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Results from the NSTX X-ray Crystal Spectrometer

by

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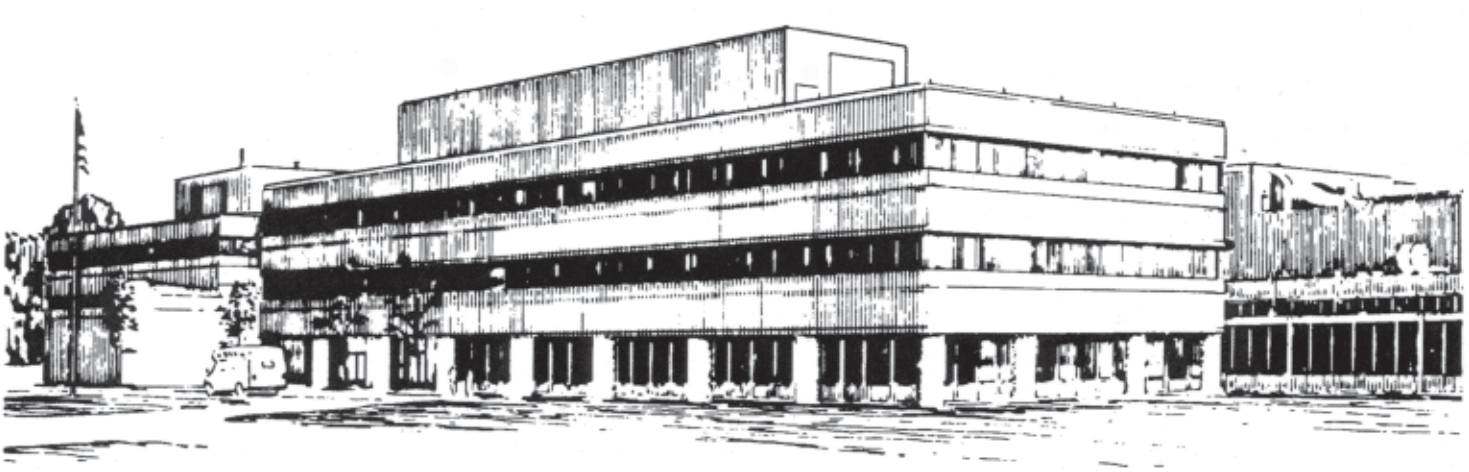

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Results from the National Spherical Torus Experiment x-ray crystal spectrometer

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(Presented on 10 July 2002)

A high-resolution x-ray crystal spectrometer has recently been installed at the National Spherical Torus Experiment to record the satellite spectra of helium-like argon, ArXVII, in the wavelength range from 3.94 to 4.00 A for measurements of ion and electron temperatures, and measurements of the ionization equilibrium of argon, which is of interest for studies of ion transport. The instrument presently consists of a spherically bent quartz crystal and a conventional one-dimensional position-sensitive multiwire proportional counter, but it will soon be upgraded to a new type of x-ray imaging crystal spectrometer by the installation of a large size (10 cm$\times$30 cm) two-dimensional position-sensitive detector that will allow us to obtain temporally and spatially resolved spectra from a 80 cm high cross-section of the plasma. In its present configuration, the spectrometer has been optimized for high throughput so that it is possible to record spectra with small statistical errors with a time resolution of 10 ms by adding only small, nonperturbing amounts of argon to the plasma. The spectrometer is most valuable for measurements of the ion temperature in the absence of a neutral beam in ohmically heated and rf heated discharges, when charge exchange recombination spectroscopy does not function. Electron temperature measurements from the satellite-to-resonance line ratios have been important for a quantitative comparison with (and verification of) the Thomson scattering data. The paper will describe the instrumental details of the present and future spectrometer configurations and present recent experimental results. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1535242]

