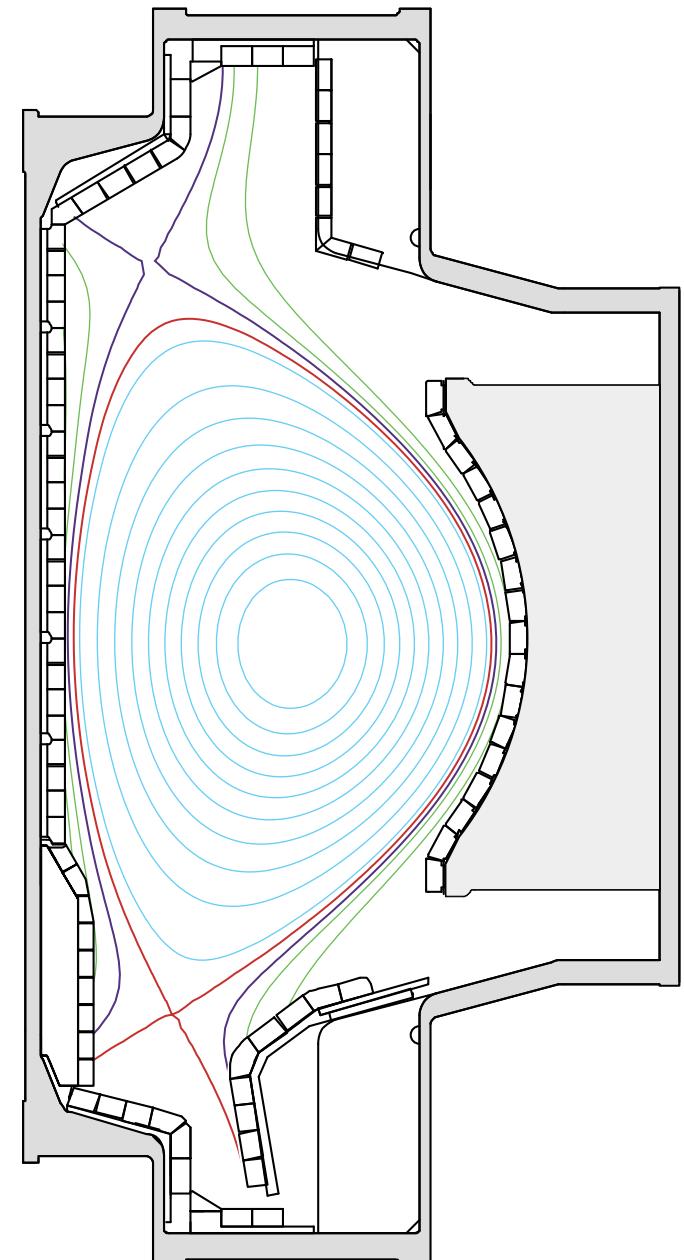
$-80 \text{ km/s} < V_{\text{Tor}} < 140 \text{ km/s}$

Macroscopic transport times  $\sim 50 \text{ ms}$

Argon injection,  $\sim 10^{-4} n_e$

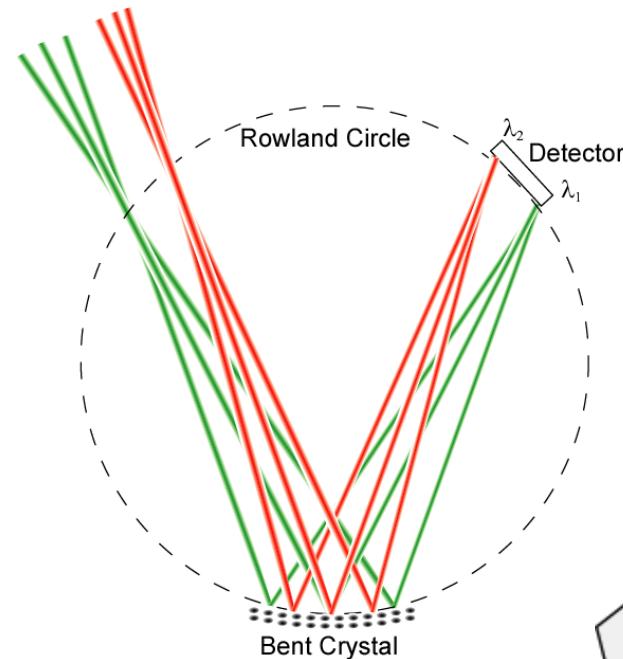
Neutron rates  $< 10^{14}/\text{s}$

Fusion Sci. Technol. 51 (2007) 261-508.



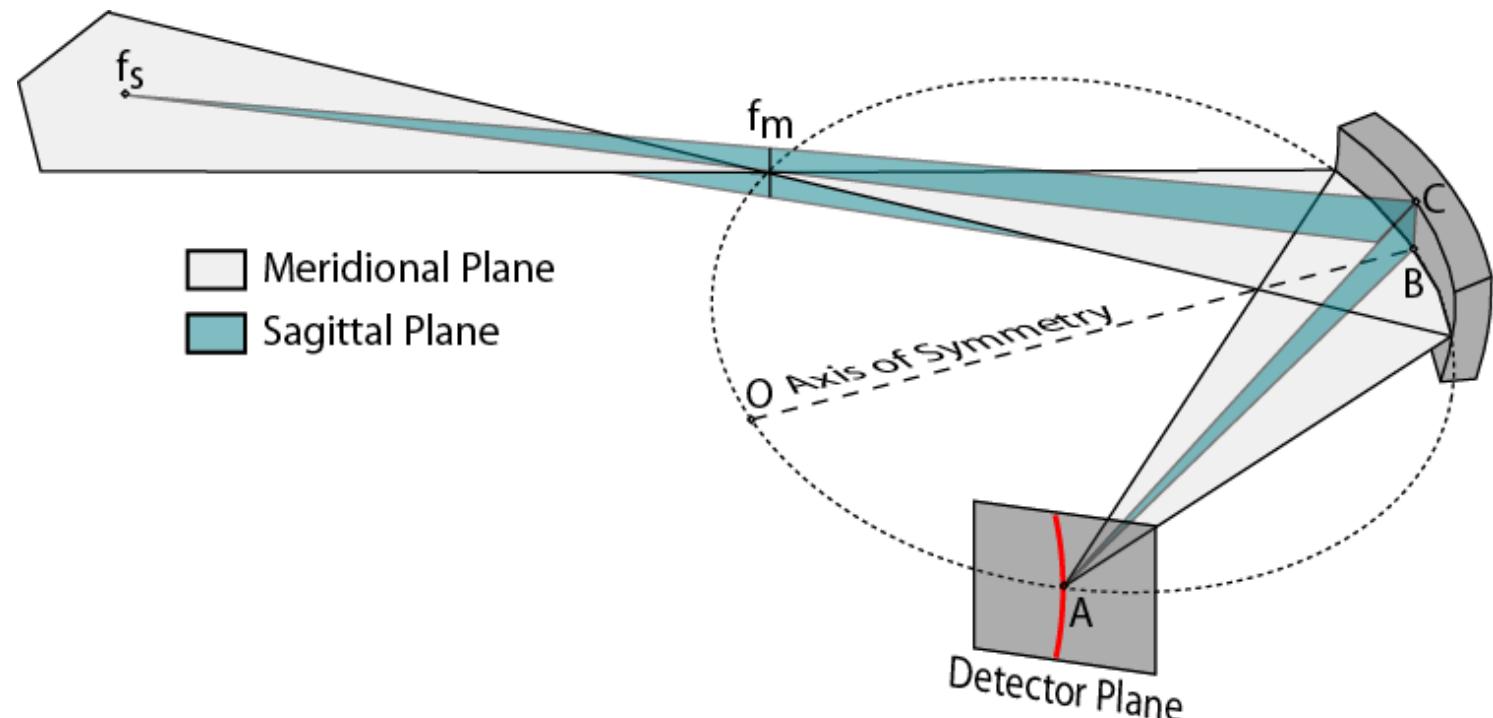
# Johann-type Spectrometers

Conventional Johann spectrometer  
with 1-D detector and cylindrically  
bent crystal on the Rowland circle.

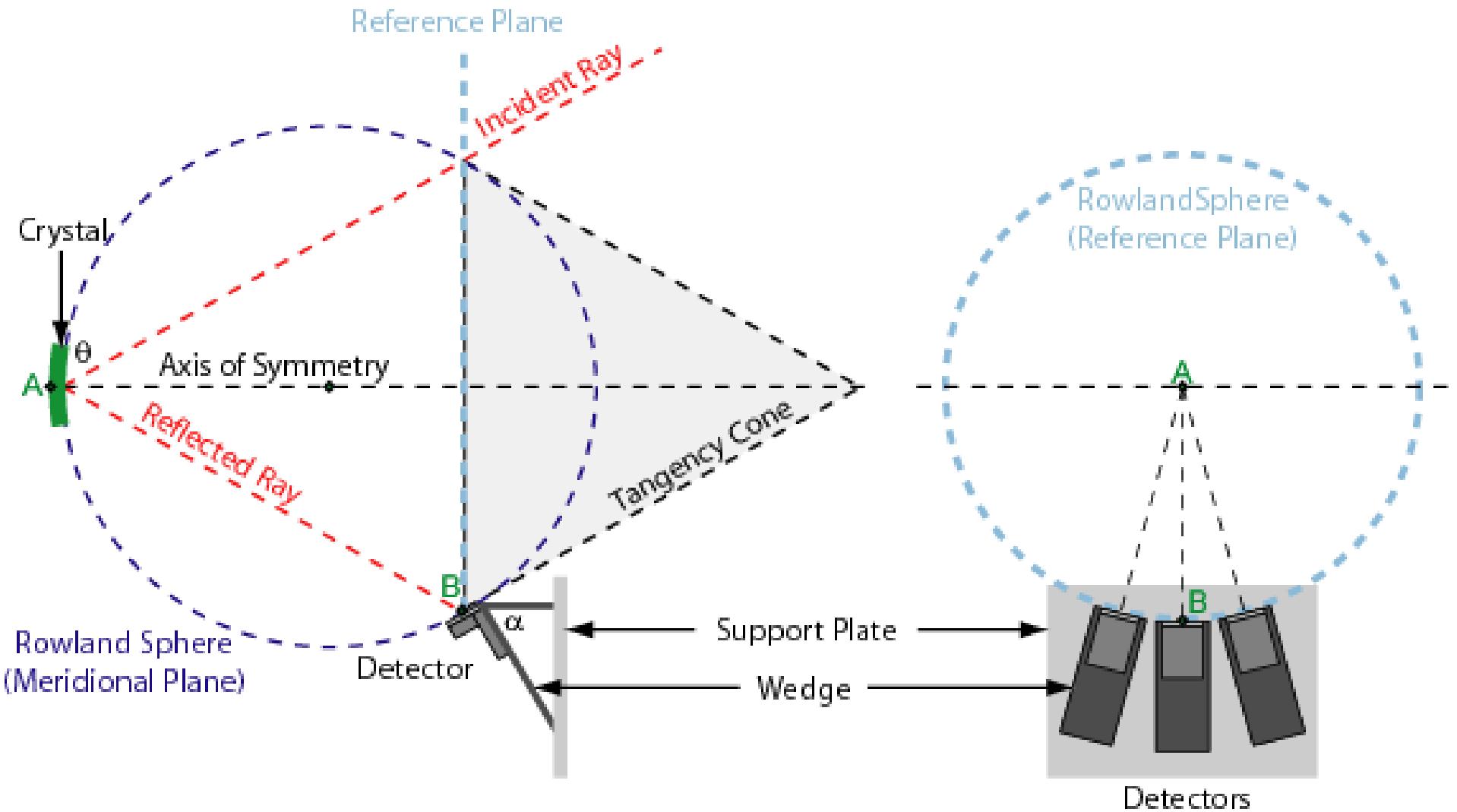


Spatially imaging system with spherically bent crystal  
and 2-D detector on the Rowland sphere.

M.Bitter et al., Rev. Sci. Instrum. **75** (2004) 3660.

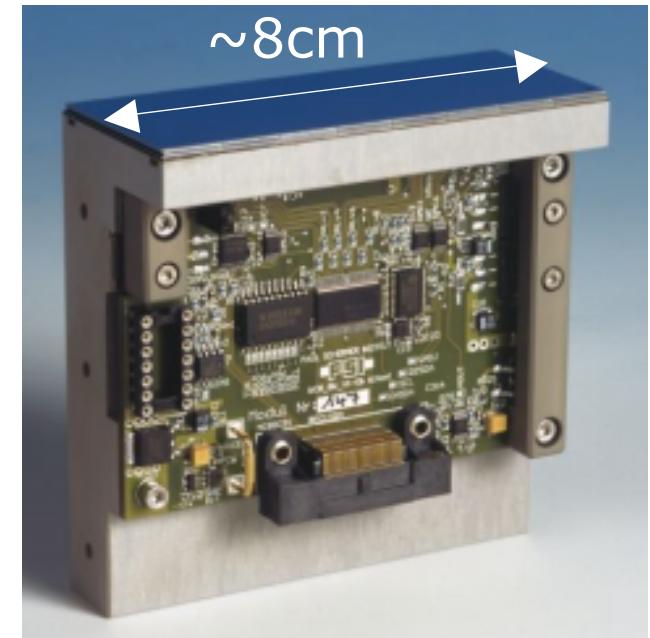


# Rowland Sphere and Finite Detector Size



# Dectris 'Pilatus' 100k Detector Module

Sensor type	Reverse biased silicon diode array
Sensor thickness	320 microns
Pixel size	172 microns x 172 microns
Format	487 x 195 = 94,965 pixels
Area	83.8 mm x 33.5 mm
Dynamic range	20 bits (1:1,048,576)
Count rate per pixel	> 2x10 <sup>6</sup> X-rays/s
Energy range	3-30 keV
Quantum efficiency	3 keV: 80% 8 keV: 99%
Energy resolution	~ 500 eV
Adjustable threshold	2-20 keV
Readout time	2.7 ms
Maximum frame rate	300 Hz
Point spread function	1 pixel



Individual pixel readout  
Insensitive to hard X-rays/neutrons  
No dark current/readout noise  
Shutterless operation



[www.dectris.com](http://www.dectris.com)

C.Broennimann et al., J. Synchrotron Radiat. **13** (2006) 120.

