

LAWRENCE LIVERMORE NATIONAL LABORATORY

### Final Report of B548129: Spectral Analysis of Soft X-Ray Data from NSTX

J. K. Lepson, J. G. Jernigan, P. Beiersdorfer

November 14, 2007

### Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

### Final Report of B548129 : Spectral Analysis of Soft X-Ray Data from NSTX

J. K. Lepson, J. G. Jernigan

University of California, Space Sciences Laboratory Berkeley, CA

P. Beiersdorfer

Lawrence Livermore National Laboratory Livermore, CA

We present a summary of work performed under subcontract B548129 "Spectral Analysis of Soft X-Ray Data from NSTX." This summary is comprised of papers and poster presentations prepared under this subcontract.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

### Abstract Submitted for the DPP07 Meeting of The American Physical Society

Sorting Category: 5.6.5

Time-dependent measurements of the B, C, N, and O Lyman- $\alpha$  emission P. BEIERSDORFER, M.-F. GU, LLNL, M. BIT-TER, K. W. HILL, R. KAITA, H. KUGEL, L. ROQUEMORE, PPPL, J. K. LEPSON, UC Berkeley — The X-ray and Extreme Ultraviolet Spectrometer (XEUS) has been used to monitor the line emission from various impurity ions on NSTX, in particular the K-shell emission of heliumlike and hydrogenlike B, C, N, and O. While C VI typically dominates the spectrum, unusually strong emission from N VII has been observed in multiple disharges during the past run campaign. In this case, the nitrogen concentration can exceed that of carbon by an order of magnitude. Time-dependent measurements show that the nitrogen concentration builds up over the course of the discharge and coincides with a build up of boron. In a few cases we observed several unknown lines. These are clearly lines from heavy impurities, possibly molybdenum. Some of these lines can be explained by the emission from Ti XIII. This work was performed under the auspices of the U.S. DOE by UC-LLNL under contract W-7405-Eng-48 and by PPPL under contract DE-AC02-76CHO3073.



Prefer Oral Session Prefer Poster Session Peter Beiersdorfer beiersdorfer@llnl.gov Lawrence Livermore National Laboratory

Date submitted: July 17, 2007

Electronic form version 1.4

### ABSTRACT

The X-ray and Extreme Ultraviolet Spectrometer (XEUS) has been used to monitor the line emission from various impurity ions on NSTX, in particular the K-shell emission of heliumlike and hydrogenlike B, C, N, and O. While C VI typically dominates the spectrum, unusually strong emission from N VII has been observed in multiple disharges during the past run campaign. In this case, the nitrogen concentration can exceed that of carbon by an order of magnitude. Time-dependent measurements show that the nitrogen concentration builds up over the course of the discharge and coincides with a build up of boron. In a few cases we observed several unknown lines. These are clearly lines from heavy impurities. Some of these lines can be explained by the emission from Ti XIII and Mo XXV, XXVI.



NSTX test cell owing the location of

# XEUS:

The spectrometer employs a 3 cm x 5 cm ruled diffraction grating from Hitachi with variable line spacing and an angle of incidence of 1.3°. The average spacing is 2400  $\ell$ /mm. The variable spacing provides a nearly flat image field, and we use a thinned, back-illuminated charge-coupled device (CCD) detector from Phtometrics with 1024x1024 pixels of 25 µm x 25 µm area each. The camera is cooled with liquid nitrogen.

A 30 µm wide entrance slit that matches the pixels size of the CCD camera is used. A pressure-driven shutter is used to gate the spectrometer. The response time is 30 ms, providing time slices as short as 60 ms.

The wavelength range covered by XEUS ranges from 8 Å to 135 Å, depending on the camera setting. We can observe the K-shell lines of B, C, and O, as shown below. The K-shell lines of Li can be observed in a second setting



	100-
units	80 -
Intensity (arb.	60 -
	40 -
	20 -
	0-

### TIME-DEPENDENT SPECTRA:

Operating the CCD camera in fast read-out mode, we can acquire a spectrum in 90 msec (currently limited by the processor speed of the computer). Below we show the first eight spectra recorded for shot 123629.



**Close-up of the** spectromete

is dominated by C VI.