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I. INTRODUCTION

In a previous paper,[1] we proposed a new type of x-ray imaging crystal spectrometer for the diagnosis of tokamak plasmas. This spectrometer consists of a spherically bent crystal and a large area two-dimensional (2D) position-sensitive detector and it can provide both space and time resolved spectra from highly charged ions, such as ArXVII. These spectral data can be used for measurements of radial profiles of the ion and electron temperatures, the plasma rotation velocity and the radial ion charge-state distribution. The proposed spectrometer may be of particular interest for measurements of the ion temperature profile in future, large tokamaks, such as ITER, where the presently used methods of neutral charge-exchange recombination spectroscopy will encounter difficulties due to the fact that the penetration of neutral beams into the plasma will be substantially reduced. A prototype of this x-ray imaging crystal spectrometer will now be built at the National Spherical Torus Experiment (NSTX).[2]

A high resolution x-ray crystal spectrometer with a spherically bent crystal and a conventional one-dimensional (1D) multiwire proportional counter is already operating at NSTX since 2000. This instrument has provided ion and electron temperature data for discharges with pure ohmic heating as well as discharges with auxiliary rf and neutral-beam heating, from a single *central* line of sight through the plasma. It is now planned to upgrade this spéctrometer to an x-ray imaging crystal spectrometer. The experimental data obtained so far have validated the use of a spherically bent crystal and have been most valuable for estimates of the throughput and time resolution for the upgraded system. This paper will describe the instrumental details of the present and future spectrometer configurations and present recent experimental results.

II. INSTRUMENTAL CHARACTERISTICS

The spectrometer, which is presently operating at NSTX, is equipped with a spherically bent 110-quartz crystal ($2d$-spacing$=4.913$ Å) and a conventional 1D multiwire proportional counter from the former TFTR x-ray crystal spectrometers.[3,4] The crystal is a circular disc with a diameter of 100 mm. It has a radius of curvature of 3750 mm and was spherically bent by a contact mount to a telescope mirror.[5] The spectrometer has been installed at the end of the NSTX pump duct, *see* Fig. 1, and records spectra of helium-like argon, ArXVII, in the wavelength range from 3.94 to

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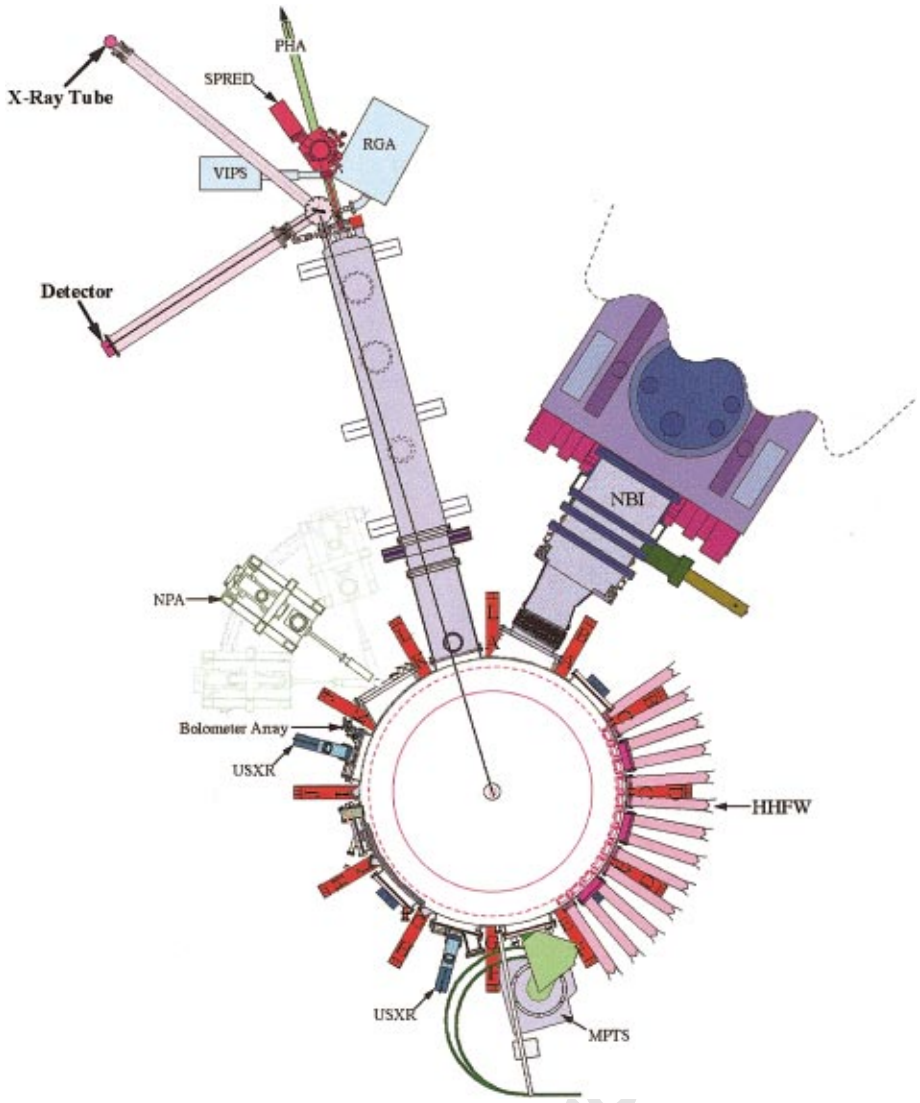

