Imaging x-ray crystal spectrometers for the National Spherical Torus Experiment

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A new type of high-resolution x-ray imaging crystal spectrometers is described for implementation on the National Spherical Torus Experiment (NSTX) to provide spatially and temporally resolved data on the ion temperature, toroidal and poloidal plasma rotation, electron temperature, impurity ion-charge state distributions, and impurity transport. These data are derived from observations of the satellite spectra of heliumlike argon, Ar XVII, which is the dominant charge state for electron temperatures in the range from 0.4 to 3.0 keV and which is accessible to NSTX. Experiments at the Torus Experiment for Technology Oriented Research (TEXTOR) demonstrate that a throughput of 2×10^5 photons/s (corresponding to the count-rate limit of the present detectors) can easily be obtained with small, nonperturbing argon gas puffs of less than 1×10^{-3} Torr ℓ/s, so that it is possible to record spectra with a small statistical error and a good time resolution (typically 50 and 1 ms in some cases). Employing a novel design, which is based on the imaging properties of spherically bent crystals, the spectrometers will provide spectrally and spatially resolved images of the plasma for all experimental conditions, which include ohmically heated discharges as well as plasmas with rf and neutral-beam heating. The conceptual design, experimental results on the focusing properties, and relevant spectral data from TEXTOR are presented. © *1999 American Institute of Physics.* [S0034-6748(99)60301-X]

I. INTRODUCTION

High-resolution x-ray spectroscopy has made significant contributions to the diagnostics of plasmas by providing data on the ion and electron temperature, plasma rotation, ionization equilibrium, and ion transport.[1–4] These data are, in general, derived from the spectra of the heliumlike ions of medium-Z elements like argon, titanium, chromium, iron, and nickel, which exist in tokamak plasmas as indigenous impurities or which are injected as trace elements, by laser ablation or gas puffs. The spectra of heliumlike ions, like Ar XVII or Fe XXV, are available for the diagnostics of tokamak plasmas with a large variety of experimental conditions, which include ohmically heated plasmas as well as plasmas with rf and neutral-beam heating. This is due to the fact that the heliumlike charge state is the predominant charge state of medium-Z elements, for plasma electron temperatures in the range from 1 to 10 keV. The accuracy of x-ray crystal spectroscopy is still unsurpassed by other diagnostic methods; and the data which were obtained from hot tokamak plasmas with high-resolution x-ray crystal spectrometers have been invaluable for both an experimental verification of detailed predictions from atomic theories and a comparison with spectral data from solar flares.[5] Recent studies have shown that heliumlike spectra can also serve as a diagnostic for the electron energy distribution. This adds novel dimensions to the physical parameters that can be inferred from high-resolution x-ray measurements and is especially important for studies of current-drive and profile modification experiments as well as for electron heating experiments.[6,7] These features and the fact that the instrumental equipment is relatively inexpensive make x-ray crystal spectroscopy also attractive as a diagnostic for spheromacs. In fact, the installation of several crystal spectrometers is planned for the experiments COMPASS and MAST at Culham.[8]

In this article, we describe the principles of a new type of imaging x-ray crystal spectrometers which are based on the imaging properties of spherically bent crystals. The advantages of this approach are that:

(1) a large number (in principle an unlimited number) of radial chords can be observed with only one spherically bent crystal,

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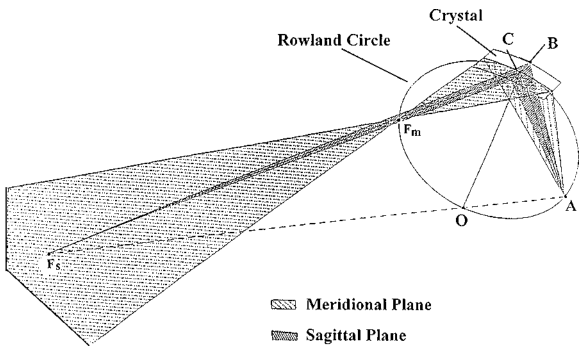

FIG. 1. Illustration of the imaging properties of spherically bent crystals.

(2) a significant enhancement of the throughput is obtained—compared with cylindrically bent crystals. Used in tandem, two such spectrometers will enable the measurement of the polarization of the emitted lines.[9] From the x-ray line polarization, deviations from the thermal electron distribution can be inferred.[10] This is of particular importance for NSTX where the emphasis on the study of plasmas with noninductive current drive and rf heating.