# Spectrometer Components for He-like and H-like Argon Spectra

(102) quartz

$2d=4.56215 \text{ \AA}$

resolving power  $\sim 10000$

Bragg angle:  
 $55.5^\circ$        $60.5^\circ$

He-like Ar  
Rowland  
circle

He-like Ar  
crystal

H-like Ar  
crystal

He-like Ar  
detectors

H-like Ar  
detector

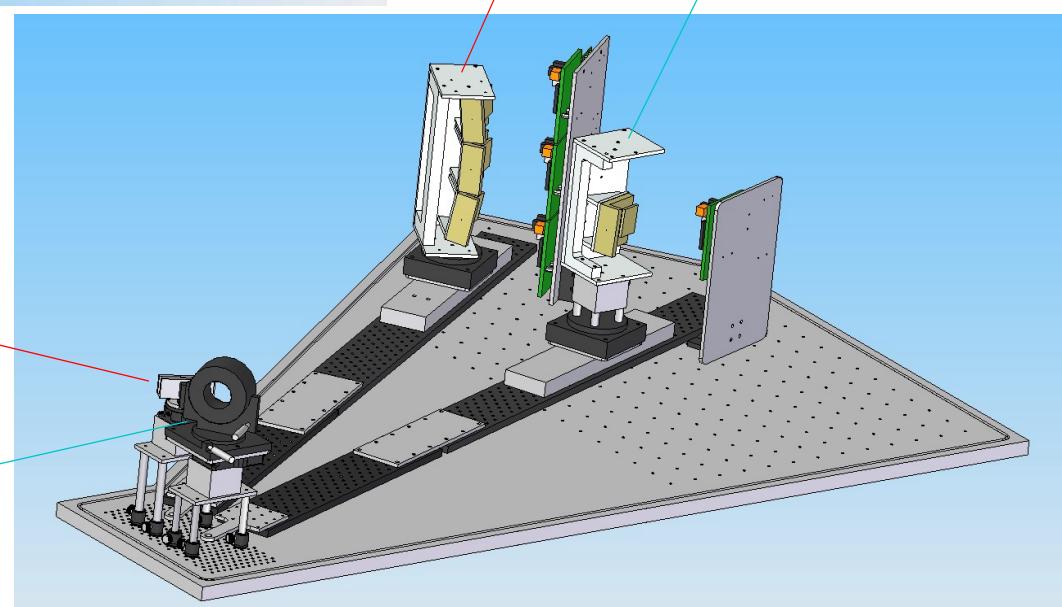
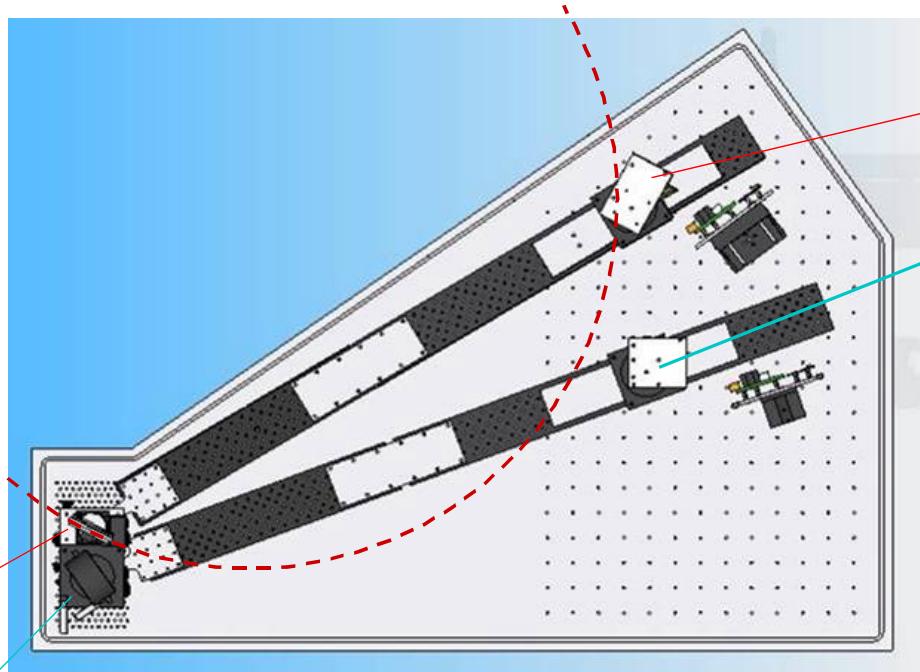
He-like Ar  
detectors

H-like Ar  
detector

curvature radius:  
 $1.385 \text{ m}$        $1.442 \text{ m}$

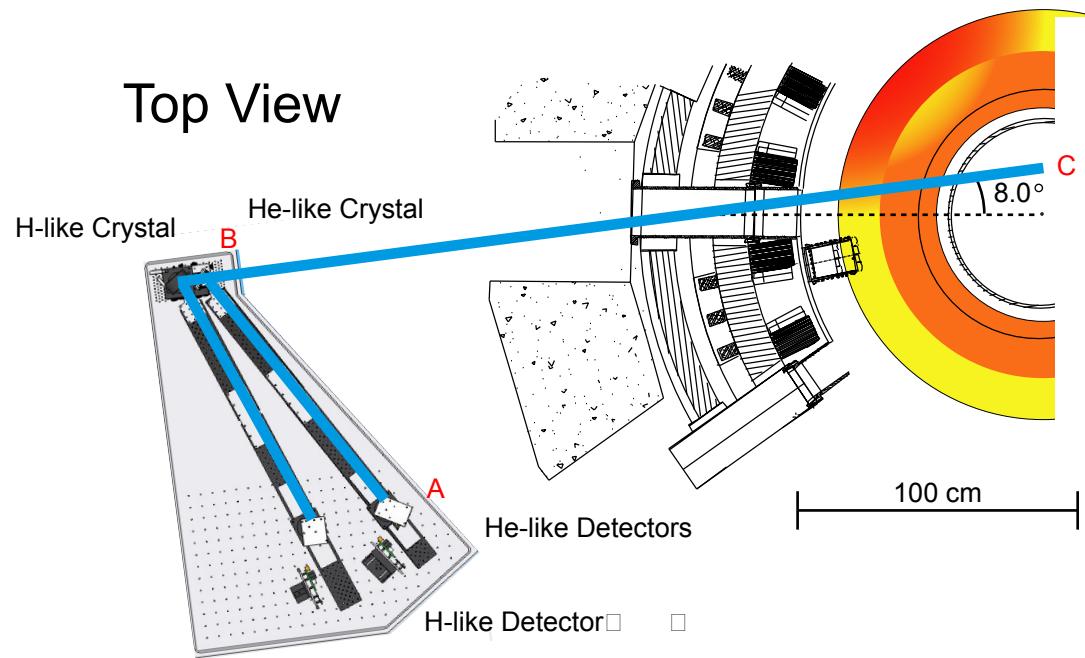
crystal area:  
 $19.6 \text{ cm}^2$        $17.3 \text{ cm}^2$

wavelength range:  
 $3.9\text{-}4.0 \text{ \AA}$        $3.7\text{-}3.8 \text{ \AA}$



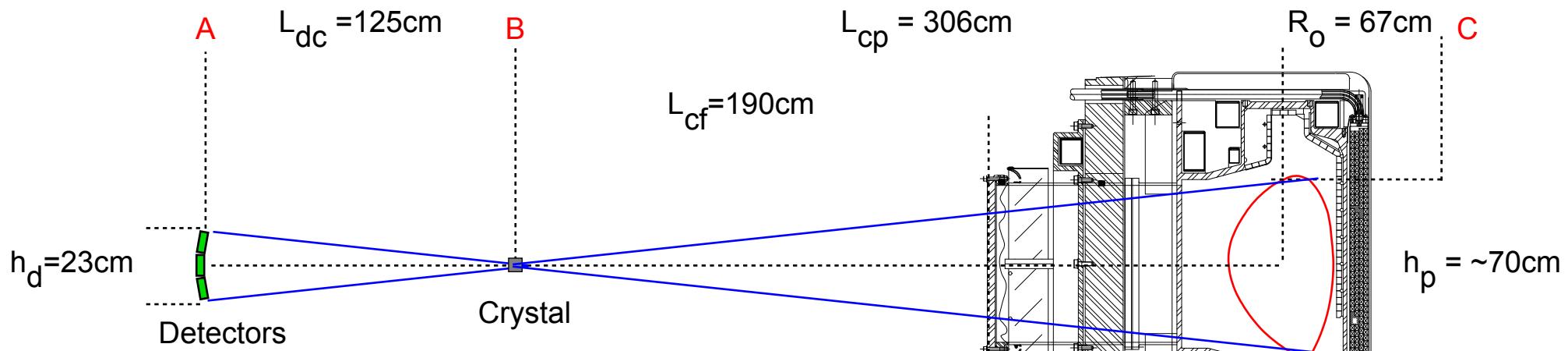
# Spectrometer Layout at C-Mod

Top View



Slight tilt allows for toroidal rotation measurements.

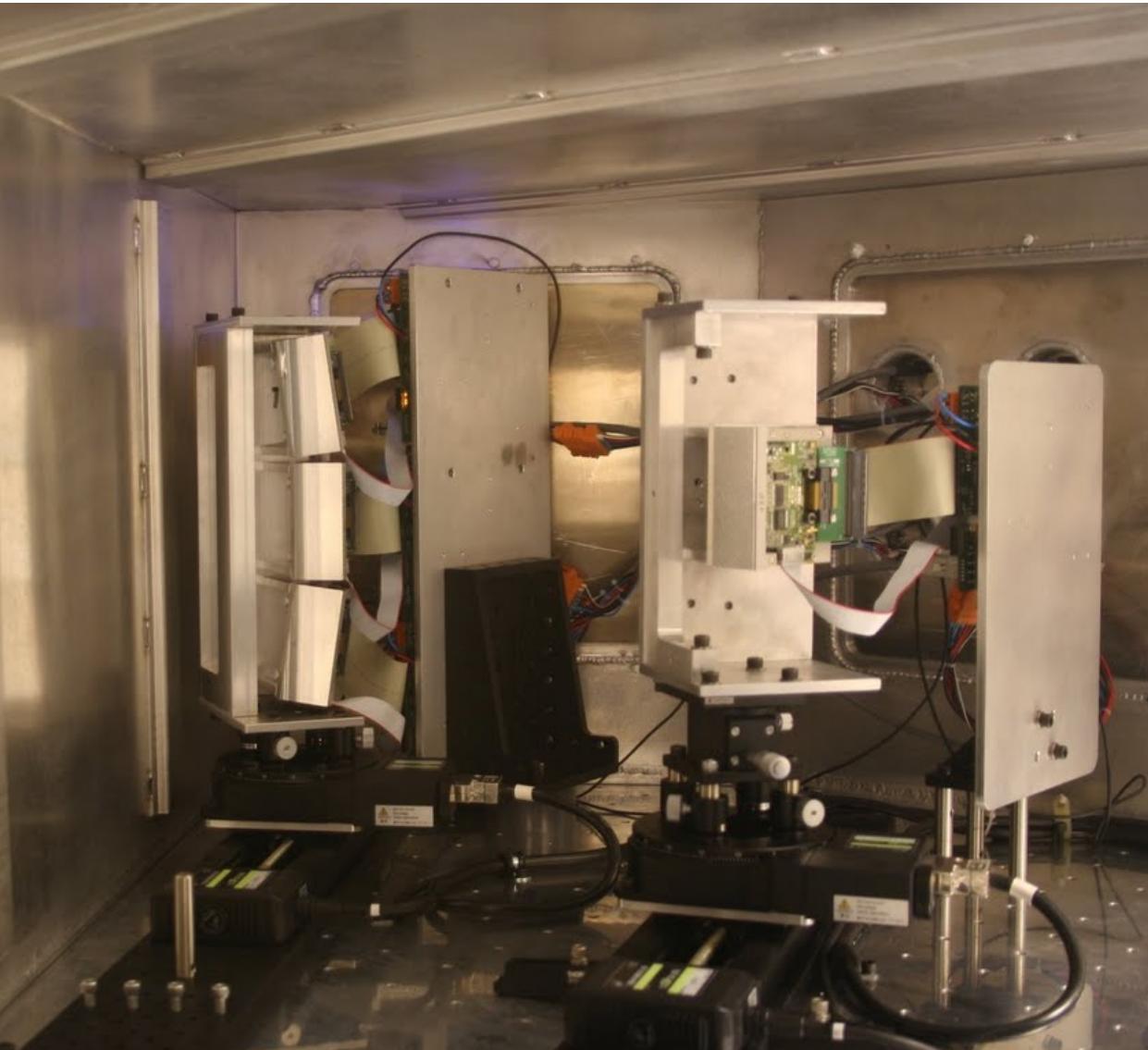
Coverage of full poloidal cross-section.



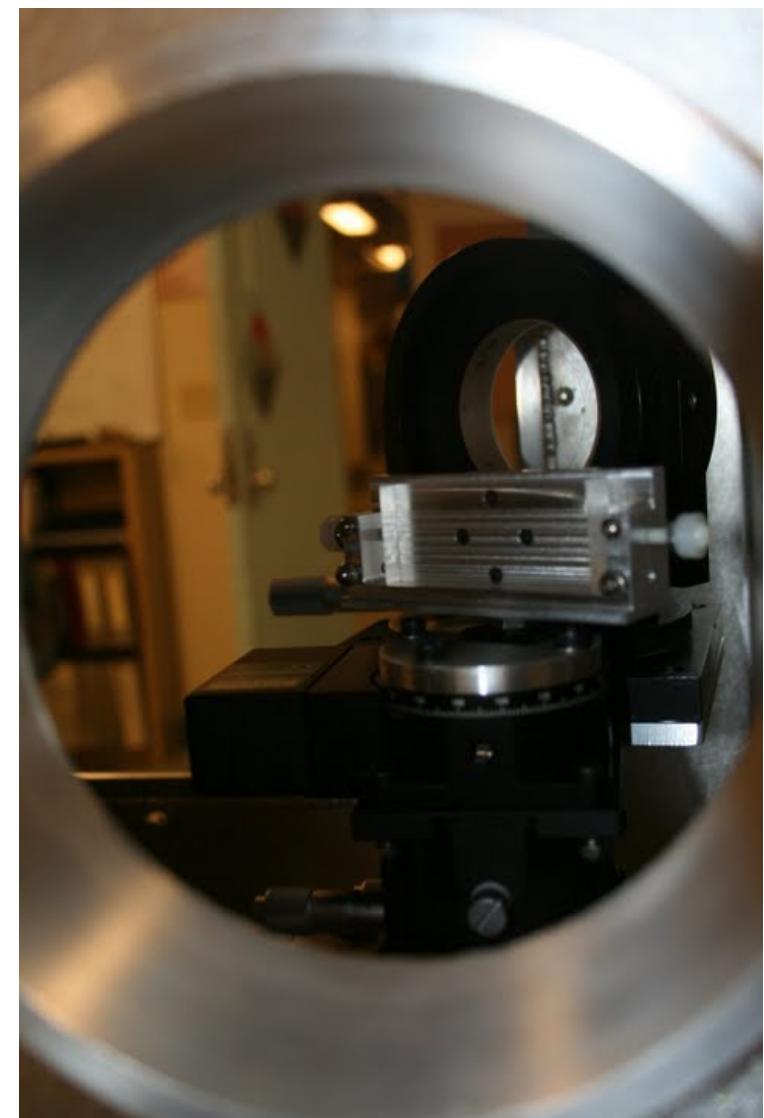
Side View

# Spectrometer Photographs (1)

Detector modules inside of spectrometer housing.



