Review of Scientific Instruments

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Citation: Rev. Sci. Instrum. **75**, 3734 (2004); doi: 10.1063/1.1781373
View online: http://dx.doi.org/10.1063/1.1781373
View Table of Contents: http://rsi.aip.org/resource/1/RSINAK/v75/i10
Published by the American Institute of Physics.

REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 75, NUMBER 10 OCTOBER 2004

A high-resolution soft x-ray spectrometer on the MAST tokamak

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(Presented on 20 April 2004; published 6 October 2004)

A curved crystal spectrometer in Johann configuration has been implemented on MAST to obtain values for electron temperature, ion temperature and toroidal velocity. The spectrometer is used to examine medium Z impurities in the soft x-ray region by utilising a Silicon (111) crystal, bent using a 4 pin bending jig, and a CCD detector ($\Delta t = 8$ ms). Helium-like Argon emissions from 3.94 to 4.00 Å have been examined using a crystal radius of 859.77 mm. The Bragg angle and crystal radius can be adjusted with relative ease. The spectrometer can be scanned toroidally and poloidally to include a radial view which facilitates absolute velocity measurements by assuming radial velocity =0. Doppler shifts of 2.3×10^{-5} Å (1.8 kms^{-1}) can be measured. The line of sight is shared with a neutral particle analyzer, which enables *in situ* ion temperature comparisons. Ray tracing has been used for the development of new imaging spectrometers, using spherical/toroidal crystals, planned to be implemented on MAST. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1781373]

I. INTRODUCTION

High resolution spectra from medium Z Helium-like ions provide a means of diagnosing dense high temperature plasmas such as those produced in fusion experiments.[1] Such spectra are widely used to measure electron temperature (T_e), ion temperature (T_i) and rotational velocity (V). Soft x-ray crystal spectroscopy is a method of measuring these parameters with spatial resolution being provided by the use of doubly curved crystals.[2] This instrument is part of a program to develop an ITER-relevant spatially resolving crystal spectrometer. It is the first stage of this program and uses a Johann[3] spectrometer design developed on JET[4] to view the He-like spectra of Argon[5] using a Peltier-cooled CCD. It is extremely compact and acts as a periscope in the line of sight of a toroidally and poloidally scanning neutral particle analyzer (NPA) and produces spectra that are a model of the spatial resolution one would expect from a doubly curved crystal spectrometer.

A second instrument using spherically curved crystals, soon to be implemented on MAST will be a model of a spectrometer proposed for ITER.[6] Because of access restrictions on ITER there is an advantage in using toroidal crystals and we have plans to test these as well.

In this paper we present the compact instrument, THEMIS and discuss ray-tracing results of the existing instrument and new designs featuring doubly curved crystals planned for MAST.

II. THE CYLINDRICALLY CURVED CRYSTAL SPECTROMETER

A schematic of the instrument is shown in Fig. 1. The instrument has been setup to observe He-like Argon (Ar^{16+}) in the wavelength range 3.94–4.00 Å using a Silicon (111) crystal and a Bragg angle $\theta_B = 39.25°$. The Ar^{16+} spectrum is characterised by four main lines labeled w, x, y, and z and several satellite lines, k, j, q, and r being the principle and has been intensively studied in the past.[7]

The crystal was bent to a radius of $R = 2r = 859.77$ mm, using a four pillar bending jig, Fig. 2. The crystal bending jig is capable of bending the crystal to an arbitrary radius, within its own elastic limit. The crystal sits between the outer and inner pillars (2) and differential pressure, applied to the outer pins by four micrometer screws (3), bends the crystal. The jig is mounted on a rotary table (5) with a twelve arc minute Vernier scale (4). It is extremely compact and is designed to fit through a 65 mm diameter aperture, to be placed in the line of sight of another instrument and act like a periscope.

The crystal bending jig sits in the flight line of the NPA which has a poloidal and toroidal scanning mechanism capable of accessing both radial and tangential views. The spectra observed with the radial line of sight are used for a zero velocity reference giving the possibility to measure absolute velocities.

