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ABSTRACT: A new type of X-ray imaging crystal spectrometer has been implemented on Alcator C-Mod for Doppler measurements of ion temperature and plasma rotation velocity profiles. The instrument consists of two spherically bent (102)-quartz crystals with radii of curvature of 1444 and 1385 mm and four 'PILATUS II' detector modules. It records spectra of He-like argon from the entire, 72 cm high, elongated plasma cross-section and spectra of H-like argon from a 20 cm high, central region of the plasma, with a spatial resolution of 1.3 cm and a time resolution of less than 20 ms. The new spectrometer concept is also of interest for the diagnosis of burning plasmas on future machines. This paper presents recent experimental results from Aclator C-Mod and discusses challenges in X-ray spectroscopy for the diagnosis of fusion plasmas on future machines.

Keywords: Plasma diagnostic techniques and instrumentation
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INTRODUCTION

A new X-ray crystal spectrometer concept [1, 2] and recent advances in X-ray detector technology [3] have made it possible to solve a longstanding problem in the X-ray spectroscopy of tokamak plasmas, namely, to record spatially resolved spectra of highly charged ions with a spatial resolution of about 1 cm and a time resolution of less than 20 ms for measurements of profiles of the ion and electron temperatures and plasma rotation velocities. A prototype of this novel X-ray imaging crystal spectrometer was implemented on Alcator C-Mod in April 2007 and has since recorded spectra of helium- and hydrogen-like argon from almost every discharge on Alcator C-Mod. The development of this diagnostic is being supported by the US Department of Energy Diagnostics Development Initiative to address the need for non-perturbing high resolution measurements of ion temperature profiles, $T_i(R,t)$, in present and future devices of magnetic confinement fusion energy research. The advantages of X-ray crystal spectroscopy are that its diagnostic applications are not limited to plasmas with neutral-beam injection and that data can, in principle, be obtained from all discharges, which include plasmas with pure Ohmic heating as well as plasmas with auxiliary ion or electron cyclotron heating, lower-hybrid current drive, and neutral-beam injection. X-ray spectroscopy has therefore become a valuable complement or viable alternative to methods of charge exchange recombination spectroscopy, which are currently most commonly used for measurements of ion temperature profiles. However, with respect to the plasma diagnosis on future machines, X-ray spectroscopy will, as most other diagnostics, face new challenges, namely, to make an adequate choice of spectral lines from impurity ions for the diagnosis of the different high-temperature plasma scenarios on devices, like ITER, and to find appropriate crystals and radiation hardened, high count rate detectors, which can operate in a harsh environment of high neutron and gamma radiation.

DESIGN PARAMETERS OF THE X-RAY IMAGING CRYSTAL SPECTROMETER ON ALCATOR C-MOD

The layout of the new X-ray imaging crystal spectrometer on Alcator C-Mod is shown in Fig. 1. It consists of two spherically bent (102)-quartz crystals with radii of curvature of 1444 and 1385 mm and four 'PILATUS II' detector modules, which record spectra of He-like argon from the entire, 72 cm high, elongated plasma cross-section and spectra of H-like argon from a 20 cm high, central region of the plasma, with a spatial resolution of 1.3 cm and a time resolution of less than 20 ms. The spectra of H-like argon are used for reliable measurements of the central ion temperature in plasmas with high electron temperatures when the emissivity profile of He-like argon is hollow. The 'PILATUS II' detector modules are pixellated semiconductor diode arrays of 35 mm x 85 mm with a pixel size of 0.172 mm x 0.172 mm, which can handle single photon count rates up to 1 MHz per pixel [3]. The dimensions of the spectrometers on ITER will be similar to those of the present C-Mod spectrometer, so that the instrument on C-Mod can also be considered as a prototype for the ITER spectrometers.