FIG. 1. (Color) Experimental arrangement of the x-ray crystal spectrometer at NSTX.

4.02 Å, which includes the resonance line **w** $1s^2\,{}^1S_0-1s2p\,{}^1P_1$ at 3.9494 Å and the forbidden line **z** $1s^2\,{}^1S_0-1s2s\,{}^3S_1$ at 3.9944 Å. The Bragg angles for the lines **w** and **z** are 53.5° and 54.4°, respectively, so that the spectrum of main interest is included in a narrow range of Bragg angles of 1°. The detector, which has a sensitive volume of 180 mm (width)×90 mm (height) ×12 mm (depth), was positioned at a distance of 3015 mm from the crystal, so that the resonance line **w**, which is used for Doppler measurements of the ion temperature, is focused at the center of the detector. Since the detector has a depth of 12 mm, it was not placed tangentially to the Rowland circle but perpendicular to the central ray for the mean Bragg angle $\theta=54°$ in order to avoid a deterioration of the spectral resolution for the line **w** by parallax. The distance between the lines **w** and **z** on the detector is 47 mm and the line **z** is therefore slightly out of focus. Since the NSTX center stack has a diameter of only 381 mm, special care was taken to assure that *all* the lines of sight, which contribute to a spectral line, end at the center stack. For instance, the separation at the center stack between the central lines of sight and the outermost lines of sight for the lines **w** and **z** is 120 and 270 mm, respectively. Each spectral line is therefore emitted from a plasma volume of the same size, so that measurements of line ratios are accurate.

The spectrometer chamber is evacuated by a roughing pump to a pressure of 0.1 Torr in order to reduce the attenuation of the 3 keV photons in air. The chamber is separated from the NSX vacuum vessel by a 0.025-mm-thick beryllium window, which is mounted between the crystal and a gate valve to NSTX, and it is therefore not subject to the high-vacuum requirements that apply to NSTX. The vacuum boundary on the detector side is a thin mylar foil, which was introduced to protect the $180\times90\ \mathrm{mm}^2$ large and 0.1-mm-thick beryllium entrance window of the detector, since the window was not designed to withstand a pressure difference of 1 atm. Between mylar foil and detector window is presently a 25-mm-deep air gap. The total transmission for 3 keV photons of the beryllium and mylar foils, the foil support structures, and the air gap is 15%. The mylar foil and air gap will be eliminated in the upgraded version of the spectrometer, since the entrance window of the new 2D detector will also serve as the vacuum boundary; the transmission and throughput will therefore be increased by a factor of 4. The

