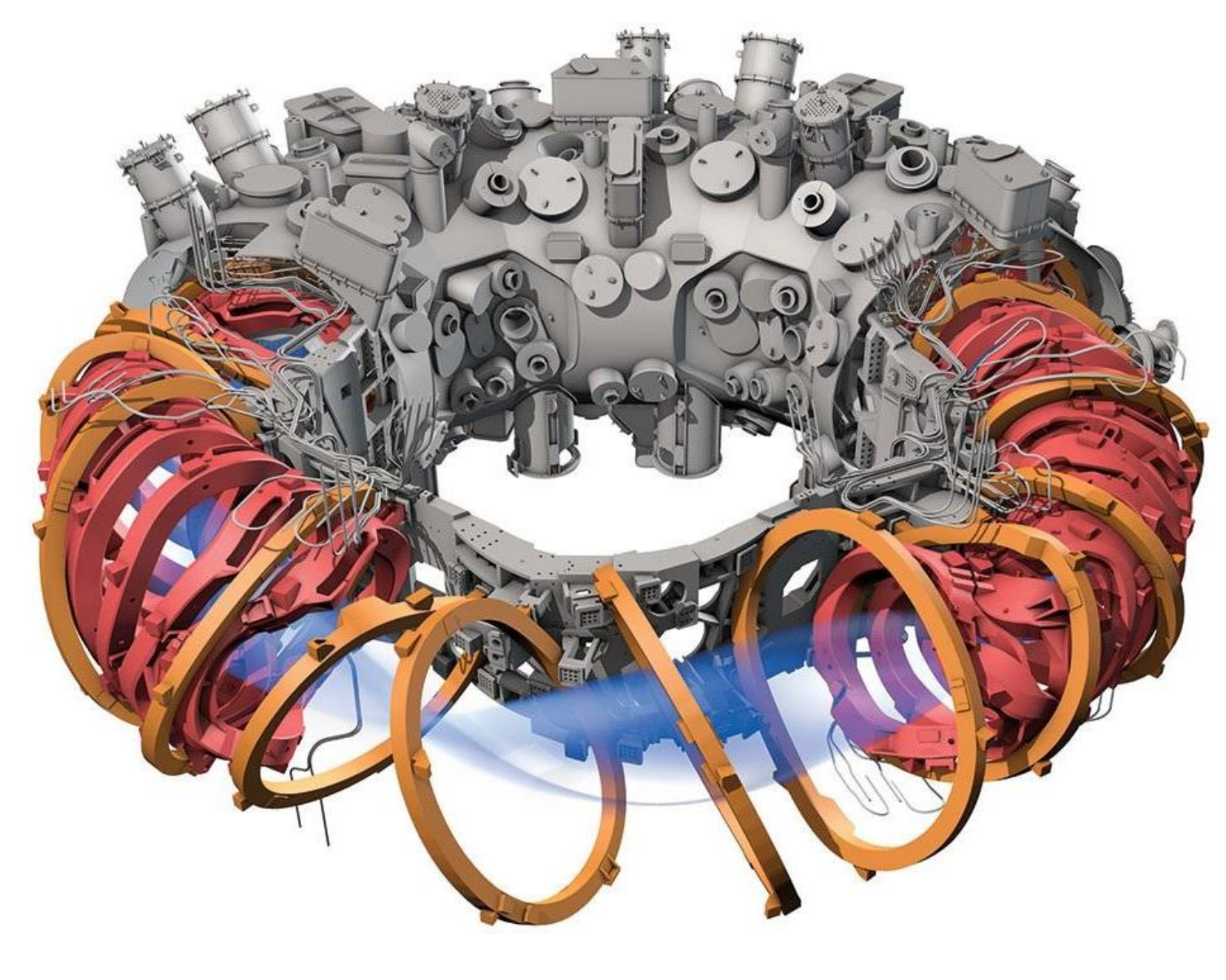
Wendelstein 7-X



W7-X is the largest and most advanced stellarator ever built

First large scale optimized stellarator [1,2]

Technical System Parameters	
Major plasma radius	5.5 meters
Minor plasma radius	0.53 meters
Plasma Volume	30 cubic meters
Magnetic field	3 Tesla
Plasma Temperature	60 – 130 million degrees

The plasma shape and the coil set have been optimized for the following:

- Neoclassical confinement
- Drift (isodynamic) at high beta
- Plasma stability up to ~5%
- Minimization of bootstrap current and Shafranov shift

Physics research goals:

- Verify stellarator optimizations.
- Demonstrate plasma density control.
- Explore impurity confinement.

Engineering research goals:

- Demonstrate high power, high performance steady state operation.
- Verify operation of island divertor design for steady state density control and high heat flux handling