Shot 123629 was one of several shots during the FY07 run period, which were dominated by nitrogen emission. The dominance of nitrgogen can be seen in the spectrum from shot





# N VII - ENHANCED SPECTRA

The time dependence enabled us to determine that the enhenced nitrogen emission was coupled to enhanced boron emission. Both occurred later in the discharge. Boronnitride is used for shielding various components inside the discharge vessel, including the RF antenna shields. A strong enhancement of nitrogen and boron indicates that the plasma is eroding some of the boron nitride coating.







### LINES FROM HEAVY-ION IMPURITIES

Apart from enhanced nitrogen and boron, spectra were seen in the FY07 run period with lines not seen in earlier years. If the boron nitride coating of the RF antennae were eroded by the plasma, the underlying titanium and molybdenum might be exposed. In shot 123721 we indeed found lines that might be explained by the emission from Ti XIII and Ti XIV as well as by Mo XXIV, Mo XXV, and Mo XXVI.

The Mo XXV spectrum has a strong line predicted at 73 Å. We shifted the detector to find this line. Indeed, a candidate line appeared in shot 125036.





Emissio of sho 125036 shows a line at 73.85 dentifications i the 20 Å region.

### Abstract Submitted for the DPP06 Meeting of The American Physical Society

Sorting Category: 5.6.5

Measurements of impurity line emission in the EUV on NSTX P. BEIERSDORFER, LLNL, M. BITTER, L. ROQUEMORE, PPPL, J. K. LEPSON, UC Berkeley — The X-ray and Extreme Ultraviolet Spectrometer (XEUS) has been used to monitor the line emission from various impurity ions on NSTX, in particular the K-shell emission of B, C, N, and O. The wavelength range of the instrument has recently been extended from 65 Å to 135 Å allowing measurements of the K-shell emission of the Lyman lines of hydrogenlike Li ions following lithium deposition on the plasma-facing components as well as of the 2-2 transitions of L-shell Fe ions. The latter transitions are of special interest as diagnostics of stellar coronae and other astrophysical plasmas. Our measurements provide information on impurity behavior in NSTX plasmas under various discharge conditions. Moreover, they calibrate the intensities of astrophysical lines in an intermediate density regime not accessible by other laboratory sources.

This work was performed under the auspices of the U.S. DOE by UC-LLNL under contract W-7405-Eng-48 and by PPPL under contract DE-AC02-76CHO3073.

Prefer Oral Session Prefer Poster Session

Х

:

Peter Beiersdorfer beiersdorfer@llnl.gov Lawrence Livermore National Laboratory

Electronic form version 1.4

### ABSTRACT

The X-ray and Extreme Ultraviolet spectrometer (XEUS) has been used to monitor the line emission from various impurity ions on NSTX, in particular the K-shell emission of B, C, N, and O. The wavelength range of the instrument has recently been extended from 65 Å to 135 Å allowing measurements of the K-shell emission of the Lyman lines of hydrogenlike Li ions following lithium deposition on the plasma-facing components as well as of he 2-2 transitions of L-shell Fe ions. The latter transitions are of special interest as diagnostics of stellar coronae and other astrophysical plasmas. Our measurements provide information on impurity behavior in NSTX plasmas under various discharge conditions. Moreover, they calibrate the intensities of astrophysical lines in an intermediate density regime not accessible by other laboratory sources such as EBIT.



NSTX test cell howing the location of

### **INSTRUMENT DESIGN:**

The spectrometer employs a 3 cm x 5 cm ruled diffraction grating from Hitachi with variable line spacing and an angle of incidence of 1.3°. The average spacing is 2400 /mm. The variable spacing provides a nearly flat image field, and we use a thinned, back-illuminated charge-coupled device (CCD) detector from Phtometrics with 1024x1024 pixels of 25 µm x 25 µm area each. The camera is cooled with liquid nitrogen.

Either a 30 µm wide entrance slit that matches the pixels size of the CCD camera or a 100 µm entrance slit for better light collection is used. A pressure-driven shutter is used to gate the spectrometer. The response time is 30 ms, providing time slices as short as 60 ms.