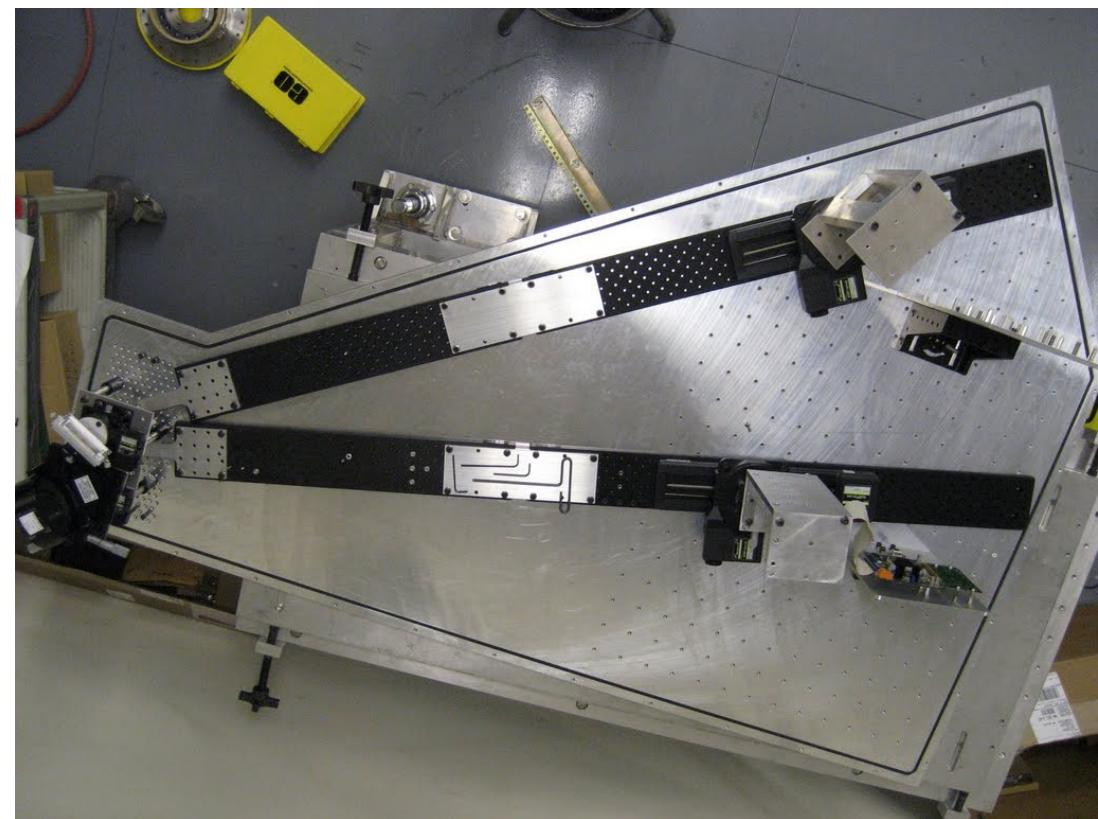
Crystals seen through entrance hole.



# Spectrometer Photographs (2)

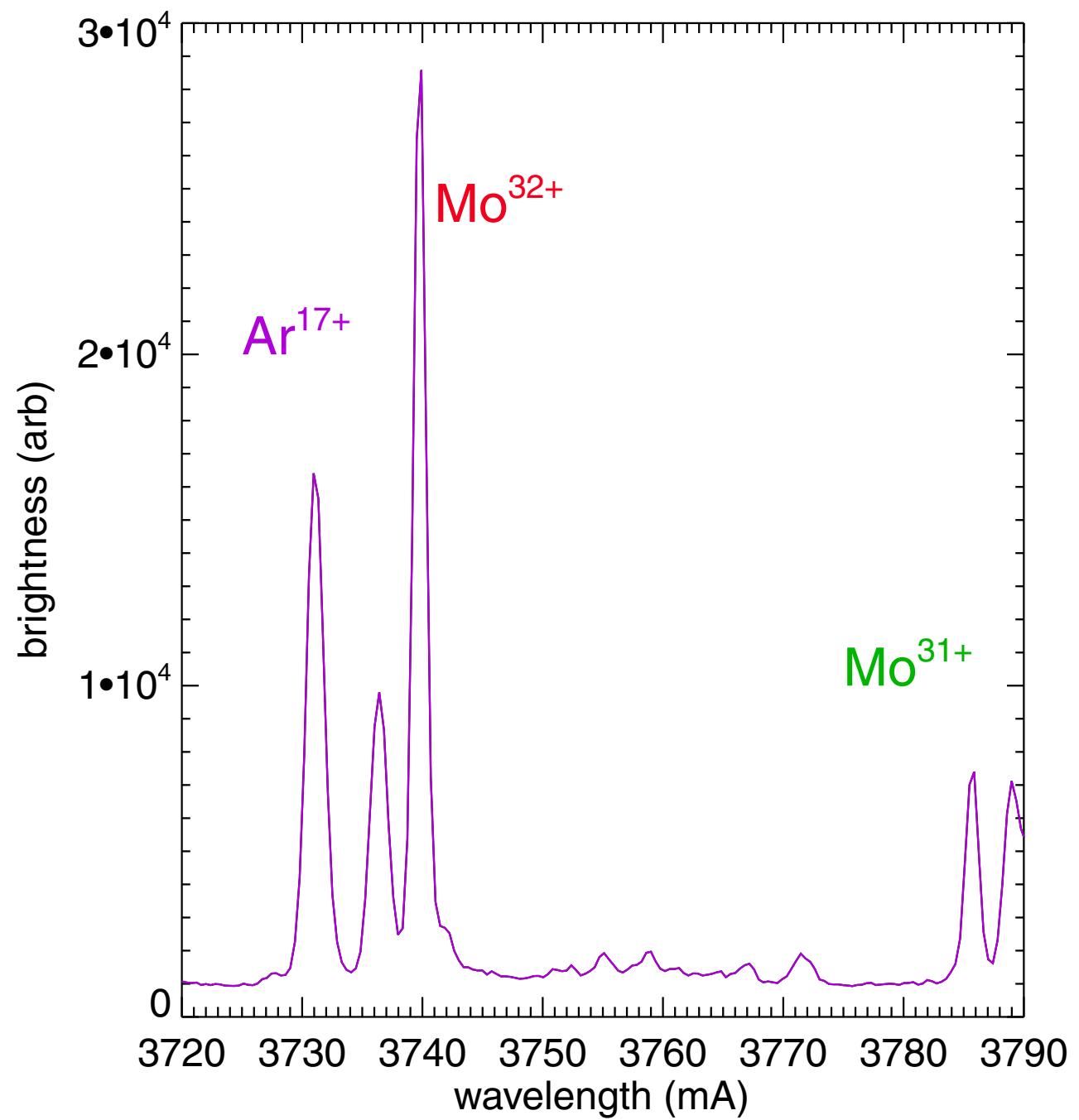
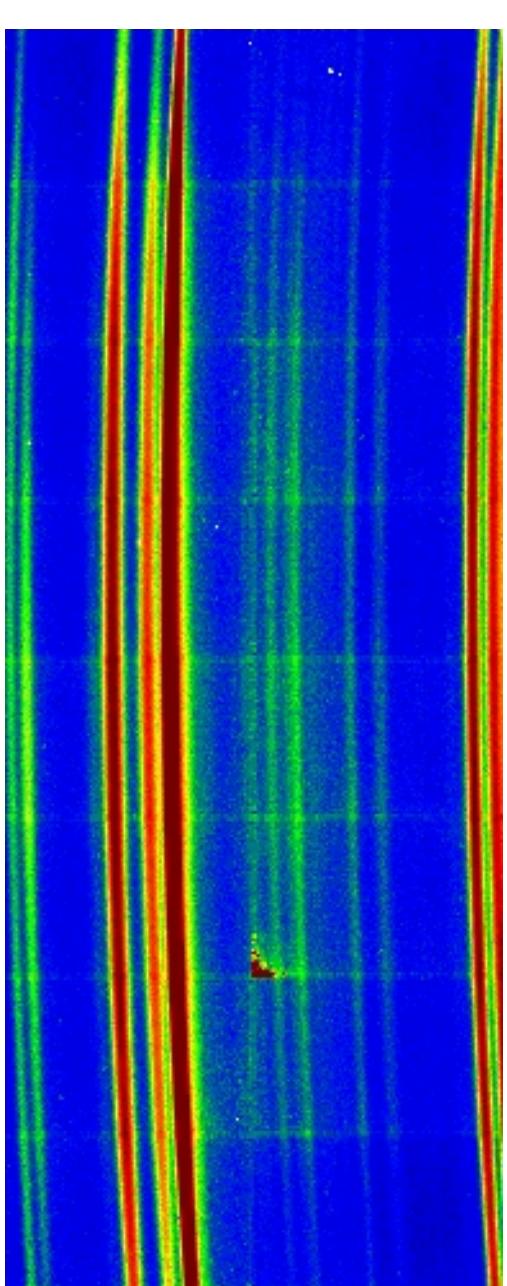
Mounting plate with crystals and detector modules.

Spectrometer installed on C-Mod, with helium filled cover.



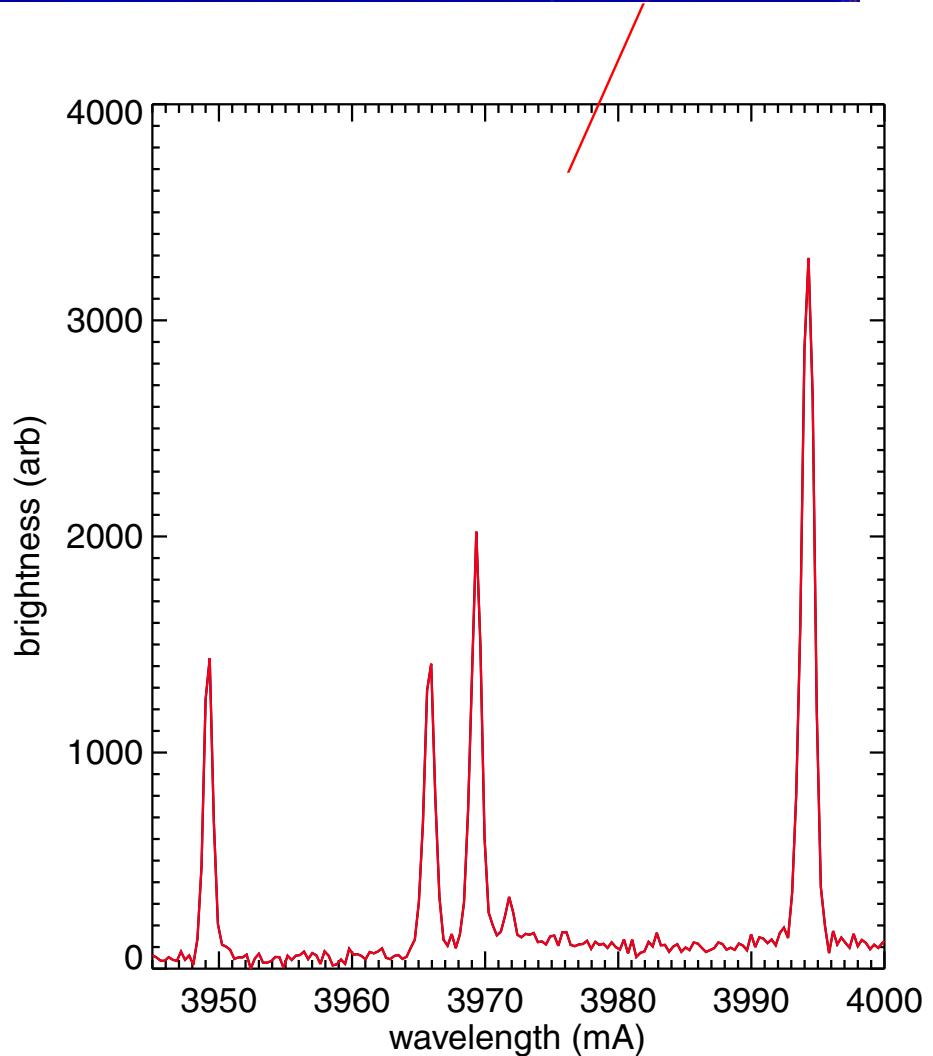
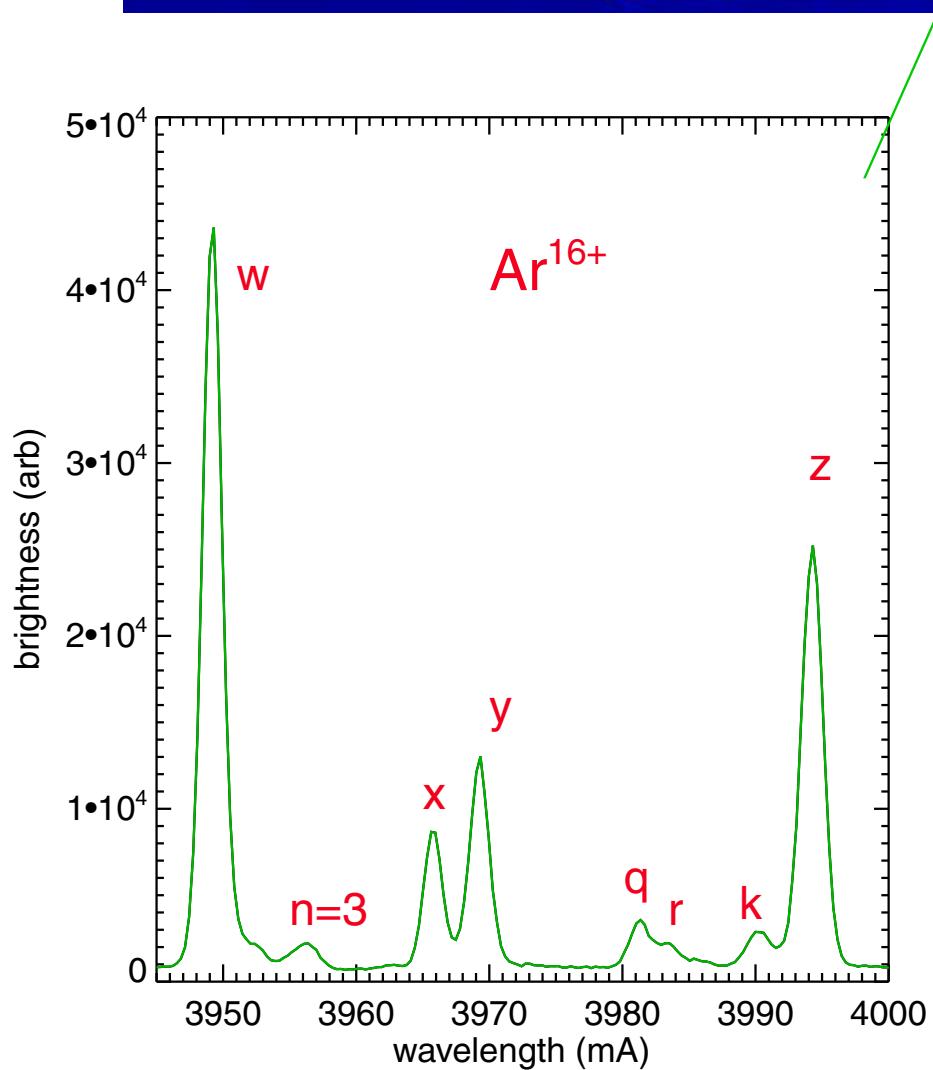
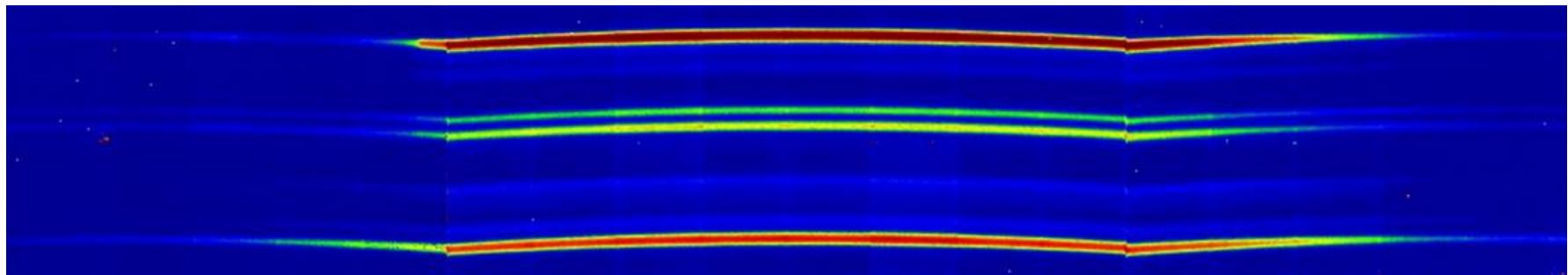
# H-like Argon Module Image and Spectrum

