Layout and expected performance of the recently installed high-resolution x-ray imaging crystal spectrometer on the Large Helical Device

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Introduction

A high-resolution x-ray imaging crystal spectrometer (XICS) has recently been installed on the Large Helical Device (LHD) for measurements of the ion and electron temperature profiles with a spatial resolution of $\sim$2cm and a time resolution of $\geq$ 10ms. The installation and alignment of the x-ray imaging crystal spectrometer (XICS) on LHD was completed in May 2011. In addition an in-vessel spatial calibration was performed to check the final alignment of the system and the true viewing volume in the plasma.

Measurements of ion and electron temperature profiles can provide valuable information in the investigation of stellarator plasmas. These measurements are particularly important for the understanding of plasma heating and heat transport within the plasma. While direct measurement of the main ion species (hydrogen or deuterium) is difficult, measurements of impurity species can, in most cases, be used as a proxy measurement. In current tokamak and stellarator devices, including LHD, measurement of the impurity ion temperature are most commonly made using diagnostics based on charge exchange recombination spectroscopy (CER). Recent advances in diagnostic design, detector technology and atomic physics calculations have allowed the XICS diagnostic to provide local ion temperature measurements with a precision comparable with CER. XICS is now used as a primary ion temperature diagnostic on several existing fusion devices, including Alcator C-Mod, EAST and KSTAR, and will be the primary core ion temperature diagnostic for ITER.

In LHD, XICS is expected to provide ion temperature profiles in both high and low density plasma conditions where measurements from CER are currently not available or difficult to make. At high densities, the neutral beams cannot penetrate to the core and CER is available only in the plasma edge. At low densities, the use of the perpendicular neutral beam injection (NBI) results in a plasma density increase, and can significantly perturb the plasma. In addition, because neutral beam injection is not needed, XICS is an ideal diagnostic for the investigation of radio frequency heated plasmas and for studying the dynamics of neutral beam heating.

Diagnostic technique

The XICS diagnostic utilizes a spherically bent quartz crystal to provide a 1D image of line integrated spectra from highly charged impurity species in the plasma. The diagnostic concept has been explained in detail by Bitter *et al.*[1] and a conceptual layout can be found in Ref. 1, Fig. 2. Given that typical electron temperatures in LHD are in the range of T_e =1–3keV, the XICS system has been designed to view impurity emission from helium-like Ar^{16+}. Measurements of the ion-temperature (T_i) are made from the Doppler broadening of the spectral lines, while the electron-temperature (T_e) is found from the relative intensities of $n \geq 3$ dielectronic satellite lines to the resonant emission line. In addition to temperature measurements, the XICS system can also be used to monitor the argon density profile.

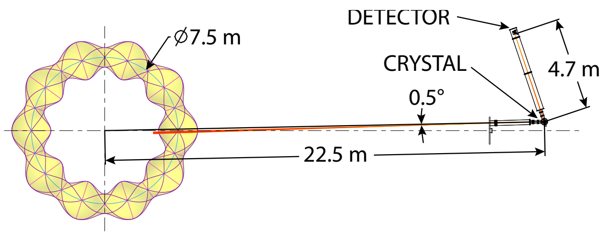

Figure 1: Top view of the layout of the XICS diagnostic.

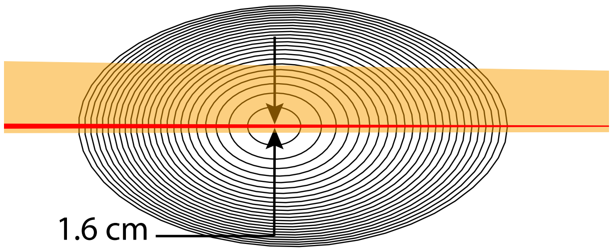

Figure 2: XICS views of the LHD plasma. The vertical viewing range is shown in yellow, the viewing volume corresponding to a pixel in the center of the detector is shown in red.

Because of the overlap of the resonance and the multiple satellite lines (see Fig.3), spectral fitting using an atomic physics based spectral model is necessary in order to extract the ion and electron temperatures. For this spectral fitting, atomic data from the MZ code will be used for the line locations and for the relative intensities of the satellite lines[2]. In order to compute the electron temperature, additional atomic physics is required, namely accurate excitation rate coefficients for both the resonance and satellite lines. This data will be taken from calculations done using the AUTOSTRUCTURE code[3].

In order to find local values for T_i and T_e from the line integrated spectrum, an inversion of the data is required. This is possible with a reconstruction of the plasma equilibrium and a few assumptions: that the plasma emissivity and temperature are constant on flux surfaces and that the ion temperature distribution is Maxwellian. Plasma reconstructions will be done using a set of reconstruction tools being developed for LHD at PPPL: VMEC, STELLOPT and PIES[4]. As a future improvement, data from the XICS diagnostic will be integrated directly into the reconstruction routines and used as a constraint in the minimization process.