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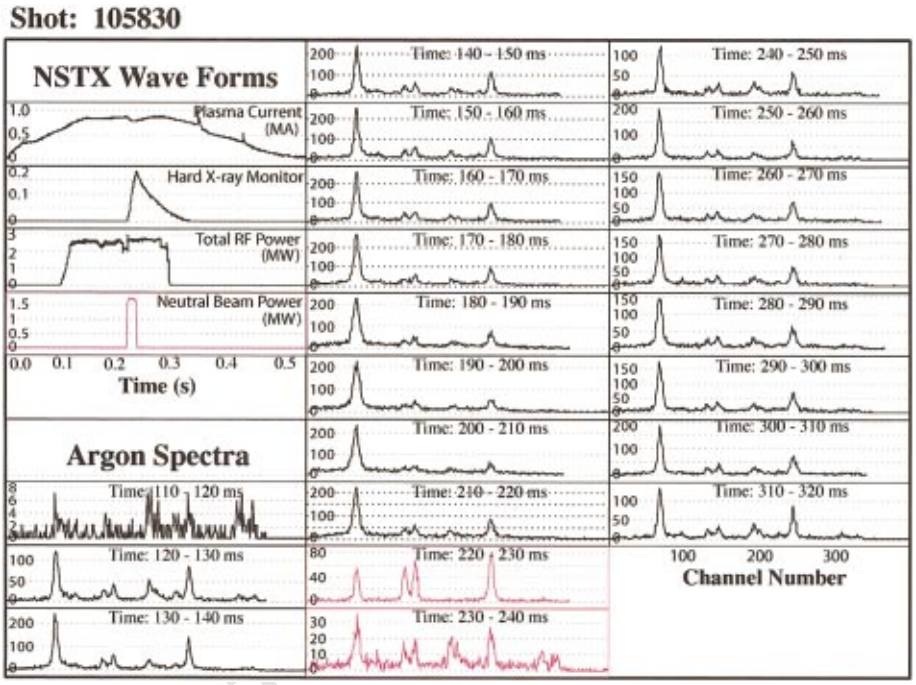

FIG. 2. (Color) NSTX wave forms and raw spectral data for the rf heated discharge 105830. Of particular interest is the spectrum during the time interval from 220 to 230 ms, which is produced by charge-exchange recombination of ArXVIII with the energetic deuterium atoms from the neutral beam.

detector is operated with a mixture of 90% krypton and 10% CO_2, which has a detection efficiency of 99% for 3 keV photons.

Argon is introduced into NSTX by a single gas puff at -0.5 s prior to a discharge for a duration of 10 ms. The argon puff causes a small pressure blip of 1×10^{-7} Torr on a fast ion gauge and does not perturb the plasma. For discharges with auxiliary rf heating, where the electron temperature is raised above 1 keV, it is possible to obtain spectra with small statistical errors with a time resolution of 10 ms.

An *in situ* calibration can be performed by mounting an x-ray tube to the crystal housing and rotating the crystal by an angle of 72°, see Fig. 1, so that the photons, which emanate from the x-ray tube, are reflected by the crystal under the Bragg angle of interest of $\Theta=54°$. A 0.2-mm-wide slit, which corresponds to half the spatial resolution of the detector, is mounted in front of the x-ray tube. The slit and x-ray tube are rigidly connected and can be moved together relative to the crystal. This movement is facilitated by bellows mounted in crystal-detector arm. The calibration measurements are performed with use of the bremsstrahlung continuum from the x-ray tube. As the slit approaches a position on the Rowland circle, both the energy band of the Bragg reflected radiation and the image of the slit on the detector become narrower. The minimum width, which is a measure for the instrumental resolution, is obtained, when the slit is on the Rowland circle. The image of the slit obtained under this condition could be well approximated by a Gaussian with a full width at half maximum of 1.1 mm, which corresponds to a spectral resolution of $\lambda/\Delta\lambda=3800$. For the evaluation of Doppler measurements we assume that the observed line profiles are convoluted with a Gaussian instrumental function of an effective ion temperature of 500 eV, which is subtracted from the measured *apparent* ion temperature. Since the instrumental correction is presently comparable with the ion temperature of ohmically heated plasmas, we intend to improve the spectral resolution for the upgraded version of the spectrometer by a factor of 2. This will be achieved by using a more perfectly bent spherical crystal[6] and a detector with a better spatial resolution of about 0.2 mm. An improvement of the spectral resolution by a factor of 2 will reduce the ion temperature correction by a factor of 4.