II. INSTRUMENTAL DESIGN

A. Imaging properties of spherical crystals

The instrumental design is based on numerical studies[11–13] as well as laboratory tests[14] of the imaging properties of spherical and toroidally bent crystals in a Johann geometry.[15] The Johann geometry offers advantages for extended plasma sources due to the fact that (1) a high throughput can be obtained, since the instrument does not require a slit and (2) a range of spectral lines is measured simultaneously. Moreover, each spectral line is reflected from the entire crystal, so that accurate measurement of line ratios can be performed.

The standard Johann spectrometer operates with a cylindrically bent crystal and provides only focusing for the meridional rays parallel to the diffraction plane, while the sagittal rays, which are oblique to the diffraction plane, are not focused. Focusing of the sagittal rays, and therefore imaging of the plasma, can be obtained with spherically or toroidally bent crystals. The focal lengths $\mathbf{f_m}$ and $\mathbf{f_s}$ of the meridional and sagittal rays are related by

$$\mathbf{f_s} = -\mathbf{f_m}/\cos(2\Theta) \tag{1}$$

with $\mathbf{f_m} = R_c \sin(\Theta)$, where Θ is the Bragg angle and R_c is the radius of curvature of the crystal. The imaging properties of a spherical crystal are illustrated in Fig. 1. Focusing of the sagittal rays is obtained for $\Theta > 45°$. For $\Theta < 45°$, the rays are divergent. For $\Theta = 45°$, the sagittal rays are parallel.

For the case of $\Theta = 45°$, it is possible to focus a bundle of parallel (sagittal) rays that emerges from the plasma to a point—the point A in Fig. 1—on the Rowland circle. A bundle of parallel (sagittal) rays that is oblique to the diffraction plane is focused to a point above or below the central diffraction plain. The case of $\Theta = 45°$ is of particular interest for plasma imaging. The height of the cross section of the plasma that is imaged to a point on the detector is given by the height of the crystal.

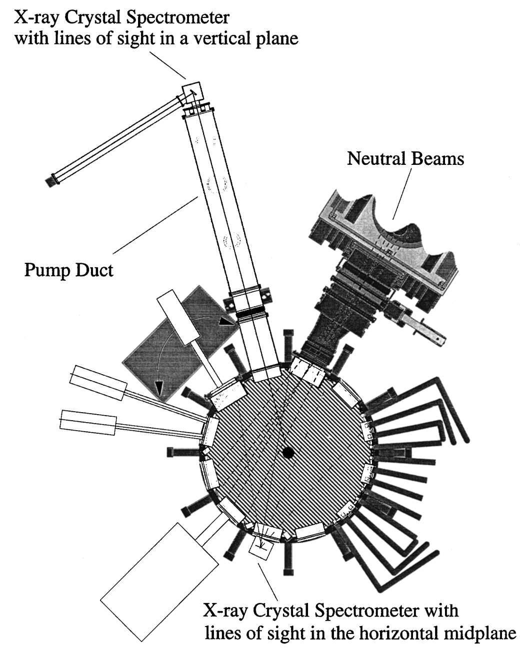

FIG. 2. Experimental arrangement of the NSTX horizontal and vertical x-ray crystal spectrometers.

B. Experimental arrangement

Figure 2 shows the experimental arrangement of the two x-ray crystal spectrometers at NSTX. One spectrometer, the so-called horizontal NSTX crystal spectrometer, is located at the end of the NSTX pump duct. Its central diffraction plane is parallel to the horizontal midplane of NSTX. This spectrometer provides spatial resolution in a plane perpendicular to the horizontal midplane with the lines of sight shown in Fig. 3.

