Progress in X-Ray Imaging Crystal Spectrometer (XICS) Development and Measurements of Ion-Temperature and Flow-Velocity Profiles in Tokamaks and Stellarators

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Introduction

Plasma rotation and velocity shear can have important beneficial effects in tokamak plasmas by stabilizing destructive MHD and enabling improved confinement operation by suppressing turbulence [1,2]. Measurements of profiles of rotation velocity (v) and ion temperature (T_i) are important in understanding and optimizing intrinsic rotation and enhanced confinement regimes. Present techniques of charge-exchange recombination spectroscopy require an expensive neutral beam (NB), and will be problematic in large, high density plasmas, such as ITER, and reactors, due to attenuation of the NB's neutral density in the plasma core.

Thus a spatially resolving or 1D imaging high-resolution x-ray crystal spectrometer (XICS) has been developed for measurement of full profiles of T_i and v with a single instrument, without the need for a NB, and capable of measurement throughout the plasma with any type of heating. [3,4,5] This type of instrument has been successfully implemented on several tokamaks [9,11] and a stellarator [6], throughout the world, and the data are providing new information on intrinsic toroidal rotation, as well as providing routine measurement of profiles of T_i and T_e. Also, this type of instrument is a primary diagnostic for measurement of profiles of T_i, v_{tor}, and v_{pol} on ITER and a secondary instrument for Te profiles, and a US-ITER team is developing the conceptual design for the ITER XICS. [7]

Concept of instrument

The principle of the XICS has been discussed previously. [3,4,5,8] A spherically bent x-ray diffracting crystal diffracts x rays from the plasma onto a 2D imaging x-ray detector. By the Bragg relation, the crystal disperses the x rays according to wavelength in the horizontal plane, and by its astigmatic imaging properties, images the x rays vertically. Thus the vertical

location on the 2D detector corresponds to vertical position in the plasma, and the horizontal local corresponds to spectral wavelength. Present instruments use either a delay-line encoded multiwire proportional counter (MWPC) [9] or Pilatus [10] silicon hybrid pixel array detectors for detecting the 2D x-ray image.

Measurements from the Alcator C-Mod tokamak

Measurements and analysis of data from C-Mod have been presented previously [4,5]. We illustrate and discuss two examples in Fig 1.
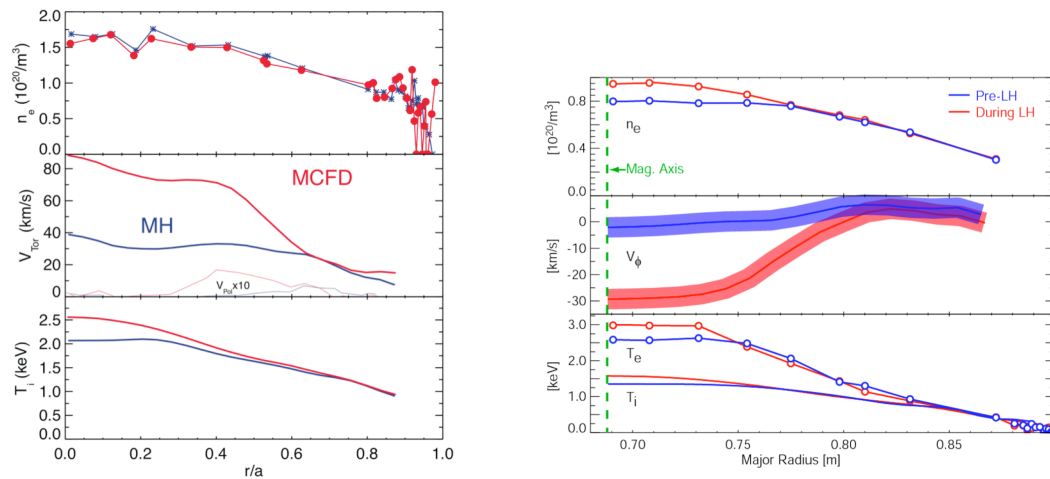

Figure 1 Examples illustrating toroidal v profile measurements from C-Mod. Left, center, illustration that, for the same RF power level, mode conversion flow drive (MCFD) is more than twice as efficient in generating central toroidal flow as is minority heating (MH), and the v profiled is more centrally peaked. [2] Right, center, lower hybrid current drive (LHCD) generates a negative (counter current), centrally peaked toroidal flow. [1]

More recently, measurements from a partially toroidally viewing XICS on the EAST tokamak in China have shown that LHCD at power levels of ~1 MW induce a co-current change in toroidal flow of up to 40 km/s in the core and up to 20 km/s at the edge of L-mode plasmas. [11]

ITER XICS design

A recent design concept for the ITER XICS is illustrated in Fig. 2. Because of the 7-m height of the ITER plasma, two instruments are required to view the plasma up to r/a ~ 0.9. Another edge viewing XICS to be built by a team from India, will focus on the range r/a > 0.9.