III. EXPERIMENTAL RESULTS

The main diagnostic applications of the x-ray spectroscopy at NSTX are nonperturbing ion temperature measurements in the absence of a neutral beam from discharges with pure ohmic heating and discharges with auxiliary rf heating. In this section, we discuss only data from such discharges.

Figure 2 shows the wave forms of the plasma current, hard x-ray intensity, total rf power, and total neutral-beam power from a NSTX discharge (shot: 105830) with high-harmonic-fast wave (rf) heating of 2.6 MW, and spectra of ArXVII, which have been obtained with a time resolution of 10 ms. The plasma current reaches a flattop of 800 kA after 120 ms. A neutral beam of 1.5 MW was injected during the short time interval from 220 to 240 ms for diagnostic purposes to facilitate a measurement of the ion temperature profile by charge-exchange recombination spectroscopy (CHERS). Correlated with the injection of the neutral beam is a burst of hard x rays. Argon was injected for 10 ms at 0.5 s prior to the discharge. The first spectrum of ArXVII is observed during the time interval from 110 to 120 ms at the onset of the rf heating, which leads to a rapid increase of the electron temperature. During the rising phase of the plasma current the electron temperature is too low to produce

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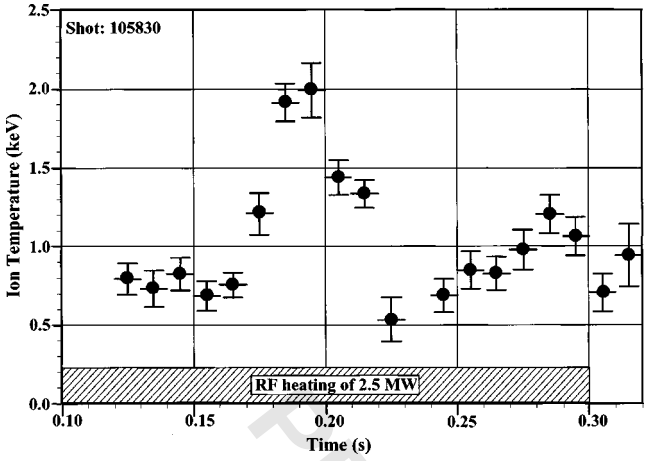

FIG. 3. Time history of the ion temperature from Doppler broadening measurements of the ArXVII resonance line **w**.

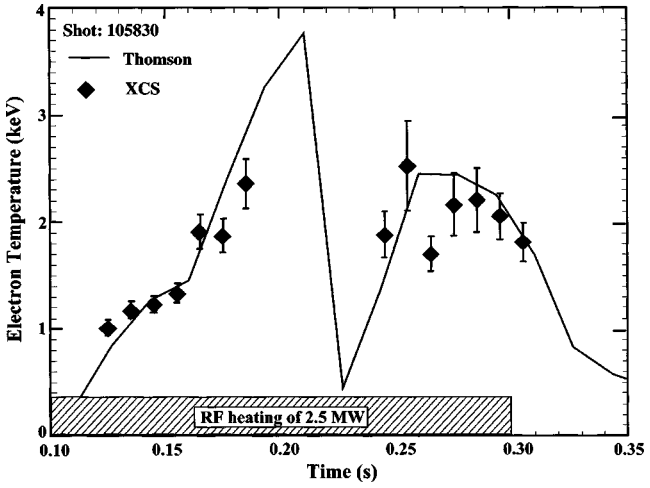

FIG. 4. Time history of the electron temperatures obtained from the satellite-to-resonance line ratios and Thomson scattering measurements.

helium-like argon. The observed x-ray spectra include the helium-like lines **w**, **x**: $1s^2\,{}^1S_0-1s2p\,{}^3P_2$, **y**: $1s^2\,{}^1S_0-1s2p\,{}^3P_1$, and **z**, *and* the associated lithium-like satellites, which are due to transitions of the type: $1s^2nl-1s2l'nl''$. A detailed description of these lines is given in Refs. 7–9.