The flight line needs to be open to MAST and, therefore, requires $P < 10^{-8}$ mbar. A 75 μm, 20 mm diameter Beryllium window has been incorporated into a valve. It blocks visible light from the detector and separates the higher vacuum of the flight line from the lower vacuum in the detector chamber ($P = 10^{-2}$ mbar). The valve has been tested up to 1.5 atmospheres and allows alterations in the detector position and alignment while ensuring that the sightline remains in a high vacuum.

As both the crystal and the detector must sit on the Rowland circle (r), the crystal radius (R) is determined by the instrument design and the Bragg angle being used. The de-

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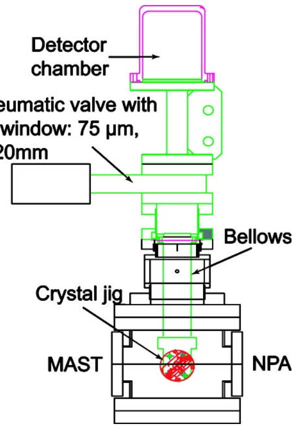

FIG. 1. (Color online) A schematic of the spectrometer showing the crystal jig in the line of sight of the NPA, the hinged bellows assembly, the Beryllium window and the detector chamber.

tector is mounted on a sliding table so that the crystal to detector distance (R sin θ_B) can be varied by ±11 mm for fine adjustment of the detector position.

The detector arm is mounted on a hinged bellows assembly with 48° rotation, see Fig. 1. This allows for the alignment of the instrument with respect to the line of sight for a range of Bragg angles, $45° \pm 12°$. The flight line, including the bending jig and crystal, must be baked at temperatures of approximately 100 °C for up to 24 h. The focusing set in the laboratory must be stable to such conditions, as *in situ* focusing can not be carried out once the crystal is in the flight line. Extensive thermal stability tests were carried out prior to installation and the focus was found to be resilient to such conditions. It is also worth noting that the baking tests were not carried out *in situ* and the crystal focus was also stable to being manhandled and moved between laboratories.

The detector is a CCD array of 1040×256, 26 μm square pixels. It is Peltier-cooled and the water cooling passages for the Peltier system are not exposed to the vacuum. The integration time with no binning is about 2 s, which is useful to check the alignment but for routine plasma measurements higher time resolution is required. $\delta t = 8$ ms is achieved by using a vertical binning technique, were the pixel charges for the whole chip are binned into one row and then read out.

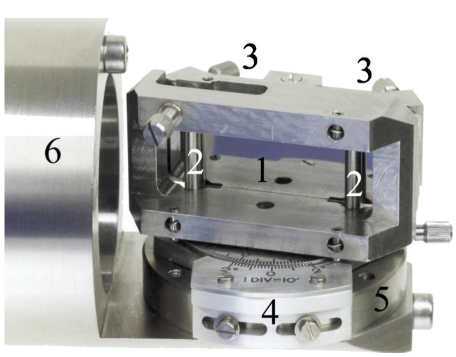

FIG. 2. (Color online) The crystal bending jig with crystal (1), pillars (2), micrometer screws (3), Vernier scale (4), rotary table (5), and output collimator (6).

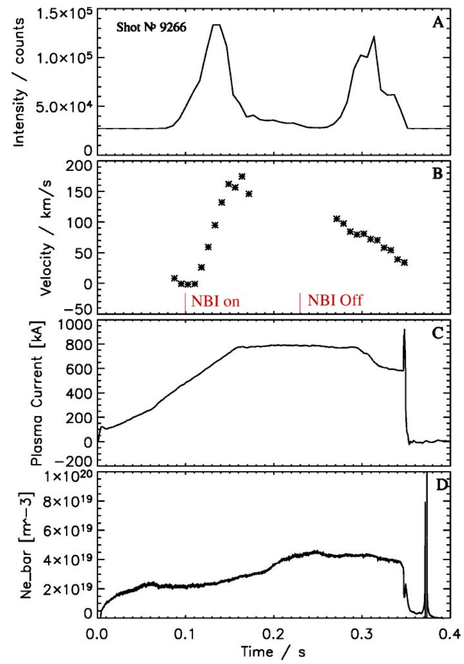

FIG. 3. (Color online) Typical rotations seen on the Argon spectra of an NBI heated plasma. (A) Spectral intensity. (B) Acceleration is seen when NBI begins and deceleration at a slower rate is observed when NBI finishes, no measurement are made when the intensity is low. (C) Plasma current. (D) Plasma density.

