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***Abstract*– A new type of X-ray imaging crystal spectrometer for Doppler measurements of the radial profiles of the ion temperature and plasma rotation velocity in tokamak plasmas is presently being developed in a collaboration between various laboratories. The spectrometer will consist of a spherically bent crystal and a two-dimensional position sensitive detector; and it will record temporally and spatially resolved X-ray line spectra from highly-charged ions. The detector must satisfy challenging requirements with respect to count rate and spatial resolution. The paper presents the results from a recent test of a PILATUS II detector module on Alcator C-Mod, which demonstrate that the PILATUS II detector modules will satisfy these requirements.**

I. INTRODUCTION

The diagnosis of tokamak plasmas, which are studied in nuclear fusion energy research, requires measurement of ion temperature and plasma rotation velocity profiles with spatial and temporal resolutions of 10 mm and 10 ms, respectively. To accommodate these needs a new high-resolution X-ray imaging crystal spectrometer is being developed at the Alcator C-Mod tokamak in a collaboration between various research institutes. The spectrometer consists of a spherically bent crystal and a 2D position-sensitive detector and provides X-ray spectra from highly charged ions from multiple sightlines through the plasma. The ion temperature and plasma rotation velocity are determined from the Doppler width and Doppler shift of the observed X-ray lines. This spectrometer is also of interest for ion-temperature measurements on the International Thermonuclear Experimental Reactor (ITER).

The proof of principle of the imaging spectrometer was demonstrated on Alcator C-Mod in 2003, using a multi-wire proportional counter [1]. However, the global count rate capability of this detector of 400 kHz has limited the time resolution of the spectrometer to > 100 ms. Recently, a new semiconductor pixel array, a PILATUS II detector module [2,3], with a count rate capability of 1 MHz per pixel was tested on Alcator C-Mod by recording high-resolution spectra of helium-like argon, Ar XVII, at 3.1 keV. Based on these results, an X-ray imaging crystal spectrometer is now being designed to measure full radial profiles of the ion temperature and rotation velocity on Alcator C-Mod. The detector test results and layout of this X-ray imaging crystal spectrometer are presented in section II and section III, respectively.

II. TESTS OF A PILATUS II DETECTOR MODULE ON ALCATOR C-MOD

The Alcator C-Mod tokamak is presently equipped with five von Hamos type X-ray crystal spectrometers (see Fig. 1), which record high-resolution spectra of helium-like and hydrogen-like argon, ArXVII and ArXVIII, at X-ray energies of 3.1 and 3.7 keV from different sightlines through the plasma for Doppler measurements of the ion temperature and the toroidal plasma rotation velocity [4]. With this experimental arrangement one obtains only limited information (five points) on the radial profiles of these important plasma parameters, which is not sufficient for detailed comparisons with predictions from modern transport codes. It is, therefore, planned to replace the von Hamos spectrometers by a X-ray imaging crystal spectrometer with a spherically bent crystal and a two-dimensional, position-sensitive detector [1] that would record spectra with a much higher throughput and spatial resolution. However, the lack of appropriate detectors has delayed a realization of this project until now, since the requirements, namely, a single-photon count rate capability of > 500 kHz per mm^2, a spatial resolution of < 0.2 mm, a high detection efficiency for X-ray energies of 3.1 keV, and a large detector area of at least 35 mm x 240 mm, are very challenging. Fortunately, the new PILATUS II detector modules [2,3], which are now becoming available, can satisfy these requirements. The PILATUS II detector modules (see Fig. 2) are semi-conductor pixel arrays of 35 x 85 mm^2 with a pixel size of 0.172 x 0.172 mm^2. The modules are operated at room temperature. Each (hybrid) pixel comprises a preamplifier, a comparator and a counter, so that single-photon counting up to 1 MHz per pixel is possible.

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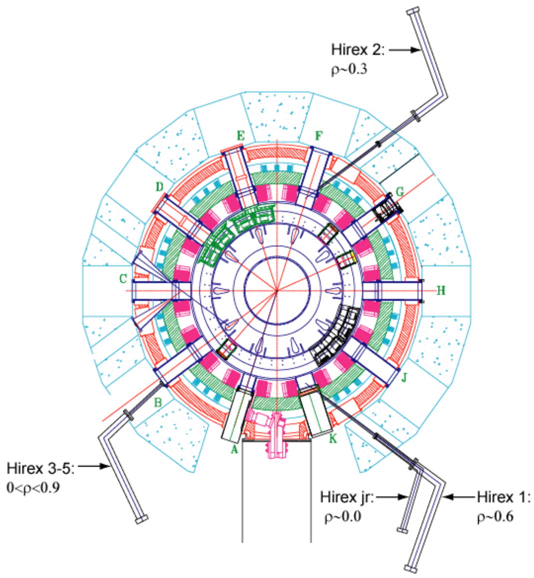

Fig. 1. Top view of the Alcator C-Mod Tokamak with five von Hamos type X-ray crystal spectrometers.

