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LLNL-CONF-432605

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May 18, 2010

18th Topical Conference on High-temperature Plasma Diagnostics
Wildwood, NJ, United States
May 16, 2010 through May 20, 2010

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Tungsten transport in the NSTX tokamak*

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(Dated: May 16, 2010)

Abstract

Tungsten particles have been introduced into the National Spherical Torus Experiment (NSTX) in Princeton with the purpose to investigate effects of tungsten injection on subsequent plasma discharges. An experimental setup for the study of tungsten particle transport is described where the particles are introduced into the tokamak using a modified particle dropper, otherwise used for lithium-powder injection. Employing a grazing-incidence extreme ultraviolet spectrometer, the time-resolved emission from highly charged tungsten ions could serve to infer particle transport from the edge to the hot central plasmas of NSTX.

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* Contributed paper, published as part of the Proceedings of the 18th Topical Conference on High-Temperature Plasma Diagnostics, Wildwood, New Jersey, May 2010

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I. INTRODUCTION

The design of heat-resistant components is an outstanding task in nuclear fusion research. Tungsten is the leading candidate material for plasma-facing surfaces expected to receive high thermal loads in magnetic fusion reactors. For instance, tungsten tiles are integral in the design of the ITER divertor [1] where the tungsten surfaces will intercept the plasma flow from the scrape-off layer. When energetic particles impinge on the surfaces tungsten particles are likely to sputter off and become introduced into the plasma. Whether the ions will get redeposited on the surfaces or penetrate into the hot core of the plasma deserves attention, because if significant amounts of tungsten ions reach the core, the resulting strong x-ray emission could cool the plasma enough to prevent fusion burn. Investigations of tungsten particle transport in present-day tokamaks could therefore provide important data for the design and control of the next-generation devices with tungsten or other high-Z material interiors.

Tungsten ions were first observed in a fusion device at the ORMAK tokamak in Oak Ridge in the 1970s by Isler *et al.* [2], where it was released into the plasma from the limiters. Strong emission was observed between 40 and 70 Å and was attributed to complex $n = 4$ - $n' = 4$ transition arrays from several charge states around thirty times ionized tungsten. Similar spectra were also observed at the Princeton Large Torus (PLT) by Hinnov *et al.* [3, 4] where, again, the tungsten ions arose from the plasma limiters. Sugar and Kaufman later evaluated the data and suggested the radiation to mainly originate from Ag-like W^{27+} [5]. In the 1980s tungsten was injected by means of laser blow off in the TEXT tokamak and the extreme ultraviolet (EUV) features were studied by Finkenthal *et al.* [6]. These investigations were followed by injection experiments by Sugar, Kaufman, and Rowan, who performed high-resolution spectroscopic studies of Ag-like W^{27+}, Pd-like W^{28+}, and Rh-like W^{29+} [7–9]. Laser-ablation injection of tungsten has furthermore been performed at the ASDEX Upgrade tokamak by Asmussen *et al* [10] and, more recently, Chowdhuri *et al.* studied tungsten between 24 and 80 Å in pellet-injection experiments at the LHD device [11]. The complex tungsten emission around 50 Å has also been investigated at the Livermore and Berlin electron beam ion trap facilities [12–14].

Here we present an experimental setup for the study of tungsten particle transport in the National Spherical Torus Experiment (NSTX) tokamak using EUV spectroscopy. Injection of tungsten particles can be achieved by means of a particle dropper located at the top of NSTX. Time-resolved observations of the tungsten emission around 50 Å could be used to infer transport of the tungsten particles.

II. EXPERIMENTAL SETUP

The NSTX device has a near spherical shape with a major radius $R = 0.86$ m and minor radius $a = 0.685$ m [15]. Typical electron densities are around 2×10^{13} cm^{-3} with electron temperatures around 1 keV. Tungsten is not used as a plasma-facing material in NSTX and does therefore not interfere with injection experiments.