The spectrum observed during the time interval of the neutral-beam injection from 220 to 230 ms is of particular interest, since it consists of *only* the helium-like lines **w**, **x**, **y**, and **z**. The lithium-like, dielectronic and inner-shell excited, satellites are absent. The strong enhancement of the helium-like lines is ascribed to charge-exchange recombination of hydrogen-like argon, ArXVIII, with deuterium atoms from the neutral beam. This process leads to a population of the $2s$ and $2p$ levels in ArXVII, which are the upper levels for the helium-like transitions **w**, **x**, **y**, and **z**. This line excitation process can be directly observed due to the fact that the neutral beam intersects the sightlines of our spectrometer (see Fig. 1). A detailed comparison of the experimental data with theoretical predictions for neutral-charge exchange recombination will be presented in a separate paper.[10] To our knowledge, these data represent the first observation of charge-exchange recombination of ArXVIII with energetic deuterium atoms from a neutral beam. Charge-exchange recombination of ArXVIII with intrinsic neutral hydrogen was observed previously by Rice *et al.*[11,12]

Figure 3 shows the ion temperature results as a function of time. These results were obtained from a Voigt-function fit to the resonance line **w** and include a correction of 500 eV for the instrumental width. The ion temperature is constant during the first part of the rf pulse but increases rapidly from 0.8 to 2.0 keV during the time interval from 0.17 to 0.20 s. The subsequent decrease of the ion temperature from 2.0 to about 1.4 keV during the time interval from 0.20 to 0.22 s is correlated with a magnetohydrodynamics (MHD) event. Note that the ion temperature assumed a minimum of 0.5 keV during the time of the neutral-beam injection from 220 to 230 ms. During this time interval an independent measurement of the ion temperature profile was obtained from the CHERS diagnostic with a peak value of 0.5 keV, which is in good agreement with the ion temperature value obtained from the x-ray crystal spectrometer (XCS). We note that the ion temperature value from the XCS for the time interval from 220 to 230 ms was derived from the line **z** and not from the line **w**, since **z** was stronger than **w** (see Fig. 2). During the time interval from 230 to 240 ms, the intensity of the argon spectrum was too low for a reliable ion temperature measurement.

It is not known whether the decrease of the ion temperature to a minimum value of 500 eV was caused by the injection of the neutral beam or the MHD event. But it is evident from our experimental data that a neutral beam, even if it is injected for only a short time, causes a significant change of the ionization equilibrium. CHERS can therefore not be considered as a nonperturbing ion temperature diagnostic for plasmas with pure ohmic heating or additional rf heating. We also note that CHERS provides an ion temperature profile only for the predetermined time of the neutral beam injection, so that it may miss interesting dynamic developments during a plasma discharge, whereas the XCS—in its present configuration—provides a complete time history of the *central* ion temperature.

Electron temperature measurements from the ratios of the lithium-like dielectronic satellites, $1s^2nl-1s21'nl$, and the resonance line **w**, have been performed for electron temperatures up to 2 keV.[13] Figure 4 shows these results for the NSTX discharge 105830 as a function of time and, for comparison, the data for the peak electron temperature from Thomson scattering. The time histories of the electron and ion temperatures are quite similar. The peak electron temperature assumes a maximum of 3.8 keV at 210 ms and a minimum of 0.35 keV at 227 ms, the time of the neutral beam injection. During the time intervals from 190 to 220 ms and from 220 to 240 ms, it was not possible to obtain electron temperature values from the argon spectra. During the first time interval, the dielectronic satellites were too weak due to the fact that the electron temperature was well above 2 keV and during the second time interval, the dielectronic satellites were entirely absent due to a change of the ionization equilibrium by neutral charge-exchange recombination with the injected deuterium atoms.