$n_e = 1.2 \times 10^{20}/m^3$   $T_e = 2.2$  keV

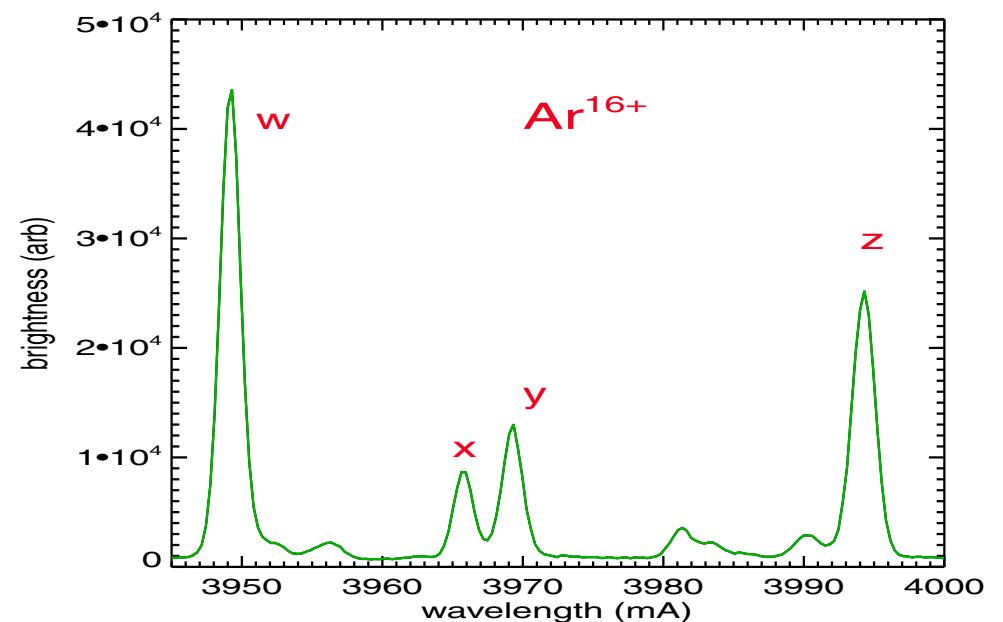
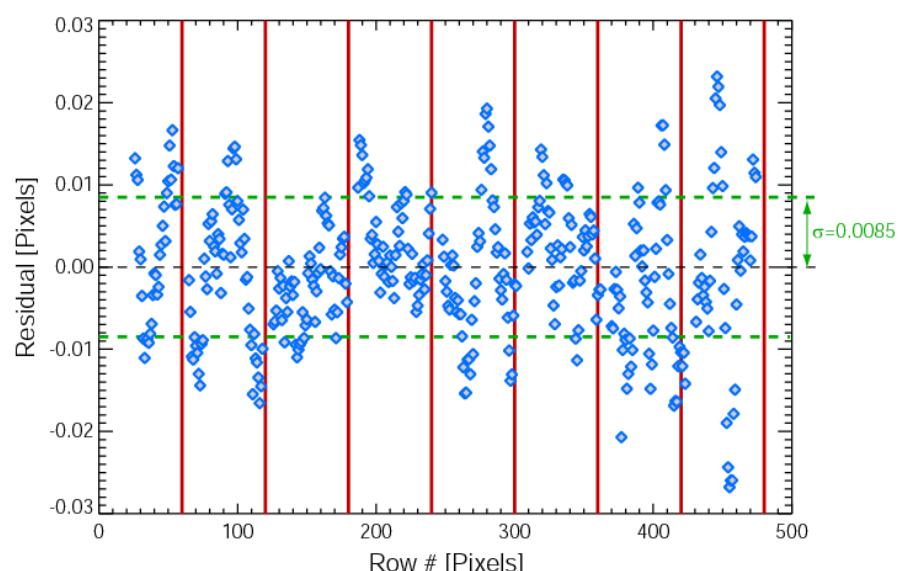
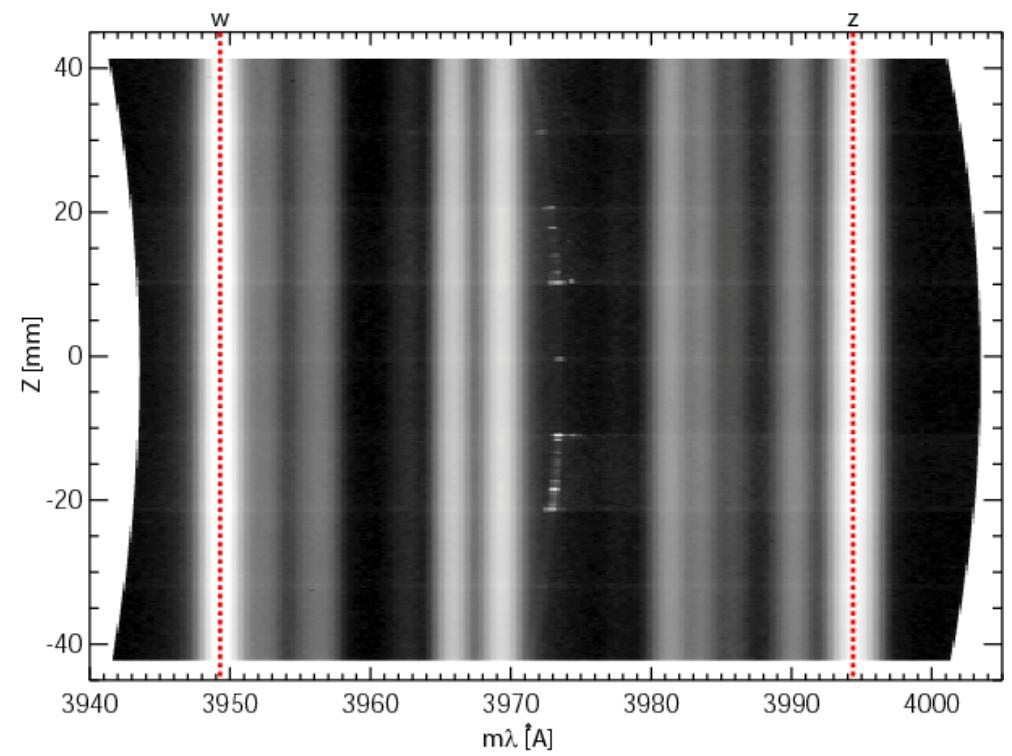
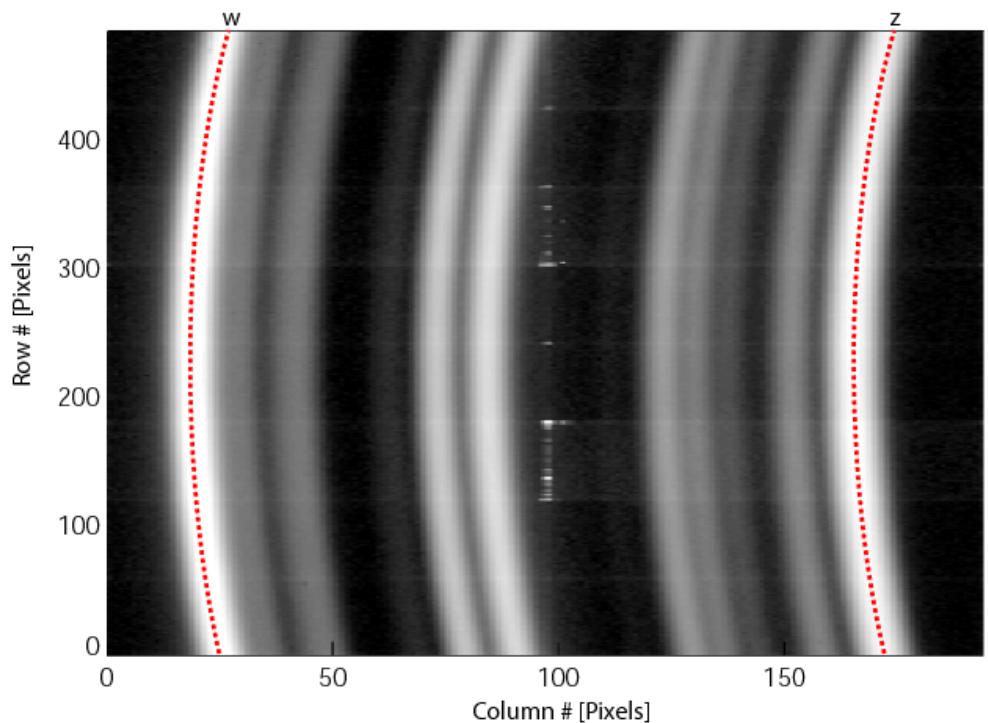


# He-like Argon Images and Spectra

## 3 detector images



# Lines of Constant Wavelength Trace Out Elliptical Curves on the Detector Plane



# Spectral Tomography

R.Bell et al., Rev. Sci. Instrum. **68** (1997) 1273.

I.Condrea et al., Phys. Plasmas **7** (2000) 3641.

Non-iterative least squares matrix inversion algorithm

Uses moment approach to extract emissivity, velocity and temperature profiles

Assume Gaussian line shape:

$$P_{in}^{\lambda} = V \sum_k^p \Delta l_k \frac{\varepsilon_{o,k}}{w_k \sqrt{2\pi}} \exp \left[ -\frac{(\lambda - \lambda_o - \frac{\lambda_o}{c} (\hat{l} \cdot \mathbf{v}_k))^2}{2w_k^2} \right]$$

0<sup>th</sup> moment - emissivity

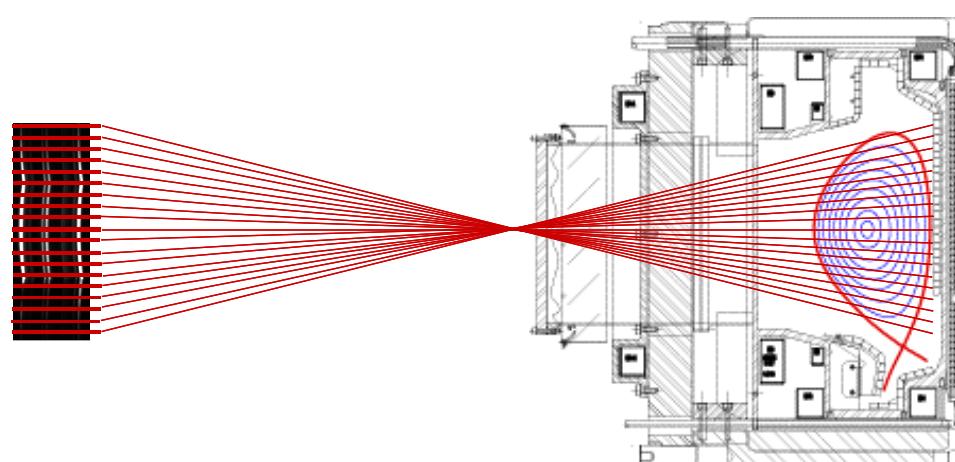
$$P_{0,j}^{\lambda} = \sum_k^p V_{jk} \varepsilon_{o,k}$$

1<sup>st</sup> moment - velocity

$$P_{1,j}^{\lambda} = \frac{\lambda_o}{c} \sum_k^p V_{jk} (\hat{l}_j \cdot \mathbf{v}_k) \varepsilon_{o,k}$$