Tungsten can be introduced into NSTX by employing a modified particle dropper, otherwise used for lithium-powder injection [16]. The primary component of this powder dropper is a piezo crystal in the shape of a disk 63.5 mm in diameter and 0.41 mm thick with a 2.5 mm circular aperture in the center. The crystal forms the bottom of a reservoir that stores the tungsten powder. The crystal is made to vibrate by applying a sinusoidal voltage of 1 - 20 V across the opposite faces at the crystal resonant frequency of 3.8 kHz. The amplitude of the oscillation is controlled by increasing the voltage with a corresponding linear increase in the amount of powder released to the plasma. The injection system is located on one of the upper NSTX ports. This allows for the tungsten particles, each with a radius of about 2.5 μm and weight of about 1 ng, to be dropped into the plasma, where they will brake up into smaller fragments. Each dust grain contains about 4×10^{12} tungsten atoms.

The tungsten ions are monitored by the LoWEUS spectrometer, a grazing-incidence EUV instrument. LoWEUS was previously part of the diagnostics suite of the SSPX spheromak in Livermore (then known as the Silver Flat Field Spectrometer) and is described in Ref. [16]. At NSTX, LoWEUS has been used for impurity monitoring and laboratory astrophysics measurements [17]. The spectrometer is currently equipped with a 1200 lines/mm spherical Hitachi grating [18], a 30 μm entrance slit, and a Princeton Instruments charge-coupled device (CCD) detector with a 1300×1340 pixel camera chip. The CCD is controlled by Winwiew software that allows for fast readout using only part of the chip, thereby achieving time resolutions up to around 50 ms. LoWEUS can be set up to cover the 20 - 450 Å spectral range with a resolution of around 0.3 Å.

III. INITIAL TEST

The first test of the tungsten transport setup was conducted during the last three shots of the NSTX 2009 campaign. The purpose was to investigate whether tungsten stays in the machine in subsequent plasmas after injection. For the first of these discharges, shot # 136158, the particle dropper did not release enough tungsten for detection. The number of tungsten particles dropped into the machine was therefore increased in the following shot, # 136159. A voltage of 15 V was applied to the crystal of the dropper and the tungsten was released throughout the entire 700 ms discharge at a rate of around 3 mg per second. Strong EUV emission was now observed with the LoWEUS spectrometer. A plasma with the same parameters was recreated in the next shot, # 136160, but this shot had no tungsten injection (a few particles were shaken down unintentionally). The plasmas were 1 MA neutral beam heated discharges initially with 6 MW injection power that was reduced to 4 MW at 300 ms to produce a quiescent flat-top plasma that lasted out to 700 ms.

A back calibration of the particle dropper indicated that 2 -3 milligrams of tungsten were released into NSTX, almost all of which got injected during #136159. This corresponds to roughly 2 million tungsten particles, equivalent of a concentration of 5 % relative the electron density, n_e.

The NSTX multi-point Thomson scattering (MPTS) system measured the electron-temperature and density distributions for the shots. Traces for #136159 and #136160 of T_e and n_e at 0.2, 0.4, and 0.6 s are shown in Fig. 1. The temperatures peak near the magnetic axis at around 0.8 keV after 0.4 s. The similarity between the two plasmas is remarkable.

The data from the LoWEUS instrument show strong emission from tungsten in the expected region around 50 Å from the $\Delta n = 0$ N-shell transitions from ions around Ag-like W^{27+}. The spectrometer, which was set up to cover the 30 - 190 Å region, observed the tungsten emission in first, second, and third diffraction order. The spectrometer wavelength scale was *in situ* calibrated using K-shell lines from lithium and carbon ions. The first 50 ms spectra show only intrinsic low-Z plasma impurities and first after 400 ms appear indications of tungsten. The great number of transitions in this narrow interval from many tungsten ions results in quasicontinua and a very high-resolution spectrometer is required to distinguish between individual charge states. In subsequent frames the addition of emission from higher tungsten charge states (or the accumulation of tungsten in the core plasma) increases the features and raises the background. Tungsten around the silverlike ion requires energies of 800 eV to ionize [19].