Hardware layout

The XICS system on LHD is unique in that it is the first application of this diagnostic to a stellarator configuration. A discussion on the consequences of the stellarator geometry and the original design goals for the LHD XICS diagnostic system have been presented previously in Ref. 1. Because of the lack of toroidal symmetry, as well as the available installation locations, a modification to the diagnostic design typically used on tokamak systems was required. In particular, the system is designed with a smaller spectral extent, but with a higher spectral resolution. With this configuration the toroidal extent of the views in the plasma is matched to the toroidal spread due to the variation in Bragg angle across the spectral range. In the current configuration the system will have spectral coverage from 3.943–3.964$\mathring{A}$, as shown in Fig.3. With this spectral range only the w-line and the $n \geq 3$ satellites will be visible on the detector.

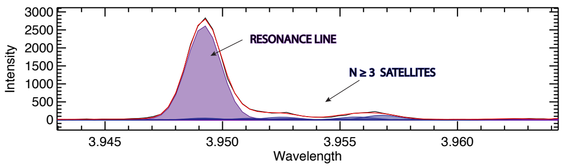

Figure 3: Expected spectral range for the LHD XICS diagnosic. Plot shows data from Alcator C-Mod, with the spectral range reduced to that of the LHD system. In this spectrum the resonance line and the $n \geq 3$ satellites can be seen. The raw data (black) is fit using an spectral model based on results from the MZ code (red). The individual lines making up the spectral model are shown in purple.

In the current system the installed crystal is a 150μm thick 110-quartz crystal with a 2d-spacing of 4.91352$\mathring{A}$[5]. The crystal dimensions are 4cm in the spectral direction and 10cm in the spatial direction. The crystal is placed onto a spherical substrate and held in place though electrostatic forces. The radius of curvature of the crystal has been measured to be 5896$\pm$2mm.

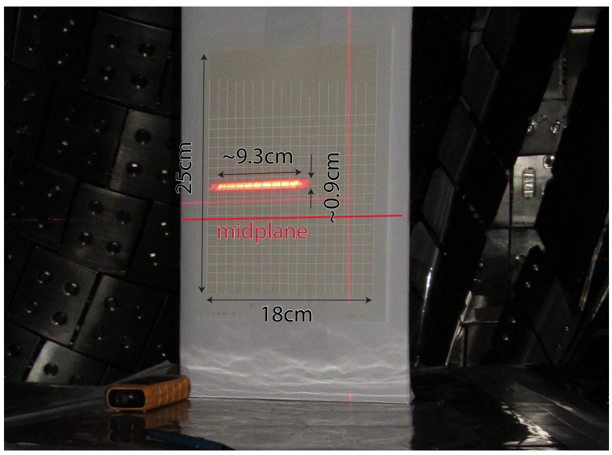

Figure 4: Illumination of target during the in-vessel calibration. In this image, the target is placed near the outside plasma edge, $\sim$1.5m from the sagittal focus.

The crystal is placed at a distance of 22.48m from the center of LHD. The crystal is oriented so that the w-line, at 3.9492$\mathring{A}$[2], will have an angle of 0.5° from the radial direction at the crystal surface, see Fig.1. The detector is placed on the Rowland circle at a distance of 4.74m from the crystal.

An in-vessel calibration was completed by illuminating the crystal from a point source at the final detector location. The illumination created through this procedure can be seen in Fig.4. The measured viewing volume from the in-vessel calibration matched the expected viewing volume, giving us confidence in our alignment accuracy and ability to determine flux-surface weighting necessary for inversions.

In the current configuration a single Pilatus 100K detector system will be used[1 6]. For the initial part of the experimental campaign the detector has been placed so as to have a view from $z \approx -160$mm to $z \approx +160$mm at the plasma center. This will allow the plasma center to be clearly seen, and therefore provide an in-situ calibration of the detector location. Once the detector location has been verified, the camera will be adjusted so as to have a view from $z \approx -30$mm to $z \approx +290$mm. This configuration will give coverage out to $\sim a \times 0.6$ and is expected to be used for the remainder of the 2011 experimental campaign (see Fig.2).

Expected performance

There is an existing single chord x-ray crystal spectrometer (XCS) diagnostic system installed on LHD (see Ref. 7) from which we can estimate the signal expected for the new diagnostic installation. From these data we can reasonably expect that for many plasma conditions the time resolution of the system will be limited by the readout time of our camera system, which is 2.7ms. In order to retain a reasonable overall detection efficiency given this readout time, data will be acquired with a time resolution of 10-20ms. Binning of the data in the spatial or temporal directions can then be done to improve the photon statistics. In addition to photon statistics, the total measurement accuracy is also dependent on spectral fitting quality and the accuracy of the inversion techniques.

Future plans

First data from this diagnostic installation is expected at the beginning of the LHD experimental campaign in August 2011.

An order has been placed for a larger detector as an upgrade for the LHD XICS system. This detector, a Pilatus 300K-W with water cooling, will allow the entire plasma to be imaged, allowing more accurate inversion of the line integrated spectra. In addition this detector will allow for long pulse operation, which is not currently possible. This new detector is expected to be installed for the 2012 LHD experimental campaign.

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