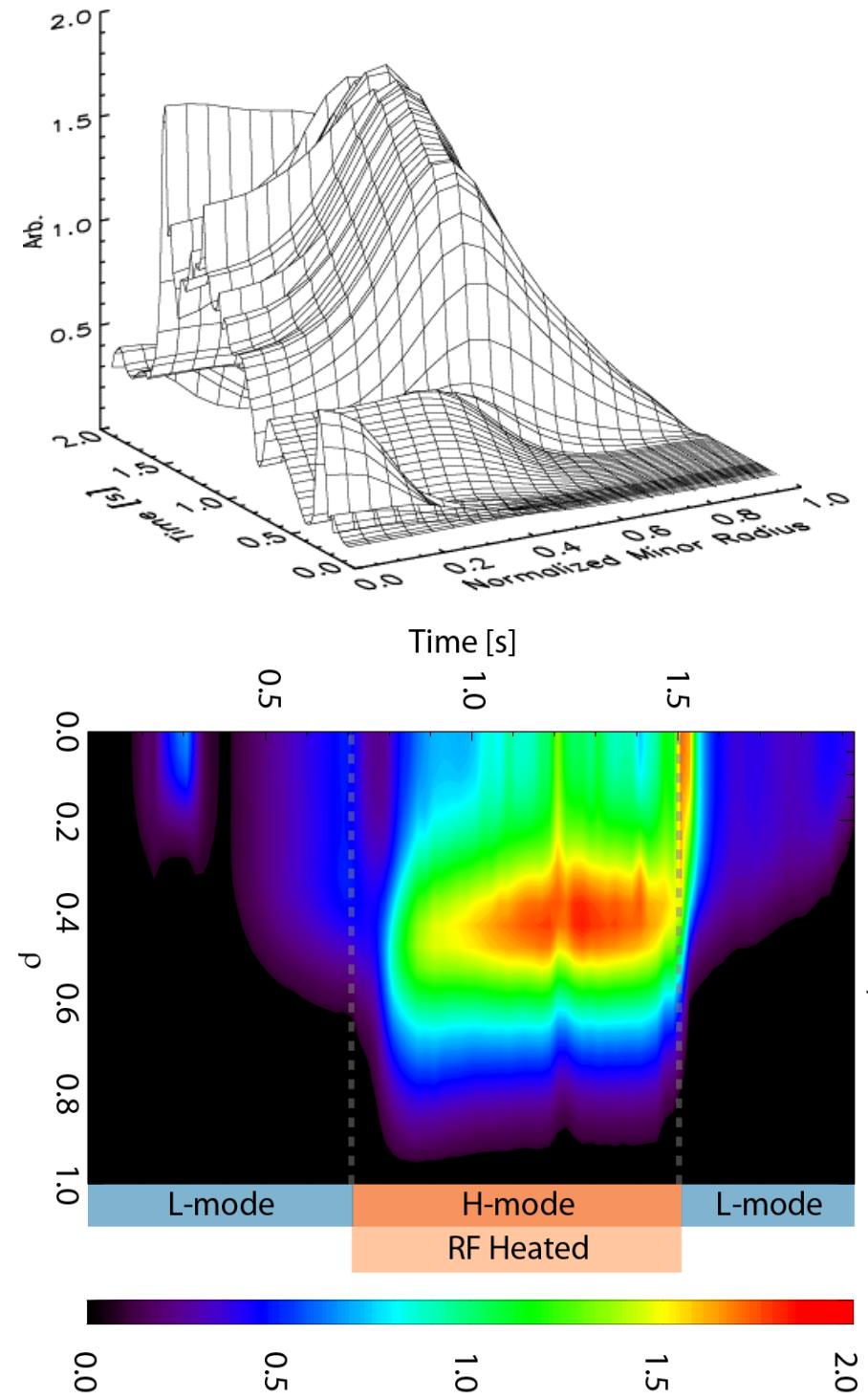
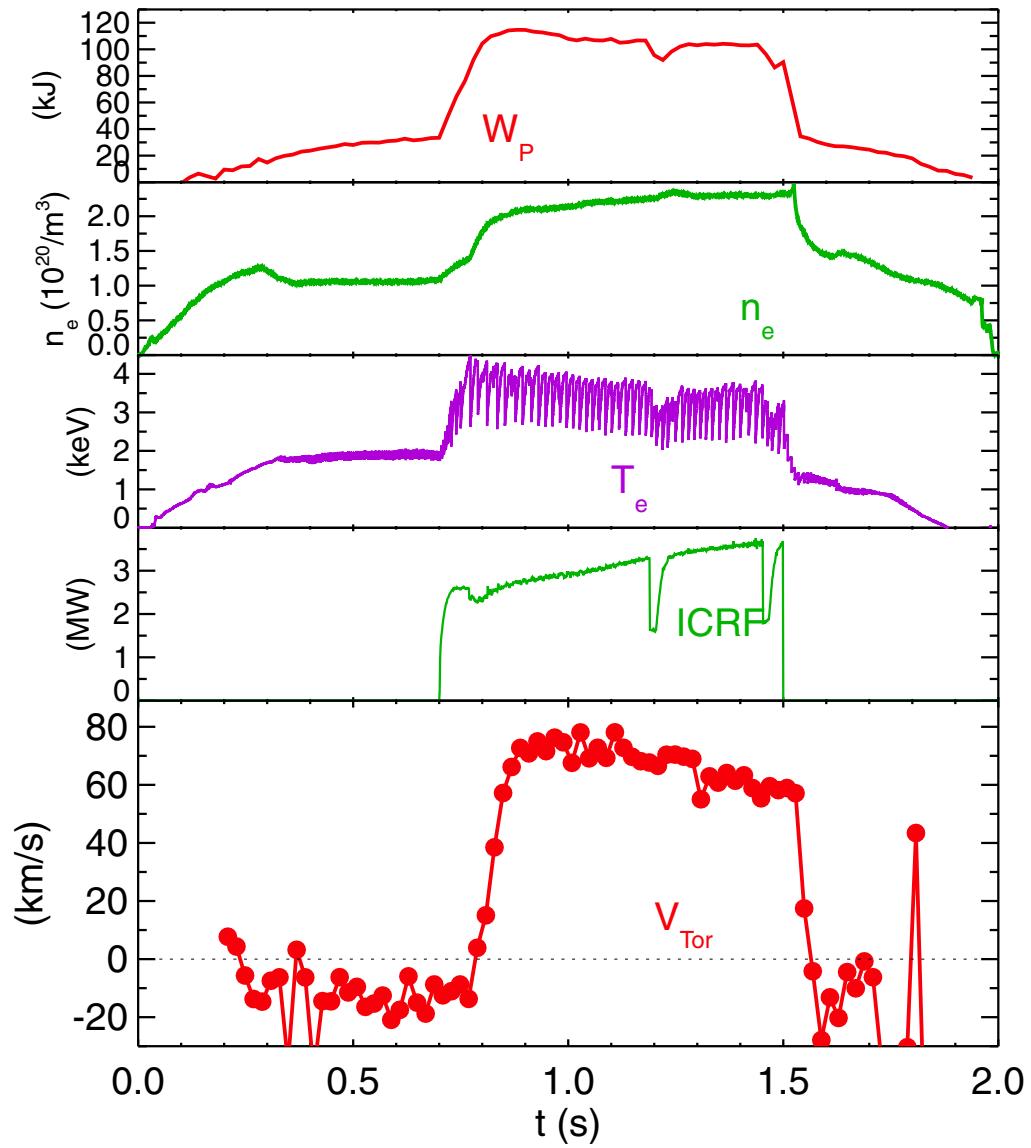
2<sup>nd</sup> moment - temperature

$$P_{2,j}^{\lambda} = \sum_k^p V_{jk} \varepsilon_{o,k} \left( \frac{\lambda_o^2}{c^2} (\hat{l}_j \cdot \mathbf{v}_k)^2 + w_k^2 \right)$$

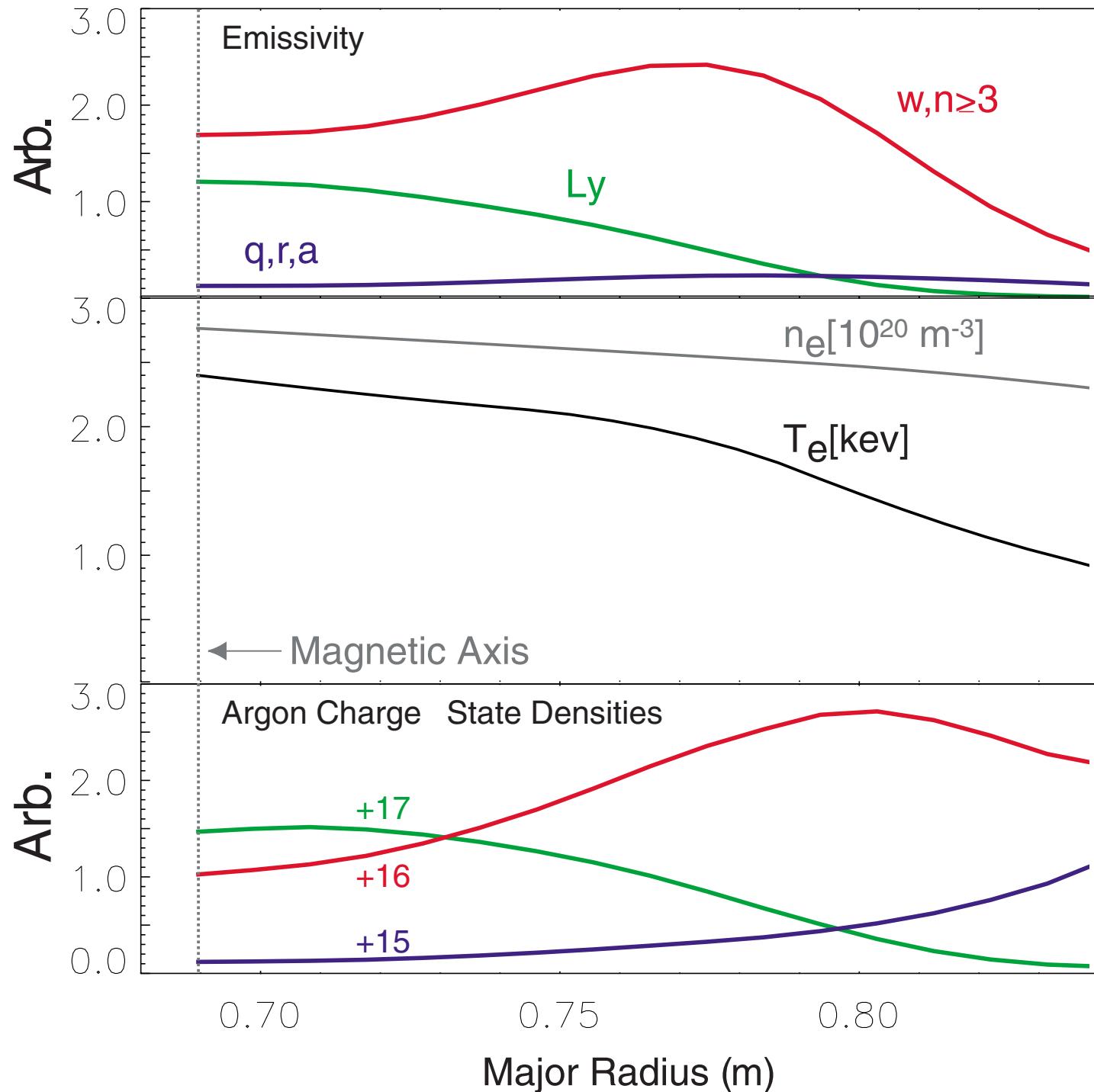


# Forbidden Line 'z' Emissivity Profiles

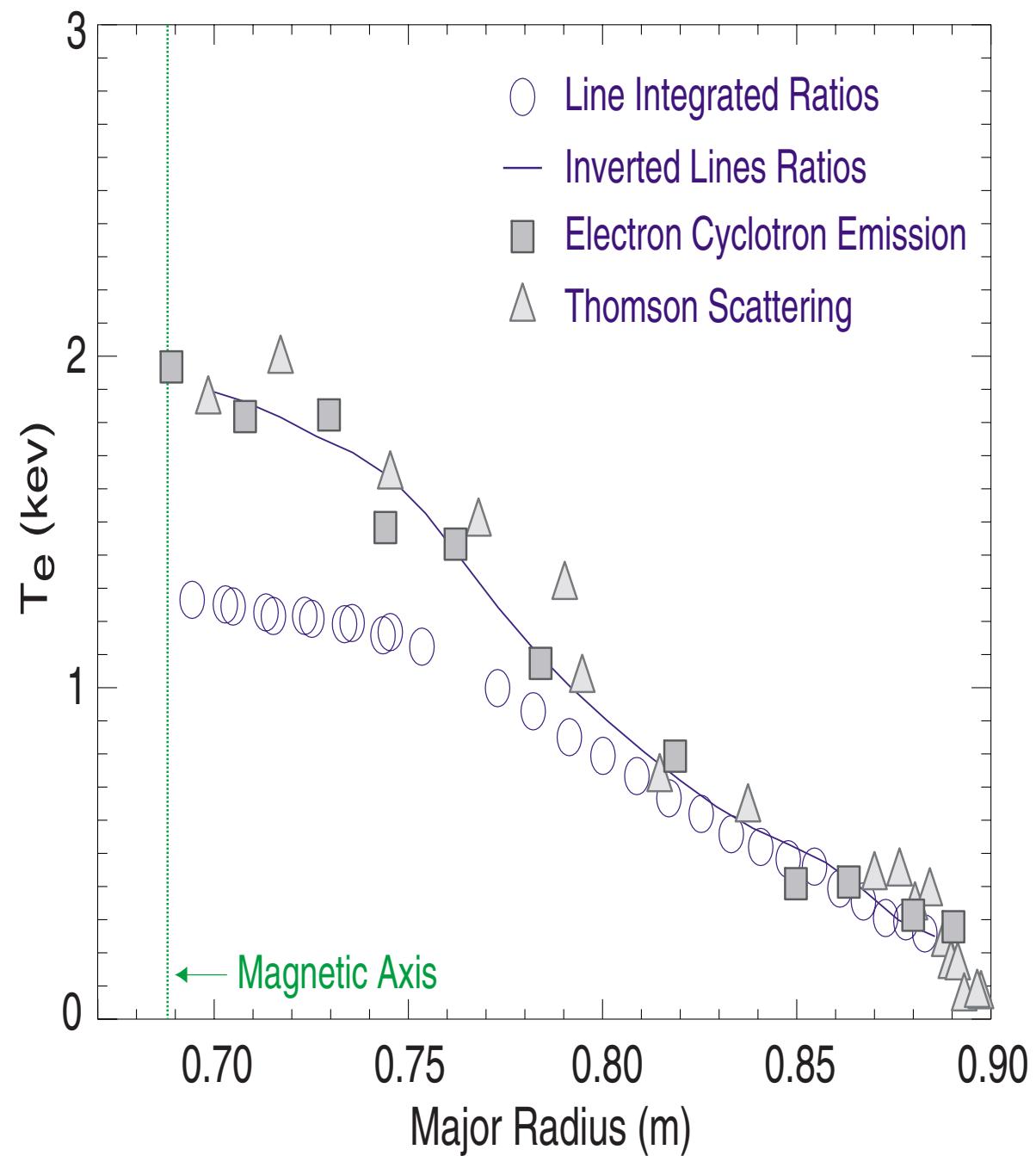
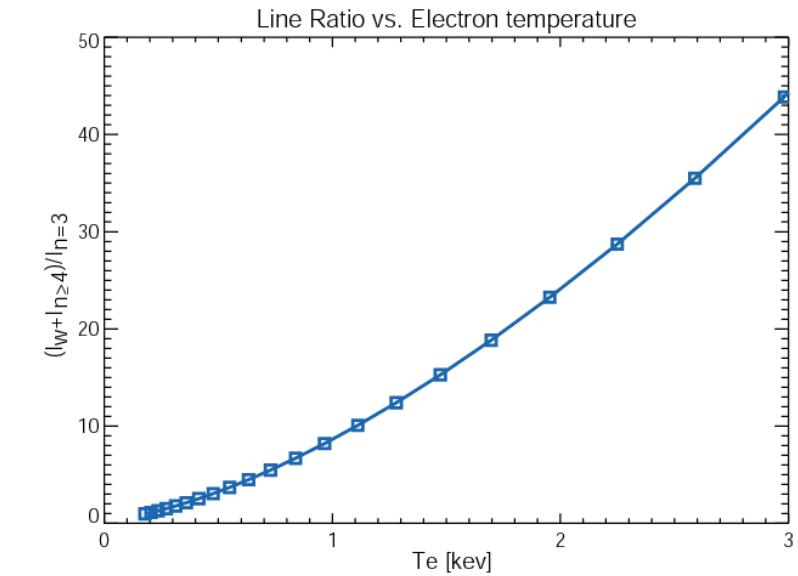
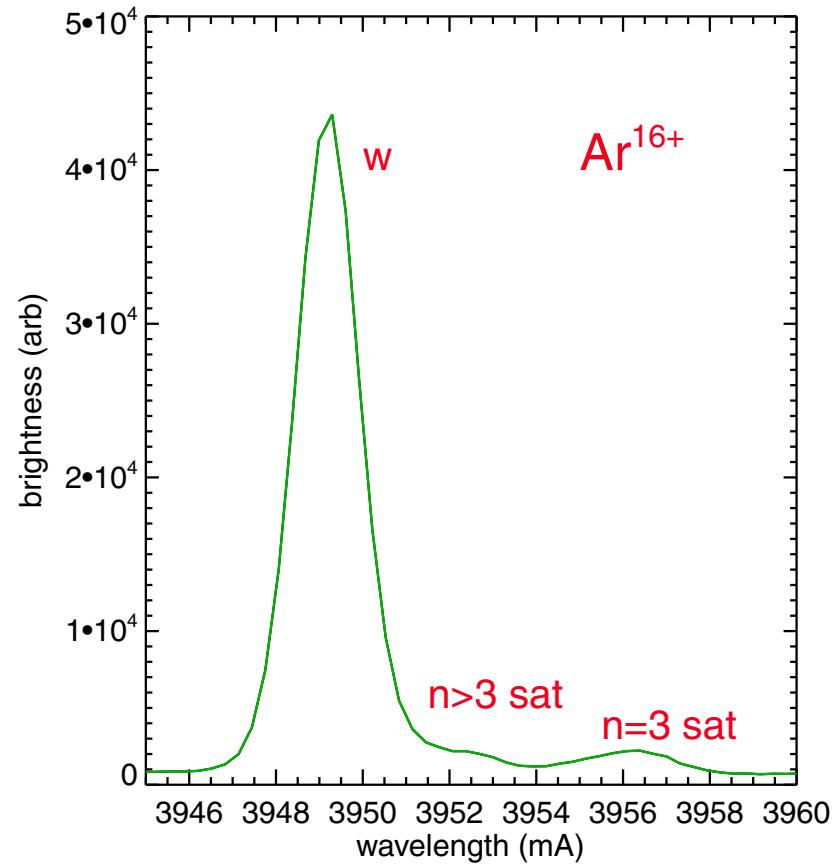
## Discharge time histories