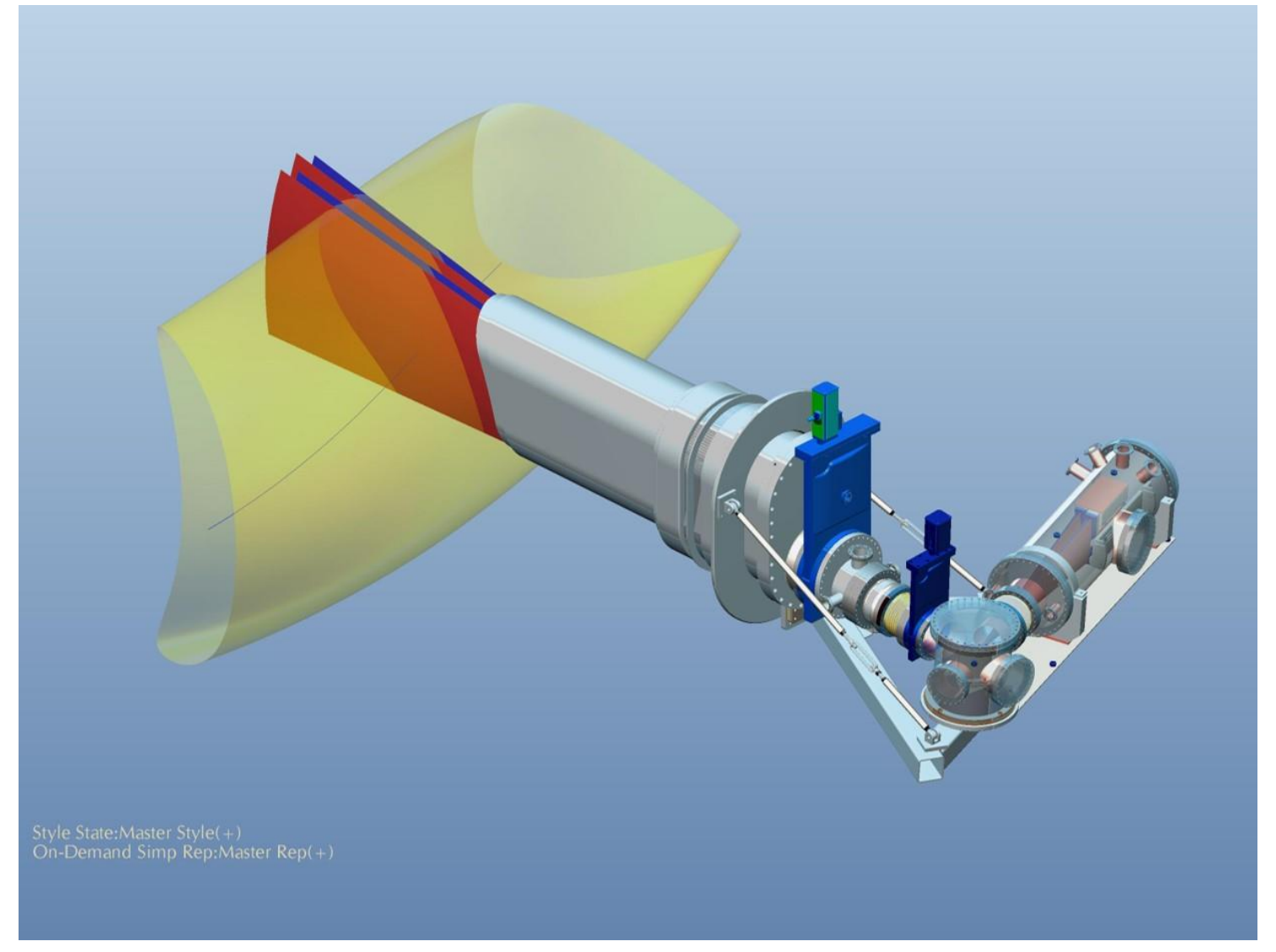
X-ray Imaging Crystal Spectrometer

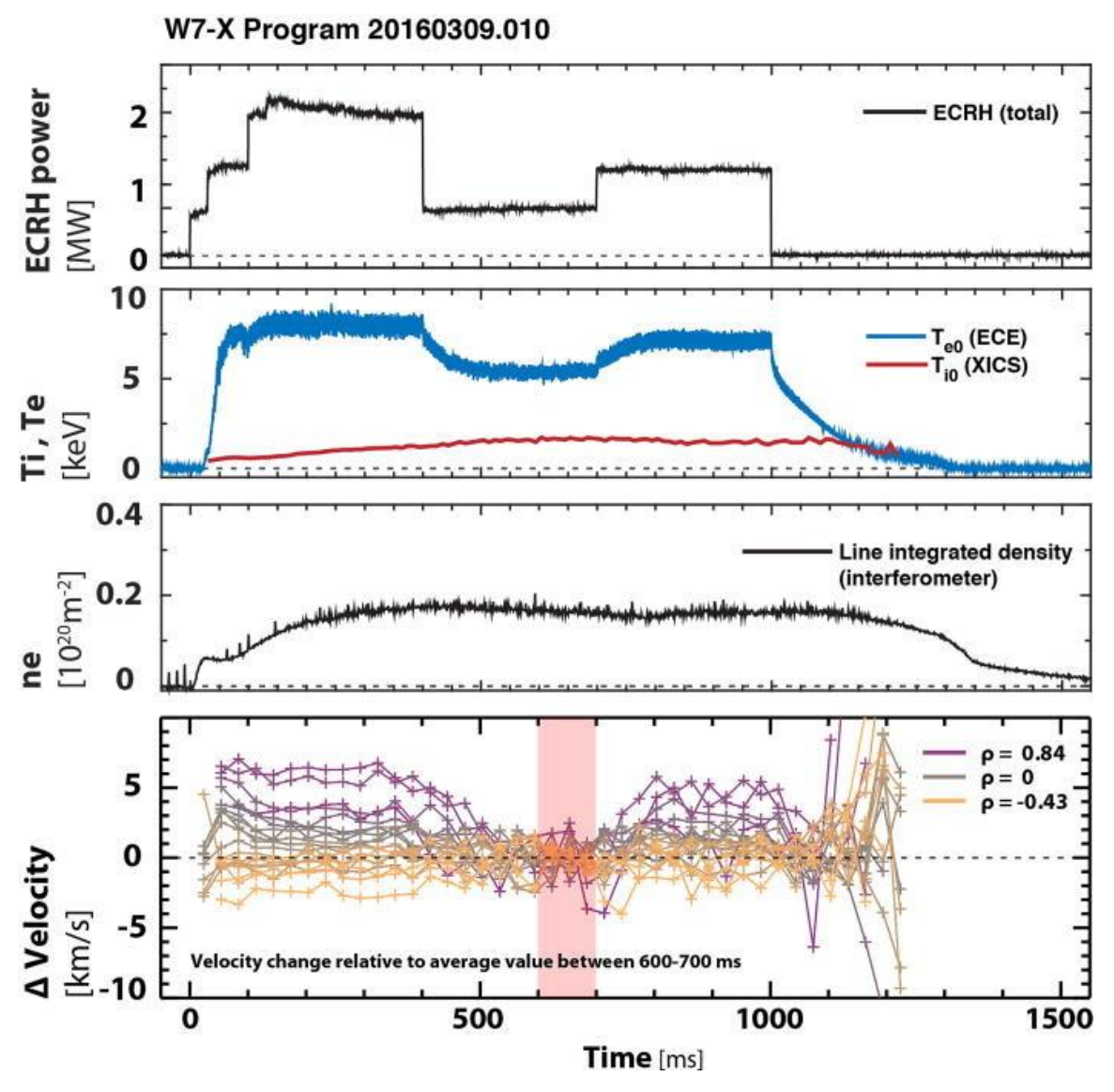
XICS can measure time resolved profiles of:

- Ion Temperature (T_i)
- Electron Temperature (T_e)
- Perpendicular Flow Velocity ($u_\perp$)
- Argon Impurity Density (n_{Ar})

XICS relies on x-ray emission from highly charged impurity species in the plasma

XICS profiles are available for nearly all plasma conditions of W7-X [3]





System Parameters	
Crystal to magnetic axis	3582mm
Ar^{16+} System	
Bragg Angle (Ar^{16+})	53.49°
Radius of curvature	1450mm
Crystal to detector	1165mm
Sagittal focus (Ar^{16+})	3991mm
Ar^{17+} and Fe^{24+} System	
Bragg Angle (Ar^{17+})	54.86°
Bragg Angle (Fe^{24+})	54.19°
Radius of curvature	1450mm
Crystal to detector	1185mm
Sagittal focus (Ar^{17+})	3514mm
Sagittal focus (Fe^{24+})	3730mm

Wavelength Calibration System

XICS can be used to infer the radial electric field (E_r) from the perpendicular plasma flow ($u_\perp$) [4]

