Conceptual Design of an X-ray imaging Crystal Spectrometer for Ti-profile measurements at the Large Helical Device

M. Bitter, K. W. Hill

Princeton Plasma Physics Laboratory, Princeton, NJ, USA

S. Morita, M. Goto

National Institute for Fusion Science, Oroshi-cho, Toki, Japan

J. E. Rice, A. Ince-Cushman, M. Reinke,

MIT Plasma Science and Fusion Center, Cambridge, MA

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ABSTRACT

A new x-ray imaging crystal spectrometer is being proposed for LHD to measure radial profiles of the ion temperature with a spatial resolution of 1 cm and a time resolution of ≥ 10 ms. This instrument can be installed at an equatorial port, which provides an unimpeded view of the whole plasma. It will record spectra of Ar^{16+}, which are spatially resolved in a direction perpendicular to the equatorial plane. In addition to ion temperature profiles, the spectrometer can also provide profiles of the electron temperature and the argon ion charge state distribution, which is of interest for impurity transport studies; and it may also be possible to obtain pofiles of the poloidal rotation velocity. The spectrometer could be operational on LHD by October 2010. The design, construction, and operation of the spectrometer is being planned as part of the NIFS-PPPL collaboration. The proposed type of spectrometer was thoroughly tested on Alcator C-Mod, where it has made significant contributions to the experimental program.

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OUTLINE

I. Working principle

II. Results from Alcator C-Mod

III. Layout of an x-ray imaging crystal spectrometer for LHD

IV. Anticipated benefits

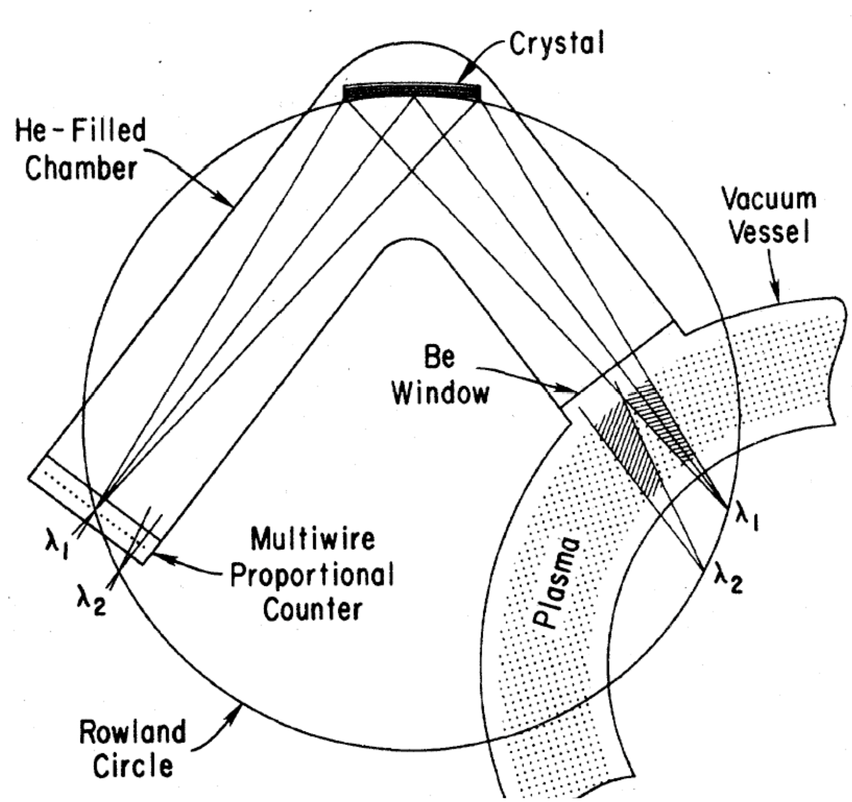
I. Working Principle

The new x-ray imaging crystal spectrometer is a natural development of the standard Johann crystal spectrometer, which has been used on tokamaks and on LHD for many years.

The essential innovations are the replacement of the cylindrically bent crystal with a spherically bent crystal, which provides both spectral and spatial resolution, and the use of novel, two-dimensional, high-count rate Pilatus detectors.

The following Figures show the standard Johann spectrometer and the imaging properties of a spherically bent crystal.

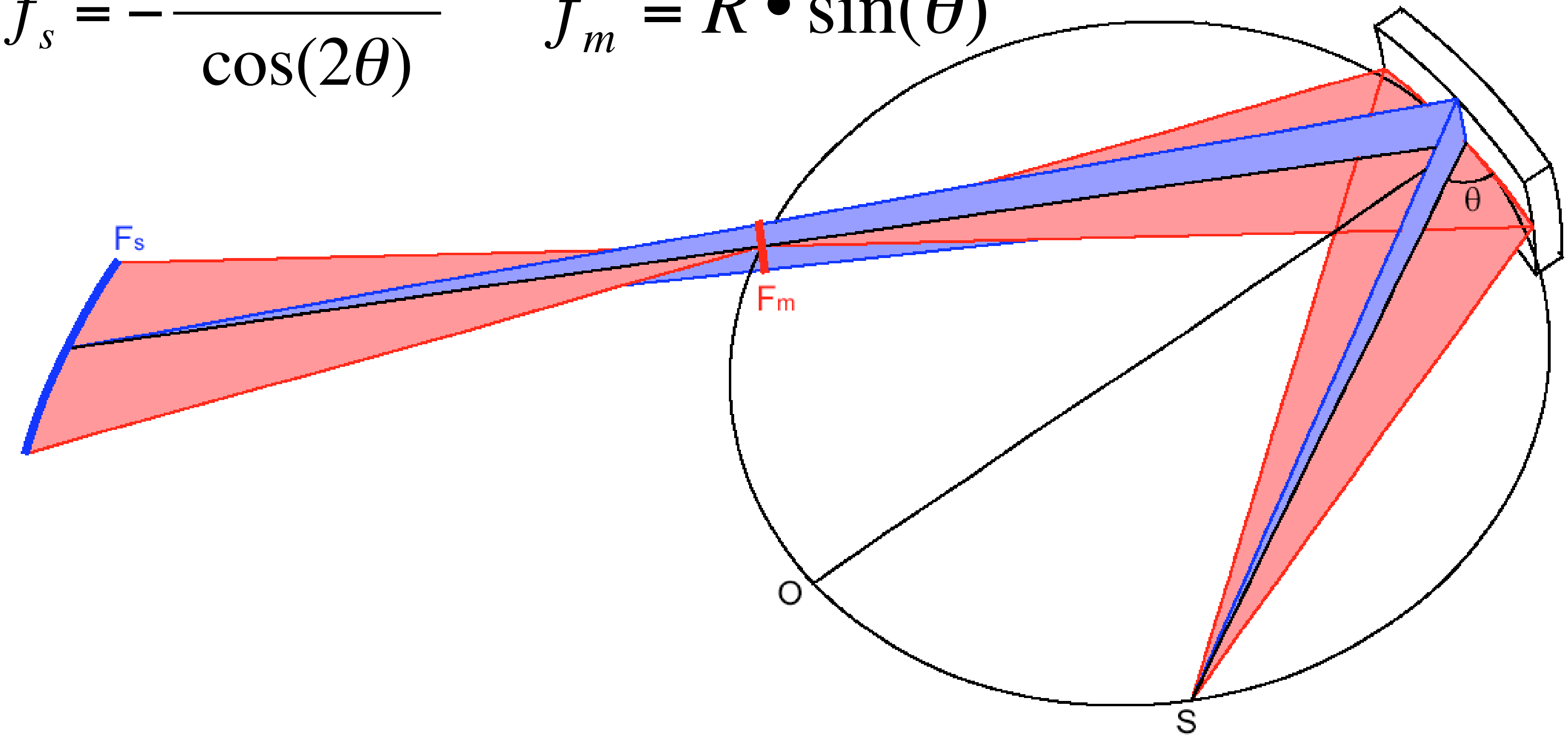
Conventional Johann Crystal Spectrometer



- with cylindrically bent crystal and one-dimensional, position-sensitive, multi-wire proportional counter is standard for Ti(0) measurements on tokamaks
- It does not provide spatial resolution.

Imaging Properties *(Astigmatism)* of a Spherical Crystal

$$f_s = -\frac{R \bullet \sin(\theta)}{\cos(2\theta)} \qquad f_m = R \bullet \sin(\theta)$$



Because of the astigmatism two mutually perpendicular line images, F_m and F_s, are produced of a point source S on the Rowland circle. The rotational symmetry of the ray pattern about the normal of the crystal is used to obtain spatial resolution.

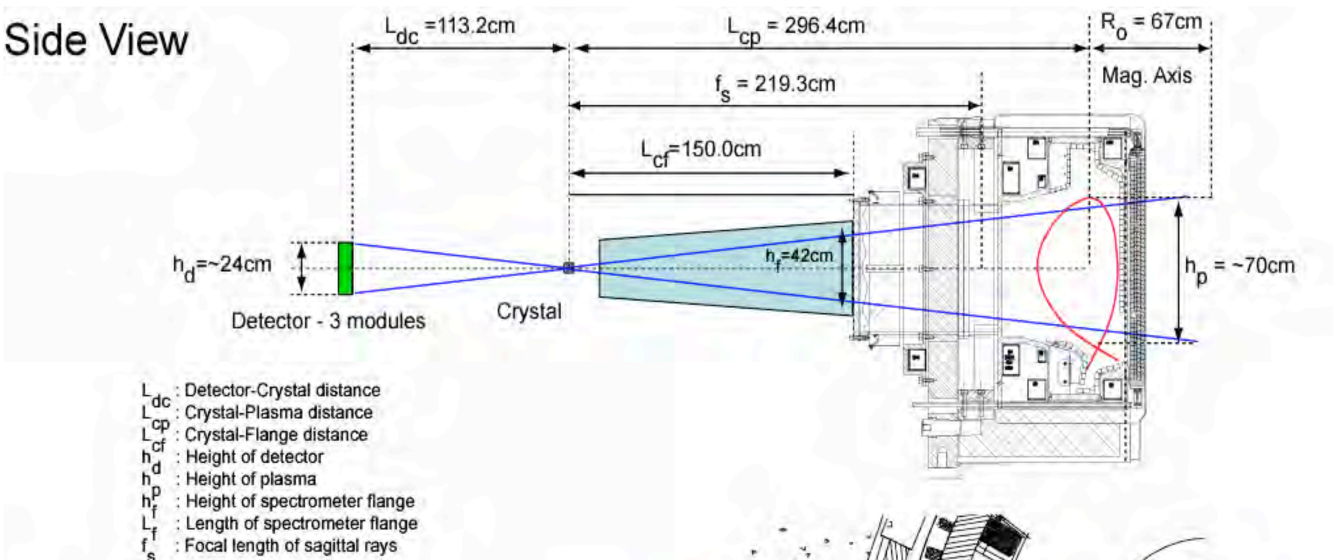
II. Results from Alcator C-Mod

A prototype of the new x-ray imaging crystal spectrometer, consisting of two spherically bent crystals and four Pilatus detectors, was installed on Alcator C-Mod in April 2007 to record spatially resolved spectra of He-like argon from the whole plasma cross-section and spectra of H-like argon from the plasma center.

