Experimental setup for tungsten transport studies at the NSTX tokamak[a]

J. Clementson,[1,b] P. Beiersdorfer,[1] A. L. Roquemore,[2] C. H. Skinner,[2] D. K. Mansfield,[2] K. Hartzfeld,[2,c] and J. K. Lepson[3]
[1]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[2]*Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA*
[3]*University of California, Berkeley, Berkeley, California 94720, USA*

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Tungsten particles have been introduced into the National Spherical Torus Experiment (NSTX) in Princeton with the purpose to investigate the 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. An initial test employing a grazing-incidence extreme ultraviolet spectrometer demonstrates that the tungsten-transport setup could serve to infer particle transport from the edge to the hot central plasmas of NSTX. © *2010 American Institute of Physics.* [doi:10.1063/1.3499607]

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 target plates are integral in the design of the ITER divertor,[1,2] 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 is a question that 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 construction materials.

Tungsten ions were first observed in a fusion device at the ORMAK tokamak in Oak Ridge in the 1970s by Isler *et al.*,[3] where it was released into the plasma from the limiters. Strong emission was observed between 40 and 70 Å and was attributed to ions with 4d configurations from charge states around 32 times ionized tungsten. Similar spectra were also observed at the Princeton Large Torus by Hinnov *et al.*,[4,5] where, again, the tungsten ions arose from the plasma limiters. Sugar and Kaufman[6] later evaluated the data and suggested the radiation to mainly originate from Ag-like W^{27+}. In the 1980s, tungsten was injected into the TEXT tokamak by means of laser blow off, and the extreme ultraviolet (EUV) emission was studied by Finkenthal *et al.*[7] This investigation was followed by additional injection experiments at TEXT by Sugar, Kaufman, and Rowan,[8–10] who performed high-resolution spectroscopic measurements of Ag-like W^{27+}, Pd-like W^{28+}, and Rh-like W^{29+}. Tungsten injection experiments have later been performed at the ASDEX Upgrade tokamak by Asmussen *et al.*,[11] who used a laser-ablation system, and in LHD plasmas by Chowdhuri *et al.*[12] using pellet injection. More recently, Harte *et al.*[13] studied tungsten spectra from the LHD, and Podpaly *et al.*[14] observed EUV tungsten spectra at the Alcator C-Mod tokamak. The complex tungsten emission around 50 Å has also been investigated at the Livermore and Berlin electron beam ion trap facilities.[15–18]

Here, we present an experimental setup for the study of tungsten particle transport in the National Spherical Torus Experiment (NSTX) tokamak using EUV spectroscopy. The 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 EUV 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.[19] 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 not, therefore, indigenously exist in the plasmas.

Tungsten can be introduced into NSTX by employing a modified particle dropper, otherwise used for lithium-powder injection.[20] 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

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[b]Also at the Department of Physics, Lund University, SE-221 00 Lund, Sweden. Electronic mail: clementson@llnl.gov.
[c]Present address: Toms River High School North, Toms River, New Jersey 08753, USA.

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 with a radial line-of-sight in the horizontal plane of NSTX plasmas. 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. 21. At NSTX, LoWEUS has been used for impurity monitoring and laboratory astrophysics measurements.[22] The spectrometer is currently equipped with a 1200 lines/mm spherical Hitachi grating,[23] a 30 μm entrance slit, and a Princeton Instruments charge-coupled device (CCD) detector with a 1300 $\times$1340 pixel camera chip. The CCD is controlled by the WINWIEW software that allows for fast readout using only part of the chip, thereby achieving time resolutions of 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.

The dust particles are also monitored using a fast camera system.[24] When the tungsten particles enter the scrape-off layer of the NSTX plasmas, they become incandescent, allowing high frame rate optical cameras to track the complicated particle trajectories.[25]

III. TEST OF SETUP

The first test of the tungsten-transport setup was conducted during the last few shots of the NSTX 2009 campaign. The purpose was to investigate whether tungsten stays in the machine in subsequent plasmas after injection. Two plasmas with identical conditions were studied where tungsten was injected during shot No. 136159 and compared to the following noninjection discharge shot No. 136160. 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 up to 700 ms. The NSTX multipoint Thomson scattering system measured the electron-temperature and density distributions for the shots. The temperatures peaked at around 0.8 keV near the magnetic axis after 0.4 s.

