

Spatially Resolved Spectra of ArXVI and ArXVII from a New Type of Imaging X-Ray Crystal Spectrometer at TEXTOR-94

M. Bitter¹, G. Bertschinger², W. Biel², G. Fuchs², S. von Goeler¹,
H.-J. Kunze³, D. Rusbüldt², and J. Weinheinmer³

¹ Princeton Plasma Physics Laboratory, Princeton University,
P.O. Box 451, Princeton, New Jersey 08543, USA

² Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, Ass. Euratom-KFA
D-52425 Jülich, Germany, Trilateral Euregio Cluster

³ Institut für Experimentalphysik V, Ruhr-Universität Bochum,
D-44780 Bochum Germany

Introduction

The design of imaging x-ray crystal spectrometers for the diagnostics of extended plasma sources, such as tokamaks, has recently been considered in references 1 and 2. At the heart of these spectrometers is a spherically or toroidally curved crystal, which provides an image of the plasma in a direction perpendicular to the main diffraction plane. In principle, the spectrometers provide an unlimited number of lines of sight through the plasma making it possible to perform very accurate measurements of the radial profiles of crucial plasma parameters, such as the ion temperature, plasma rotation velocity, electron temperature, and the charge-state distribution of impurity ions. The spatial resolution in the plasma is determined by the height of the crystal and also depends on the radii of the crystal curvature and the Bragg angle. For instruments with a high spectral resolution, which is required for Doppler-broadening measurements, the imaging properties are uniform for the entire spectral range due to the fact that the spectral range and corresponding range of Bragg angles are sufficiently narrow. The spherical crystals must have a large area of about 50 cm² and the crystal surfaces must be accurate to within 10 arc sec. In order to project a large cross-section of the plasma onto a detector, an appropriate demagnification is necessary, which is determined by the distance between crystal and detector and the distance between crystal and plasma. Since, for a high-resolution spectrometer, the distance between crystal and detector is of the order of several meters, the distance between crystal and plasma must be even larger, which in turn requires a diagnostic port of adequate height. The detector must have a large area and must be position-sensitive in two directions to provide both spectral and spatial information. Different types of detectors are presently under consideration: stacks of one-dimensionally position-sensitive multi-wire proportional counters, X-ray imaging tubes, and new large flat-panel detectors. The latter detectors are already available for medical imaging, but they have to be adapted to lower x-ray energies, which are of interest for plasma spectroscopy. Although some of these requirements are challenging, imaging x-ray crystal spectrometers offer substantial advantages over the presently used arrays of single-chord x-ray crystal spectrometers, which provide only a very limited number of lines of sight through the plasma. The need for a cross calibration of spectra from different lines of sight is eliminated, since all the spectra are obtained by the same crystal. Compared to an array of crystal spectrometers, an imaging x-ray crystal spectrometer requires less of the precious diagnostic space and only a fraction of the installation and operating costs. Imaging crystal spectrometers have therefore been proposed for NSTX and TEXTOR-94. In this paper, we present recent experimental results from an imaging x-ray crystal spectrometer at TEXTOR-94.

X-ray imaging by a spherically curved crystal.

In addition to providing focusing for the meridional rays, which are parallel to the main diffraction plane, a spherically curved crystal also provides focusing for the sagittal rays, which are inclined to the main diffraction plane. The imaging properties are illustrated in Fig. 1. Rays of a certain wavelength, which are emitted from the plasma and which pass through the focal points F_m and F_s for the meridional and sagittal rays, are Bragg reflected from the crystal and imaged to a point on the detector. The focal lengths f_m and f_s , which correspond to the distances of F_m and F_s from the crystal, depend on the Bragg angle θ and the radius of curvature R_c of the crystal, and they are related by

$$f_s = -f_m / \cos(2\theta) \quad (1)$$

where $f_m = R_c \sin(\theta)$. f_s is positive for $\theta > 45^\circ$, infinite for $\theta = 45^\circ$, and negative for $\theta < 45^\circ$. In the latter case, the focal point F_s is located behind the crystal. For $\theta = 45^\circ$, the incident rays are parallel to the main diffraction plane. The imaging properties are symmetric with respect to a rotation about the normal of the crystal. Shown in Fig. 1 is the x-ray tracing for the rotation angle $\theta = 0$ where F_m and F_s are in the main diffraction plane. The ray tracing for an arbitrary angle of rotation is sketched by the lines in green. The relative size of the arrows is a measure for the demagnification of the image.