IV. CONCLUSION

The initial test with the tungsten injector shows that tungsten emission can be monitored using time-resolved EUV spectroscopy. By comparing the spectral emission from #136159 with tungsten injection to the subsequent shot #136160 without tungsten injection, it seems that very little tungsten would still exist in the plasma, see Fig. 2. Where the strong quasicontinua showed in #136159 only weak lines from low-Z impurities can be seen in #136160. Interestingly, the tungsten impurities did not seem to affect the temperature or density of the plasmas, as indicated by the Thomson measurements, shown in Fig. 1, even though the tungsten concentration was very high in shot #136159.

After these optimistic results are improvements of the system considered. First, a different readout technique of the CCD image frames or a camera with faster readout should improve the time-resolved signals. A very high resolution grating spectrometer for NSTX is also currently under construction. This instrument will have a resolving power of around 3000 at 50 Å, which is where most of the tungsten emission occurs. This is very useful as the tungsten emission from many charge states is entangled. The LoWEUS spectrometer could then focus on the long wavelength range between 120 and 140 Å, where emission from higher charge states have been observed at the ASDEX Upgrade tokamak [10], and above 150 Å where line radiation from low charge states of tungsten can be expected [20].

ACKNOWLEDGMENTS

This work was performed under the auspices of the United States Department of Energy by Princeton Plasma Physics Laboratory under Contract No. DE-AC02-09CH11466 and Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344. The authors would like to acknowledge support with the experiment from Ed Magee, Gretchen Zimmer, and the NSTX division. Joel Clementson would like to thank Manfred Bitter, Ken

Hill, Hans Lundberg, Sven Huldt, and Sune Svanberg for their support.

[1] C. H. Skinner, Can. J. Phys. **86**, 285 (Jan 2008).

[2] R. C. Isler, R. V. Neidigh, and R. D. Cowan, Phys. Lett. **63 A**, 295 (Nov 1977).

[3] E. Hinnov and M. Mattioli, Phys. Lett. **66 A**, 109 (May 1978).

[4] E. Hinnov, K. Bol, D. Dimock, R. J. Hawryluk, D. Johnson, M. Mattioli, E. Meservey, and S. von Goeler, Nucl. Fusion **18**, 1305 (1978).

[5] J. Sugar and V. Kaufman, Phys. Rev. A **21**, 2096 (Jun 1980).

[6] M. Finkenthal, L. K. Huang, S. Lippmann, H. W. Moos, P. Mandelbaum, J. L. Schwob, M. Klapisch, and TEXT Group, Phys. Lett. A **127**, 255 (Feb 1988).

[7] J. Sugar, V. Kaufman, and W. L. Rowan, J. Opt. Soc. Am. B **10**, 799 (May 1993).

[8] J. Sugar, V. Kaufman, and W. L. Rowan, J. Opt. Soc. Am. B **10**, 1321 (Aug 1993).

[9] J. Sugar, V. Kaufman, and W. L. Rowan, J. Opt. Soc. Am. B **10**, 1977 (Nov 1993).

[10] K. Asmussen, K. B. Fournier, J. M. Laming, R. Neu, J. F. Seely, R. Dux, W. Engelhardt, J. C. Fuchs, and ASDEX Upgrade Team, Nucl. Fusion **38**, 967 (Jul 1998).

[11] M. B. Chowdhuri, S. Morita, M. Goto, H. Nishimura, K. Nagai, and S. Fujioka, Plasma and Fusion Res. **2**, S1060 (2007).

[12] S. B. Utter, P. Beiersdorfer, and E. Träbert, Can. J. Phys. **80**, 1503 (Dec 2002).

[13] R. Radtke, C. Biedermann, J. L. Schwob, P. Mandelbaum, and R. Doron, Phys. Rev. A **64**, 012720 (Jul 2001).

[14] C. Biedermann, R. Radtke, J. L. Schwob, P. Mandelbaum, R. Doron, T. Fuchs, and G. Fußmann, Phys. Scr. **T92**, 85 (2001).

[15] M. Ono and NSTX Team, APS Meeting Abstracts(Nov 1996), abstract 2R.18.

