Measurement of core plasma temperature and rotation on W7-X made available by the x-ray imaging crystal spectrometer (XICS)

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I. Introduction

A new x-ray imaging crystal spectrometer diagnostic (XICS) is currently being built for installation on W7-X. This diagnostic will contribute to the study of ion and electron thermal transport and the evolution of the radial electric field by providing high resolution temperature and rotation measurements under many plasma conditions, including ECH heated plasmas. Installation is expected before the first experimental campaign (OP1.1), making an important set of measurements available for the first W7-X plasmas. This diagnostic will also work in concert with the HR-XCS diagnostic to provide an excelent diagnostic set for core impurity transport on W7-X[1, 2].

The XICS diagnostic will provide profiles of the ion-temperature (T_i), electron-temperature (T_e), poloidal flow velocity (V_p) and impurity ion density for the Ar^{16+}, Ar^{17+} and Fe^{24+} charge states. This system will have a maximum time resolution of 5ms, a spatial resolution of approximatly 2cm, and spatial coverage from the core to a normalized minor radius of $\rho \approx 0.82$.

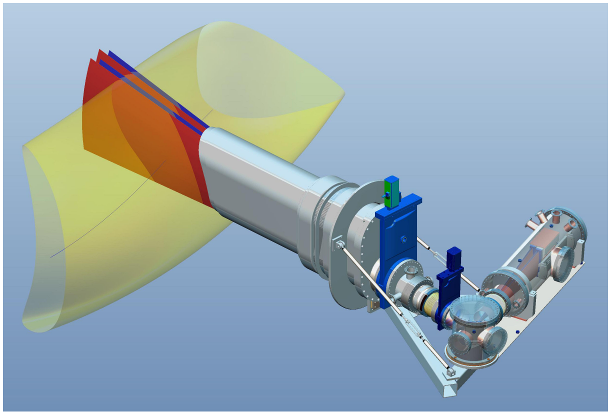

Figure 1: *CAD model showing the design of the XICS diagnostic on W7-X. The viewing cones (small crystal approximation) corresponding to the w (red) and z (blue) lines of the Ar^{16+} and Fe^{24+} are shown.*

The XICS diagnostic will consist of two channels which view different emission spectra. The first channel will view Ar^{16+} emission, while the second channel will simulteaniously view both Ar^{17+} and Fe^{24+} emission. Each channel consists of a crystal and detector, and both channels are held within a single housing and use common mounts. For the first W7-X operational period (OP1.1), scheduled for spring 2015, a single detector will be installed for the Ar^{16+} channel. For the following campaign (OP1.2), scheduled for 2016, two detectors are expected to be installed, providing both channels. Once both channels are installed, the XICS system is expected to provide measurements for nearly all plasma conditions on W7-X.

II. Diagnostic Method

The XICS diagnostic on W7-X relies on impurity emission from highly charged impurity ions, and is designed to measure emission from both injected argon and intrinsic iron. The diagnostic concept has been explained in detail by Bitter *et al.*[3] and a conceptual layout can be found in Ref. 3, Fig. 2.

For each diagnostic channel, a spherically bent crystal is used to create a one dimensional image of line integrated emission. Doppler spectroscopy techniques are used to determine the T_i, V_P and the density of the charge state. T_e is found from the relative intensities of $n \geq 3$ dielectronic satellite lines to the resonant emission line. Tomographic inversion, using a known plasma equilibrium, is used to infer the local plasma parameters from the line integrated data[4].

III. Hardware Description

The designed system parameters for the W7-X installation are summarized in Table 1. All of these parameters have been finalized, and the final installation is expected to match within design tolerances.

The W7-X XICS diagnostic design is similar to the installation on the Large Helical Device (LHD), and the details of the basic hardware, configuration, calibration and analysis on LHD have been reported previously in Refs. 4–6. The W7-X installation is placed closer to the plasma, and is therfore of a smaller size than the LHD system. In addition a copper mesh ECH shield has been added to the system after the primary gate valve for diagnostic protection.

The diagnostic will be installed at the AEK-31 port, which is a large radially viewing midplane port. Given the limited space in the W7-X experimental hall, the diagnostic will be supported directly off of the cryostat as shown in Fig.1. To improve the viewing range, the entire diagnostic, including the supporting structure, will be tilted upwards at an angle of 5.0° from the horizontal (see Fig.2).

System parameters	
crystal to magnetic axis	3582mm
Ar^{16+} System	
Bragg Angle (Ar^{16+})	53.49°
radius of curvature	1450=mm
crystal to detector	1165=mm
sagittal focus (Ar^{16+})	3991=mm
Ar^{17+} and Fe^{24+} System	
Bragg Angle (Ar^{17+})	54.86°
Bragg Angle (Fe^{24+})	54.19°
radius of curvature	1450=mm
crystal to detector	1185=mm
sagittal focus (Ar^{17+})	3514=mm
sagittal focus (Fe^{24+})	3730=mm
Expected Resolution	
Electron Temperature	100eV
Ion Temperature	20eV
Poloidal Rotation	5km/s
Spatial	2cm
Time	5ms