The following Figures show the spectrometer layout and profiles of the ion temperature and toroidal plasma rotation velocity, which were obtained for different experimental condition.

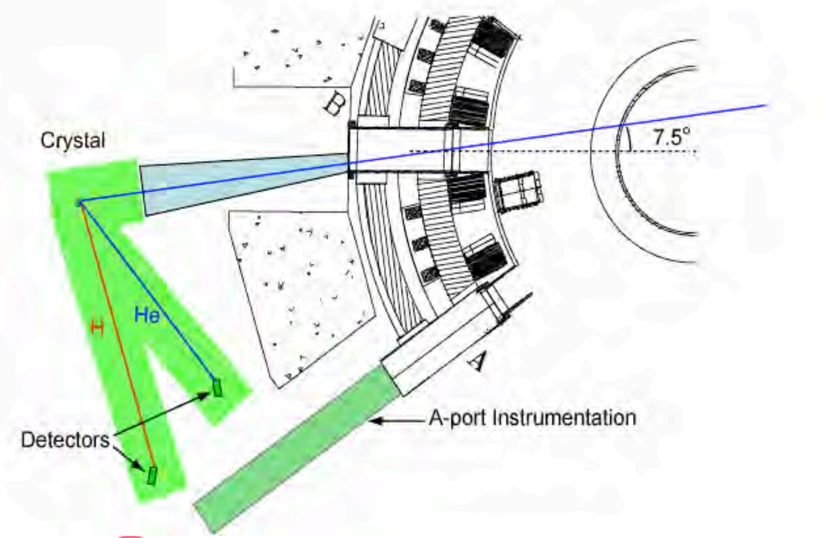
X-ray Imaging Crystal Spectrometer on C-Mod

Side View



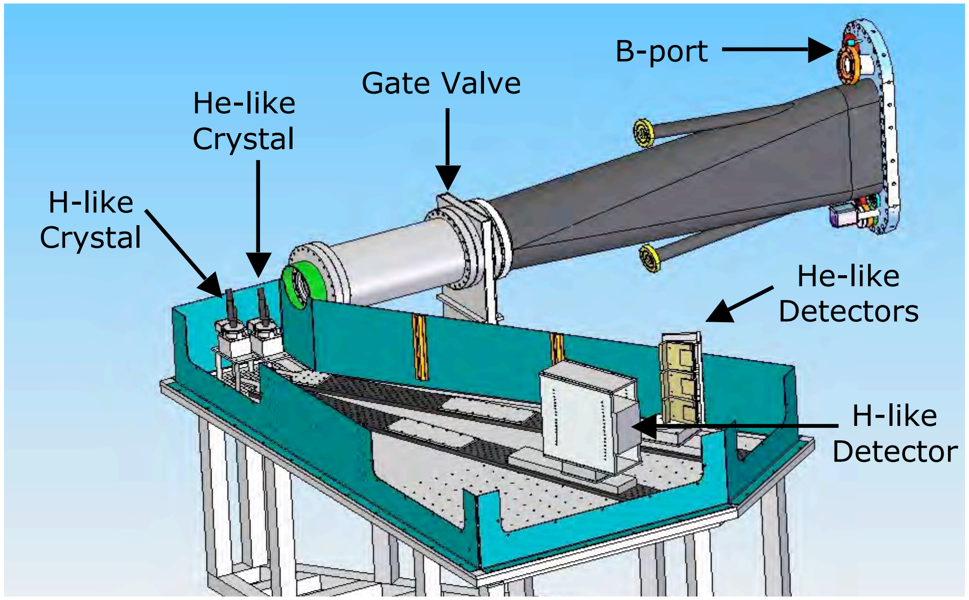
Top View

He		H	
Rad Curv	: 1300	Rad Curv	: 1800
2d Spacing	: 4.562	2d Spacing	: 4.913
Brag Angle	: 60.53	Brag Angle	: 49.46
Res. power	: 9600	Res. power	: 7800
Sag Focus	: 219.3cm	Sag Focus	: 881.6cm
Magnif	: 0.42	Magnif	: 0.513
Spec wid	: 22.69mm	Spec wid	: 2.3 mm

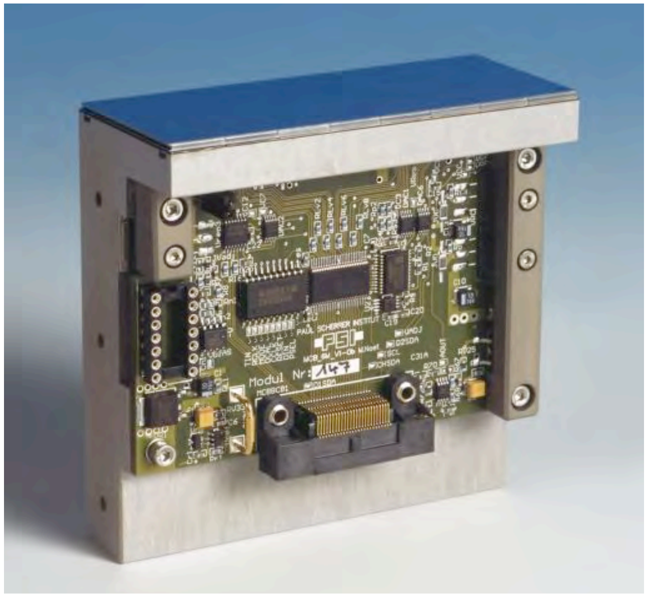


X-ray Imaging Crystal Spectrometer on C-Mod

- Spherically bent crystals provide ion-temperature and
- rotation profiles from H & He-like Argon emissions lines



Spectrometer Layout



Pilatus X-ray Detector Module

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X-ray Imaging Crystal Spectrometer on C-Mod

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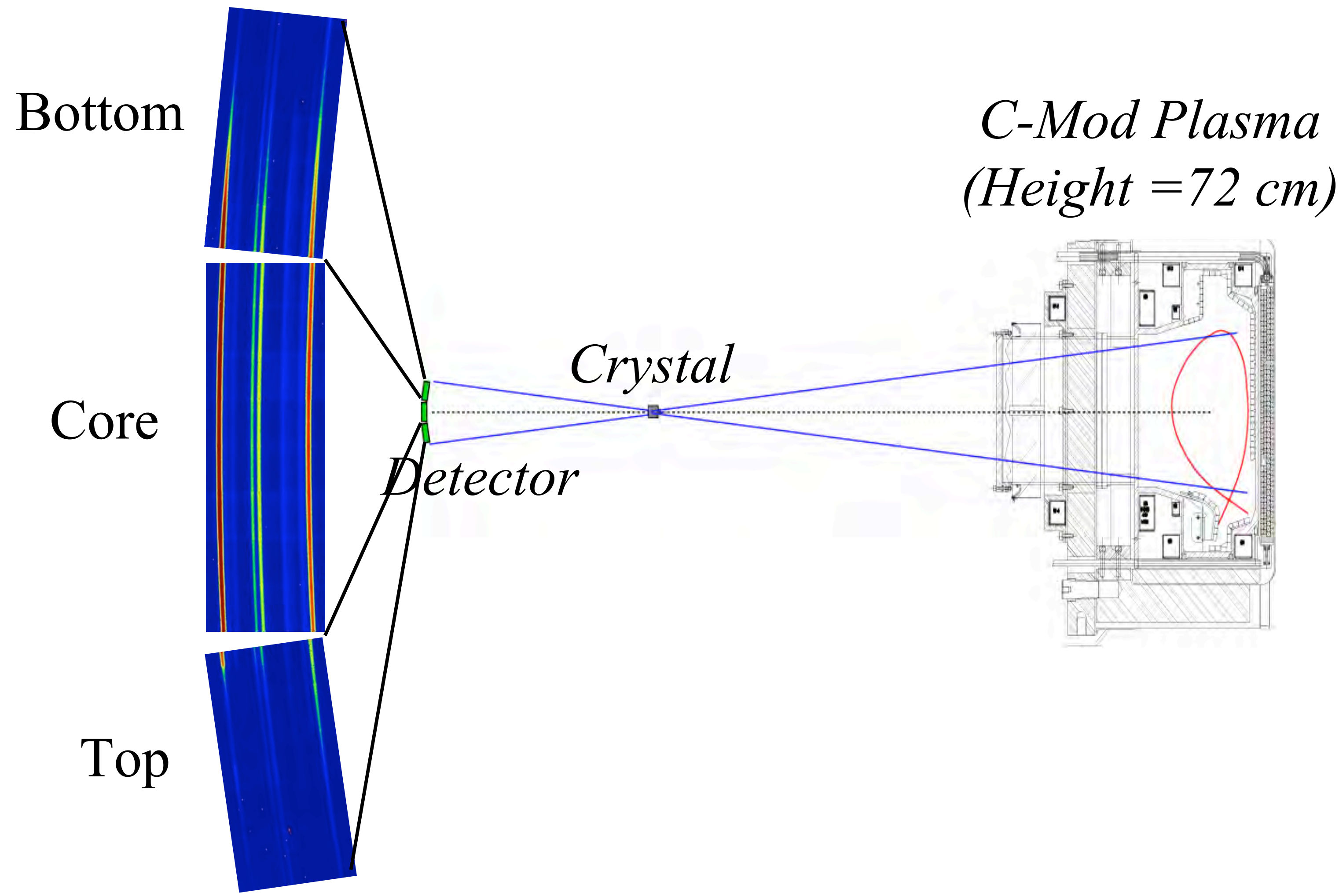
X-ray Imaging Crystal Spectrometer on C-Mod