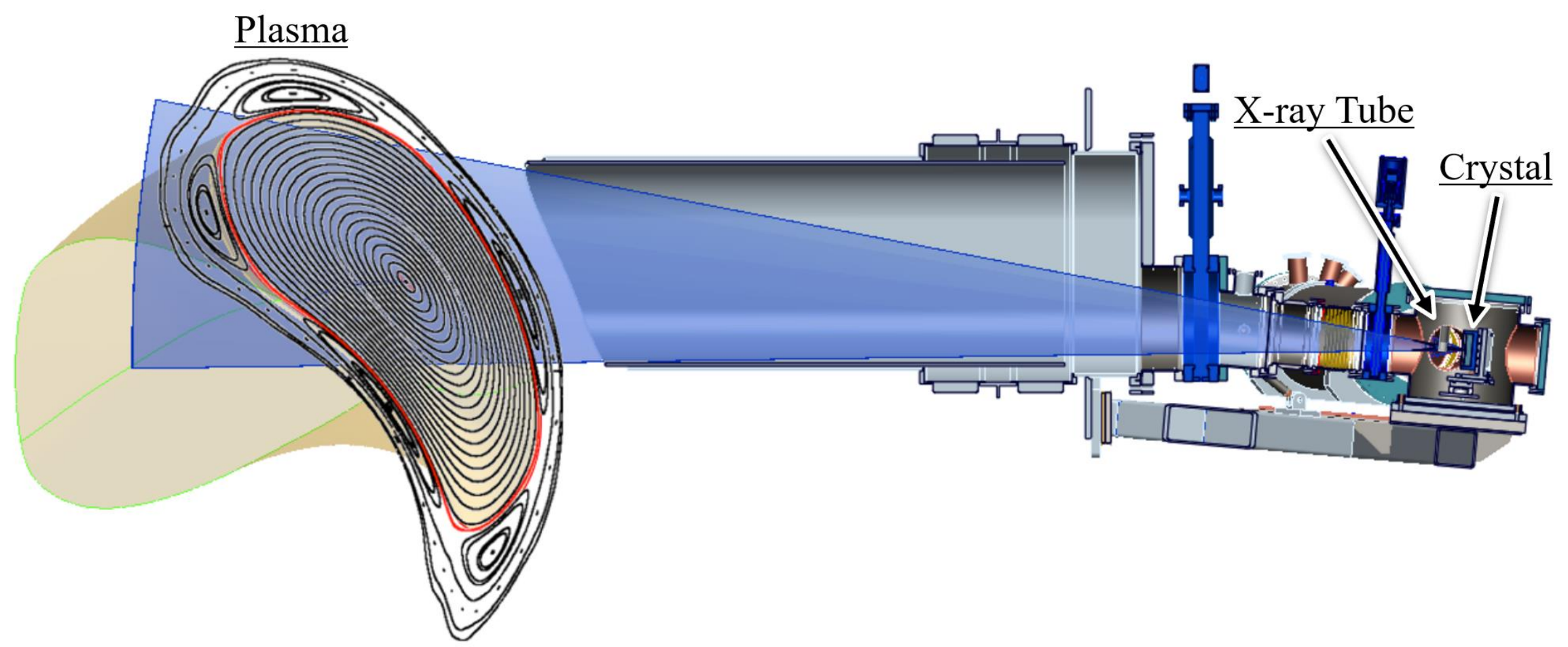
- E_r is important for many aspects of stellarator physics
- E_r is used to study the neoclassical optimization of W7-X

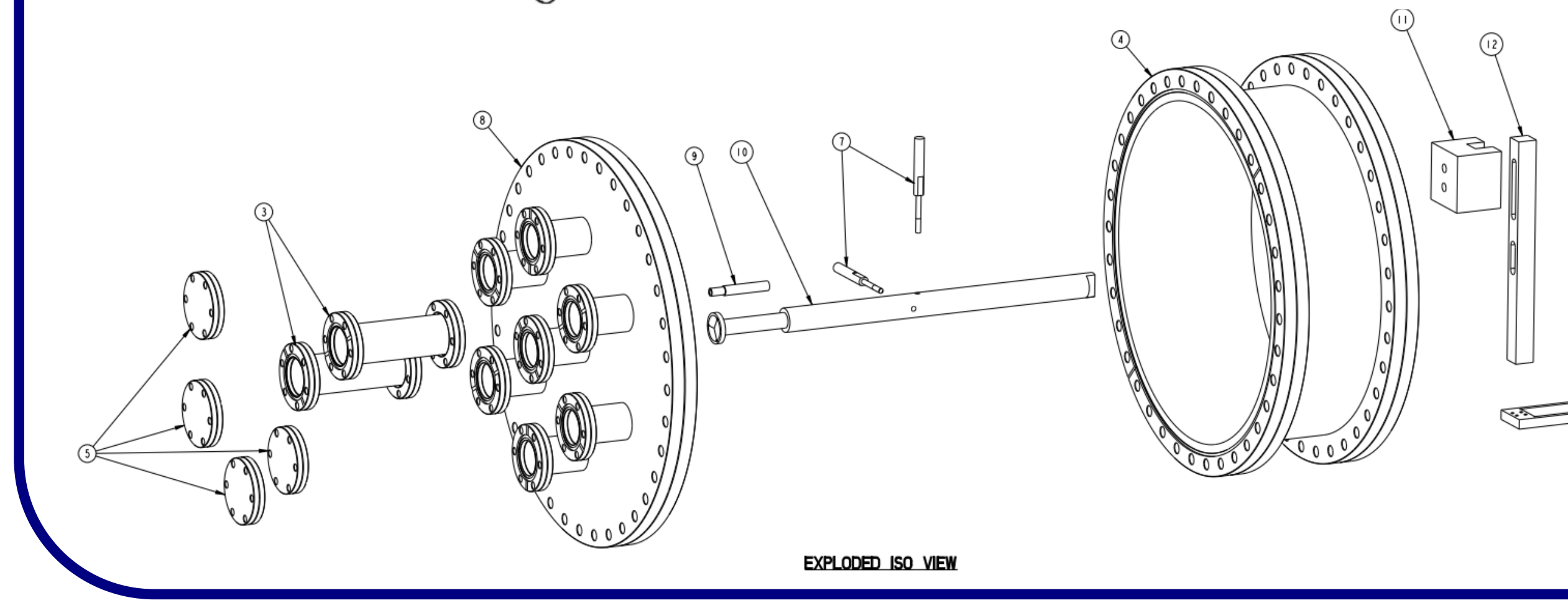
XICS lacks an independent wavelength calibration for perpendicular plasma flow measurements

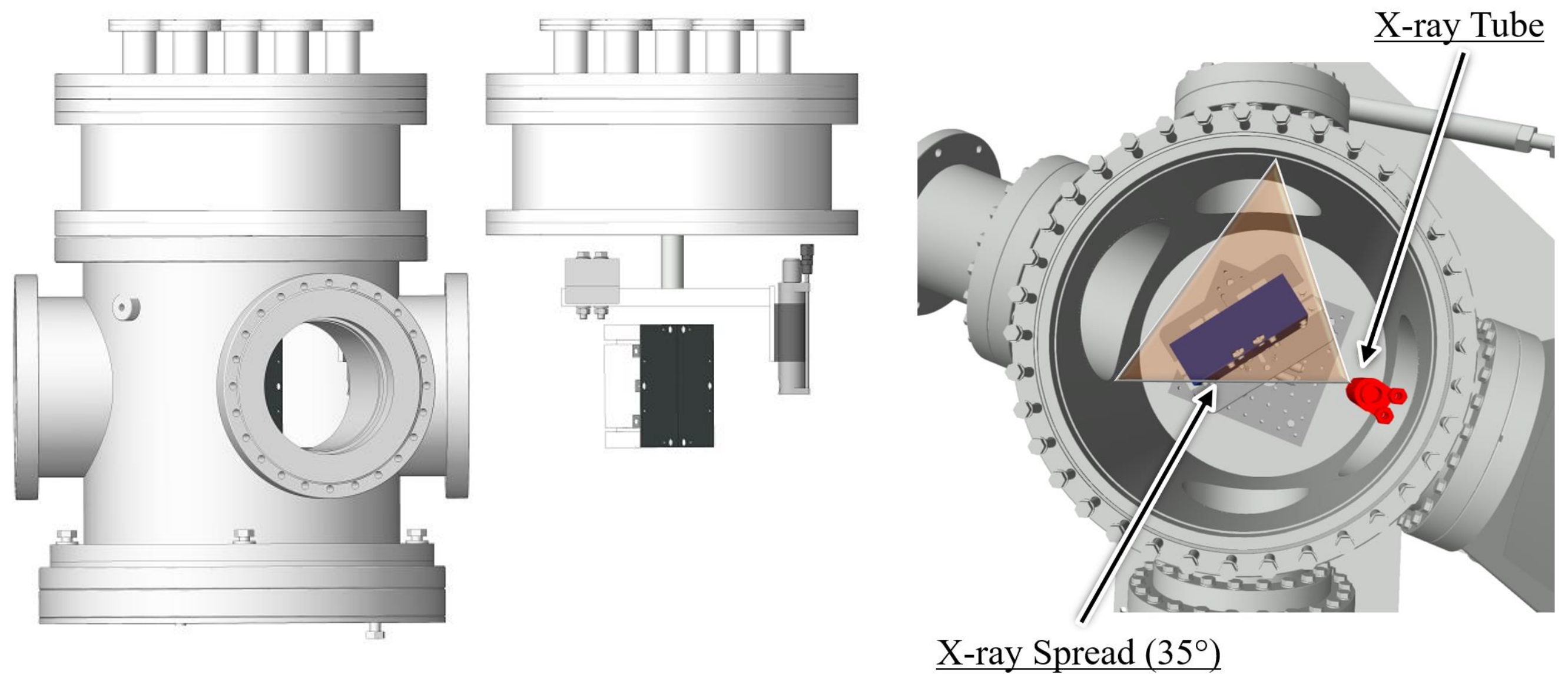
- Stellarators lack locked mode plasmas (calibration method used on tokamaks)
- Current calibration scheme assigns the perpendicular plasma flow to be zero at the magnetic axis
- No accounting for the potential thermal expansion of the crystal which has been shown to produce spectral shifts on the order of plasma flow [5]