Layout showing XEUS at the end of the NSTX pump duct

# **MEASUREMENTS OF IMPURITY LINE EMISSION IN THE EUV ON NSTX**

### P. BEIERSDORFER\*, M. BITTER†, L. ROQUEMORE†, J. K. LEPSON‡

\*LAWRENCE LIVERMORE NATIONAL LABORATORY, Livermore, CA 94550 *+LAWRENCE LIVERMORE NATIONAL LABORATORY, Livermore, CA 94550* <sup>‡</sup>UNIVERSITY OF CALIFORNIA, Berkeley, CA 94720

Close-up of the pectromete



**NSTX** shot

### **PERFORMANCE:**

A typical CCD image obtained during an NSTX shot is shown below. We make cuts from each two-dimensional CCD image and sum channels perpendicular to the dispersion direction in order to extract spectral information. For image manipulation we used IPLab software running on a G3 Macintosh computer, which is also used for data acquisition and camera control. Typical spectra display the K-shell lines of B, C, and O, as shown below.



evaporation.



The spectrometer coverage was shifted toward 135 Å in order to be able to observe the Li III line near 132 Å after lithium

### Impurity ratios after lithium evaporation

We have been monitoring the O VIII to CVI ratio before and after lithium evaporation in May 2006. This ratio had been declining for several weeks befor the May experiments, dropping from about 0.8 early April to 0.2 early May. Below is the O VIII to CVI ratio before and after lithium evaporation on May 4, 2006. Two shots seems to be needed to distribute the lithium in the vessel, then oxygen seems to vanish for the subsequent seven beam-heated discharges. The





### L-SHELL ARGON EMISSION

Argon has been injected into NSTX in order to use its K-shell emission for ion temperature measurements of the plasma core. We have observed the Ar L-shell emission with our instrument, as shown below. The higher density of the NSTX measurements allows us to calibrate astrophysically important density-sensitve line ratios in a way not afforded by EBIT sources. Using data from both sources thus provides definitve calibrations of such line ratios in regimes relevant to solar flare densities.







### Grazing-Incidence Spectrometer for Soft X-Ray and Extreme Ultraviolet Spectroscopy on the National Spherical Torus Experiment

P. Beiersdorfer<sup>1</sup>, M. Bitter<sup>2</sup>, L. Roquemore<sup>2</sup>, J. K. Lepson<sup>3</sup>, M.-F. Gu<sup>4</sup>

<sup>1</sup>Lawrence Livermore National Laboratory Livermore, CA 94550, USA <sup>2</sup>Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA <sup>3</sup>University of California, Berkeley, CA 94720, USA <sup>4</sup>Stanford University, Palo Alto, CA 94305, USA

A compact grazing-incidence spectrometer was implemented on the National Spherical Torus Experiment (NSTX) for spectral measurements in the 6–65 Å spectral region. The spectrometer employed a 2400 l/mm grating designed for flat-field focusing and a cryogenically cooled charge couple device (CCD) camera for readout. The instrument was used for recording the K-shell lines of boron, carbon, nitrogen, and oxygen, as well the L-shell lines from iron and nickel that fall into this spectral band. Spectral resolution as high 300 and temporal resolution as fast as 50 ms was obtained.

Work performed under the auspices of the US Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

### ABSTRACT

A compact grazing-incidence spectrometer was implemented on the National Spherical Torus Experiment (NSTX) for spectral measurements in the 6–65 Å spectral region. The spectrometer employed a 2400 I/mm grating designed for flat-field focusing and a cryogenically cooled charge couple device (CCD) camera for readout. The instrument was used for recording the K-shell lines of boron, carbon, nitrogen, and oxygen, as well the L-shell lines from iron and nickel that fall into this spectral band. Spectral resolution as high 300 and temporal resolution as fast as 50 ms was obtained.



NSTX test cell ng the location o the new spectrometer



ayout showing the new spectrometer at the end of the NSTX pump duct

# **INSTRUMENT DESIGN:**

The spectrometer employs a 3 cm x 5 cm ruled diffraction grating from Hitachi with variable line spacing and an angle of incidence of 1.3°. The average spacing is 2400 /mm. The variable spacing provides a nearly flat image field, and we use a thinned, back-illuminated charge-coupled device (CCD) detector from Phtometrics with 1024x1024 pixels of 25 µm x 25 µm area each. The camera is cooled with liquid nitrogen.

Either a 30 µm wide entrance slit that matches the pixels size of the CCD camera or a 100 µm entrance slit for better light collection is used. A pressure-driven shutter is used to gate the spectrometer. The response time is 30 ms.





### **PERFORMANCE**:

A typical CCD image obtained during an NSTX shot is shown below. We make cuts from each two-dimensional CCD image and sum channels perpendicular to the dispersion direction in order to extract spectral information. For image manipulation we used IPLab software running on a G3 Macintosh computer, which is also used for data acquisition and camera control. Typical spectra display the K-shell lines of B, C, and O, as shown below.