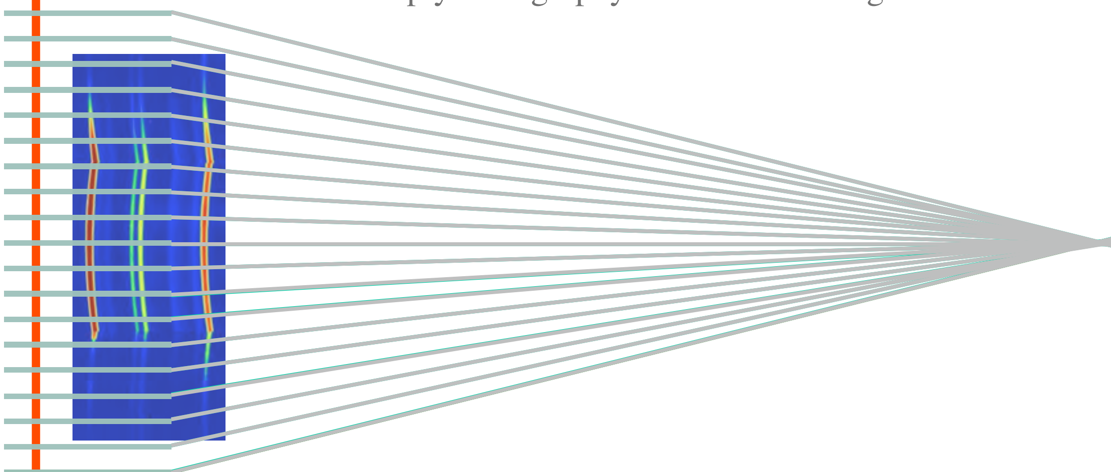
Raw Data: He-like Argon Spectra

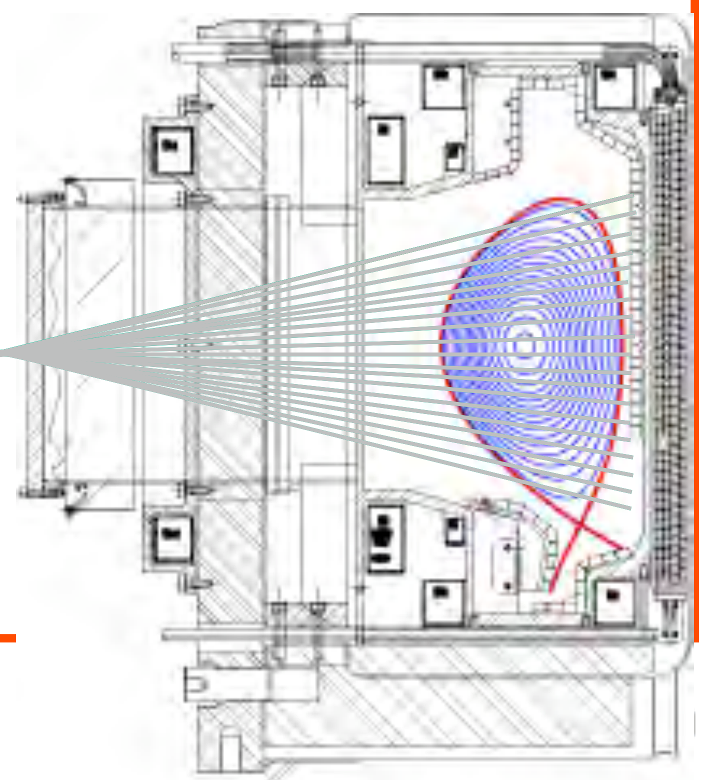


Spectral Tomography

†

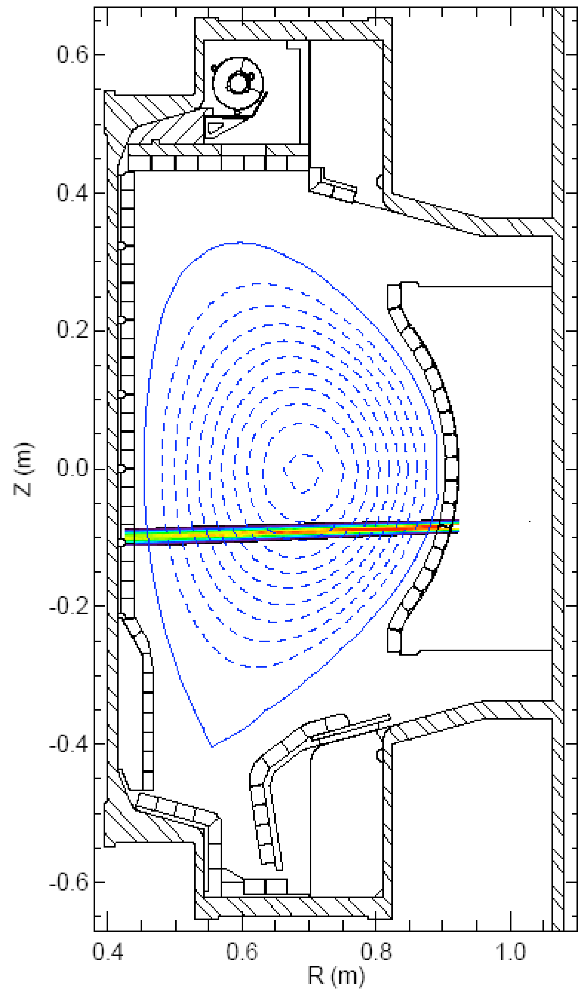
- Multiple line integrated spectra require tomography to obtain flux surface averaged measurements
  - Flux surface provided by magnetic measurements
  - Assume emissivity, toroidal rotation frequency and impurity temperatures are constant on a flux surfaces
  - Assume impurity distribution function is Maxwellian
    - Not simply tomography on each wavelength

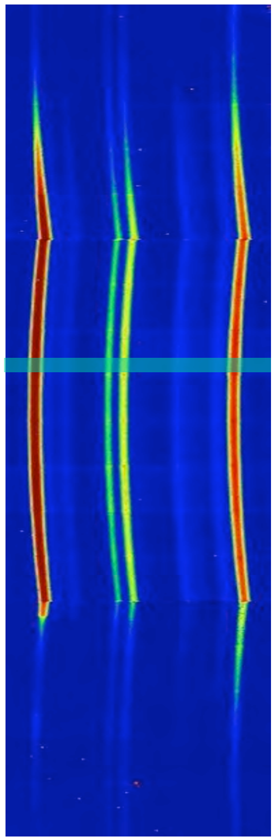




†I. Condrea, Physics of Plasmas, V7, #9, 3641

Ray Tracing/Spatial Resolution





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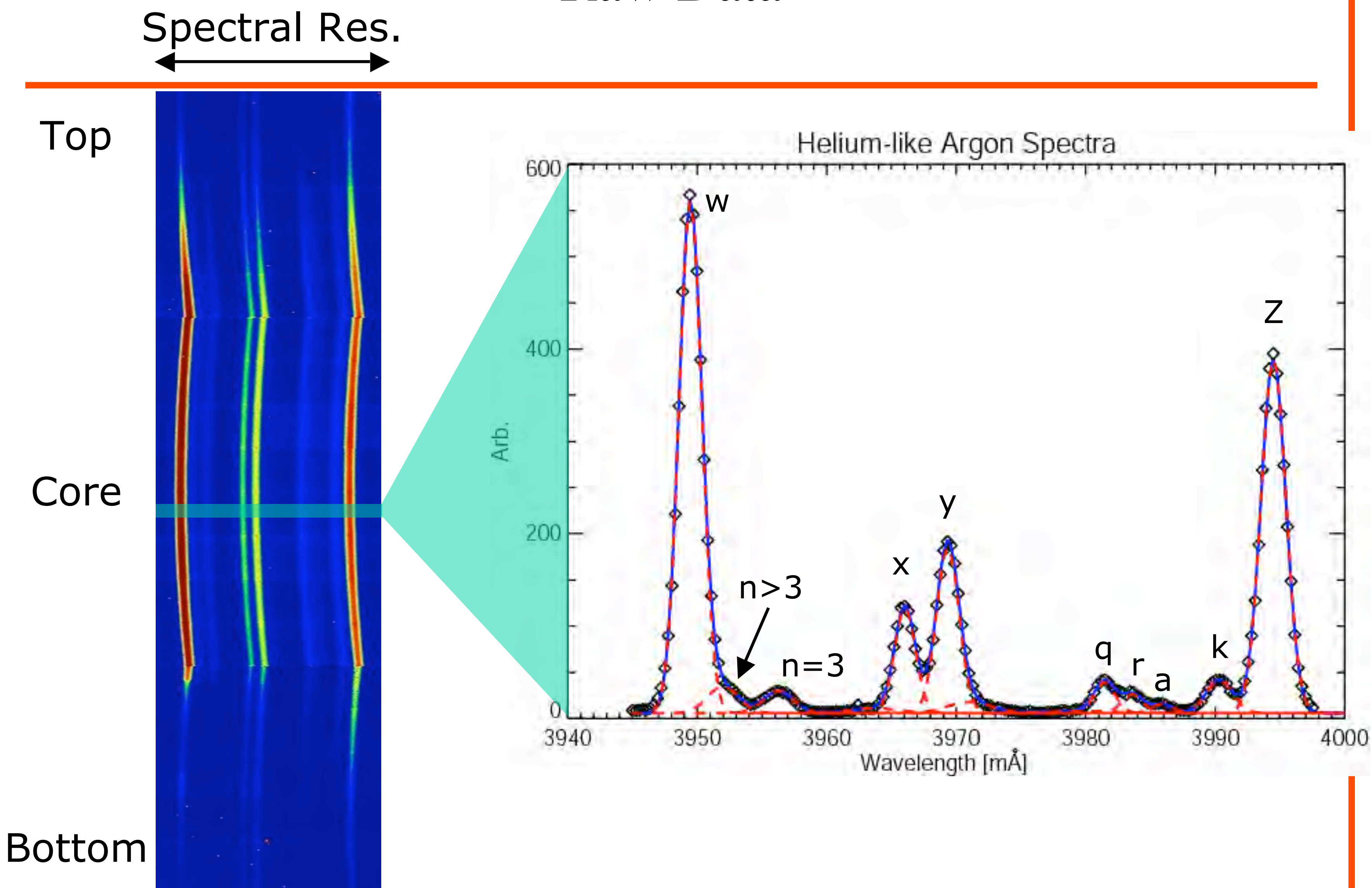
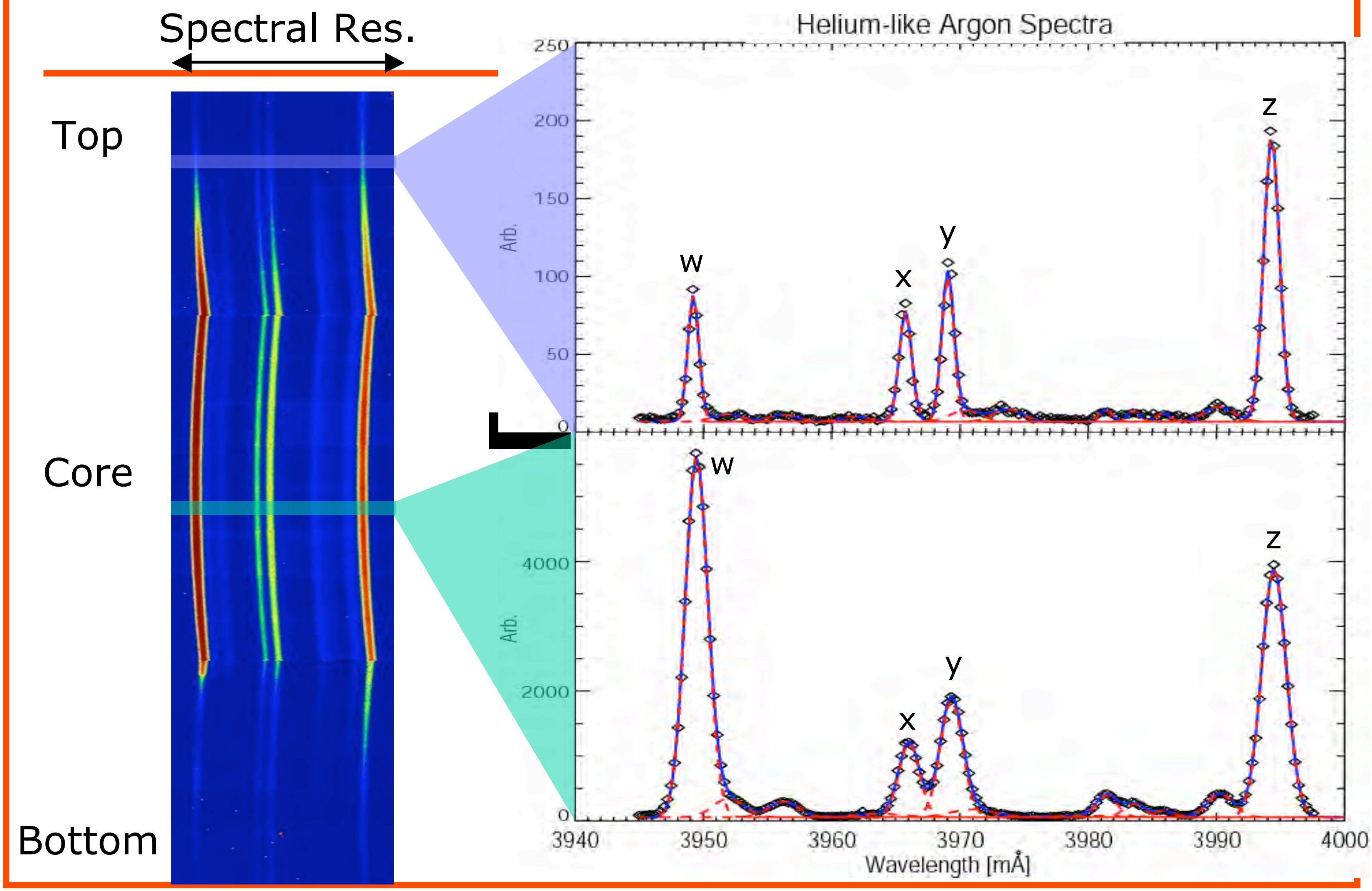
Raw Data