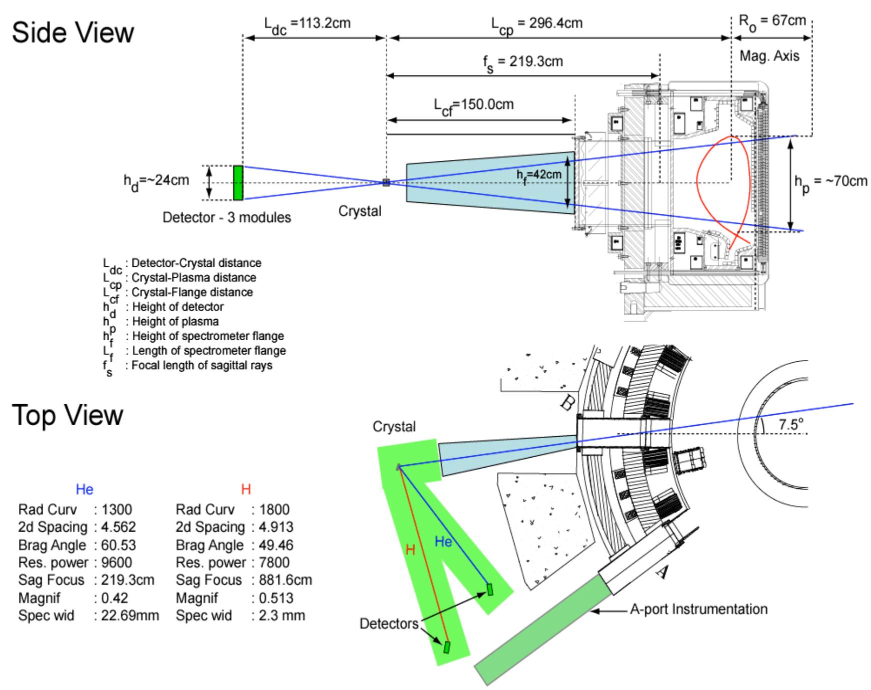

Figure 1: X-ray imaging Crystal spectrometer on Alcator C-Mod

RECENT EXPERIMENTAL RESULTS FROM ALCATOR C-MOD

Spectra of He- and H-like argon are now being recorded from almost every Alcator C-Mod discharge. Typically a small amount of argon is puffed into a discharge during the time interval from 300 to 400 ms. Since Alcator C-Mod operates at high magnetic fields of 5.7 Tesla, the electron density ($\sim 5 \times 10^{20}$ m^{-3}) and therefore the radiation intensity, which is proportional to the square of the electron density, are by a factors of 10 and 100 higher than on other tokamaks, so that the observed count rates for the resonance lines of He-like and H-like argon are in the range from 10 to 200 kHz/pixel (or 0.36 to 7.2 MHz/mm^2). Figure 2 presents data from an Alcator C-Mod discharge (shot: 1080123021) with lower-hybrid heating and current drive during the period from 0.8 to 1.3 s, as an example. A more detailed review of the results from Alcator C-Mod will be presented in forthcoming paper [4].