The resolving power of the new instrument (100 µm slit) in this wavelength region ranges from about 150 near 15 Å to above 400 near 60 Å, as summarized in Table I below.

Line	Wavelength	Line width	$\lambda/\Delta$
	$(\text{\AA})$	$(\text{\AA})$	
$O^{7+}$ Ly- $\gamma$	15.14	0.10	151
$O^{7+}$ Ly- $\beta$	16.11	0.10	161
${ m O}^{7+}$ Ly- $lpha$	19.00	0.13	146
$C^{5+}$ Ly- $\alpha$	33.73	0.09	387
$C^{4+} w$	40.31	0.10	403
$B^{4+}$ Ly- $\alpha$	48.77	0.14	356
${ m O}^{7+}$ Ly- $lpha$	$56.97^{*}$	0.11	540
$B^{3+} w$	60.25	0.13	465

### L-SHELL IRON SPECTRA

While in most shots the observed emission is limited to lines from low-Z impurities B, C, and O, emission lines from Fe can be seen fairly regularly, especially in RFheated discharges. Even less often we have been able to see emission lines from N. A spectrum where both Fe and N are seen in addition to the lines from the other elements is shown below.



Below we show an expanded view of the L-shell iron emission observed with the new grating spectrometer.

The spectrum was fitted with a model spectrum generated by the Flexible Atomic Code. Agreement could only be obtained, if L-shell emission from nickel was included in the model. The nickel lines are labeled in boldface below.



### L-SHELL ARGON EMISSION

Argon has been injected into NSTX in order to use its K-shell emission for ion temperature measurements of the plasma core. We have observed the Ar L-shell emission with our instrument, as shown below. This allowed us to observe the Ar IX emission, which is density sensitive. Unlike spectra from EBIT sources, the magnetic quadrupole line (M2) is absent from the present spectrum.







### Grazing-Incidence Spectrometer for Soft X-Ray and Extreme Ultraviolet Spectroscopy on the National Spherical Torus Experiment

P. Beiersdorfer<sup>1</sup>, M. Bitter<sup>2</sup>, L. Roquemore<sup>2</sup>, J. K. Lepson<sup>3</sup>, M.-F. Gu<sup>4</sup>

 $^1Lawrence\ Livermore\ National\ Laboratory,\ Livermore,\ CA\ 94550,\ USA$ 

<sup>2</sup>Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA
 <sup>3</sup>University of California, Berkeley, CA 94720, USA
 <sup>4</sup>Stanford University, Palo Alto, CA 94305, USA

### Abstract

A compact grazing-incidence spectrometer has been implemented on the National Spherical Torus Experiment (NSTX) for spectral measurements in the 6–65 Å spectral region. The spectrometer employed a 2400  $\ell/\text{mm}$  grating designed for flat-field focusing and a cryogenically cooled CCD camera for readout. The instrument was tested by recording the K-shell lines of boron, carbon, nitrogen, and oxygen, as well the L-shell lines from argon, iron, and nickel that fall into this spectral band. The observed line width was about 0.1 Å, which corresponds to a resolving power of 400 for the C V lines. A temporal resolution as fast as 50 ms was obtained.

### I. INTRODUCTION

Spectroscopic measurements of soft x-ray and extreme ultraviolet radiation have been established as excellent ways of monitoring the concentration of impurities in hot plasma [1], because a wealth of lines from many ionization stages of numerous elements fall into this wavelength band. As a result, instrumentation to monitor this wavelength band has been commonly implemented on magnetic fusion devices [2–8]. Many of these instruments cover a broad spectral region in order to survey as many elements and ionization stages as possible. For similar reasons, the soft x-ray and extreme ultraviolet wavelength region is of interest to astrophysics, where such measurements provide values for elemental abundances and charge balances. Additional interest derives from the fact that many lines in this wavelength region are sensitive to changes in the electron density and can be used as diagnostics of the plasma conditions.

In the following we describe a compact grazing-incidence spectrometer for use on the National Spherical Torus Experiment (NSTX). The instrument has been set up for monitoring line emission in the 6 to 65 Å region. In particular, we are interested in the emission from hydrogenlike and heliumlike boron, carbon, nitrogen, and oxygen, as well as the emission from lithiumlike through neonlike ions of the transition metals, i.e., Ti, V, Cr, Mn, Fe, Co, Ni, and Cu.