An in-situ wavelength calibration system has been designed

- Calibration lines will be over all spatial channels
- Calibration can routinely be done during and between discharges



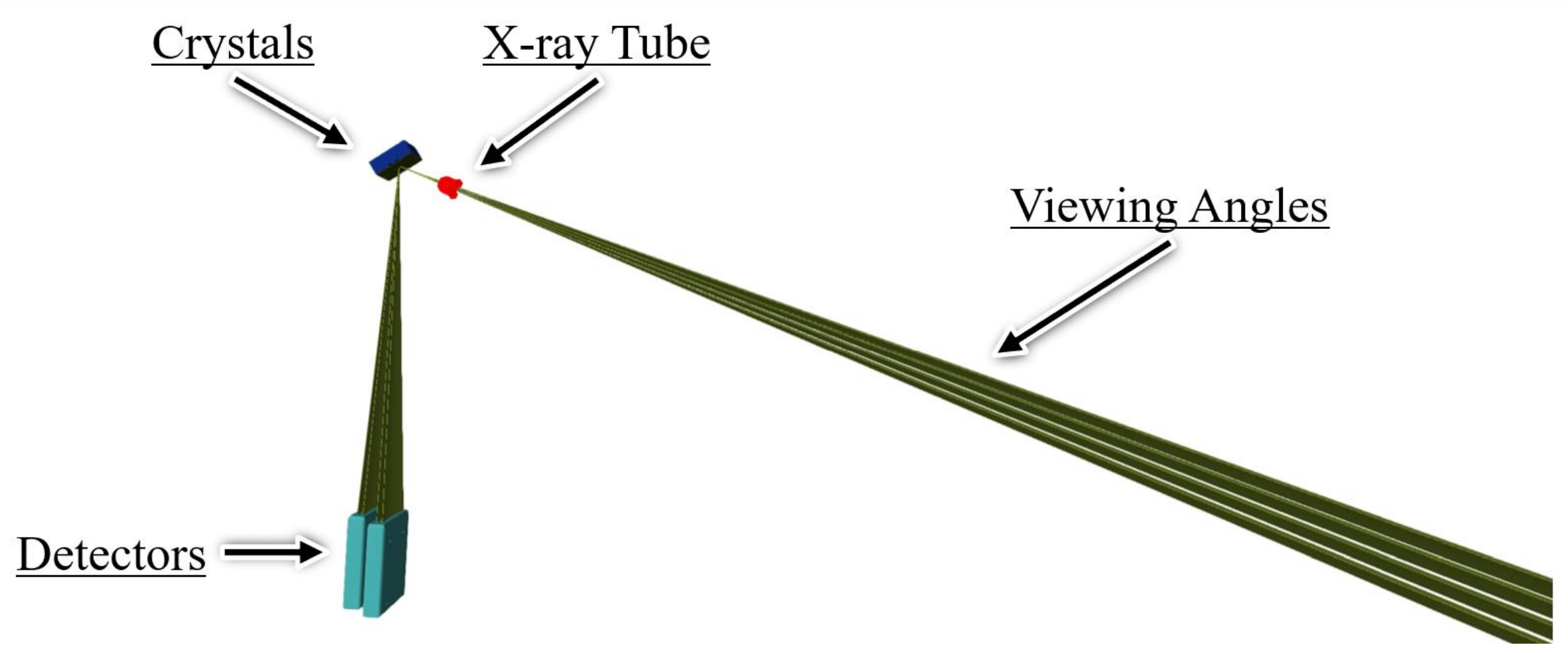




The calibration x-ray source will be an x-ray tube with a Cadmium anode

- The Cd $L\alpha$ and $L\beta$ lines will calibrate the Ar^{16+} and Ar^{17+}/Fe^{24+} channels respectively
- The x-ray tube will be mounted on an arm attached to a fine control rotary feedthrough that can be easily rotated into the desired position

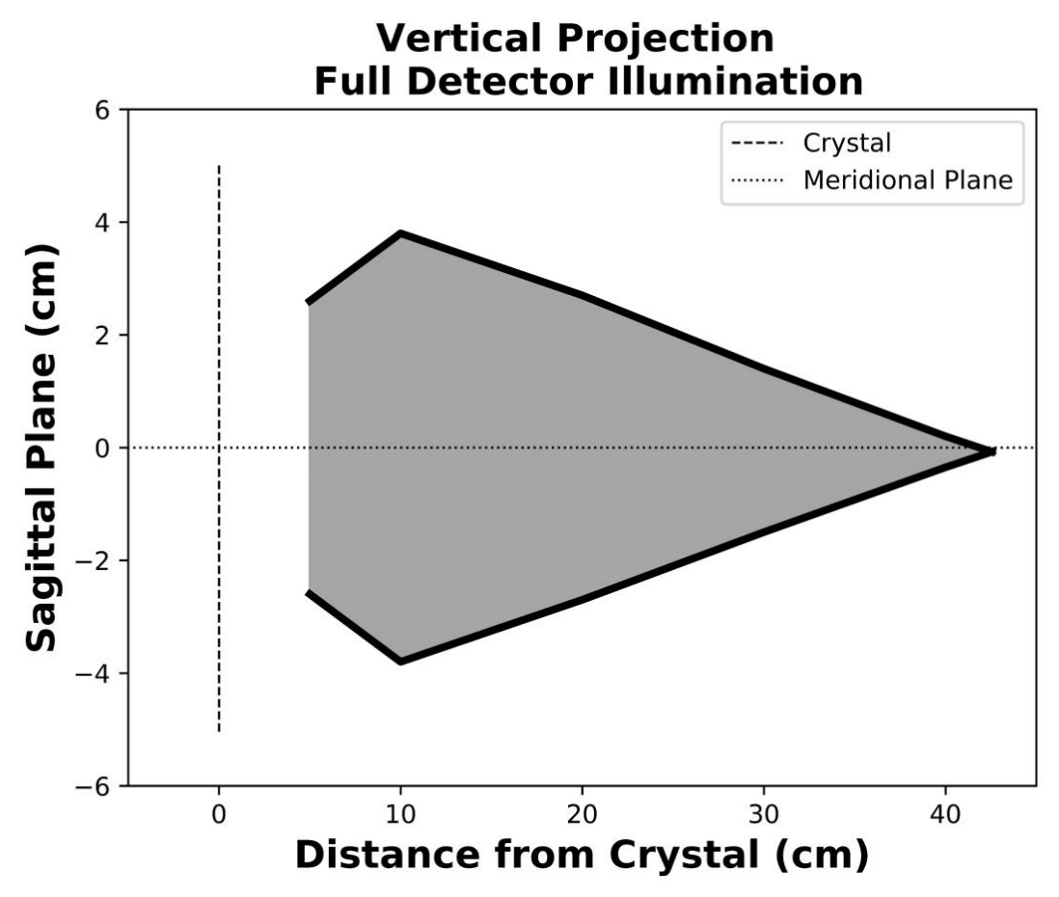
The calibration system will replace the top flange on the vacuum chamber currently holding the spherical crystals