Spectral Res.
Top
Core
Bottom
Helium-like Argon Spectra
600
400
200
0
Arb.
3940
3950
3960
3970
3980
3990
4000
Wavelength [mÅ]
w
n>3
n=3
x
y
q
r
a
k
z

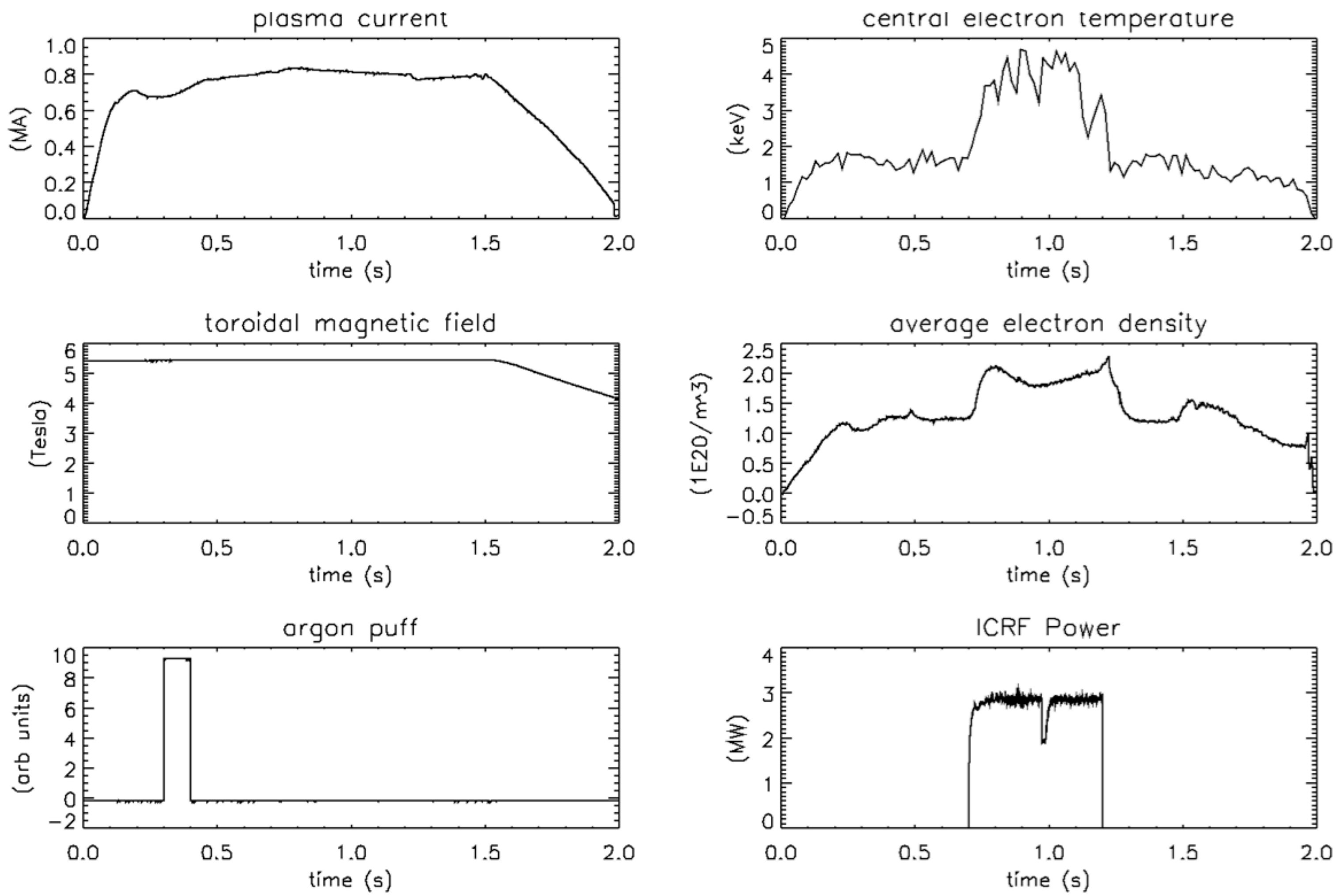
Raw Data



Spectral Res.
Top
Core
Bottom
Helium-like Argon Spectra
Arb.
250
200
150
100
50
0
w
x
y
z
4000
2000
3940
3950
3960
3970
3980
3990
4000
Wavelength [mÅ]