Because boronization and the use of carbon limiters diminish the possibility of metal ions entering the discharge during normal operation, observation of lines from metal ions in the spectra are indicators of wear on the protective coatings. Examples would be copper from the antennae used in radio-frequency (RF) heating, or titanium from the titanium carbide surface coating of the Faraday shields of the high-harmonic fast wave (HHFW) RF heating system. Observation of nitrogen lines may indicate an air leak or plasma touching limiters on the RF system, which are made of boron nitride. Alternatively, the lack of boron lines in these spectra can indicate that the effect of boronization has worn off.

The spectral range of the present instrument complements that of the high-resolution vacuum crystal spectrometer used for spectral measurements in the soft x-ray regime between about 7 and 24 Å, which has a resolving power above 1000 [6,9], and the low-resolution  $(\lambda/\Delta\lambda \approx 50-400)$  survey, poor resolution, extended domain (SPRED) instrument for measurements in the 100 to 1100 Å region [2,4]. The new spectrometer has a resolving power of about 150–500.

Because the electron temperature and density of NSTX plasmas are well known from Thomson scattering measurements [10], the instrument allows us to calibrate spectral lines ratios useful as plasma diagnostics. Tokamak plasmas have played an important role in testing atomic physics and providing well calibrated diagnostics for astrophysics [11–15]. The new instrument illustrates this possibility by studying the spectra from L-shell argon ions, whereby argon was deliberately introduced into NSTX for this purpose. The spectra of L-shell argon ions relevant to x-ray astronomy have been measured in detail before at the electron beam ion trap facility at the University of California Lawrence Livermore National Laboratory [16]. The NTSX measurements, however, provide spectral emission at considerably higher electron densities (>  $10^{13}$  cm<sup>-3</sup> versus  $10^{11}$  cm<sup>-3</sup> at the electron beam ion trap), i.e., in a density regime needed to calibrate, for example, diagnostics of high-density stellar flare plasmas.

### **II. SPECTROMETER DESIGN**

The new Livermore-NSTX extreme ultraviolet spectrometer (LINES) is similar to that employed earlier at the Livermore electron beam ion trap facility [17]. It employs a variable line spacing grating mounted on a rotary table (average line spacing of 2400  $\ell/\text{mm}$  [18]). The Hitachi grating affords flat-field focusing in the 6–100 Å range with a focal distance of about 23 cm. The angle of incidence is  $1.3^{\circ}$ . The blaze angle is 15 Å.

The LINES instrument is located at the end of the NSTX pump duct, and thus is about ten meters away from the vacuum vessel. Its line of sight follows a radial line to the center stack of the tokamak within the horizontal midplane of the plasma. A picture of the instrument on NSTX is shown in Fig. 1.

Because NSTX plasmas are extended sources, we employ either a 30  $\mu$ m or 100  $\mu$ m entrance slit in order to provide a line width commensurate with the 25  $\mu$ m pixel size of the liquid nitrogen cooled Photometrics charge couple device (CCD) camera used for spectral recording. The 1" × 1" detector allows us to monitor the region between 10 and 65 Å in a single setting. Small adjustments in the camera position are possible to access neighboring wavelength regions.

A shutter before the entrance slit is used to provide time resolution. The shutter can be opened and closed within about 30 ms. Periods of interest can be selected by opening and closing the shutter at the appropriate times during an NSTX discharge.

At present, no shielding is employed against hard x rays. These are not a problem during ohmic or RF-heated discharges. However, hard x rays generated during neutral beam conditioning or neutral beam heating penetrate the detector housing and increase the overall background of the observed spectra, albeit not enough to mask the emission of the strong K-shell lines of B, C, and O.

### **III. PERFORMANCE**

A typical spectrum obtained with the new spectrometer is shown in Fig. 2(a). It was taken during the ohmic heating phase (T=320-750 ms) of a lower single null helium plasma (NSTX shot number 117084). The spectral emission is almost exclusively comprised of the K-shell lines from hydrogenlike and heliumlike boron, carbon, and oxygen. Of interest is the emission from heliumlike  $O^{6+}$ , which is weak compared to that of H-like  $O^{7+}$ . This is surprising, given that the emission of the heliumlike B and C is strong. One explanation is that the grating is less sensitive at near 21 Å compared to its sensitivity near 19 Å, i.e., the position of the Lyman- $\alpha$  line of  $O^{7+}$ . Another is that there are relatively fewer  $O^{6+}$  ions in the plasma than there are  $B^{3+}$  or  $C^{4+}$  ions. While this is unlikely, this possibility needs to be checked with charge balance calculations.