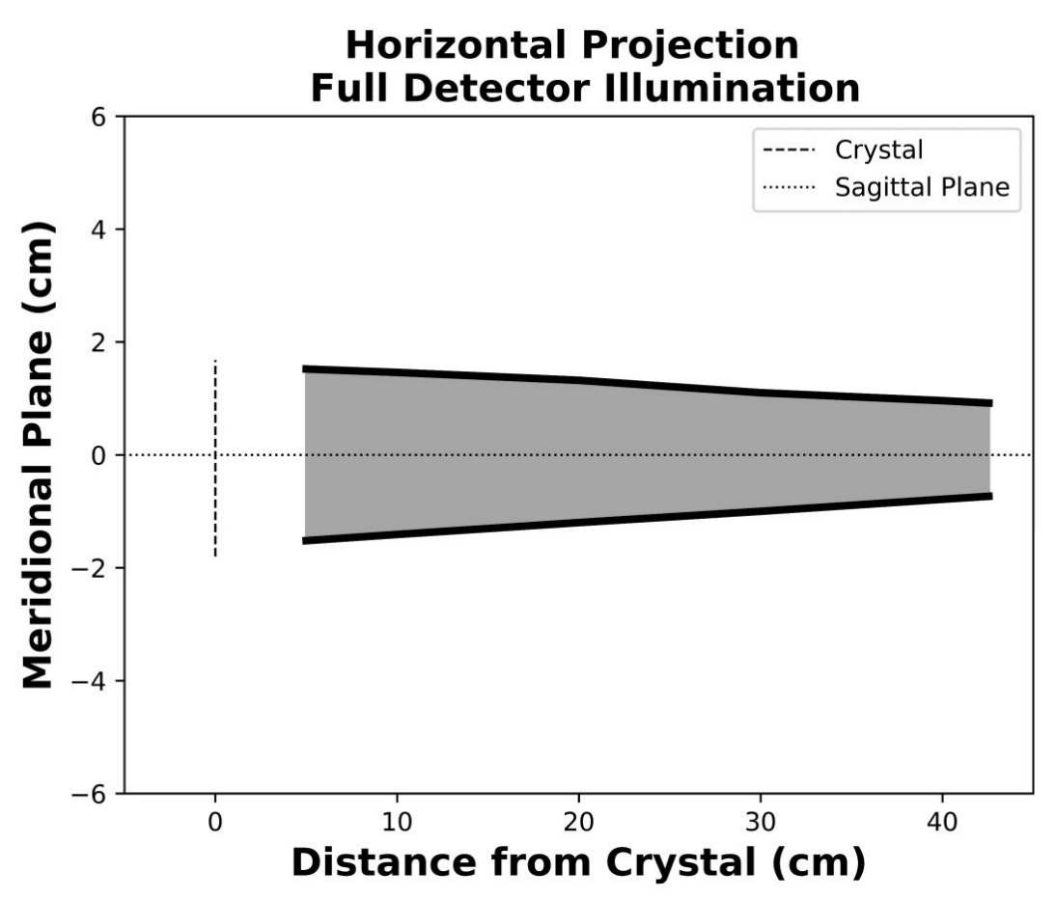


Simulation & Modeling

XICS-Ray Tracing (XICS-RT)

- Objected-oriented, ray tracing code written in Python
- Simulates the x-ray source, the spherical crystal, and the detector
- Used to analyze and test the proposed design





Configuration Space Envelopes

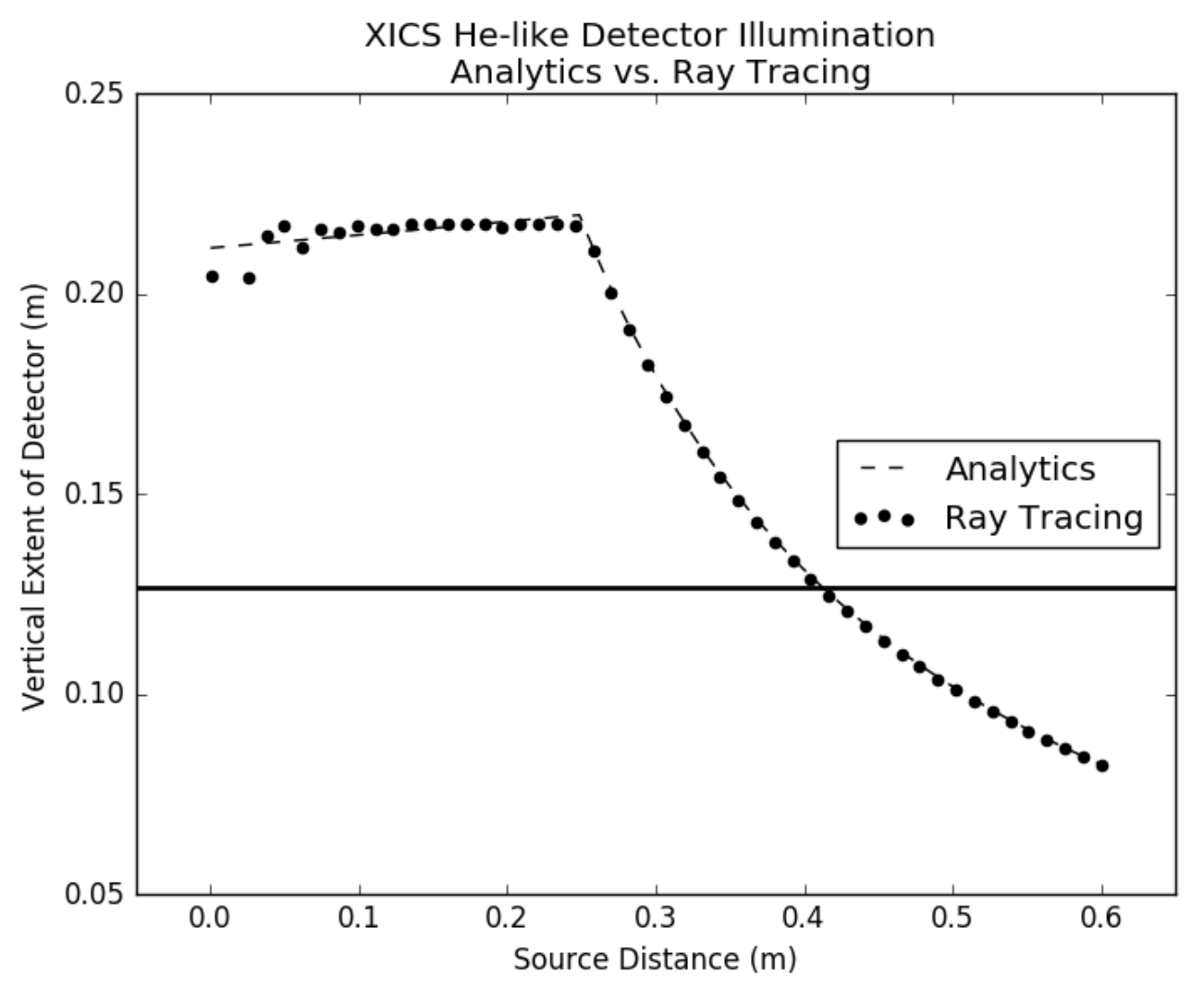
- Actual XICS geometry and physical characteristics of the X-ray Tube
- If the source is placed anywhere in the envelope and directed at the crystal, full spatial channel illumination will be achieved
- For this design, the x-ray tube will be placed 10 cm from the crystal