Performance simulations for the ITER core XICS

a. Signal intensity

Calculations of the anticipated surface brightness for He- and H-like Fe Kα and Ne-like W L spectra indicate that sufficient count rates for measurement with a few percent statistics of T_i
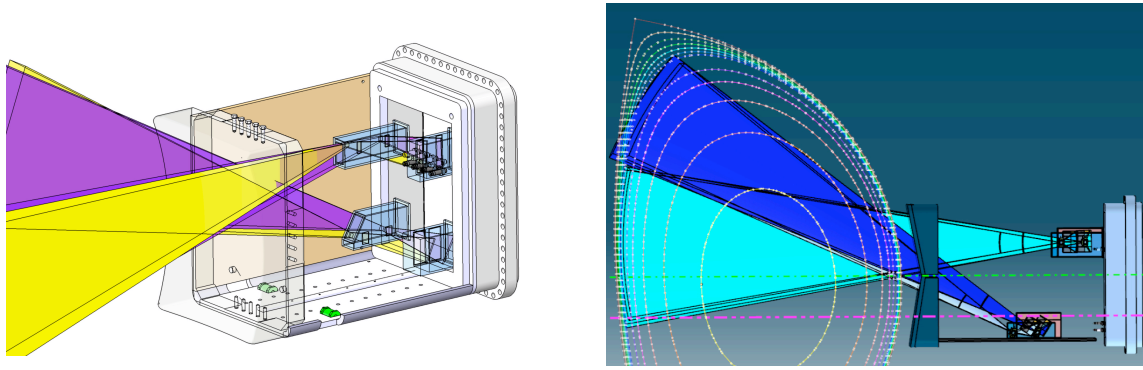
Figure 2 Left, illustration of recent design for ITER Core XICS as installed in equatorial port plug 9, and, right, possible lines of sight.

and v can be made over most of the core plasma. [12] The ITER requirements are radial spatial resolution of a/30, where a is the minor radius, 10% uncertainty in T_i in 100 ms, and 30% uncertainty in v in 10 ms. Accumulation of 1000 counts in the spectral line provides ~3% statistical uncertainty.
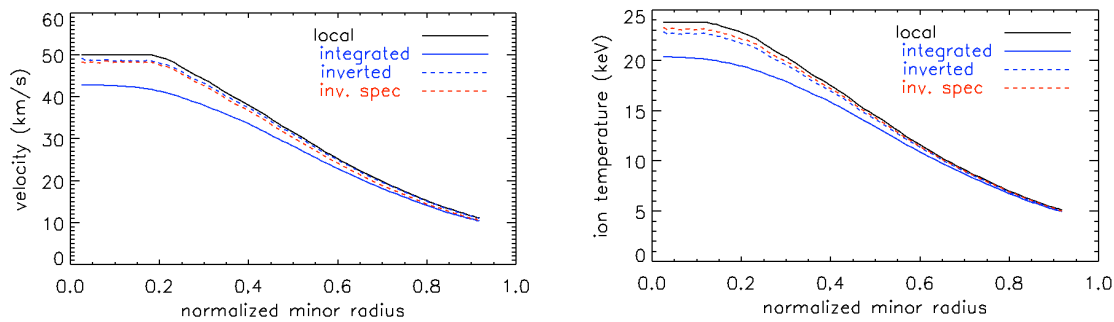

Figure 3   Local, chordally integrated apparent values, and inverted values of v and Ti for ITER scenario 2 H-mode plasma, as simulated using Ne-like W line emission at 8.3 keV

Figure 3 shows that tomographic inversion of the measured spectra yields profiles close to the local values. These are simulations of the radial profile measurements for v and T_i in an ITER scenario 2 H-mode plasma. The solid black curves represents the peak values along the lines of sight (LOS) of the XICS; the solid blue curves are the apparent values of v and T_i inferred from the chordally integrated surface brightness spectra; and the dashed curves are the result of tomographic inversions to reconstruct the local values. The blue dashed curves are calculated from Eqs. 12 and 16 of Condrea *et al.* [13], which is an inversion technique based on moments of the spectral line, and the red dashed curves are inferred from a direct inversion of the brightness spectrum to obtain local spectra. It was observed that the analysis of Condrea for inversion of T_i breaks down when the central rotation velocity is of the order or larger than the W ion thermal velocity, because the second term in Eq. 16 of Condrea, which is proportional to v^2, becomes significant. The spectral inversion technique, however, is found

to be robust to large values of rotation velocity for both v and T_i.

b. Radiation background noise

Background counts in the XICS detector from fusion neutrons and secondary gamma rays can significantly degrade the measurement. Neutronics calculations for a preliminary design of the ITER XICS with very complete neutron/gamma-ray (n/γ) shielding indicated that the XICS could successfully make measurements during the highest power ITER discharges and the detectors could survive the expected lifetime of ITER operation. In the latest configuration, however, the XICS will share a port plug with other diagnostics which will require penetrations in the neutron shielding for microwave waveguides and optical sightlines, as well as displace areas of potential neutron-shielding volume. A detailed, realistic neutronics calculation is underway, which will assess the level of radiation enhancement, relative to that of the previous, more idealistic calculation. Fortunately, recent measurements at NSTX of the n/γ generated background in a Pilatus hybrid pixel detector [10] indicate that of order 95% of this background can be eliminated electronically by use of both an upper and lower pulse height discriminator, an "energy window" in the analog circuitry. [12]

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