III. EXPERIMENTAL DATA

Spectra have been analysed using a routine that fits the Argon spectra with a pseudo-Voigt function[8] to allow for the fact that some of the contributions to the line width may be Lorentzian.

A typical set of spectral data and the corresponding pseudo-Voigt fit, for a neutral beam injection (NBI) heated plasma, is shown in Fig. 4. In total ten lines have been fitted. The two data sets show the spectra at different times. The Doppler shift of the two spectra corresponds to blue shifts (co-current rotations) of 224.8 and 132.6 ± 2 kms^{-1} with respect to spectra taken with a purely radial line of sight. The fitting routine allows shifts of as little as a tenth of a pixel to be observed, corresponding to 1.8 kms^{-1}. The additional error introduced by the finite accuracy of the zero velocity measurement of radially viewed spectrum is also of this order. Figure 3 shows the rotation measured from the Doppler shift of a He-like Argon spectra in an NBI heated MAST discharge.

Theoretically the pseudo-Voigt function used in our fitting routine should return values for the spectral line width and its Lorentzian contribution. However, it was found that the Lorentzian contribution was consistently very small. Therefore, it is reasonable to assume that the entire spectral width was Gaussian and could be expressed as an equivalent ion temperature. $T_I = (Mc^2/k_B 8 \ln 2)(\Delta\lambda^2/\lambda^2) - T_0$ where the thermal ion temperature T_I is in K, M is the ion mass in kg and T_0 is the known instrument resolution in terms of temperature. T_0 is composed of the following factors. The natural line width and Johann aberrations of 1×10^{-3} Å, which are calculated from ray tracing results (see Sec. IV for details). A tilt of 1.6° in the detector, measured from the two-

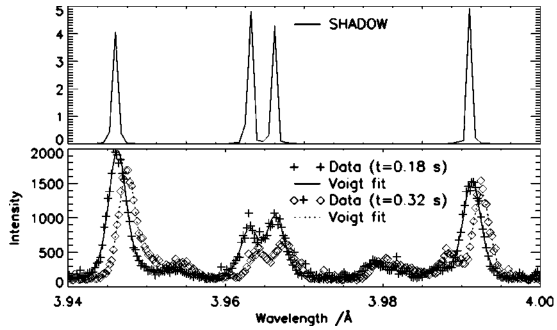

FIG. 4. The fitting of spectral data with a Voigt function at two different time slices. The Doppler shift is clearly seen.

dimensional (2D) image, adds a width equivalent to 1.16×10^{-3} Å after vertical binning. These give a combined T_0 of 0.7 keV. However, comparisons with the NPA ion temperature measurement show that the actually $T_0 = 2$ keV, therefore, it is assumed that the spectrometer is defocused by 2.1×10^{-3} Å or 1.7 keV. The ion temperature measurements from the spectrometer, show the same changes in temperature as the NPA. The two spectra shown in Fig. 4 correspond to a change in the impurity ion temperatures of 0.16 ± 0.01 keV between $t = 0.18$ s and $t = 0.32$ s which is in good agreement with measurements from the NPA.