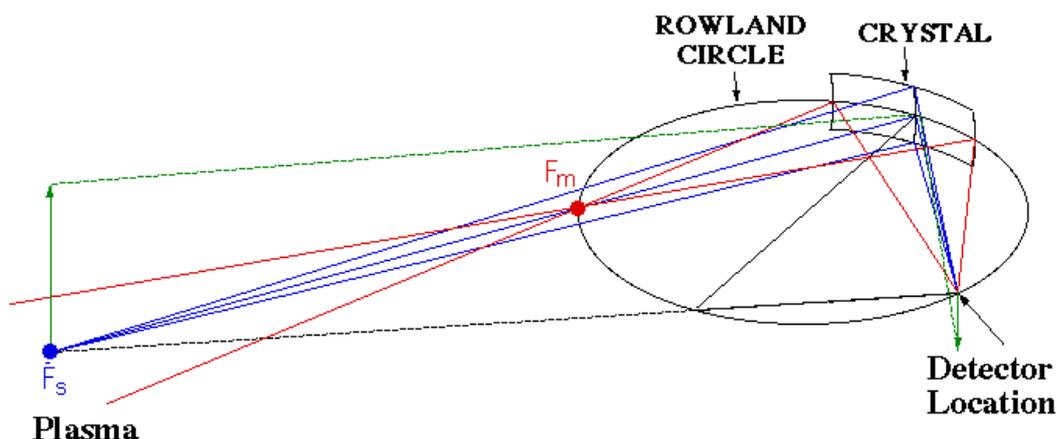


Figure 1: X-ray Imaging by a Spherical Crystal

Experimental results from TEXTOR-94

TEXTOR-94 is equipped with an X-ray polarimeter³, which consists of two Johann crystal spectrometers with diffraction planes parallel and vertical to the horizontal mid-plane of TEXTOR-94. The polarimeter records spectra of heliumlike argon, ArXVII, in the wavelength range from 3.94 to 4.0 Å, which includes the resonance line w , $1s^2 S_0 - 1s2p^1 P_1$ at 3.9494 Å and the forbidden line z , $1s^2 S_0 - 1s2^3 S_1$ as well as the lithiumlike satellites $1s^2 nl - 1s2pnl$ with $n \geq 2$. Both spectrometer arms usually operate with cylindrically bent (110)-quartz crystals with a 2d-spacing of 4.913 Å. The size of these crystals is 150 mm x 38 mm x 0.76 mm. The radius of curvature of the crystal in the horizontal spectrometer is 378 cm, and the distances between crystal and detector and between crystal and plasma are 305 cm and 437 cm, respectively. The detector is a multi-wire proportional counter with a sensitive volume of 180 mm x 90 mm x 12 mm, which is position-sensitive in the long dimension. The spatial resolution of the detector is 0.4 mm, resulting in a spectral resolution of $\Delta\lambda/\lambda = 7000$ for the horizontal spectrometer. The Bragg angles are in the narrow range from 53.5° to 54.4°. The spectrometer is very sensitive. In order to limit the count rate, crystal and detector had to be partially covered. The exposed areas of the crystal and detector are 70 x 10 mm² and

20 x 180 mm², respectively. Count rates of 2×10^5 photons/s corresponding to the count rate limit of the detector can be obtained with small argon gas puffs of 1×10^{-3} Torr Liter/s, under normal operating conditions of TEXTOR-94. The diagnostic port is rectangular, 100 mm (wide) x 160 mm (high) and is at a distance of 290 cm from the crystal, so that - at the center of the tokamak - a plasma cross-section with the height of 24 cm can be observed. In January 1999, the cylindrically bent crystal was replaced by a spherically curved 110-quartz crystal with a size of 100 x 40 mm² and a radius of curvature of 385 cm. Optical tests of the spherically curved crystal had shown that the size of the focus was 0.7 mm FWHM, while the width of the optical focus of the cylindrically bent crystal was 0.2 mm FWHM. The spectral resolution of the spherical crystal can thus not be better than 3800. Figure 2 shows two spectra which were recorded with the spherically and the cylindrically curved crystals from a central line of sight through the plasma for time intervals from 4.0 to 4.4 s and from 1.2 to 2.2 s, respectively, from two nearly identical discharges, #81416 and #81161.