Note that no nitrogen is seen. This is typical for NSTX discharges. Strong K-shell lines from hydrogenlike and heliumlike nitrogen have been seen in a few pellet-injection or RF-heated plasmas, as illustrated in Fig. 2(b).

We note that essentially no lines from metal impurities are seen in the spectrum in Fig. 2(a). Lines from L-shell iron ions, however, can be seen under different NSTX run conditions, especially when the plasma is allowed to expand toward the outer wall, as illustrated in Fig. 2(b). A typical spectrum of the  $n = 3 \rightarrow n = 2$  lines of lithiumlike through neonlike iron, which fall into the 8–17 Å region, is shown in Fig. 3. The spectrum was fitted with a spectral model produced by the Flexible Atomic Code [19], and good agreement was found. Three major features, however, could not be fitted with the iron model alone. These were determined to be  $n = 3 \rightarrow n = 2$  lines of nickel.

In Fig. 4 we present a spectrum recorded after an argon puff into NSTX. The two most prominent lines are  $3s \rightarrow 2p$  transitions of Ar<sup>8+</sup>. We note the absence of the dipoleforbidden magnetic quadrupole (M2) transition  $1s^22s^22p_{3/2}^53s_{1/2} \ {}^3P_2 \rightarrow 1s^22s^22p^6 \ {}^1S_0$ . This line is quenched at the electron densities found in NSTX, in accordance with predictions of its sensitivity on electron density [20].

From the observed spectra we measure a line width of roughly a little over 0.10 Å, as summarized in Table I. From this we infer a resolving power of about 150 near 15 Å, of 350 near 34 Å, and of more than 400 above 50 Å. This is comparable to the Schwob-Fraenkel instrument (SOXMOS) operated with a 600  $\ell$ /mm grating and a 10  $\mu$ m slit. The resolution of our instrument could be improved by about a factor of three by using a slit of similar width, at which point the resolving power would be limited by the 25  $\mu$ m pixel size of the CCD detector.

### ACKNOWLEDGMENTS

This work was performed under the auspices of the Department of Energy by the University of California Lawrence Livermore National Laboratory under contract W-7405-ENG-48 and supported by the Office of Fusion Energy Basic and Applied Plasma Science Initiative.

### REFERENCES

- [1] C. D. Michelis and M. Mattioli, Rep. Prog. Phys. 47, 1233 (1984).
- [2] R. J. Fonck, A. T. Ramsey, and R. V. Yelle, Appl. Optics **21**, 2115 (1982).
- [3] W. L. Hodge, B. C. Stratton, and H. W. Moos, Rev. Sci. Instrum. 55, 16 (1984).
- [4] B. C. Stratton, R. J. Fonck, K. Ida, K. P. Jaehnig, and A. T. Ramsey, Rev. Sci. Instrum.57, 2043 (1986).
- [5] J. L. Schwob, A. W. Wouters, S. Suckewer, and M. Finkenthal, Rev. Sci. Instrum. 58, 1601 (1987).
- [6] P. Beiersdorfer, S. von Goeler, M. Bitter, K. W. Hill, R. A. Hulse, and R. S. Walling, Rev. Sci. Instrum. 60, 895 (1989).
- [7] A. R. Field, J. Fink, R. Dux, G. Fussmann, U. Wenzel, and U. Schumacher, Rev. Sci. Instrum. 66, 5433 (1995).
- [8] W. Biel, G. Bertschinger, R. Burhenn, R. König, and E. Jourdain, Rev. Sci. Instrum. 75, 3268 (2004).
- [9] P. Beiersdorfer, M. Bitter, M. J. May, and L. Roquemore, Rev. Sci. Instrum. 74, 1974 (2003).
- [10] E. J. S. et al., Nucl. Fus. **43**, 1653 (2003).
- [11] B. C. Stratton, H. W. Moos, and M. Finkenthal, Astrophys. J. 279, L31 (1984).
- [12] P. Beiersdorfer, M. Bitter, S. von Goeler, and K. W. Hill, Nucl. Instrum. Meth. B 43, 347 (1989).
- [13] B. J. Wargelin, P. Beiersdorfer, D. A. Liedahl, S. M. Kahn, and S. von Goeler, Astrophys.