Fig. 2. A Pilatus II detector module

In order to test the performance of these new detectors at X-ray energies of 3.1 keV, a PILATUS II detector module was recently installed on one of the von Hamos crystal spectrometers on Alcator C-Mod. This spectrometer has a 0.1 mm wide entrance slit and a 10 x 50 mm^2 beryllium exit window that serves as a vacuum boundary. The PILATUS II detector module was mounted immediately behind this exit window. An example of the raw spectral data, which were obtained with a PILATUS II detector module from an Alcator C-Mod tokamak discharge, is shown in Fig. 3. The data represent images of the entrance slit at different wavelengths, produced by Bragg reflection from the cylindrically bent crystal in the von Hamos spectrometer. Figure 4 shows an overlay of the spectral data from Fig. 3 with a spectrum recorded by a second von Hamos crystal spectrometer, whose sightline passed through the same plasma volume. This second spectrometer was equipped with a one-dimensional multi-wire proportional counter. To facilitate the comparison of the two spectra, a histogram of the data shown in Fig. 3 was produced which represents the number of photon counts per wavelength interval. The two spectra were also normalized. It is evident from the overlay shown in Fig. 4 that the two spectra are in excellent agreement. This demonstrates that the PILATUS II detector module is very well suited for the detection of X-ray energies as low as 3.1 keV.

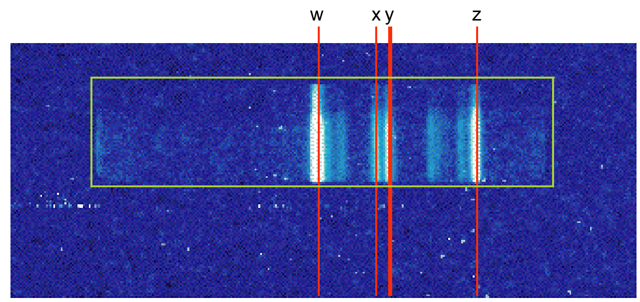

Fig. 3. Raw spectral data obtained with a PILATUS II detector module; w, x, y, and z are x-ray lines of ArXVII at 3.9494, 3.9661, 3.9695, and 3.9944 Å.

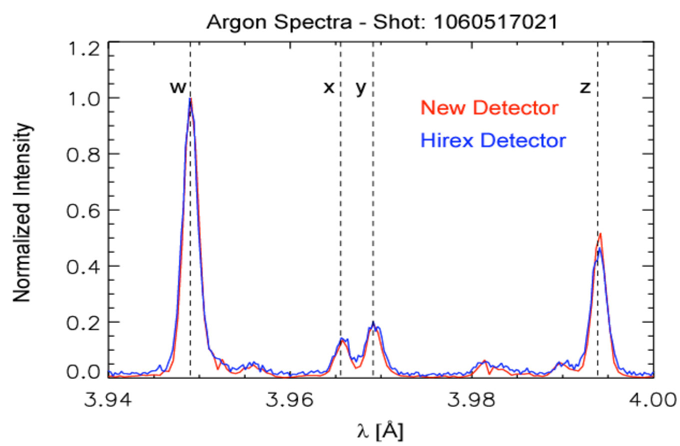

Fig. 4. A comparison of Ar XVII spectra that were recorded with a PILATUS II und a multi-wire proportional counter, respectively.

III. LAYOUT OF A NEW X-RAY IMAGING CRYSTAL SPECTROMETER FOR ALCATOR C-MOD

Based on the results described in the previous section, a new X-ray imaging spectrometer has been designed for Alcator C-Mod. This spectrometer employs two spherically bent (102)- and (110)-quartz crystals, with 2d-spacings of 4.56216 and 4.91304 Å and radii of curvature of 1400 and 1800 mm, and two separate arrays of three and one PILATUS II detector modules, respectively. The (102)-quartz crystal and array of three PILATUS II detector modules will be used to record spectra of helium-like argon, ArXVII, from the entire cross section of the plasma (with an imaging demagnification of 2:1), while the (110)-quartz and single PILATUS II detector module will record spectra of hydrogen-like argon, ArXVIII, from the hot central core of the plasma. The layout of the spectrometer is shown in Figs. 5-7.