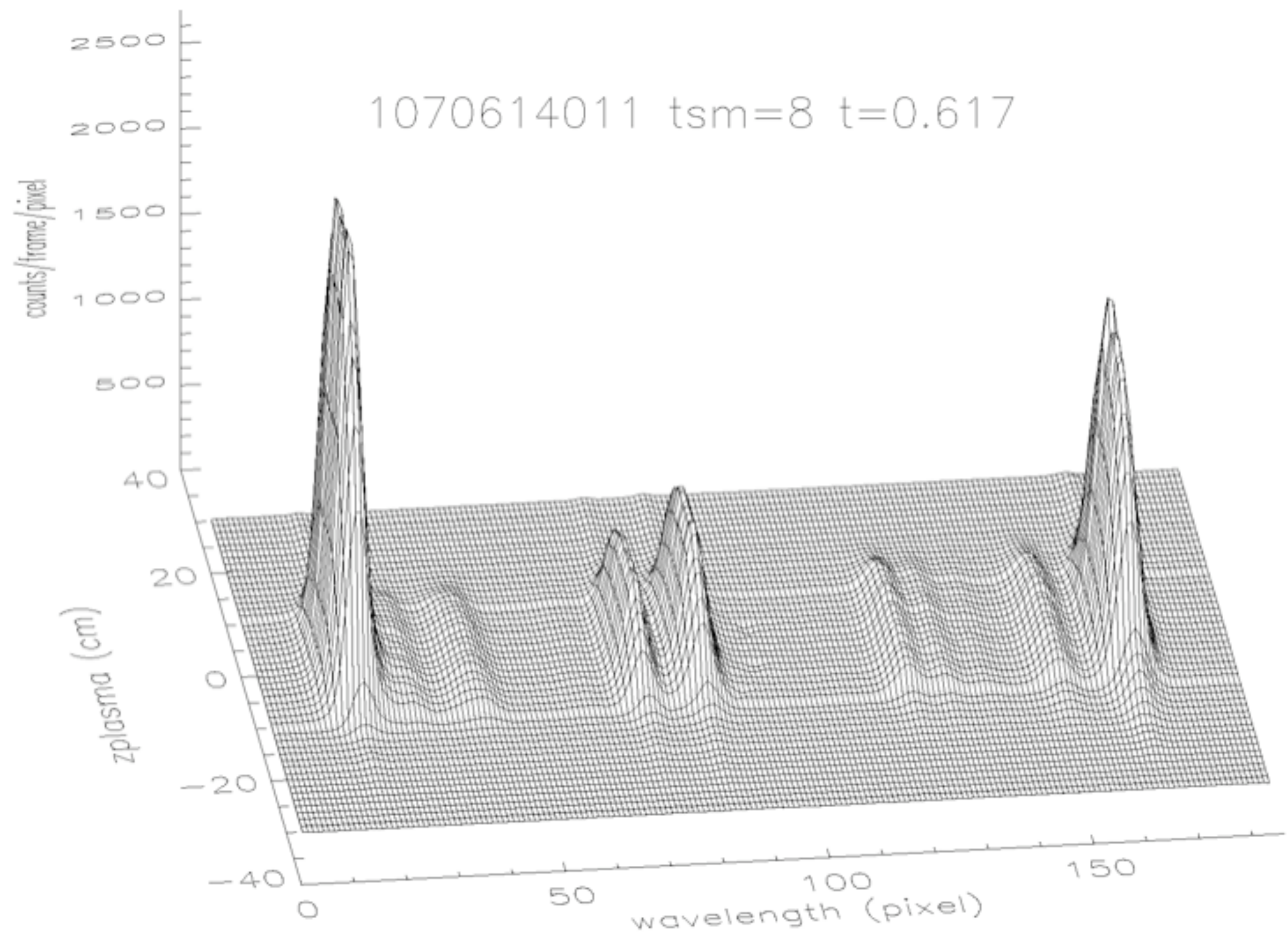
Waveforms *C-Mod Shot:1070614011*

with rf heating and argon injection



X-ray Imaging Crystal Spectrometer on C-Mod

Raw Data: He-like Argon Spectra



Alcator C-Mod

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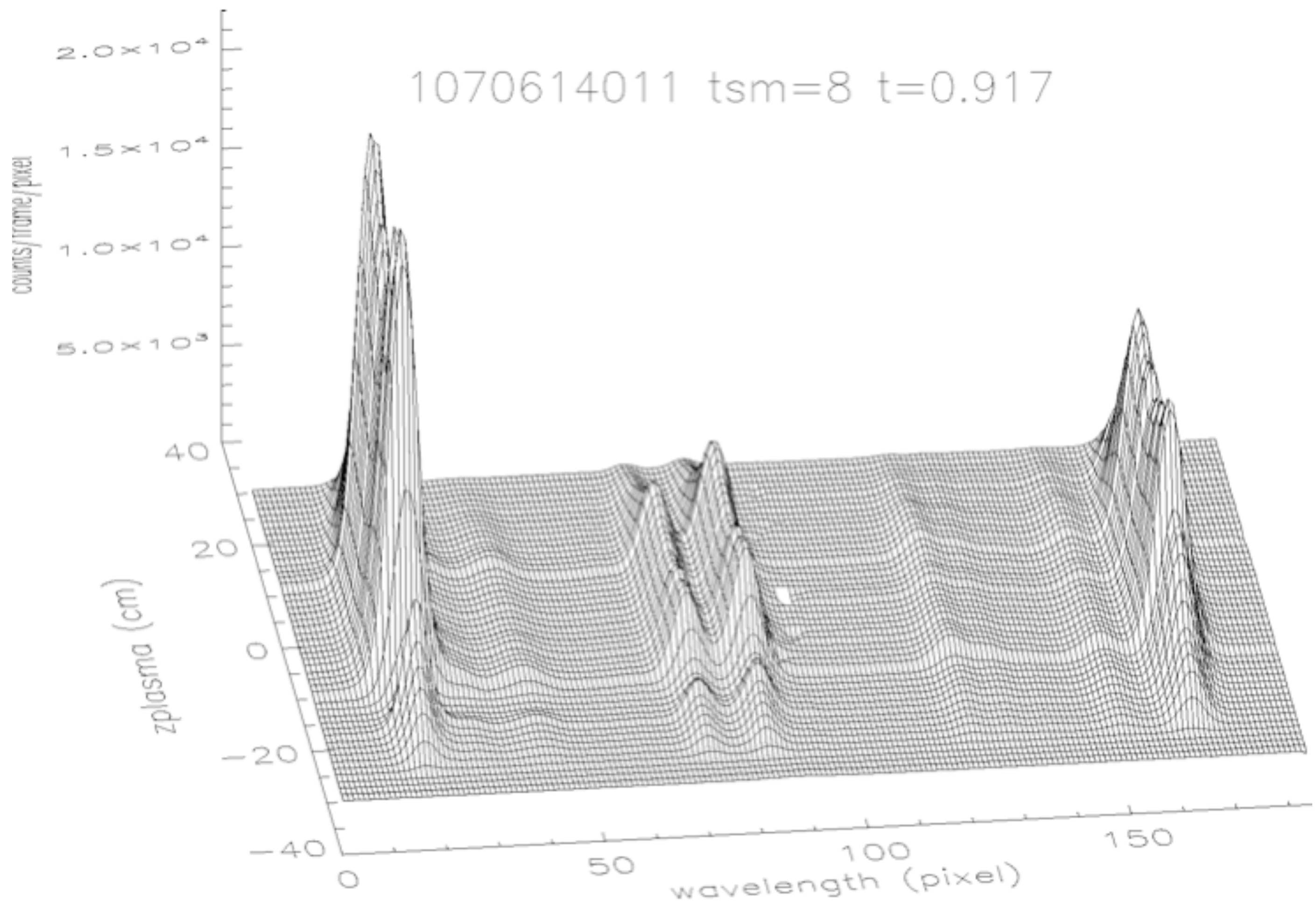
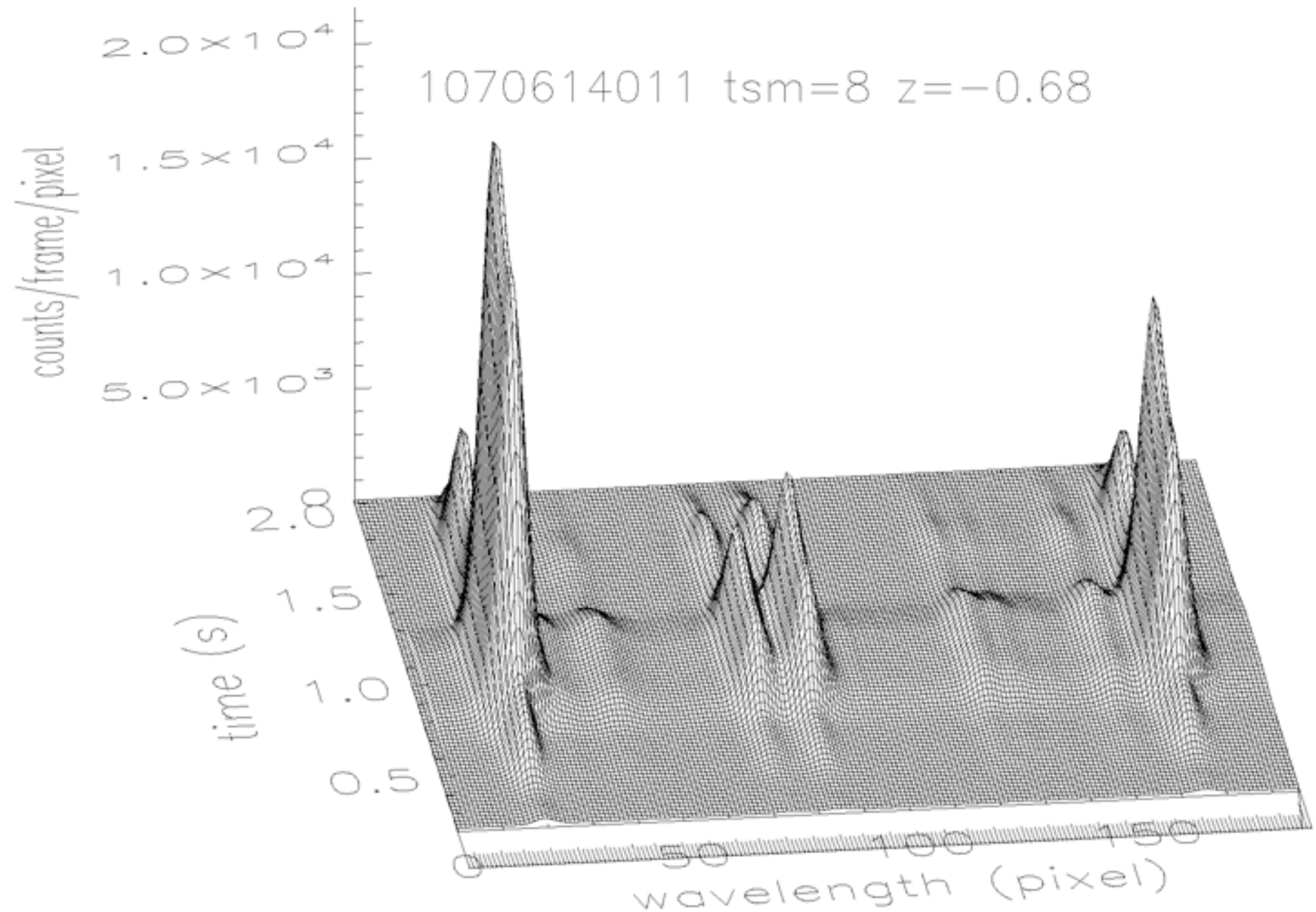
X-ray Imaging Crystal Spectrometer on C-Mod

Raw Data: He-like Argon Spectra



X-ray Imaging Crystal Spectrometer on C-Mod

Raw Data: He-like Argon Spectra



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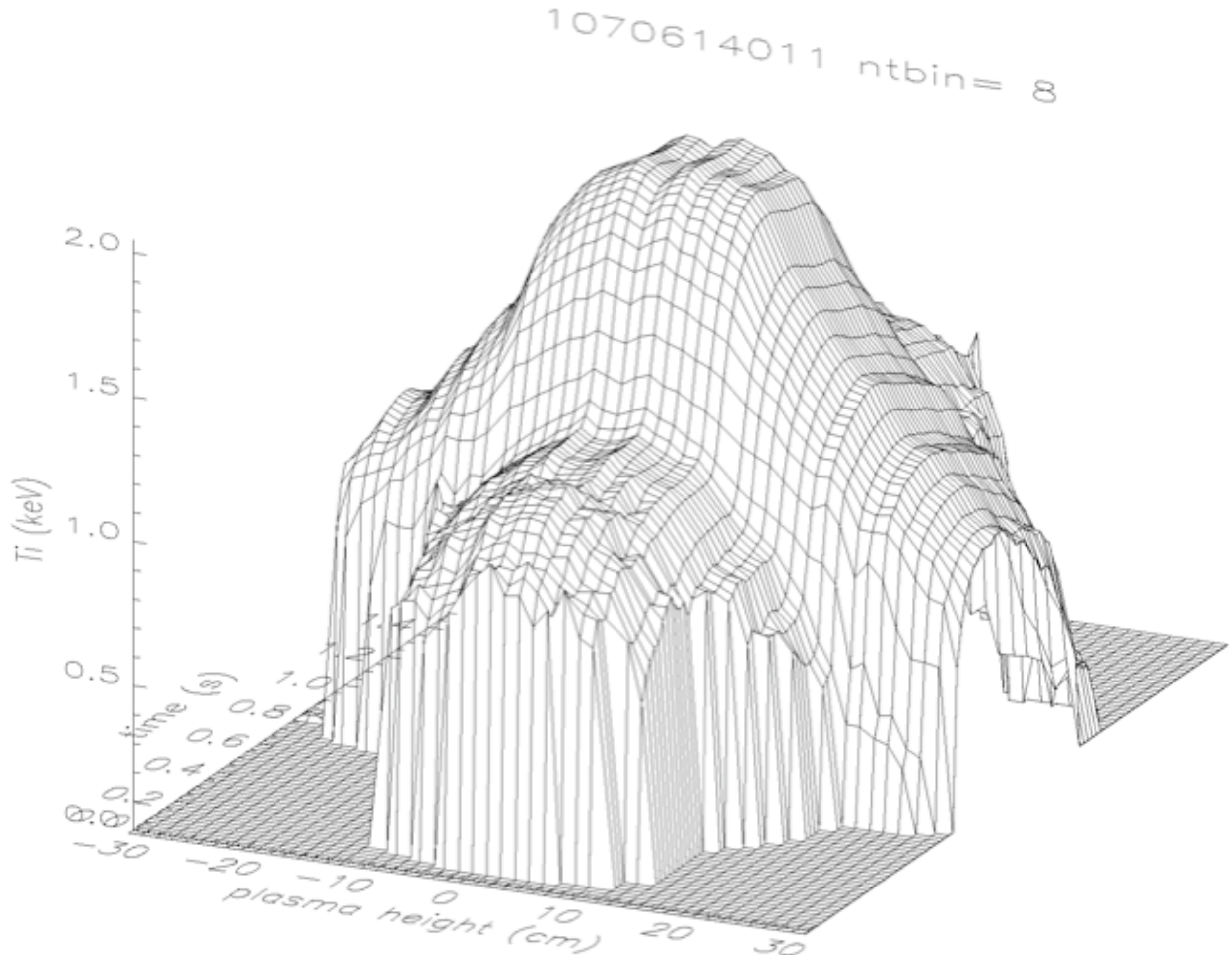
X-ray Imaging Crystal Spectrometer on C-Mod