The spectral line intensities can be fitted to an accuracy of 1%. For Fig. 4 the k/w ratios are 0.068 $(t = 0.18\ \mathrm{s}))$ and 0.235733 $(t = 0.32\ \mathrm{s})$ corresponding to electron temperatures of 1.4 ± 0.3 keV and 0.8 ± 0.1 keV. These temperatures are in good agrement with Thomson scattering data. The accuracy of the atomic data used to calculate the electron temperature is the limiting factor for the temperature calculations.[11]

IV. RAY-TRACING

Figure 4 shows the simulated diffraction of Ar 16+lines *w*, *x*, *y*, and *z*, respectively, with a SHADOW[9] ray tracing setup of the THEMIS parameters. A single Gaussian source containing these four lines in equal intensities was placed on the plasma side of the Rowland circle. The image, also on the Rowland circle, shows the diffraction pattern which gives the theoretical instrument function of 1×10^{-3} Å and resolving power $\lambda / \delta\lambda = 4000$ for the whole instrument compared to the crystal resolving power of 7000 Å.

THEMIS is being used both for diagnostic purposes but also to help develop an imaging crystal spectrometer. The principle of spherical astigmatism can be exploited in x-ray crystal spectroscopy.[10] A point source will produce two mutually perpendicular line images, the tangential focus (on the Rowland circle) and the sagittal focus (orthogonal to the tangential and at a different position along the input axis). It follows that a line of plasma at the sagittal focus can be imaged onto one point on the detector and other lines of plasma, parallel to the sagittal focus, can be imaged onto points above or below the original point on the detector. This allows a large number of radial or poloidal chords to be viewed simultaneously with a single crystal and detector.

A spherical crystal with Bragg angle less than 45° gives a virtual image (this is not a constraint for a toroidally curved crystal). Therefore, the 2*D* value for the crystal must be less than 5.61 Å to view the He-like Argon spectra. Using SHADOW several different crystal types were tested for suitability. Of the possible crystals, α-quartz was chosen as it is widely used[2] and ray tracing of the rocking curves showed that α-quartz has a higher reflectivity at this wavelength than other possible crystal choices such as ADP. Experimental and modeled emission profiles show that in a typical NBI-heated, H-mode, MAST plasma, Helium-like Argon emissions become negligible at a major radius of 1.25 m. Plasma imaged through the emission region up to this radius can be investigated with SHADOW and used to calculate the spatial resolution of the spectrometer as 0.65 cm. Initially a 12 mm CCD will be used until a larger detector is purchased and with a magnification of 3.4, 4 cm of plasma will be imaged with a spatial resolution of 0.65 cm.

ACKNOWLEDGMENTS

This work has been jointly funded by EURATOM and the UK Engineering and Physical Sciences Research Council.

[1] E. Kallne, J. Kallne, Phys. Scr. **31**, 551 (1985).
[2] M. Bitter, K. W. Hill, A. L. Roquemore, P. Beiersdorfer, S. M. Kahn, S. R. Elliot, and B. Fraenkel, Rev. Sci. Instrum. **70**, 1 (1999).
[3] H. H. Johann, Z. Phys. **69**, 185 (1931).
[4] R. Barnsley, N. J. Peacock, J. Dunn, I. M. Melnick, I. H. Coffey, J. A. Rainnie, M. R. Tarbutt, N. Nelms, Rev. Sci. Instrum. **74**, 2388 (2003).
[5] M. R. Tarbutt, R. Barnsley, N. J. Peacock, J. D. Silver, J. Phys. B **34**, 3979 (2001).
[6] R. Barnsley and M. O'Mullane, Rev. Sci. Instrum., these proceedings.
[7] E. Kallne, J. Kallne, and A. K. Pradhan, Phys. Rev. A **28**, 467 (1983).
[8] G. K. Wertheim, M. A. Butler, K. W. West, D. N. E. Buchanan, Rev. Sci. Instrum. **45**, 1369 (1974).
[9] M. Sanchez del Ro, R. J. Dejus, SPIE proceedings, 3448 (1998).
[10] F. Blasco, C. Stenz, F. Salin, A. Ya. Faenov, A. I. Magunov, T. A. Pikuz, I. Yu Skobelev, Rev. Sci. Instrum. **72**, 4 (2001).
[11] M. Bitter *et al.*, Phys. Rev. Lett. **91**, 26 (2003).