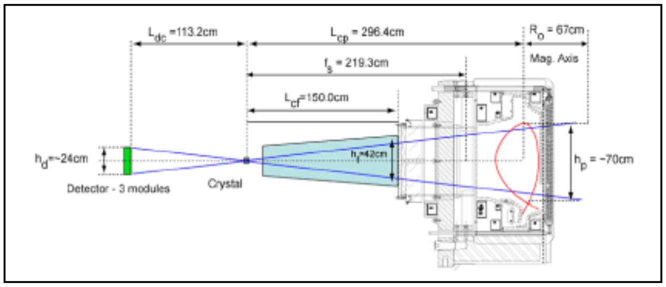

Fig. 5. Side view of the X-ray imaging crystal spectrometer for Alcator C-Mod .

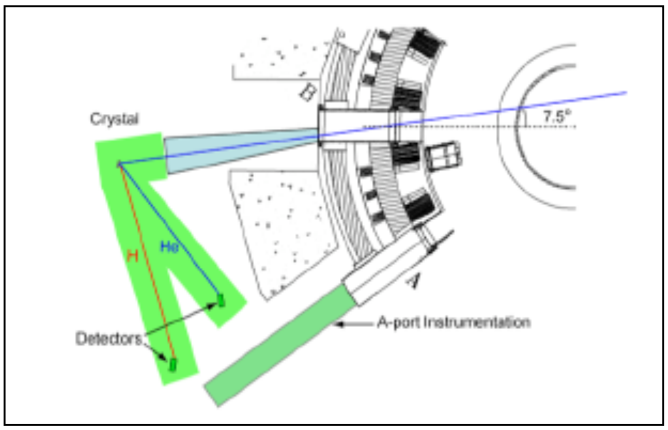

Fig. 6. Top view of the X-ray imaging crystal spectrometer for Alcator C-Mod .

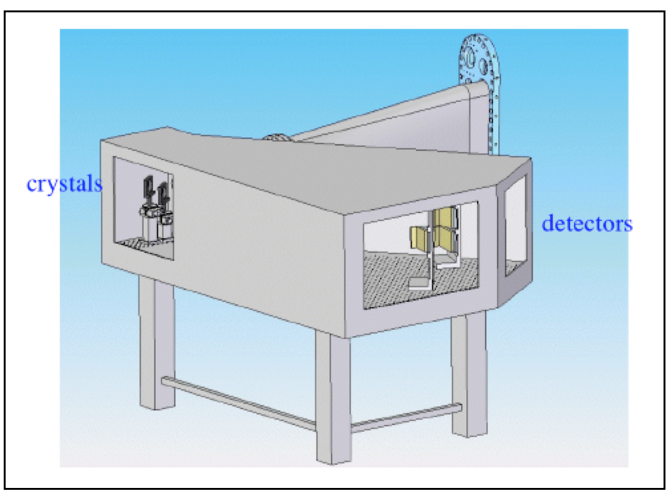

Fig. 7. Spectrometer housing with two spherically bent crystals and two separate detector arrays of three and one PILATUS II modules, respectively.

The spectrometer chamber will be separated from the high vacuum of the Alcator C-Mod tokamak vessel by a 0.001 in. thick, circular, 6 in. diameter, beryllium window, which will be mounted at the end of the conical reducer close to the crystals. The spectrometer housing will be filled with helium at 1 atmosphere to avoid attenuation of the low energy (3 keV) X-rays in air. The expected single-photon count rate is in the range from 10 to 100 kHz per pixel, so that it should be possible to obtain radial profiles of the ion temperature and plasma rotation velocity with spatial and temporal resolutions of 10 mm and 10 ms, respectively.

REFERENCES

[1] M. Bitter, et al., ”Spatially resolved spectra from a new x-ray imaging crystal spectrometer for measurements of ion and electron temperature profiles,” Rev. Sci. Instrum. **75**, 3660 (2004).

[2] Ch. Broennimann, et al., “The PILATUS 1M Detector,” J. Synchrotron Radiation, **13**, 120 (2006).

[3] http://pilatus.web.psi.ch/pilatus.htm

[4] J. E. Rice and E. S. Marmar,”Five-chord high-resolution x-ray spectrometer for Alcator C-Mod,” Rev. Sci. Instrum. **61**, 2753 (1990)

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