Ti-profile from He-like Argon Spectra



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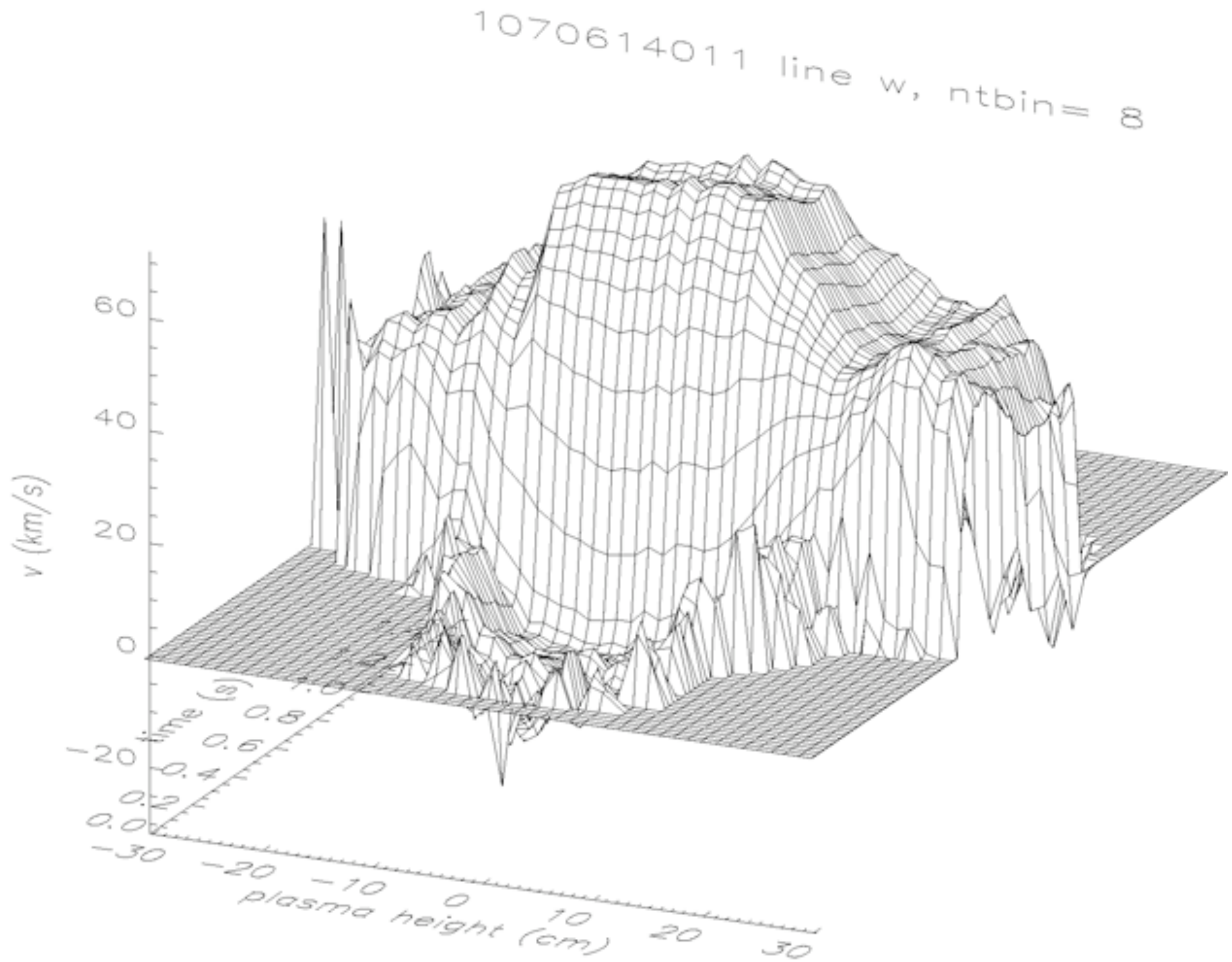
X-ray Imaging Crystal Spectrometer on C-Mod

Vtor-profile from He-like Argon Spectra



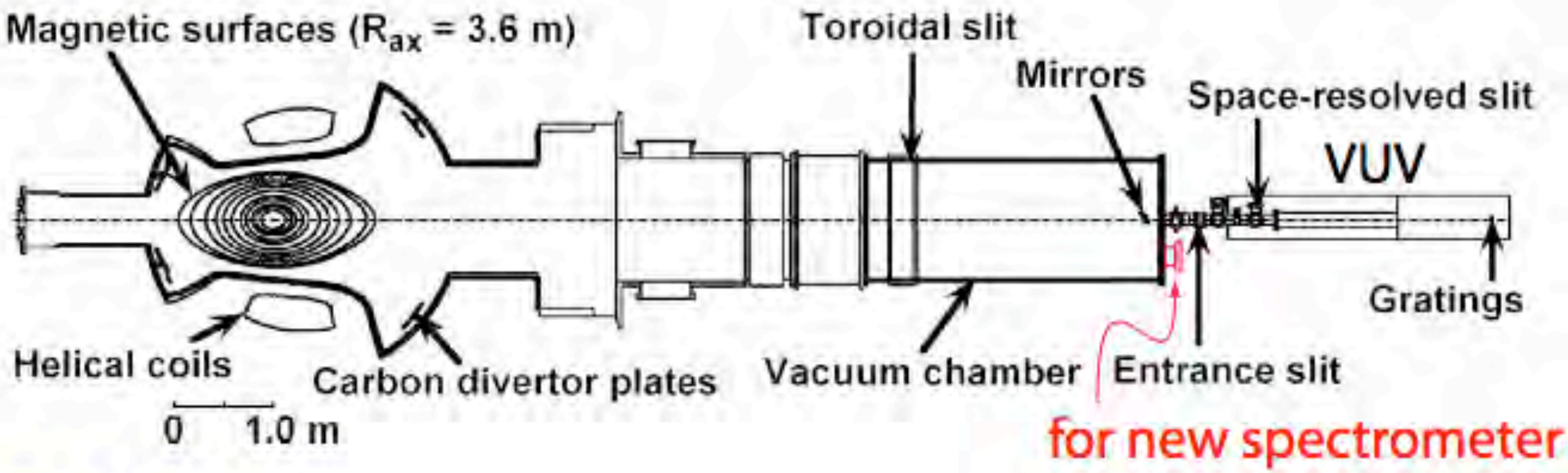
III. Layout of the X-ray Imaging Crystal Spectrometer for LHD

A major challenge for the design of an x-ray imaging crystal spectrometer for LHD is that the length of sagittal focus must be compatible with the scale length of the complicated magnetic field structure.

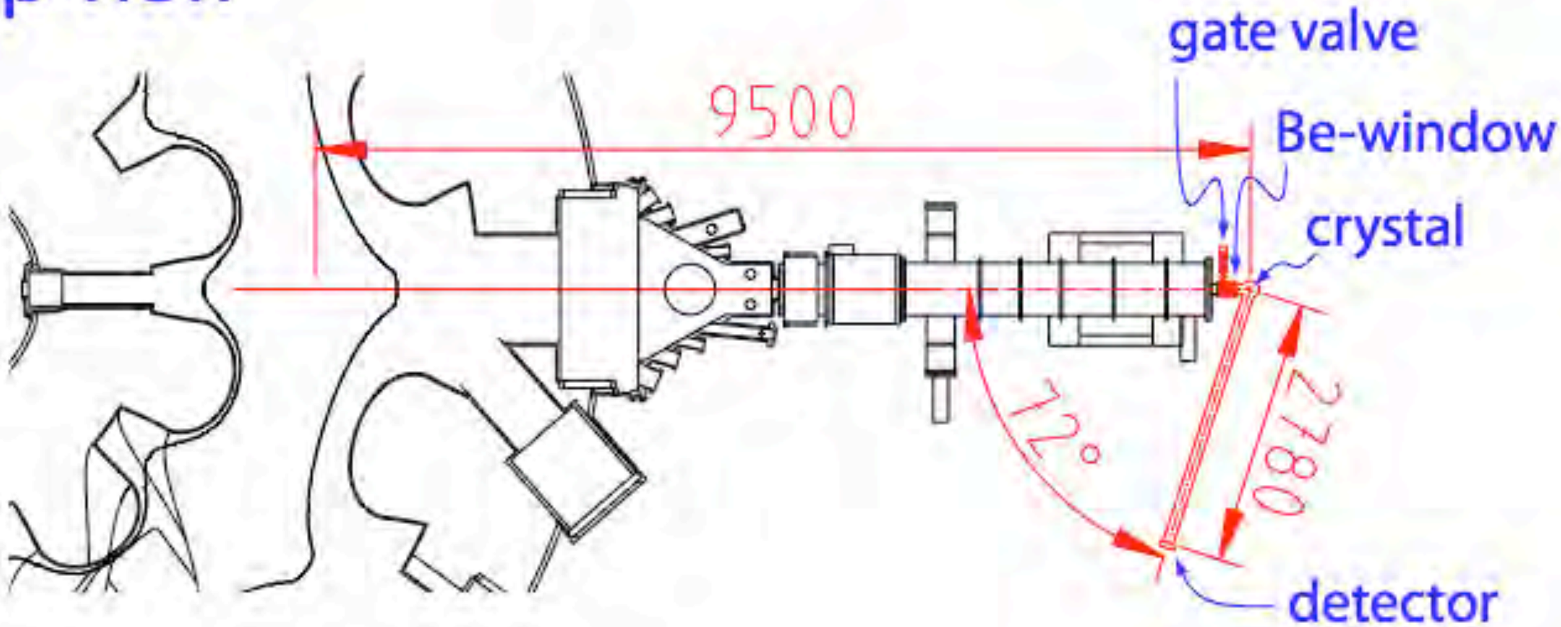
The crystal and Bragg angle, the radius of crystal curvature and crystal dimensions were chosen to meet this requirement:

With the design, described in the following Figures, the sagittal focus is at the center of the plasma and of 6 cm long, so that the spatial resolution in the plasma is 6 cm in the horizontal and 1 cm in the vertical direction.