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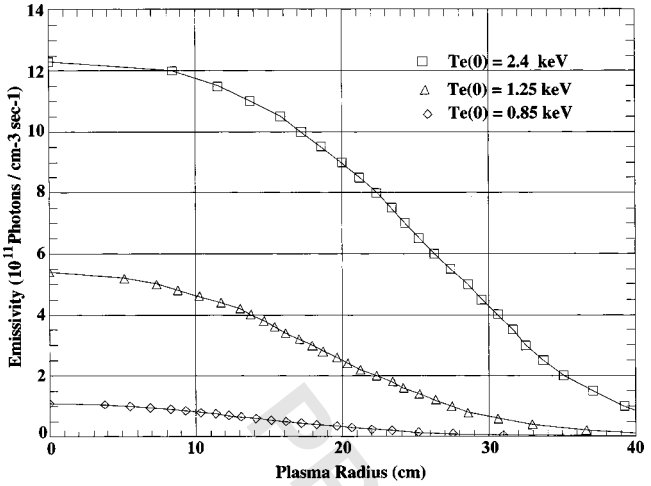

FIG. 5. Vertical emissivity profiles for the resonance line **w** for different central electron temperatures corresponding to the peak values of the electron temperature profiles measured by Thomson scattering at different times during the NSTX discharge 105830.

IV. PERFORMANCE ESTIMATES AND PLANS FOR AN X-RAY IMAGING CRYSTAL SPECTROMETER

The x-ray imaging crystal spectrometer will project an 80 cm high cross-section of the plasma onto a 2D detector with a demagnification factor of 2.5. The spatial resolution at the center of the plasma in a direction perpendicular to the horizontal midplane of NSTX will be about 2 cm. It is determined by the height of the crystal and the Bragg angle.[1]

Estimates of the vertical emissivity profiles for the resonance line **w** and other spectral lines were obtained from a Multi-Ion-Species-Transport code using the Thomson scattering data for the density and electron temperature profiles as input. The calculations were based on the assumption of coronal equilibrium and included a diffusion coefficient of $D=1\times10^4$ cm^2 s^{-1}. Figure 5 shows the calculated vertical emissivity profiles for the line **w** for different central electron temperature of 0.85, 1.25, and 2.4 keV. These values correspond to the peak electron temperature measured by Thomson scattering at 126, 143, and 176 ms during the NSTX discharge 105830. The calculations predict an increase of the (central) emissivity by an order of magnitude, from 1×10^{11} to 1.2×10^{12} photons cm^{-3} s^{-1}, if the central electron temperature increases from 0.85 to 2.4 keV. According to these calculations, which are based on our present experimental data, it should be possible to obtain ion and electron temperature profiles with a time resolution of 10 ms and sufficiently small statistical errors up to a radius of ±40 cm, if the central electron temperature is greater than 1.2 keV. The spatial resolution will be about 5 cm. We note that the spatial resolution can be selected after the discharge during the data analysis process by binning the two-dimensional spectral data according to the statistical requirements.

The x-ray imaging crystal spectrometer will first be equipped with a 2D position-sensitive multi-wire proportional counter. This detector can be manufactured in the appropriate size (10 cm$\times$30 cm) based on proven technology.[14] Multiwire proportional counters have a high detection efficiency and a high signal-to-noise ratio, but the count rate is limited to a few hundred kilohertz, so that they cannot be the final solution. It will, in fact, be necessary to develop new types of large area detectors with a count rate capability of several megahertz. New Gas Electron Multiplication (GEM) detector may satisfy these requirements. These new detectors are presently developed[15] and may be available in 2004 The data obtained with a 2D multiwire proportional counter will provide guidance for this detector development.

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[13] A detailed comparison of electron temperature data from the argon spectra and Thomson scattering for the range $0.4<T_e<2.0$ keV will be presented in a separate paper.
[14] Large area 2D multiwire proportional counters are produced at the National Laboratories in Brookhaven and Livermore and at the Korea Basic Science Institute.
[15] A multi-megahertz position-sensitive GEM detector for the imaging crystal spectrometer is being developed by O. Siegmund and Sensor Sciences, Berkeley.

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