For shot No. 136159, a voltage of 15 V was applied to the crystal of the particle dropper, and tungsten was released into NSTX throughout the entire 700 ms discharge at a rate of around 3 mg/s. For the following plasma, shot No. 136160, the plasma parameters were recreated except without tungsten injection, save for a few particles that were shaken down unintentionally as observed with the fast cameras. A back calibration of the particle dropper indicated that 2–3 mg of tungsten was released into NSTX, almost all of which got injected during shot No. 136159. This corresponds to roughly 2×10^6 tungsten particles, equivalent to a maximum concentration of $0.05n_e$.

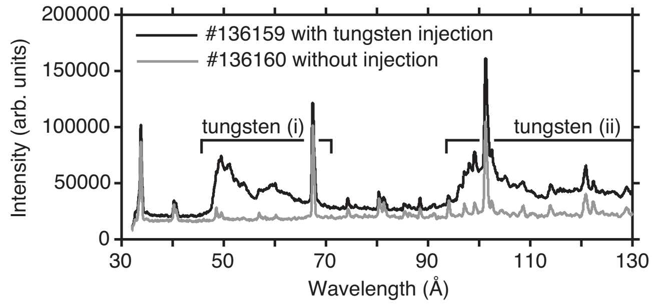

FIG. 1. Time-integrated spectra of NSTX shots No. 136159 with tungsten injection, and shot No. 136160 without tungsten injection from the LoWEUS spectrometer after 0.7 s. The tungsten quasicontinua are shown in (i) first and (ii) second orders together with line emission from low-Z ions.

The data from the LoWEUS spectrometer show strong emission from tungsten in the expected wavelength region around 50 Å during shot No. 136159. The great number of $\Delta n=0$ N-shell transitions from charge states lower than Ag-like W^{27+} [IE=881.4 eV (Ref. 26)] results in quasicontinua emission. The spectrometer, which was set up to cover the 30–190 Å region, observed the tungsten emission in first, second, and third diffraction orders. The spectrometer wavelength scale was *in situ* calibrated using K-shell lines from carbon ions. The first frames show only intrinsic low-Z plasma impurities, and after 400 ms, indications of tungsten first appear. The tungsten quasicontinua grow stronger in the subsequent frames, which is likely both due to the creation of higher charge states and to the transport of tungsten ions from the scrape-off layer to the main plasma volume. The time-resolved spectra from shot No. 136160 do not show any indications of tungsten in the main plasma volume. The injected tungsten particles have either been pumped away or gotten deposited on some plasma-facing surface.

IV. CONCLUSION

The initial test with the NSTX tungsten-transport setup shows that tungsten dust can be introduced into NSTX plasmas using the modified lithium-powder injector and the resulting EUV emission monitored using time-resolved spectroscopy. By comparing the spectral emission from No. 136159 with tungsten injection to the subsequent shot No. 136160 without tungsten injection, it seems that very little tungsten would still exist in the plasma. Figure 1 displays two spectra showing the integrated emission after 0.7 s from the two discharges in the 30–130 Å region, covering first and second diffraction orders of the tungsten emission. Where the strong quasicontinua appeared in shot No. 136159, only emission from low-Z ions can be seen in shot No. 136160. The facts that the electron temperatures of the two NSTX shots were almost identical and that most of the injected tungsten seems to have been pumped away quickly are very interesting given the large quantity of injected tungsten. The maximum concentration of $0.05n_e$ is far beyond the estimated levels of tolerable tungsten concentrations for burning plasmas, which usually range from $10^{-5}n_e$ to $10^{-4}n_e$.

After these encouraging results, improvements to the spectroscopic system are being implemented. A new CCD detector with faster readout is being tested. A very high-resolution grating spectrometer is also currently under construction. This instrument will have a resolving power possibly as high as 5000 at 50 Å, which is where most of the tungsten emission occurs. This is very useful as the radiation from many charge states is entangled and high spectral resolution is necessary to identify individual tungsten ions. The LoWEUS spectrometer could then focus on the long wavelength range between 120 and 140 Å, where emissions from higher tungsten charge states have been observed in the ASDEX Upgrade tokamak[11] and above 150 Å where line radiation from low charge states of tungsten can be expected.[27]

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