# Emissivity and Charge State Density Profiles

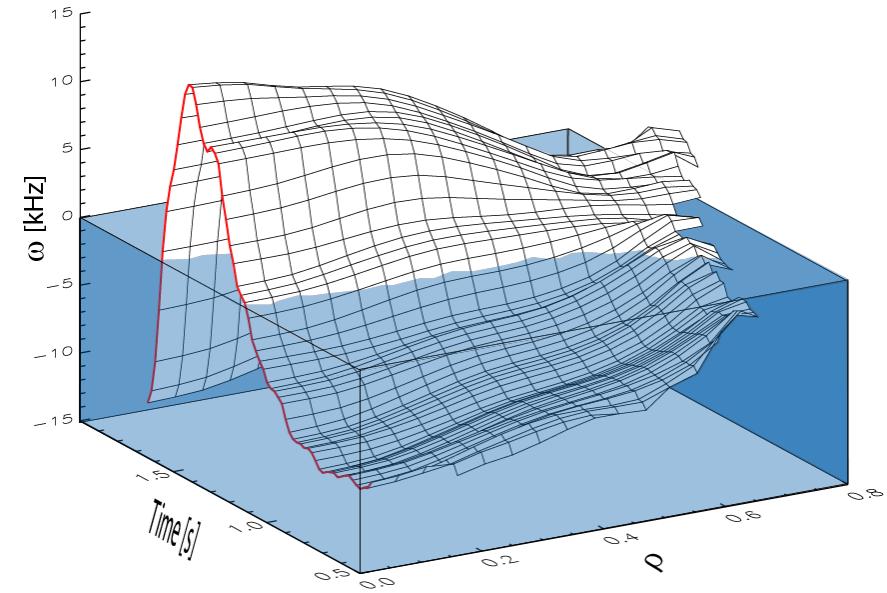
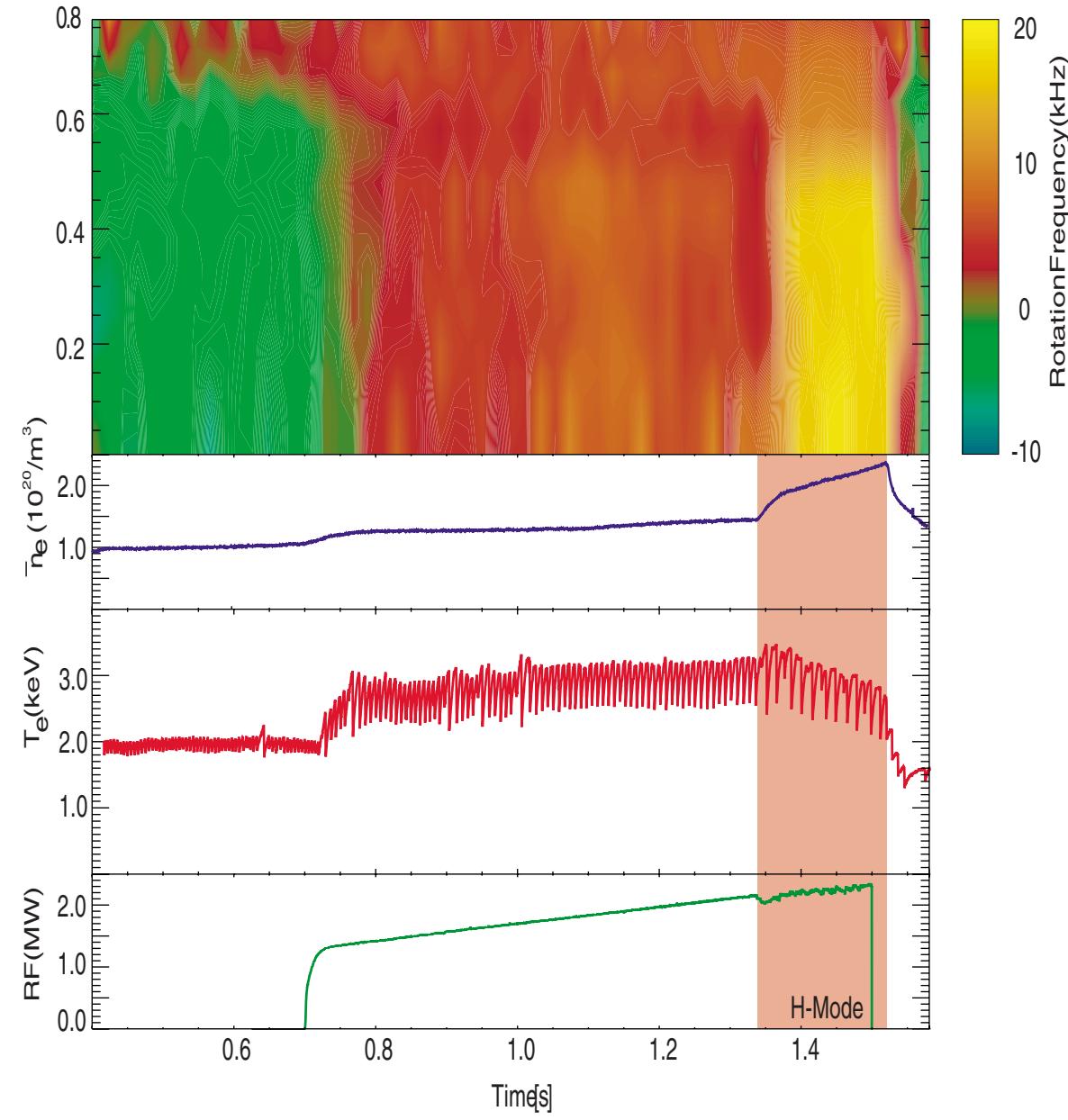


# Electron Temperature from Line Ratios

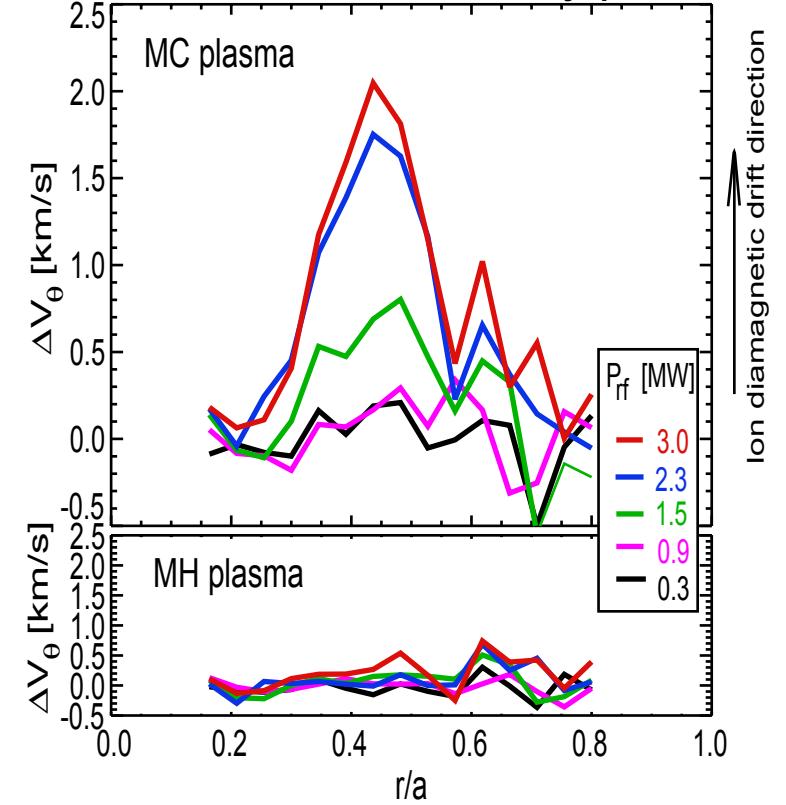


# Rotation Velocity Profile Evolution

## Toroidal rotation velocity profile evolution



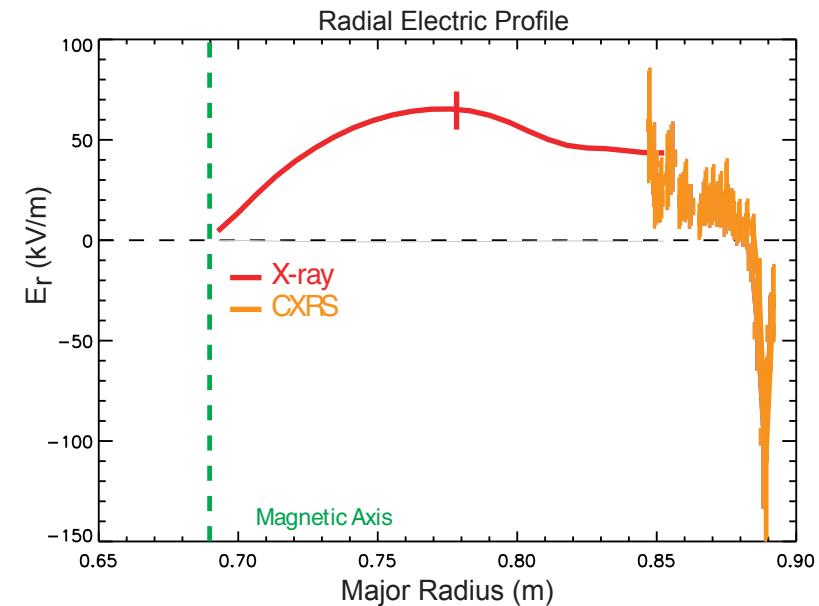
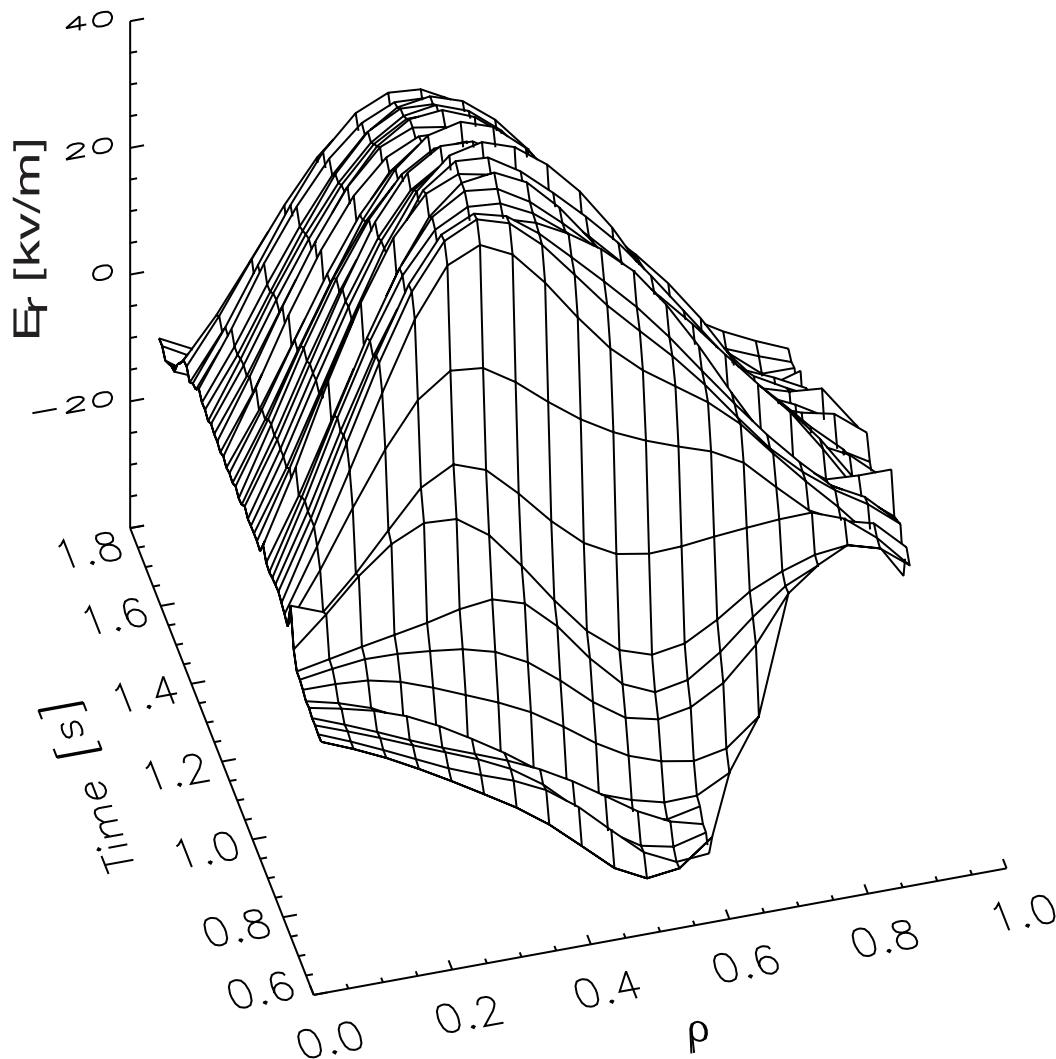
## Poloidal rotation velocity profiles