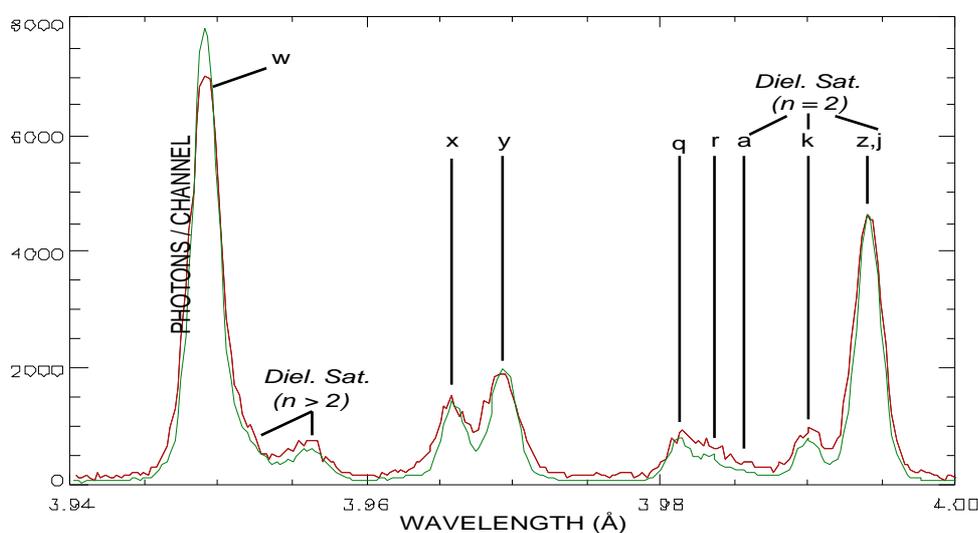


Figure 2: Spectra with a spherical (*red*) and cylindrical (*green*) crystal

For a better comparison, the spectra have been normalized to each other using the line **z**. Applying instrumental corrections only for the finite spatial resolution of the detector and neglecting focusing errors due to errors of the crystal curvature, one obtains different values for the ion temperature of 1.20 keV for the cylindrical crystal and 1.73 keV for the spherical crystal. Apart from the differences in spectral resolution, the spectra are in good agreement. Taking differences in the integration times and the size of the argon gas puffs into account, it is found that the spherically curved crystal provides an intensity enhancement in proportion to the area of the crystal. So far, only a few measurements were taken from non-central radial chords by moving the multi-wire proportional counter up and down by ± 4 cm and $+8$ cm between discharges, # 83039 - # 83047. Some of the spectral lines were blocked by the structure of the exit window to the detector due to the fact that this window had been reoriented for another experiment. However, the intensity of the line **z** was observed and found to vary from 7.33 at -4.0 cm to 8.33 at 0 cm, to 7.91 at $+4.0$ cm, and to 2.83 at 8.0 cm. To test the use of x-ray imaging tubes as 2D detectors, spatially resolved spectra of ArXVI and ArXVII were taken with the X-ray imaging tube from the soft X-ray camera⁴ at TEXTOR-94 which

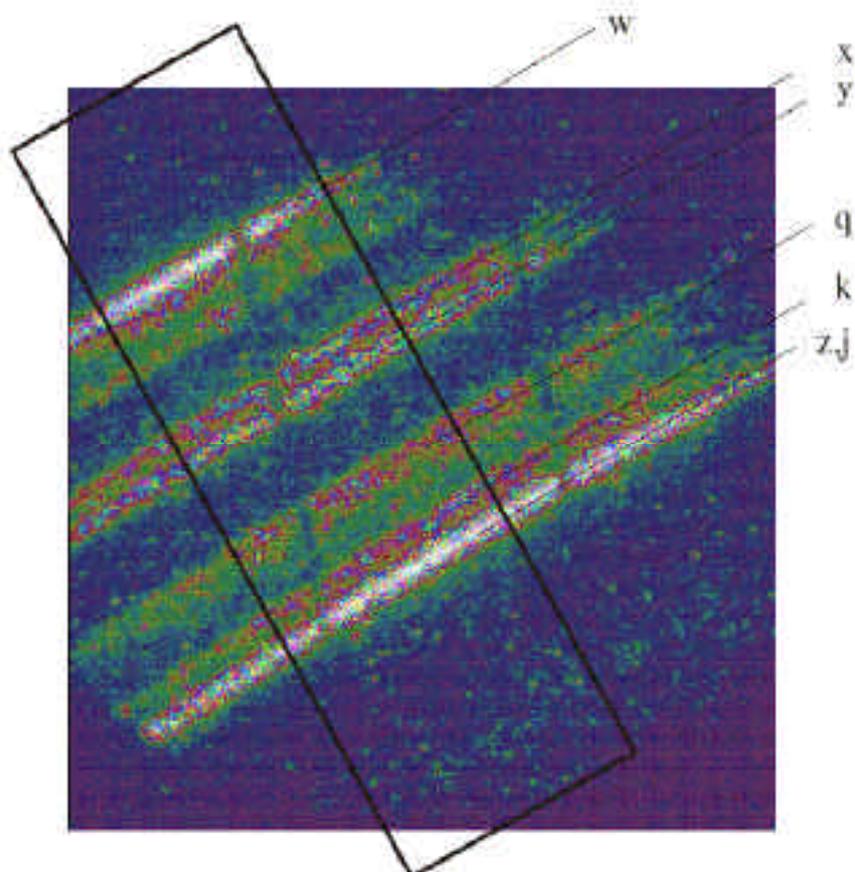


Figure 3: Two-dimensional Spectrum of ArXVI and ArXVII

was temporarily installed as detector for the X-ray crystal spectrometer. The X-ray imaging tube had a time resolution of 16 ms. An example of the observed two-dimensional spectra is shown in Fig. 3. The spectrum was taken with the cylindrically bent crystal, since the spherically curved crystal was not available at the time. The spectral lines shown in Fig. 3 are well separated and spatially resolved in the perpendicular direction. These measurements demonstrate that x-ray imaging tubes can be successfully used as a two-dimensional detector for imaging x-ray crystal spectrometers. Experimental tests of different types of two-dimensional detectors and more detailed measurements of the radial profiles of plasma parameters with the spherically curved crystal are planned.

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