Table 1: *Design parameters for the W7-X XICS diagnostic.*

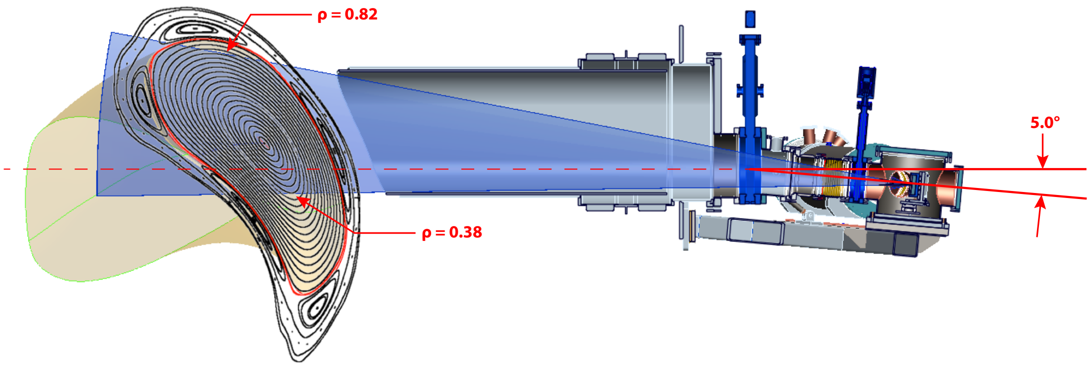

Figure 2: *Viewing range of the XICS system. The view is limited by the aperture of the port extension at the vacuum vessel.*

Two spherical quartz crystals of different cuts, will be used in the diagnostic system. A quartz $(1,1,0)$ crystal will be used for the Ar^{16+} channel, and a quartz $(1,0,2)$ crystal for the Ar^{17+}/Fe^{24+} channel. While both of the argon spectra will rely on the first order diffraction, iron spectrum will be measured in second order. The dimensions of both crystals are 100mm $\times$40mm and are approximately 100-150μm thick. Each crystal is placed onto a polished spherical substrate with a radius of curvature of 1450mm and held in place through electrostatic forces. The two substrates will be made by polishing a single large BK-7 glass block, and cutting the block in half. This ensures that both crystals will have exactly the same radius of curvature, simplifying calibration and analysis.

The two crystals will be held within a precision mounting block that holds the two crystals with a fixed 2.5°angle between them. This angle serves both to separate the spectra from each channel, so that they can be imaged on separate detectors without interference, and to align the views of both channels more towards the radial direction. The Ar^{16+} crystal will additionally be masked to reduce its vertical extent to 60mm, which will improve the range of the plasma that can be seen without vignetting (see Fig.2). This mask can be enlarged to improve the system throughput, at the expense of a slight reduction of the viewing range.

Each channel will use a water cooled Pilatus 300K-W detector from Dectris Ltd.[7, 8]. These detectors have 1475 $\times$195 pixels, with a pitch of 172μm, providing a sensitive area of 253.7mm $\times$33.5mm. The readout time for the detector is 2.3ms (Pilatus 2) or 0.95ms (Pilatus 3) depending on the generation of detector which will be used. During readout the detector is insensitive to incoming x-rays; this dead time ultimately sets the maximum available time resolution of the system.

Each pixel has an independently adjustable lower energy discriminator. This ability to adjust the sensitivity of individual pixels will provide a way to separate the Ar^{17+} and Fe^{24+} spectra, if necessary, by setting the detector threshold above the Ar^{16+} lines on every other row on the detector.

IV. Wavelength Calibration

Determination of the poloidal velocity (V_p) as an absolute quantity (as opposed to a relative measurement) requires very accurate measurements of the line shift, along with an equally accurate method of determining the unshifted line location. With a view of both the upper and lower half of the plasma, measurements of V_p can be made without an absolute wavelength calibration by utilizing the opposite spectral shifts on the opposite sides of the magnetic axis.

The W7-X diagnostic will primarily view the upper half of the plasma, with a view below the magnetic axis that only extends to $\rho \approx 0.38$ (see Fig.2). While it may be possible to determine V_p from the differential shifts even with this limited view (see Ref. 4), an absolute wavelength calibration is considered essential for optimal diagnostic operation.

The proposed wavelength calibration solution is to use x-ray reflection florescence from a cadmium foil or mesh. The Cd foil/mesh will be placed in front of the crystal, on the plasma side, and illuminated using a small copper x-ray tube. If sufficient signal can be achieved, the Cd foil/mesh will be chosen so as to be transparent to x-rays from the plasma.

V. Expected Performance

Estimated measurement accuracy for the system is summarized in Table 1. To obtain sufficient signal for these measurements, an argon density of approximately $n_{Ar}/n_e = 10^{-5}$ is required. Argon puffing will be achieved through the W7-X gas injection system or through the Helium beam diagnostic system.

The spatial resolution of an XICS system in a complicated magnetic geometry does not have a natural defintion (as it does in axisymetric configurations), but can be estimated from the cross-section of the viewing volume corresponding to a single pixel within the plasma. Using this type of analysis the spatial resolution is estimated to be 2cm.

While the time resolution of the system is ultimately limited by the readout speed as defined in Section III, in practice the integration will be set by the need to gather photon statistics. Based on experince in other machines, it is expected that the diagnostic will typically be run with a 5ms or 10ms integration time.

References

[1] Langenberg, A. et al. In *Proceedings of the 41th EPS Conference on Plasma Physics* (2014).
[2] Thomsen, H. et al. In *Proceedings of the 41th EPS Conference on Plasma Physics* (2014).
[3] Bitter, M. et al. Review of Scientific Instruments, **81**, 10, 10E328 (2010).
[4] Pablant, N.A. et al. Review of Scientific Instruments (2014). Submitted for publication.
[5] Pablant, N.A. et al. Review of Scientific Instruments, **83**, 8, p. 083506 (2012).
[6] Pablant, N.A. et al. In *Proceedings of the 38th EPS Conference on Plasma Physics* (2011).
[7] `https://www.dectris.com/pilatus3_overview.html` (2014).
[8] Broennimann, C. et al. J Synchrotron Rad, **13**, 2, pp. 120 (2006).