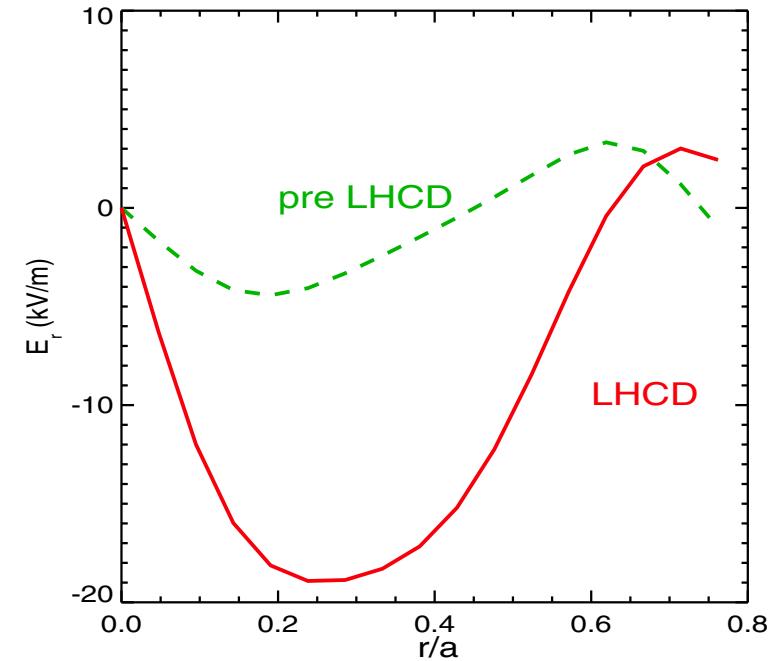
# Radial Electric Field

from force balance:

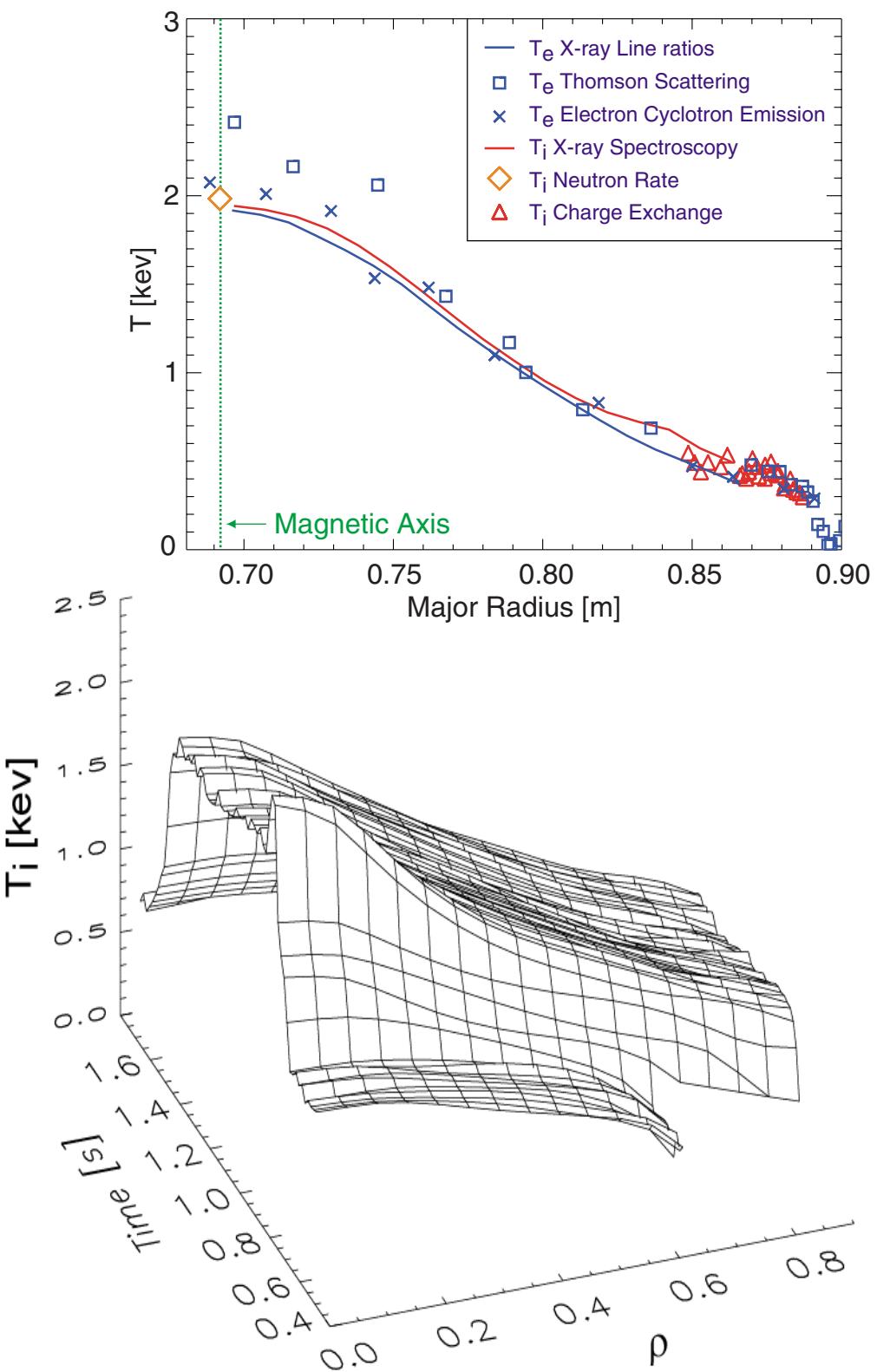
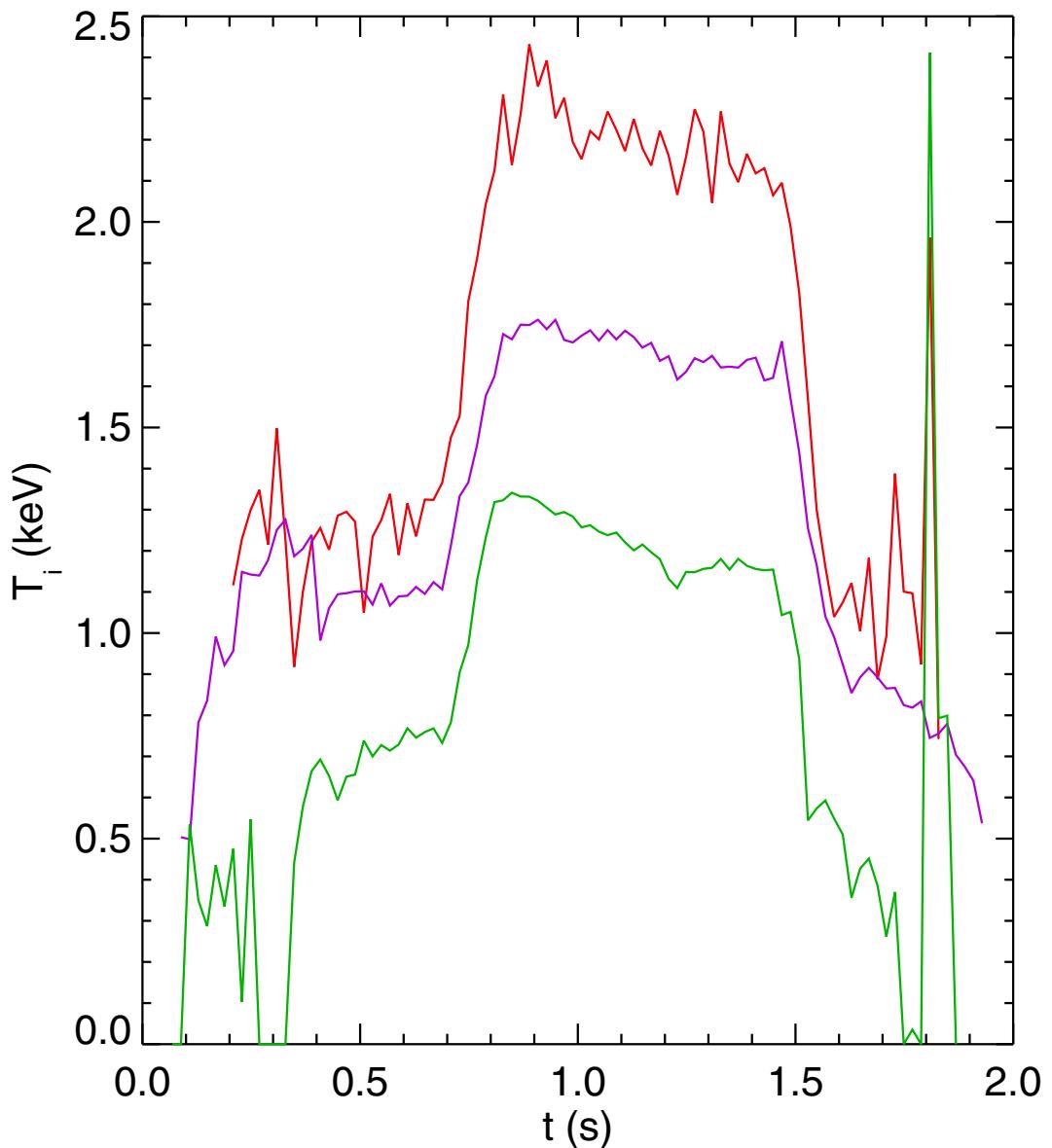
$$E_r = V_{\text{Tor}}B_{\text{Pol}} - V_{\text{Pol}}B_{\text{Tor}} + \text{grad}(P_i)/en_i Z_i$$



Counter-current rotation and negative radial electric field with LHCD

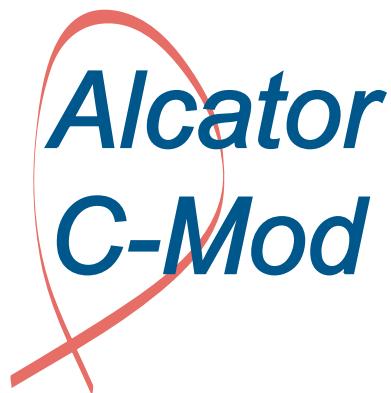


# Ion Temperature Profile Evolution

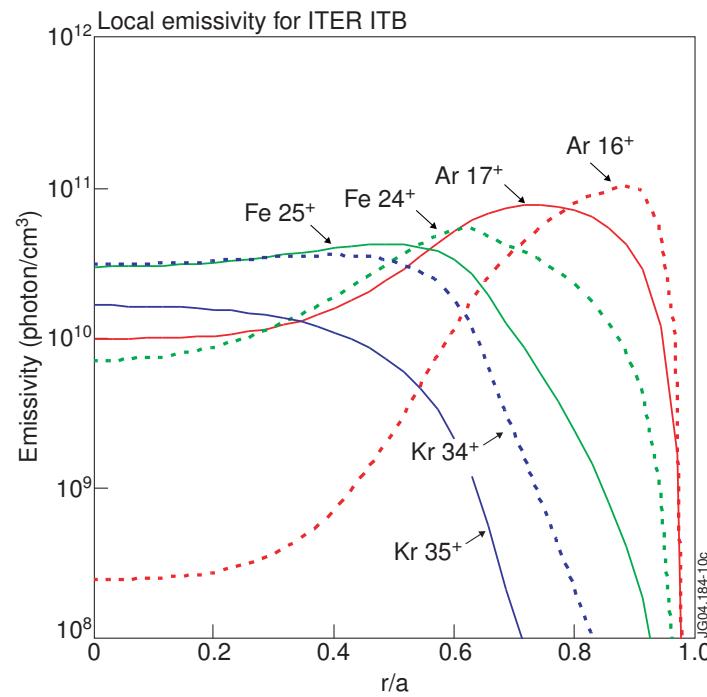
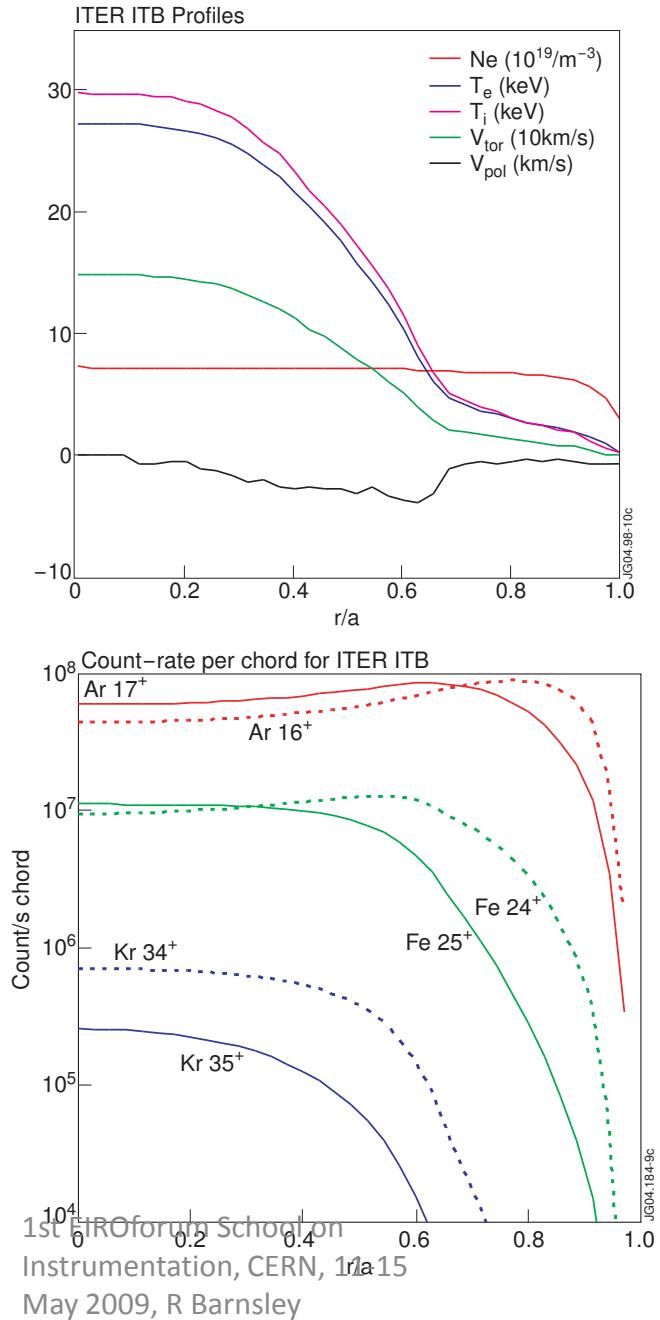