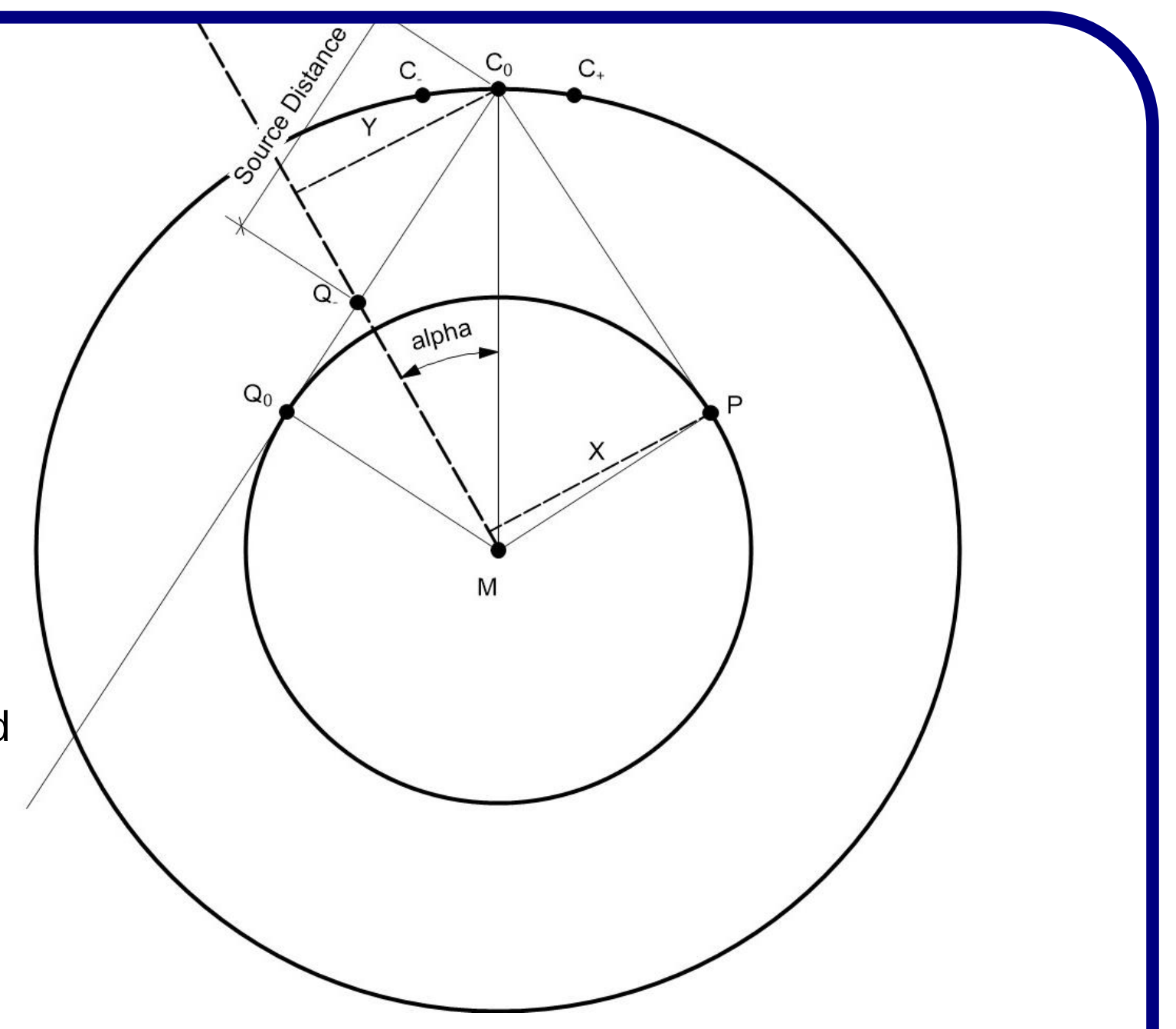
Analytical Formulation of XICS geometry (diagram to right)

- Spherically bent crystal, with radius of curvature of R, extends from C_- to C_+ having a Bragg angle Θ_B from Bragg's law
- Source must lie on the line going through points C_0 and Q_0. P is the location of the planar detector

Image Formation

- With the source at Q_-, the rotation of the ray pattern around the axis $\overline{Q\_M}$ forms a virtual image at P





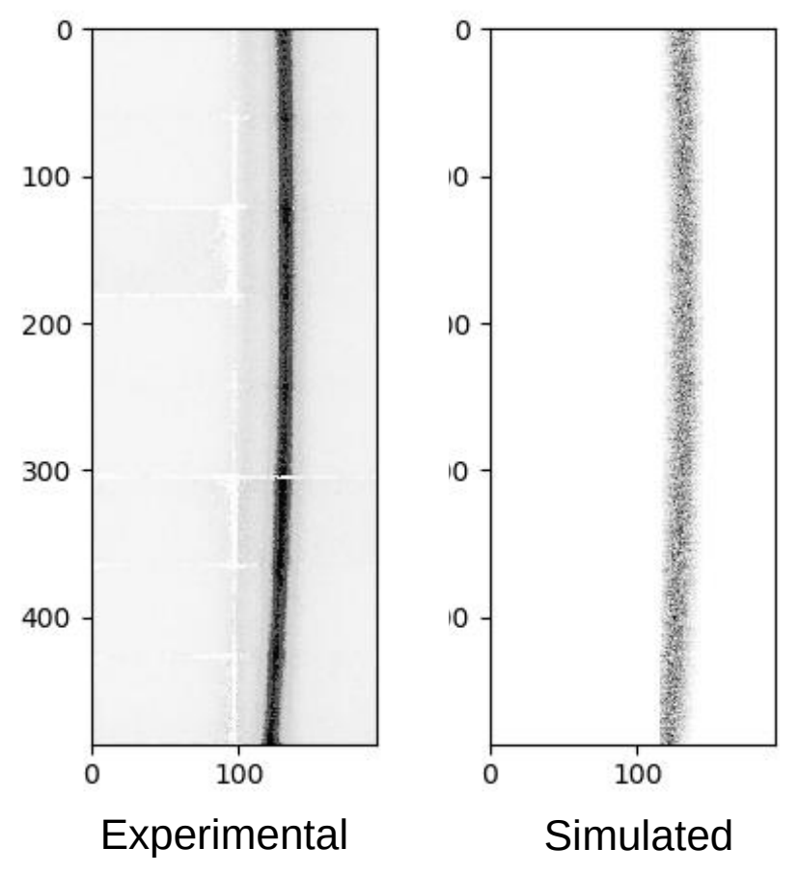
Comparison of XICS-RT to Analytical Formulation