[16] D. K. Mansfield *et al.*, in *2nd NIFS-CRC International Symposium on Plasma-Surface Interactions; NIFT, Toki, Gifu, Japan* (2010) submitted.

[17] J. Clementson, P. Beiersdorfer, and E. W. Magee, Rev. Sci. Instrum. **79**, 10F53 (Oct 2008).

[18] J. K. Lepson, P. Beiersdorfer, J. Clementson, M. F. Gu, M. Bitter, L. Roquemore, R. Kaita, P. G. Cox, and A. S. Safronova, J. Phys. B: At. Mol. Opt. Phys.(2010), in press.

[19] T. Kita, T. Harada, N. Nakano, and H. Kuroda, Appl. Opt. **22**, 512 (Feb 1983).

[20] A. E. Kramida and J. Reader, At. Data Nucl. Data Tables **92**, 457 (Jul 2006).

[21] J. Clementson, P. Beiersdorfer, E. W. Magee, H. S. McLean, and R. D. Wood, J. Phys. B: At. Mol. Opt. Phys.(2010), in press.

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[1] C. H. Skinner, Can. J. Phys. **86**, 285 (Jan 2008).

[2] R. C. Isler, R. V. Neidigh, and R. D. Cowan, Phys. Lett. **63 A**, 295 (Nov 1977).

[3] E. Hinnov and M. Mattioli, Phys. Lett. **66 A**, 109 (May 1978).

[4] E. Hinnov, K. Bol, D. Dimock, R. J. Hawryluk, D. Johnson, M. Mattioli, E. Meservey, and S. von Goeler, Nucl. Fusion **18**, 1305 (1978).

[5] J. Sugar and V. Kaufman, Phys. Rev. A **21**, 2096 (Jun 1980).

[6] M. Finkenthal, L. K. Huang, S. Lippmann, H. W. Moos, P. Mandelbaum, J. L. Schwob, M. Klapisch, and TEXT Group, Phys. Lett. A **127**, 255 (Feb 1988).

[7] J. Sugar, V. Kaufman, and W. L. Rowan, J. Opt. Soc. Am. B **10**, 799 (May 1993).

[8] J. Sugar, V. Kaufman, and W. L. Rowan, J. Opt. Soc. Am. B **10**, 1321 (Aug 1993).

[9] J. Sugar, V. Kaufman, and W. L. Rowan, J. Opt. Soc. Am. B **10**, 1977 (Nov 1993).

[10] K. Asmussen, K. B. Fournier, J. M. Laming, R. Neu, J. F. Seely, R. Dux, W. Engelhardt, J. C. Fuchs, and ASDEX Upgrade Team, Nucl. Fusion **38**, 967 (Jul 1998).

[11] M. B. Chowdhuri, S. Morita, M. Goto, H. Nishimura, K. Nagai, and S. Fujioka, Plasma and Fusion Res. **2**, S1060 (2007).

[12] S. B. Utter, P. Beiersdorfer, and E. Träbert, Can. J. Phys. **80**, 1503 (Dec 2002).

[13] R. Radtke, C. Biedermann, J. L. Schwob, P. Mandelbaum, and R. Doron, Phys. Rev. A **64**, 012720 (Jul 2001).

[14] C. Biedermann, R. Radtke, J. L. Schwob, P. Mandelbaum, R. Doron, T. Fuchs, and G. Fußmann, Phys. Scr. **T92**, 85 (2001).

[15] M. Ono and NSTX Team, APS Meeting Abstracts(Nov 1996), abstract 2R.18.

[16] D. K. Mansfield *et al.*, in *2nd NIFS-CRC International Symposium on Plasma-Surface Interactions; NIFT, Toki, Gifu, Japan* (2010) submitted.

[17] J. Clementson, P. Beiersdorfer, and E. W. Magee, Rev. Sci. Instrum. **79**, 10F53 (Oct 2008).

[18] J. K. Lepson, P. Beiersdorfer, J. Clementson, M. F. Gu, M. Bitter, L. Roquemore, R. Kaita, P. G. Cox, and A. S. Safronova, J. Phys. B: At. Mol. Opt. Phys.(2010), in press.