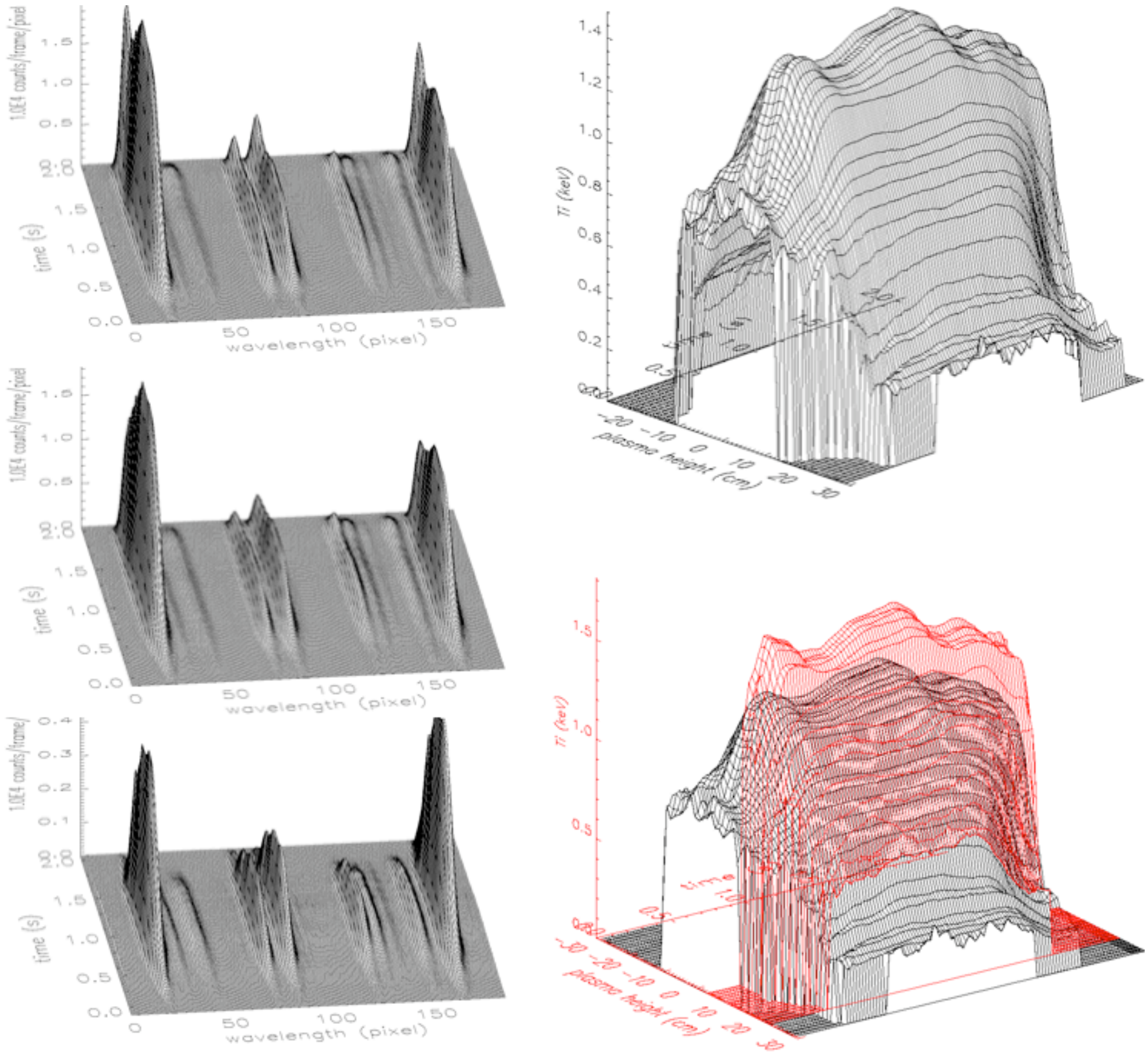

Figure 2: *Left column, top to bottom*: Time histories of He-like Ar spectra from sightlines at z = 0.61, 7.85, and 14.47 cm above the horizontal mid-plane. The spectral features are explained in ref. [2]; *Right column, top to bottom*: Ion-temperature profiles from chord-integrated spectral data of He-like and He- and H-like Ar, respectively, as a function of time.

Software for the tomographic inversion of the spectral data is presently being developed, and it was recently demonstrated that the ion temperatures, derived from the inverted spectral data of He- and H-like Ar, are in agreement. Of particular interest are observations of a reversal of the central toroidal rotation velocity during lower-hybrid heating and current drive [4].

CHALLENGENS FOR THE X-RAY DIAGNOSTICS ON FUTURE MACHINES

To select appropriate spectral lines for the X-ray diagnostics on future devices, such as ITER, will be a major task. The spectra of He- and neon-like ions are preferred, since these ions exist over a wide range of electron temperatures due to the high ionization potential of their closed-shell configurations. He-like Ar, which exists in the range $0.5 < T_e < 3$ keV, is perfectly suited for the core plasmas on Alcator C-Mod and edge plasmas on ITER. However, since the emissivity profiles of He-like Ar can be hollow, a tomographic inversion of the spectral data and therefore the use of multi-chord X-ray imaging crystal spectrometers are absolutely necessary for ion temperature measurements on Alcator C-Mod or other devices.

Helium-like krypton is the primary candidate for the diagnosis of the ITER core plasmas with electron temperatures of 4 < Te < 30 keV [5], and krypton may also be used on ITER to control the energy release to the plasma facing components by radiative cooling [6]. Experiments were therefore already conducted on TFTR to address these issues [6, 7]. These experiments showed that the krypton ion charge state distribution depended strongly on the electron density and electron temperature profiles: He-like krypton could not be observed in plasmas with peaked profiles, but only in plasmas with relatively broad profiles. More recently, modeling calculations of the ITER H-Mode and Internal Transport Barrier plasmas showed that the increase in Z_{eff}, which is small, will be of a lesser concern than the additional radiated power, since the incremental radiated powers for added impurity concentrations of $10^{-5} \times n_e$ are 0.25 MW for Ar and 1.4 MW for krypton [5]. The addition of krypton for solely diagnostic purposes to enhance the radiation from He-like krypton is therefore not efficient, as significantly more radiation will be emitted from the lower charge states of krypton. Another concern is the low ratio of the line to continuum radiation from free-free and free-bound transitions, which varies from 1 for Kr in the center to 30 for Ar in the edge of ITER plasmas [5]. Since the wavelength of the resonance line of He-like krypton is less than 0.1 nm, it is also difficult to find crystals with appropriate 2d-spacings and high reflectivity; observation in 2nd order Bragg reflection is not desirable, since the crystal reflectivities in 2nd order are small and since the background continuum will be simultaneously observed in both 1st and 2nd order Bragg reflection [7]. Another candidate for the core diagnostics on ITER is neon-like tungsten, since tungsten will be an intrinsic impurity on ITER. Neon-like tungsten exists in the electron temperature range of 11 < Te < 39 keV; and the wavelengths are near 0.15 nm, for which appropriate crystals exist. Spectrometers, which employ multiple crystals at approximately the same Bragg angle [9,10], may also be of advantage on ITER to select impurities of interest. Highly accurate atomic physics data on wavelengths and rate coefficients will also be required, since for the projected ion temperatures of 20 keV the Doppler broadening will be so large that spectral features are blended with each other and that the ion temperature can only be derived from a least-squares fits of theoretical spectra to the experimental data [11,12]. Recent neutronics calculations have shown that the PILATUS detectors can operate on ITER with appropriate shielding [13].

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