J. 496, 1031 (1998).

- [14] I. Martinson and C. Jupén, Phys. Scripta 68, C123 (2003).
- [15] P. Beiersdorfer, M. Bitter, S. von Goeler, and K. W. Hill, Astrophys. J. 610, 616 (2004).
- [16] J. K. Lepson, P. Beiersdorfer, E. Behar, and S. M. Kahn, Astrophys. J. **590**, 604 (2003).
- [17] S. B. Utter, G. V. Brown, P. Beiersdorfer, E. J. Clothiaux, and N. K. Podder, Rev. Sci. Instrum. 70, 284 (1999).
- [18] N. Nakano, H. Kuroda, T. Kita, and T. Harada, Appl. Optics 23, 2386 (1984).
- [19] M.-F. Gu, Astrophys. J. 582, 1241 (2003).
- [20] M. Klapisch, A. B. Shalom, J. L. Schwob, B. S. Fraenkel, C. Breton, C. de Michelis, M. Finkenthal, and M. Mattioli, Phys. Lett. 69A, 34 (1978).

### TABLES

Line	Wavelength	Line width	$\lambda/\Delta\lambda$
	(Å)	(Å)	
$O^{7+}$ Ly- $\gamma$	15.14	0.10	151
O <sup>7+</sup> Ly- $\beta$	16.11	0.10	161
${\rm O}^{7+}$ Ly- $\alpha$	19.00	0.13	146
C <sup>5+</sup> Ly- $\alpha$	33.73	0.09	387
$C^{4+} w$	40.31	0.10	403
B <sup>4+</sup> Ly- $\alpha$	48.77	0.14	356
O <sup>7+</sup> Ly- $\alpha$	56.97*	0.11	540
$\underline{\mathbf{B}^{3+} w}$	60.25	0.13	465

TABLE I. Measured line widths and associated instrumental resolving power using a 30  $\mu {\rm m}$  slit.

\*3rd order

### FIGURES

FIG. 1. Photograph of the NSTX tokamak showing the location of the new grazing-incidence spectrometer.

FIG. 2. K-shell emission features observed with LINES during typical NSTX discharges. The ion corresponding to a given line observed in first order reflection is indicated in bold-face type. Lyman  $\alpha$ ,  $\beta$ , and  $\gamma$  denotes the  $2p \rightarrow 1s$ ,  $3p \rightarrow 1s$ , and  $4p \rightarrow 1s$  transitions in hydrogenlike ions, respectively. w, K- $\beta$ , and K- $\gamma$  denote the  $1s2p \ ^{1}P_{1} \rightarrow 1s^{2} \ ^{1}S_{1}$ ,  $1s3p \ ^{1}P_{1} \rightarrow 1s^{2} \ ^{1}S_{1}$ , and  $1s4p \ ^{1}P_{1} \rightarrow 1s^{2} \ ^{1}S_{1}$  transitions in heliumlike ions, respectively. y denotes the  $1s2p \ ^{3}P_{1} \rightarrow 1s^{2} \ ^{1}S_{1}$ transition. (a) ohmically-heated helium discharge (shot 117083); (b) neutral-beam heated discharge (shot 117927). Note the added emission from hydrogenlike and heliumlike nitrogen as well as from high charge states of iron.

FIG. 3. Expanded view of the  $n = 3 \rightarrow n = 2$  emission of iron recorded during a discharge heated with a 6 MW neutral beam (shot 114459). The spectrum was fitted with an emission model constructed with the Flexible Atomic Code [19]. All features are from iron, except those from nickel (labeled in boldface type) and the oxygen Ly $\beta$ ,  $\gamma$ , and  $\delta$  lines.

FIG. 4. Argon emission recorded during ohmically heated discharges (sum of shots 117313 and 117320). The arrow points to the location of the forbidden magnetic quadrupole transition in Ar IX, which is collisionally quenched at the line-averaged density  $\langle n_e \rangle \approx 3 \times 10^{13} \text{ cm}^{-3}$  in this discharge. The B<sup>4+</sup> Lyman  $\alpha$  line was subtracted from the spectrum for clarity.







Fig. 2



Fig. 3



Fig. 4