[19] T. Kita, T. Harada, N. Nakano, and H. Kuroda, Appl. Opt. **22**, 512 (Feb 1983).

[20] A. E. Kramida and J. Reader, At. Data Nucl. Data Tables **92**, 457 (Jul 2006).

[21] J. Clementson, P. Beiersdorfer, E. W. Magee, H. S. McLean, and R. D. Wood, J. Phys. B: At. Mol. Opt. Phys.(2010), in press.

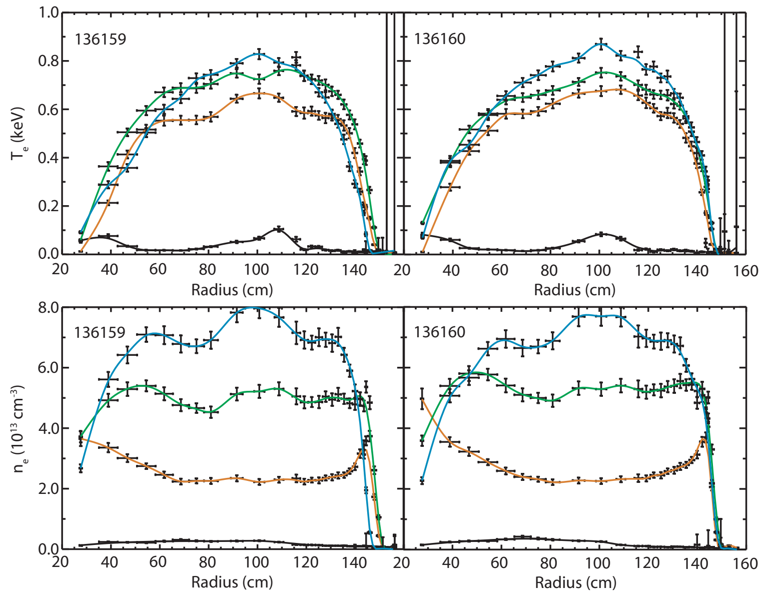

FIG. 1. Electron temperature and density profiles for NSTX shots #136159 and #136160 for 0.2, 0.4, and 0.6 s.

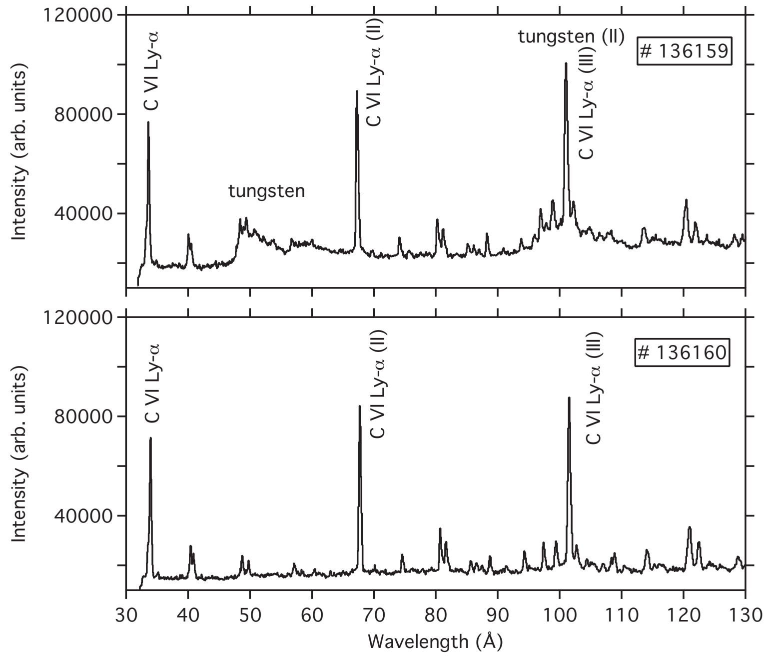

FIG. 2. Time-integrated spectra from LoWEUS after 0.6 s. **Top**: NSTX shot #136159 with tungsten injection. **Bottom**: NSTX shot #136160 without tungsten injection. The tungsten continua are not seen and only B and N show.