Also shown in Fig. 2 are the lines of sight of a second spectrometer (the vertical NSTX x-ray crystal spectrometer) which provides spatial resolution in the horizontal midplane of NSTX. In addition to the above-mentioned applications for polarization measurements, this spectrometer would be of

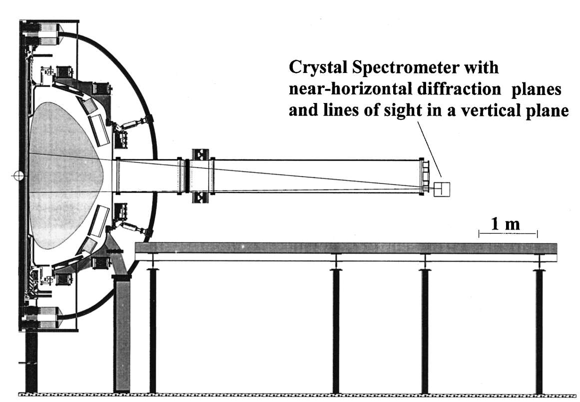

FIG. 3. Vertical cross section of NSTX showing the lines of sight of the horizontal x-ray crystal spectrometer.

special interest for measurements of the toroidal plasma rotation in experiments with neutral-beam heating, since one half of the lines of sight intersects the neutral-beam lines. One should expect to find a blueshift for these lines of sight, whereas a redshift should be observed for the other half of sight lines. A NSTX port has not yet been allocated for this spectrometer.

C. Layout of the NSTX horizontal x-ray crystal spectrometer

The layout of the NSTX horizontal x-ray crystal spectrometer corresponds to the layout of the x-ray crystal spectrometer at the Torus Experiment for Technology Oriented Research (TEXTOR 94),[16] except that the cylindrically bent crystal will be replaced by a spherically bent crystal. The spectrometer at TEXTOR 94 was built in a collaboration between the Princeton Plasma Physics Laboratory, the Institut für Plasmaphysik in Jülich, and the University of Bochum. Parts of the spectrometer at TEXTOR 94 (crystal, detectors, and electronics) are components of the former Tokamak Fusion Test Reactor (TFTR). Components of the former TFTR spectrometers will also be used for the NSTX spectrometer.

The NSTX horizontal crystal spectrometer will be equipped with a spherically bent (1120) quartz crystal with a $2d$ spacing of 4.913 Å. The crystal will be 3 cm high and 7 cm wide and the radius of curvature 378 cm. The spectrometer will record spectra of Ar XVII in the wavelength range from 3.94 to 4.0 Å, which includes the resonance line **w**, $1s^2\ {}^1S_0 - 1s2p\ {}^1P_1$ at 3.9494 Å, and the forbidden line **z**, $1s^2\ {}^1S_0 - 1s2p\ {}^3S_1$, at 3.9944 Å. Ar XVII was chosen because it is the dominant charge state over a wide range of NSTX plasma conditions. The crystal-detector distance is 305 cm for the mean Bragg angle, $\Theta = 53.95°$, to obtain a spectral resolution of $\lambda/\Delta\lambda = 6000$.

Since the Bragg angles are close to 45°, the imaging properties, which were described at the end of Sec. II A, nearly apply. If we insert for $\mathbf{f_m}$ in Eq. (1) the value for the crystal-detector distance of 305 cm, we obtain $\mathbf{f_s} = 1000$ cm. The sagittal rays are therefore slightly convergent (or almost parallel) in the plasma volume that extends up to the NSTX central column.

All the rays which contribute to a spectrum on the detector are emitted from the plasma volume that extends up to the NSTX central column. This is assured by the fact that the distance between the focal points for the lines **w** and **z** on the Rowland circle is 4.7 cm and that the width of the crystal, which determines the divergence of the rays in the diffraction plane, is 7 cm.

D. Detectors

The NSTX horizontal spectrometer requires a two-dimensional, position-sensitive detector. The length of the detector in the direction, which provides the spectral information, should be about 6 cm to accommodate the lines **w** and **z**, which are 4.7 cm apart. The height of the detector in the direction that provides the information on the spatial distribution of plasma parameters should be about 20 cm to match the height (about 60 cm) of the plasma cross section that is visible through the pump duct. The following types of detectors are presently considered.

1. Multiwire proportional counters

Multiwire proportional counters from the former TFTR x-ray crystal spectrometers will be used for the initial operation of the NSTX spectrometer. These detectors have a photon-sensitive volume of $18\ \text{cm} \times 9\ \text{cm} \times 1.2\ \text{cm}$ and are position sensitive in only one (the 18 cm long) dimension. For the first experiments, the detector will be covered by a plate with a rectangular aperture of $6\ \text{cm} \times 1\ \text{cm}$. The plate will be moved in the vertical direction to measure the throughput from different radial chords. These experiments will define the useful height of a two-dimensional detector, which may be less than 20 cm.