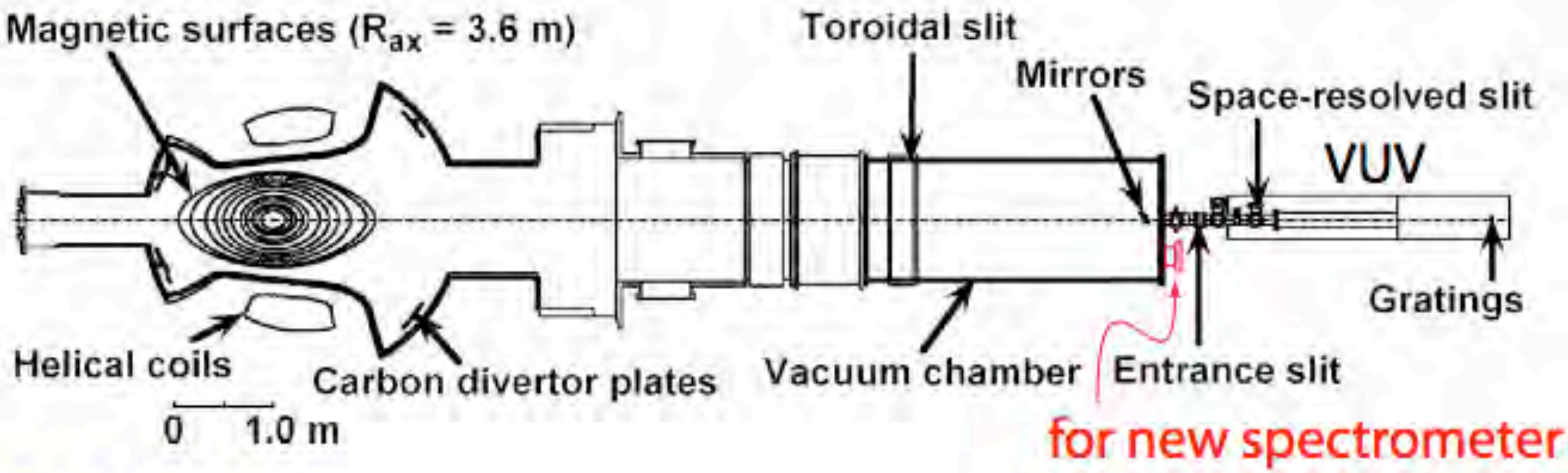
side view



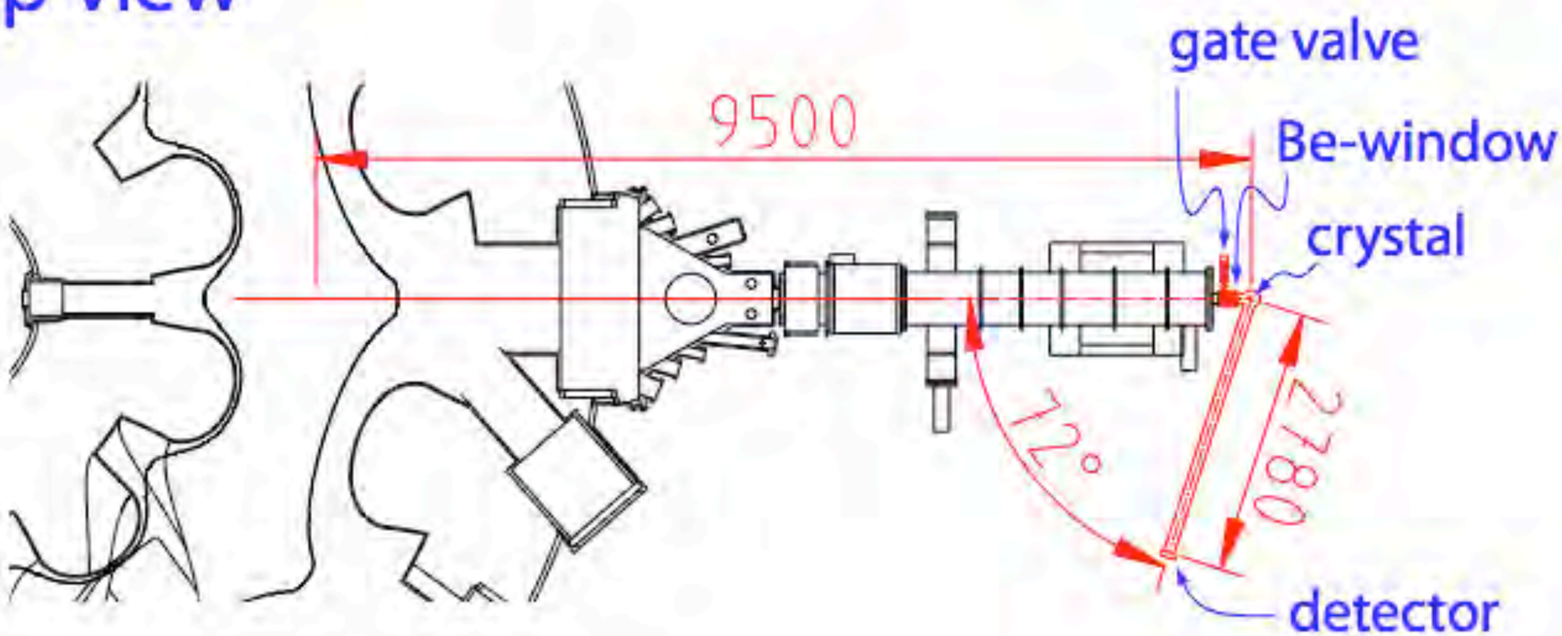
top view



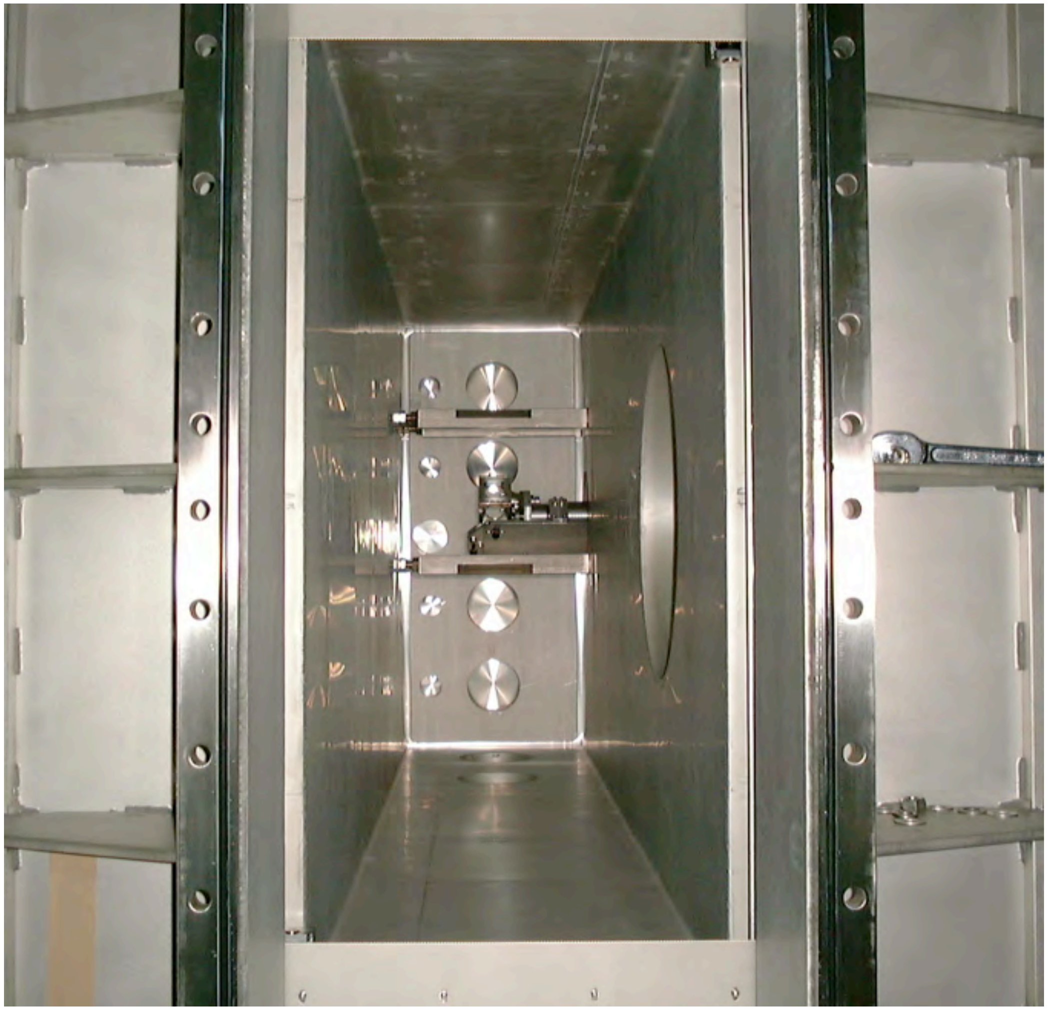
side view



top view

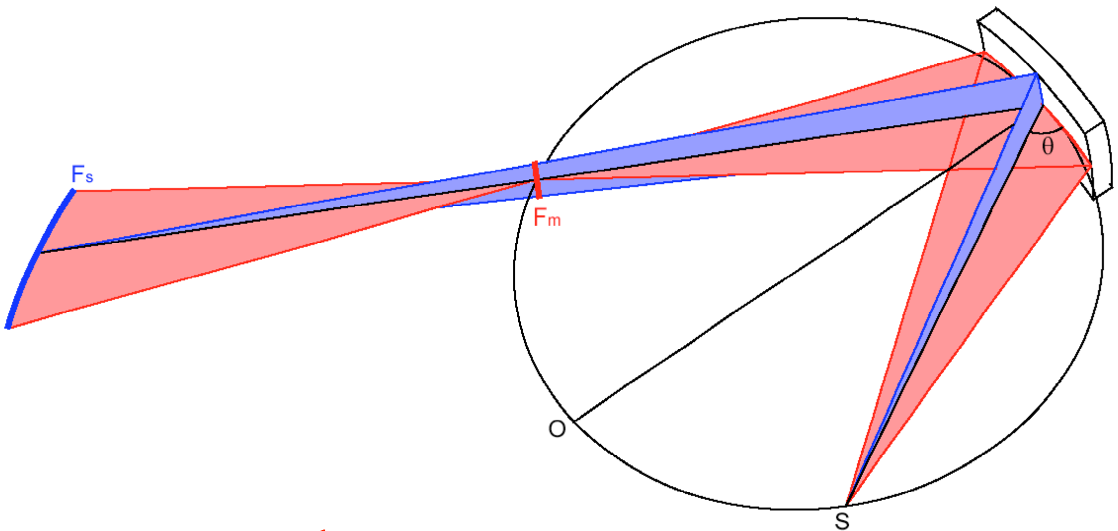


View from LHD through the Vacuum Chamber



The lowest flange from the bottom will be available for the XICS

Parameters for XICS on LHD for He-like Ar



110-Quartz Crystal:

$$R = 3.46m$$
$$w = 3.1cm$$
$$h = 10cm$$

Bragg angle: $\theta = 53.5°$

Magnification: $\frac{f_s}{f_m} = 3.4$

$$f_s = -\frac{R \bullet \sin(\theta)}{\cos(2\theta)} = 9.5m$$

$$f_m = R \bullet \sin(\theta) = 2.78m$$

Spatial Resolution in plasma:

horizontal: $\Delta x = 6cm$

vertical: $\Delta z = 1cm$

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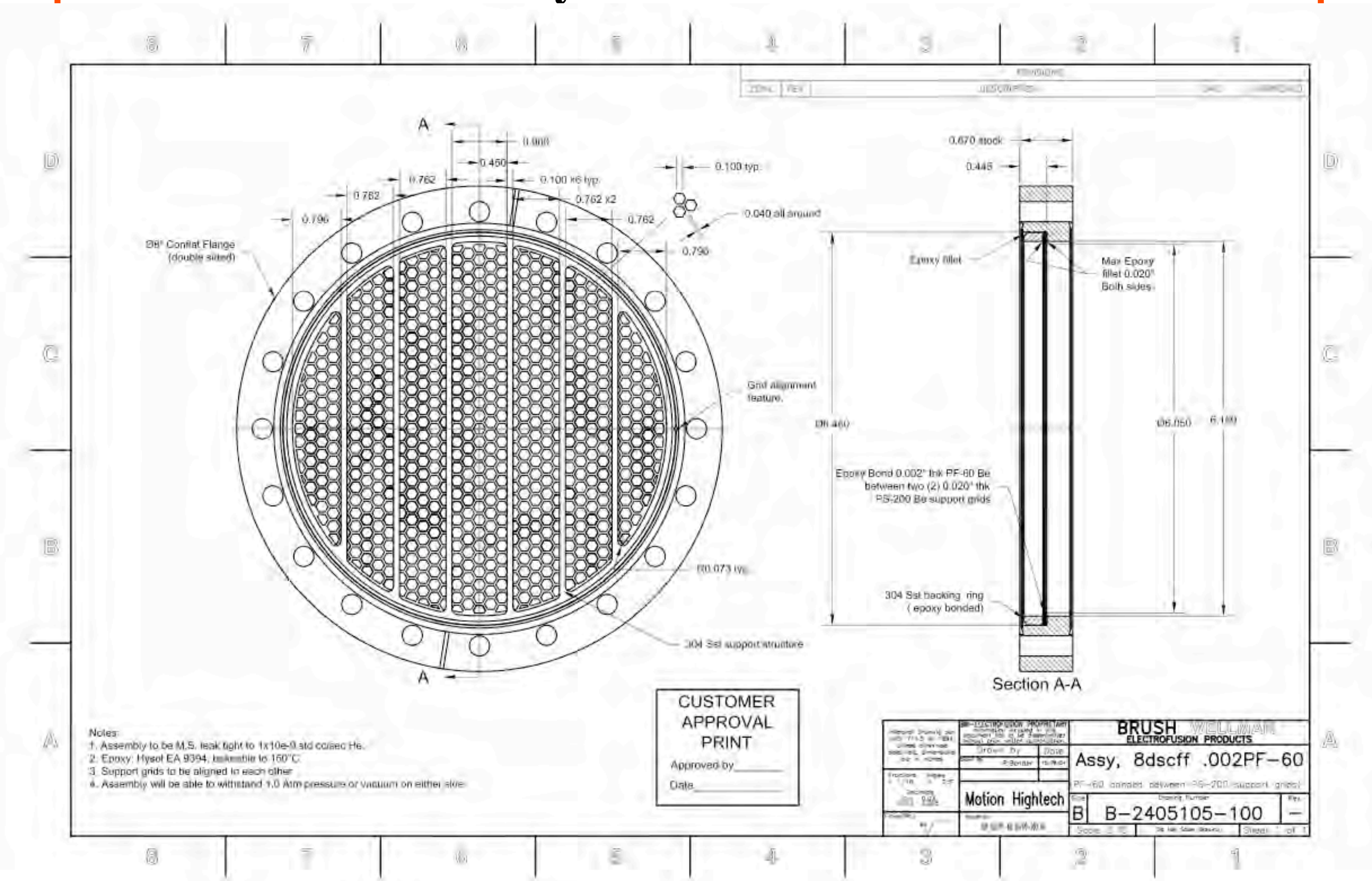
Beryllium Window



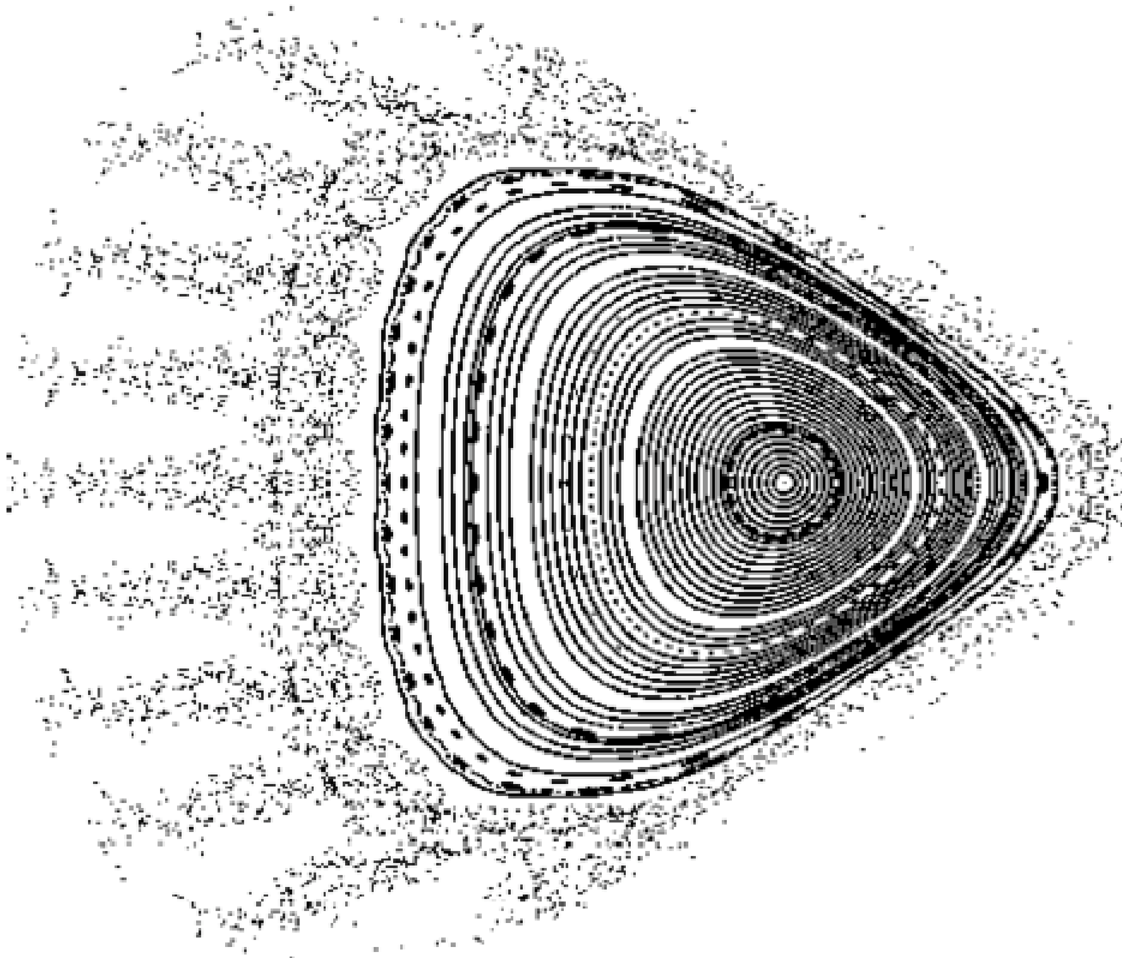
IV. Anticipated Benefits

The proposed x-ray imaging crystal spectrometer will provide profiles of Ti, Te, the argon ion distribution, and possibly the poloidal rotation velocity. These data will be obtained for all experimental conditions, including high-density plasmas.

Equilibrium reconstructions are necessary for accurately interpreting data from the x-ray crystal spectrometer and other profile diagnostics.

PPPL will develop an improved equilibrium reconstruction tool for LHD, coupling the existing STELLOPT and PIES codes, which will also allow the reconstruction of magnetic islands and stochastic regions - see Poincaré plot for a reconstructed W7AS stellarator equilibrium in next Figure.

Poincaré Plot for a W7AS Equilibrium, reconstructed with the PIES code - *A. Reiman, et al.*



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CONCLUSION

An x-ray imaging crystal spectrometer for LHD is being proposed to measure profiles of the ion temperature, electron temperature, impurity charge state distribution, and possibly the poloidal rotation velocity with a spatial resolution of 1 cm and a time resolution of < 10 ms.

The spectrometer can be operational on LHD by October 2010.

The design, construction, and operation of the spectrometer and data analysis, using an improved reconstruction tool, based on the STELLOPT and PIES codes, will be pursued in a NIFS-PPPL collaboration.