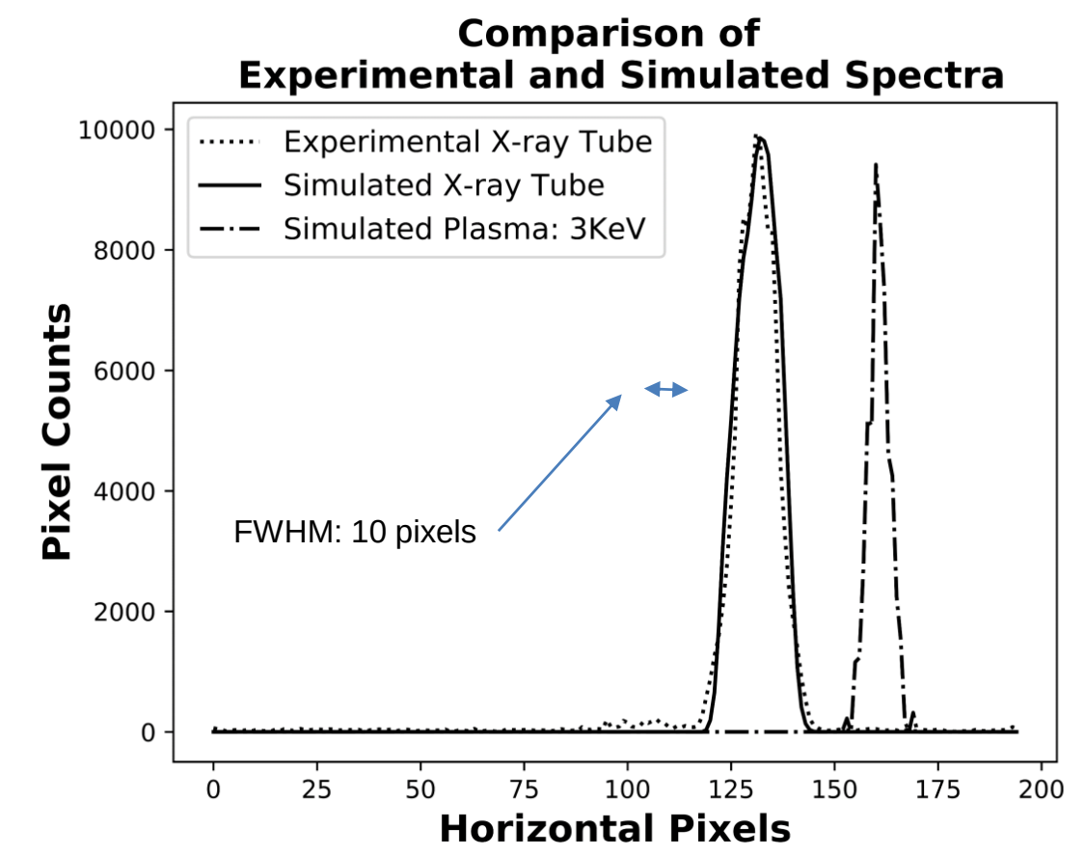
- The vertical extent is the height on the detector plane that is illuminated by an x-ray source at a particular source distance
- Horizontal line is the physical height of the detector
- The plateau region is from the finite width of the detector plane
- The decaying region is from the fixed spread of the x-ray source

Experimental Testing

Direct Illumination

- Testing was done at Alcator C-Mod using HIREX-SR (almost identical system to XICS)
- X-ray tube (same model as in the calibration design) with a Cd anode at 9.5 kV, 0.5 mA was positioned 4 cm from the crystal with an exposure length of 500s
- XICS-RT was used to generate a simulated image with a x-ray source of comparable features
- A graph showing the vertically centered rows from each of the two images is shown along with the principle Ar^{16+} line from a plasma simulated using XICS-RT