# Summary

- ▶ X-ray spectroscopy provides a wealth of diagnostic information
- ▶ Details of spherical crystal imaging system for C-Mod
- ▶ Key component 2-D detector
- ▶ Similar system for ITER

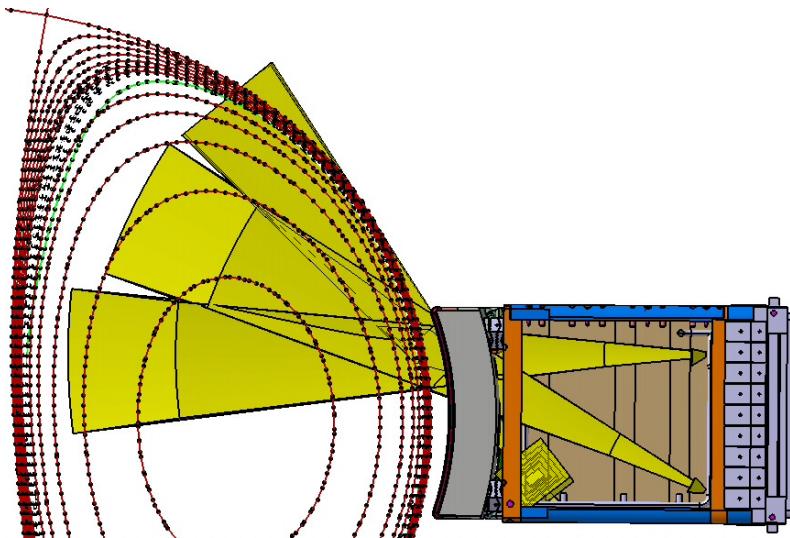


## ITER impurity line emission and spectrometer signals

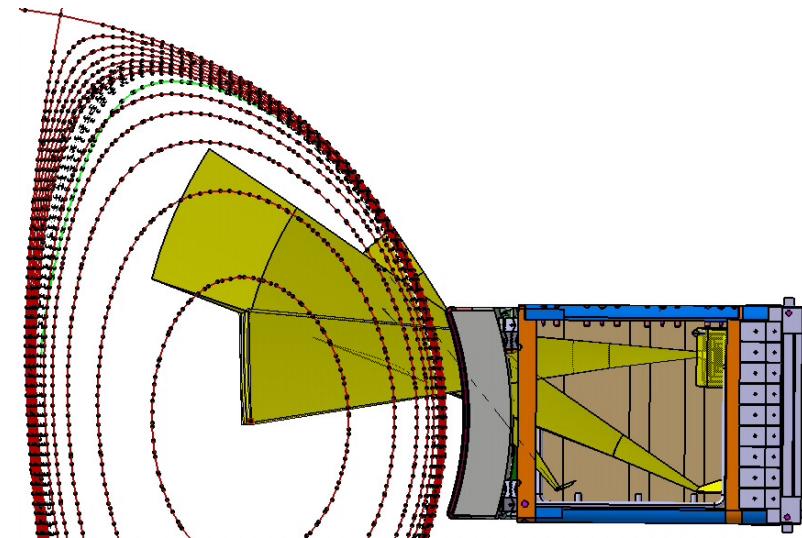


- Top left** Modelled ITER radial profiles
  - Top right** Local emissivity of impurity spectral lines  
(O'Mullane, ADAS-SANCO)
  - Bottom** Simulated signals for imaging x-ray crystal spectrometer
- Incremental radiated powers for added impurity concentrations of  $10^{-5} n_e$  are:
- |            |           |           |
|------------|-----------|-----------|
| Ar 0.25 MW | Fe 0.8 MW | Kr 1.4 MW |
|------------|-----------|-----------|

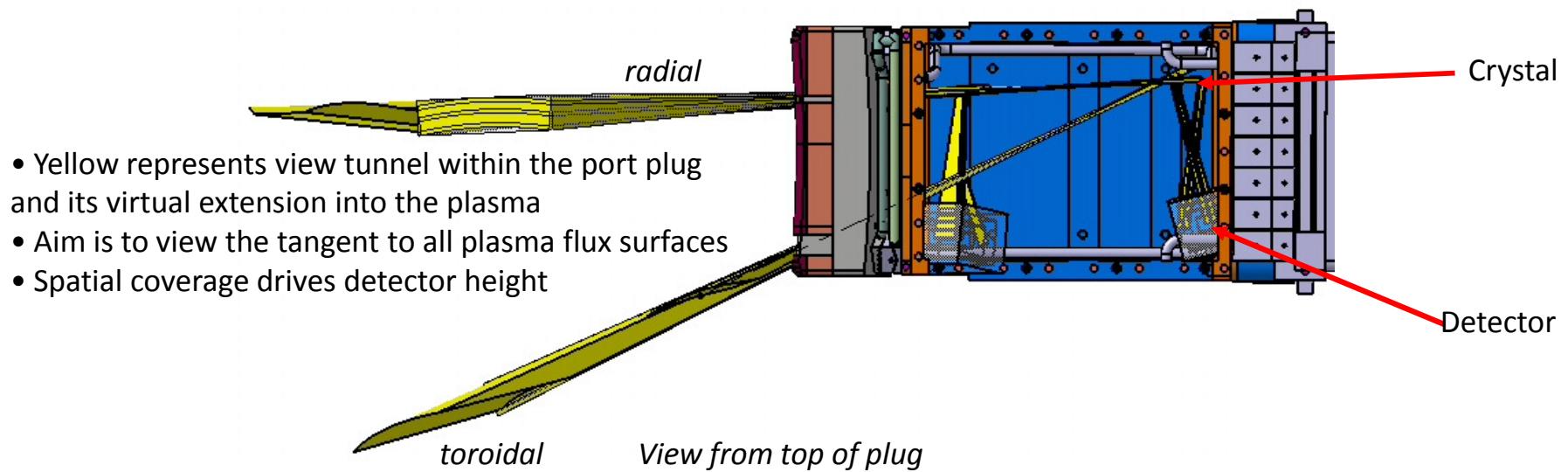
## High resolution imaging crystal spectrometer for ITER



*Plasma coverage by radial views*



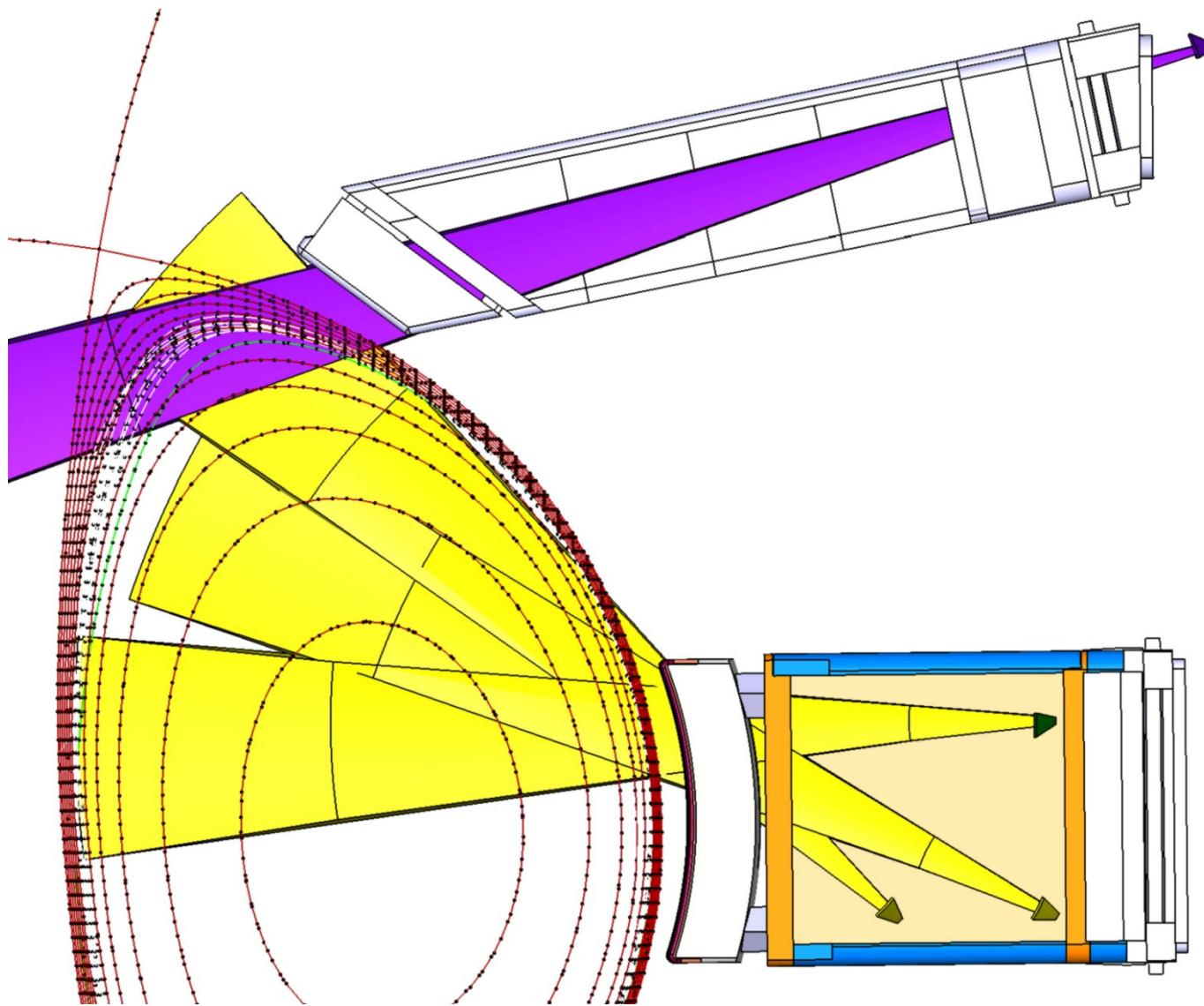
*Plasma coverage by toroidal views*



- Yellow represents view tunnel within the port plug and its virtual extension into the plasma
- Aim is to view the tangent to all plasma flux surfaces
- Spatial coverage drives detector height

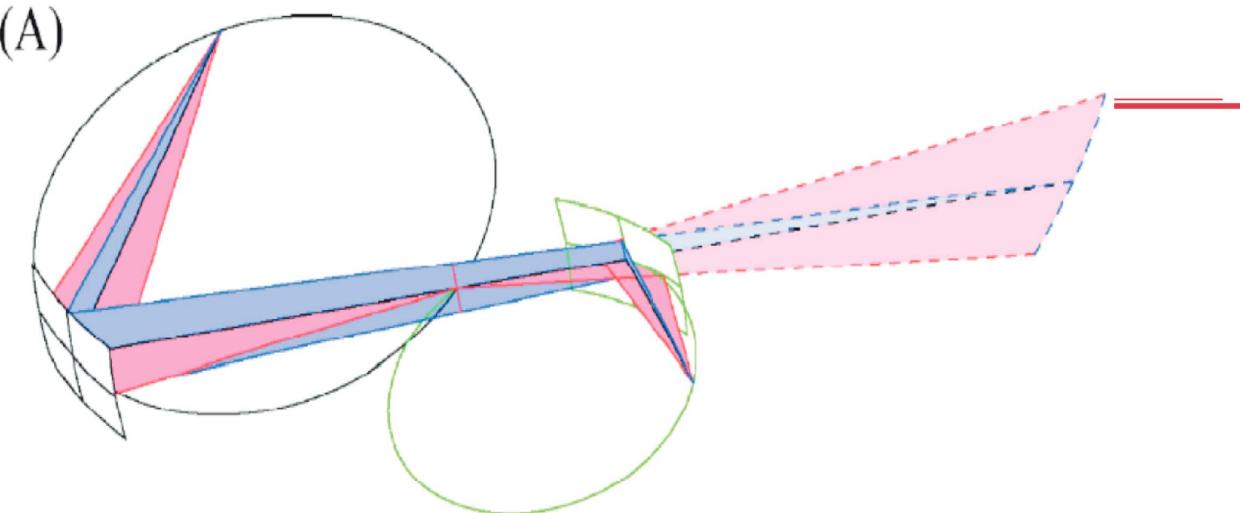
*View from top of plug*

Imaging Crystal Spectrometer Layout,  
with overlap between upper and equatorial views

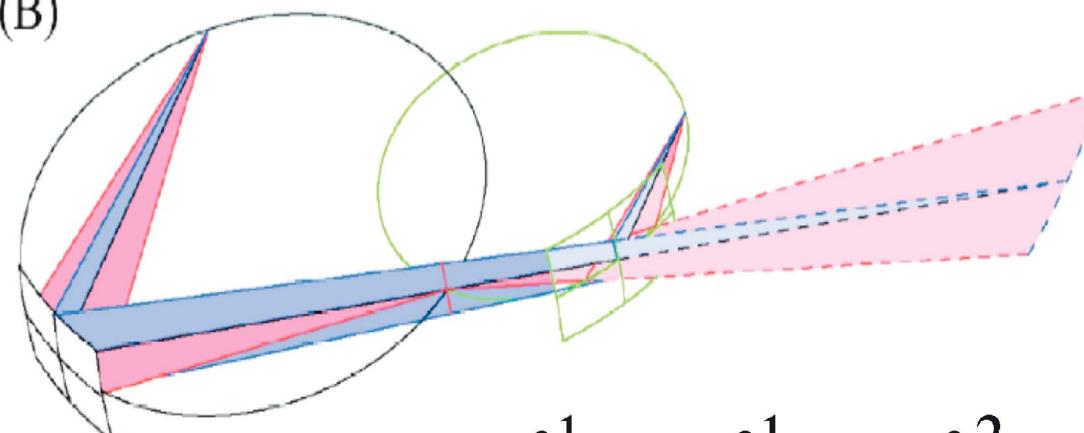


## 2 Crystal Spectrometer to Eliminate Astigmatism

(A)



(B)



$$f_s^1 = f_m^1 + f_m^2 + |f_s^2|$$