Multiwire proportional counters can, in principle, be operated as two-dimensional detectors by making use of the signals from the anode wires. However, it may then be difficult to optimize the dynamic range of the system. A better solution would be obtained with a stack of small multiwire proportional counters of about $6\ \text{cm} \times 1\ \text{cm}$. Such small detectors could be optimized with regard to both count rate capability and position resolution; a count rate capability of 1×10^6 photons/s and a position resolution of 0.2 mm is achievable with a delay-line readout system. The position resolution of 0.2 mm represents an improvement by a factor of 2 over that of the presently used detector from TFTR, and it would offer the following advantages:

(1) The size of the spectrometer could be reduced by a factor of 2, maintaining same spectral resolution, and
(2) the height of a two-dimensional detector could then also be reduced by a factor of 2, since the height of the plasma image on the detector would decrease in proportion with the length of the crystal-detector arm.

2. Microchannel-plate detectors

Microchannel-plate detectors have also been developed for use with crystal spectrometers. Coupled with a phosphor screen and a photodiode-array readout such detectors have been successfully used to make high-resolution images of soft x-ray spectra on the pulsed laser treatment (PLT) tokamak.[2] Equipped with a wedge and strip anode plane microchannel plates serve as position-sensitive single-photon detectors similar in performance to multiwire proportional counters. Their use has been demonstrated, for example, to record high-resolution soft x-ray spectra on the Livermore electron beam ion trap facility.[17] The quantum efficiency of microchannel detectors was found to be lower than gas proportional counters, but because microchannel plates can be made rather large, such detectors could also be adapted for use on the NSTX x-ray spectrometers.

3. X-ray imaging tubes

X-ray imaging tubes with a photosensitive area of $10 \times 10\ \text{cm}^2$ are manufactured by Hamamatsu for medical imaging. These tubes are also applicable for plasma

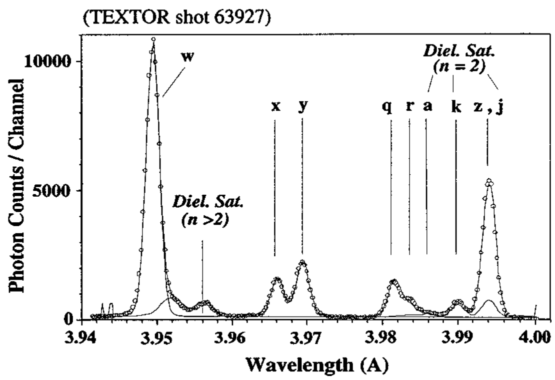

FIG. 4. Dielectronic satellite spectrum of Ar XVII. The data were obtained with the x-ray crystal spectrometer at TEXTOR 94 from a discharge with neutral-beam heating, shot: 63927.

diagnostics.[18] A Hamamatsu tube will be temporarily installed in the x-ray crystal spectrometer at TEXTOR 94 to test its performance as a detector for the spectra of Ar XVII at 3 keV.

4. Flat-panel detectors

New types of solid state detectors, so-called flat-panel detectors, have been developed by Rowlands and Kasap[19] and by EG&G for medical imaging. The detectors consist of an active matrix array of thin film transistors and a layer of *amorphous* selenium or silicon. They can therefore be manufactured in large sizes of 40 cm×40 cm. The detectors operate at x-ray energies of 60 keV. Flat-panel detectors with a good signal-to-noise ratio for lower energies would have to be developed.

III. EXPECTED PERFORMANCE BASED ON EXPERIMENTAL RESULTS FROM TEXTOR 94

Since the plasma parameters (electron temperature and electron density) and the plasma volumes of NSTX and TEXTOR 94 are similar, we expect that the performance of the x-ray crystal spectrometers at these two machines will be comparable. The x-ray crystal spectrometer at TEXTOR 94 is sensitive to small concentrations of argon so that a throughput of 2×10^5 photons/s—corresponding to the maximum count rate capability of the detector—is typically obtained with argon–gas puffs of less than 1 mTorr ℓ/s.