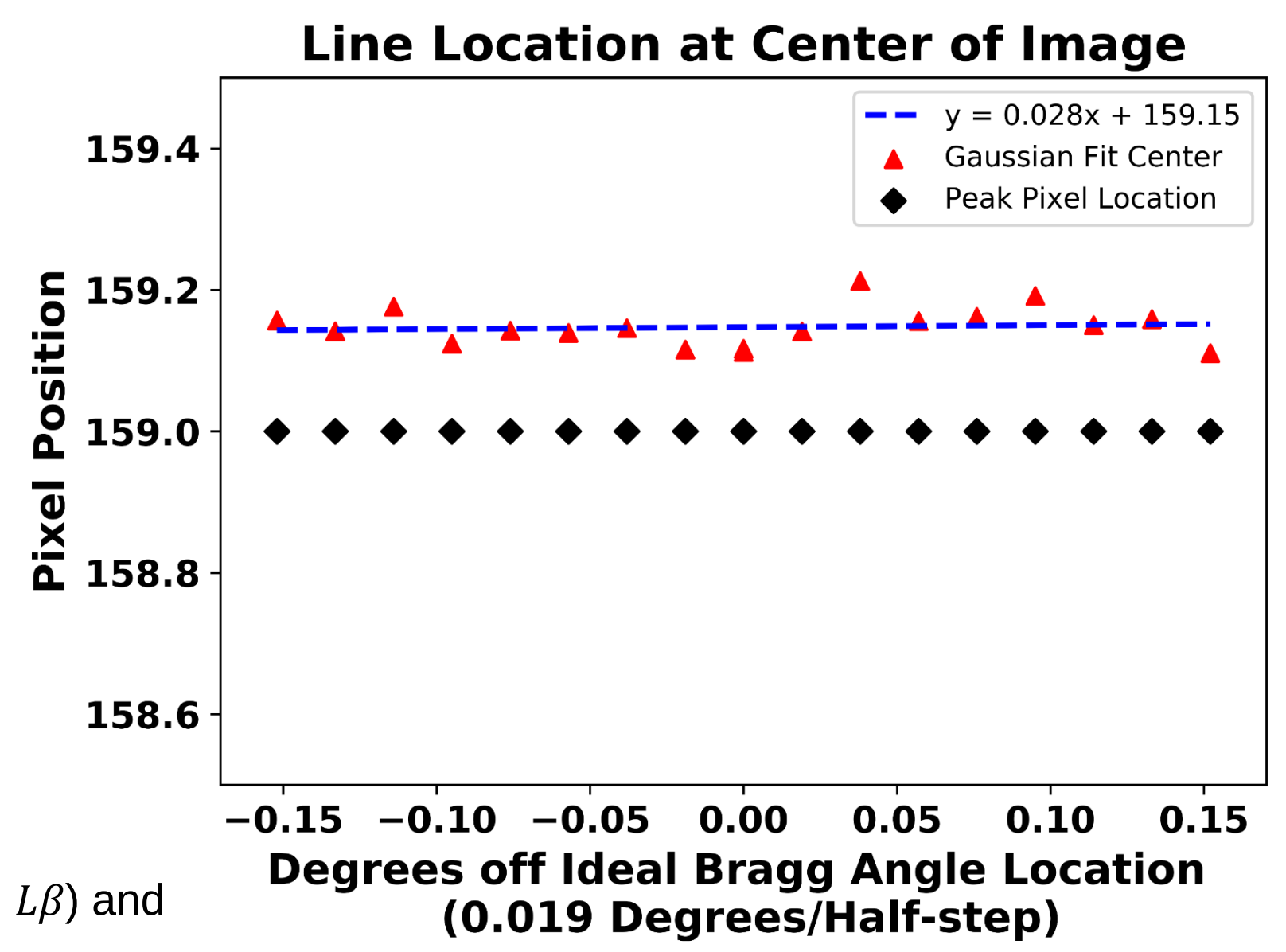
Indirect Illumination

- Additional testing was done using HIREX-SR for other calibration methods that would allow the position of the x-ray source to be to the side of the crystal while taking calibration data
- A 2 mm thick Cadmium sheet was positioned in front of the crystal
- X-ray tube with a Cd anode was positioned off to the side of the crystal and aimed at the Cadmium sheet in an attempt to excite x-ray fluorescence
- With the x-ray tube at 15 kV and 4 mA, no Cadmium lines were observed even after hours of integration time

Wavelength Calibration Accuracy

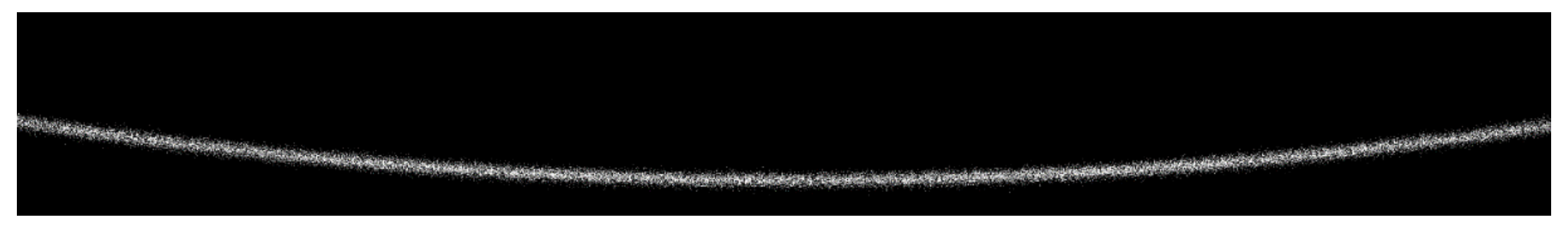
Random Errors

- Repeatedly positioning the x-ray tube at the optimal Bragg angle location (2×10^{-7} Å)
- Thermal expansion of crystal or support structure limits the maximum integration time (can be potentially mitigated through characterization of thermal effects)
- Spectral line fitting capabilities limited by photon statistics (1.5×10^{-7} Å)



Systematic errors

- Known wavelength precision of Cadmium lines ($L\alpha$ and $L\beta$) and Argon lines (Ar^{16+} and Ar^{17+}) (5×10^{-5} Å)
- Spectral line shift due to x-ray tube positioning (1×10^{-5} Å)
- Change in shape of spectral lines due to the difference in illumination geometry and shape of the spectral line emission from the plasma and x-ray tube (will be characterized using XICS-RT)



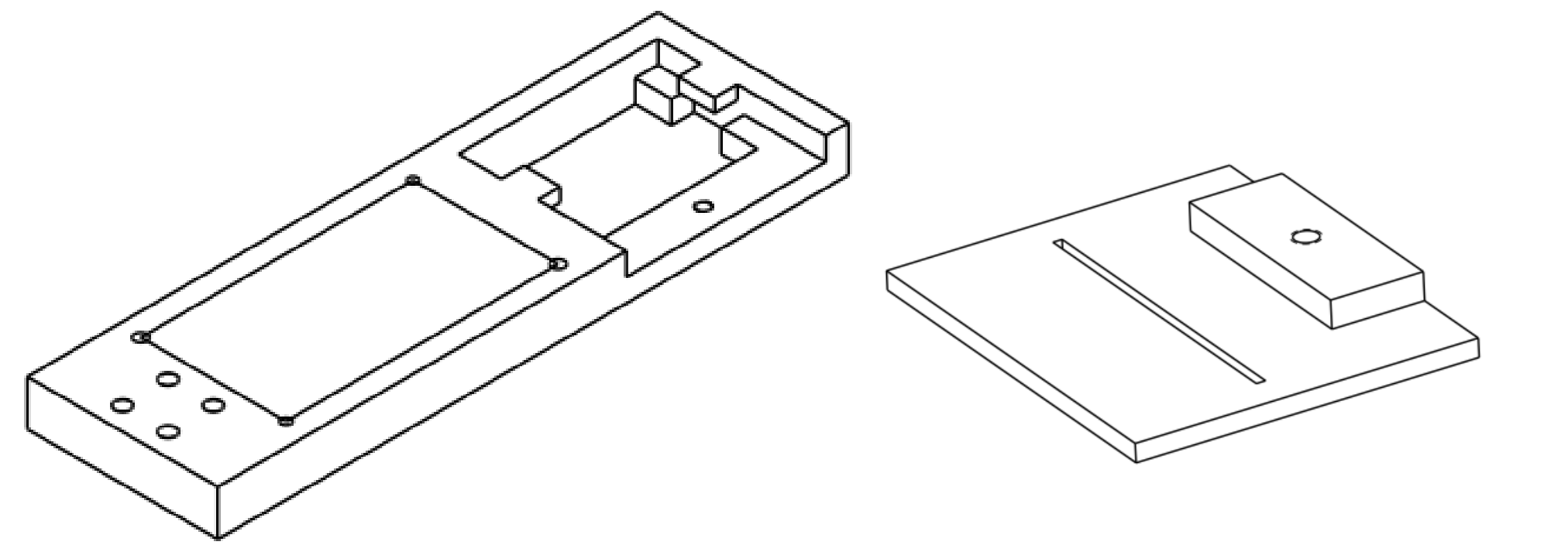
An XICS-RT generated image modeling the plasma as a slab plasma emitting only one spectral line. The spectral line show here is the principle line of Ar^{16+}.

Total Impact

Random Errors	Systematic Errors
3×10^{-7} Å	1×10^{-5} Å
50 m/s	1 km/s

Future improvements that can reduce the systematic errors:

- A survey of x-ray tube positioning using the removable slit
- Cross calibration with other diagnostics
- More precise measurements of the wavelength of the Cadmium lines



References

[1] J. Neuhrenberg and R. Zille, Phys. Lett. A 114, 129 (1986).
[2] C. Beidler, et.al., Fusion Technol. 17, 148 (1990)
[3] N. Pablant, et.al., 41st EPS Conference on Plasma Physics, 38F:P1.076, 2014
[4] N. A. Pablant, et.al., Physics of Plasmas, 25(2):022508, 2018.
[5] L Delgado-Aparicio, et.al., Plasma Physics and Controlled Fusion, 55(12):125011, 2013.
[6] J.A. Bearden. X-ray wavelengths. Review of Modern Physics, pages 86–99, 1967.

Acknowledgements

Research supported by the U.S. DOE under Contract No. DE-FG02-00ER54610 with Auburn University and Contract No. DE-AC02-09CH11466 with Princeton University. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission

We thank MIT PSFC for the use of their facilities in testing the calibration schemes.

EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.