Figure 4 shows a spectrum of Ar XVII, which was obtained from the TEXTOR 94 discharge 63 927. The data were accumulated for the time of neutral-beam heating from 2 to 3 s. The active area of the cylindrically bent (1120)—quartz crystal was 7 cm×3.8 cm. The photon flux was collimated by a beryllium window (size: 10 cm×3.2 cm) on the vacuum vessel of TEXTOR 94 and the entrance window (size: 18 cm×2 cm) of the detector. [The (18 cm×9 cm) entrance window of the detector was covered except for an area of 18 cm×2 cm.] A count rate near 2×10^5 photons/s was obtained under these conditions as can be inferred from Fig. 4.

Also shown in Fig. 4 is a synthetic spectrum (solid line) which represents a least squares fit of theoretical predictions[20] to the experimental data. The values for the ion and electron temperatures obtained form the fit are 1.9 and 1.65 keV, respectively. These values are in good agreement with results obtained by other diagnostics.

We point out that the throughput of the x-ray crystal spectrometer at TEXTOR 94 would be increased by a factor of 4 if the cylindrical crystal were replaced by a spherically bent crystal of the same active area. The throughput of the x-ray crystal spectrometer at TEXTOR 94 could be further improved by a factor of 2 by eliminating a small air gap of 2.4 cm in front of the entrance window of the detector, which absorbs about 50% of the 3 keV photons. With these improvements one would obtain count rates of 1.5×10^6 photons/s, which is far beyond the count rate capability of the presently used detector.

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[1] C. de Michelis and M. Mattioli, Nucl. Fusion **21**, 677 (1981).
[2] P. Beiersdorfer, S. von Goeler, M. Bitter, K. W. Hill, R. A. Hulse, and R. S. Walling, Rev. Sci. Instrum. **60**, 895 (1989).
[3] M. Bitter, H. Hsuan, K. W. Hill, and M. Zarnstorff, Phys. Scr. **T47**, 87 (1993).
[4] J. E. Rice, E. S. Marmar, and L. Qu, Nucl. Fusion **37**, 421 (1997).
[5] E. Atonucci and D. A. Dodero, Astrophys. J. **438**, 480 (1995).
[6] P. Beiersdorfer, D. A. Vogel, K. J. Reed, V. Decaux, J. H. Scofield, K. Widmann, G. Hölzer, E. Förster, O. Wehrhan, D. W. Savin, and L. Schweikhard, Phys. Rev. A **53**, 3974 (1996).
[7] A. S. Shlyaptseva, R. C. Mancini, P. Neill, P. Beiersdorfer, J. Crespo López-Urrutia, and K. Widmann, Phys. Rev. A **57**, 888 (1998).
[8] Nick Hawkes (private communication).
[9] M. K. Inal and J. Dubau, J. Phys. B **20**, 4221 (1987).
[10] P. Beiersdorfer, J. Crespo López-Urrutia, V. Decaux, K. Widmann, and P. Neill, Rev. Sci. Instrum. **68**, 1073 (1997).
[11] M. Bitter, B. Fraenkel, K. W. Hill, H. Hsuan, and S. von Goeler, Rev. Sci. Instrum. **86**, 530 (1995).
[12] B. Fraenkel, M. Bitter, S. von Goeler, and K. W. Hill, J. X-Ray Sci. Technol. **7**, 171 (1997).
[13] B. Fraenkel *et al.*, Rev. Sci. Instrum. (these proceedings).
[14] M. Bitter, B. S. Fraenkel, K. W. Hill, S. G. Lee, and S. von Goeler, Phase I Work Report/STTR Project No. 03007-96-1.
[15] H. H. Johann, Z. Phys. **69**, 185 (1931).
[16] O. Herzog, G. Bertschinger, M. Bitter, H.-J. Kunze, and F. Rosmej (unpublished).
[17] T. E. Cowan, C. L. Bennett, D. D. Dietrich, J. V. Bixler, C. J. Hailey, J. R. Henderson, D. A. Knapp, M. A. Levine, R. E. Marrs, and M. B. Schneider, Phys. Rev. Lett. **66**, 1150 (1991).
[18] S. von Goeler *et al.*, Rev. Sci. Instrum. (these proceedings).
[19] J. Rowlands and S. Kasap, Phys. Today **50**, 24 (1997).
[20] L. A. Vainshtein and U. I. Safronova, P. N. Lebedev Institute of Spectroscopy Report No. 2 (1985).