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Three new extreme ultraviolet spectrometers on NSTX-U for impurity monitoring

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Three extreme ultraviolet (EUV) spectrometers have been mounted on the National Spherical Torus Experiment–Upgrade (NSTX-U). All three are flat-field grazing-incidence spectrometers and are dubbed X-ray and Extreme Ultraviolet Spectrometer (XEUS, 8–70 Å), Long-Wavelength Extreme Ultraviolet Spectrometer (LoWEUS, 190–440 Å), and Metal Monitor and Lithium Spectrometer Assembly (MonaLisa, 50–220 Å). XEUS and LoWEUS were previously implemented on NSTX to monitor impurities from low- to high-Z sources and to study impurity transport while MonaLisa is new and provides the system increased spectral coverage. The spectrometers will also be a critical diagnostic on the planned laser blow-off system for NSTX-U, which will be used for impurity edge and core ion transport studies, edge-transport code development, and benchmarking atomic physics codes. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4960755]

I. INTRODUCTION

National Spherical Torus Experiment–Upgrade (NSTX-U) is a significant advancement from NSTX, which once fully operating will provide increased toroidal field (0.5 T → 1.0 T), plasma current (1 MA → 2 MA), and neutral beam injector power (NBI, 7 MW → 14 MW).[1] The improvements are likely to generate more intense plasma conditions, providing increased challenge to plasma facing components (PFCs) and potentially enhance impurities penetrating into the core. Along with these upgrades, improvements have been made to the previously implemented extreme ultraviolet (EUV) spectrometer assembly, which included the X-ray and Extreme Ultraviolet Spectrometer (XEUS)[2] and Long-Wavelength Extreme Ultraviolet Spectrometer (LoWEUS).[3] These two spectrometers were used primarily for a series of laboratory measurement experiments to calibrate spectral density diagnostics used for studying astrophysical sources and for monitoring low and high-Z impurities.[4] Other related spectrometers have been used on various other tokamaks to study similar physics.[5,6]

The improvements to the EUV spectrometer assembly include increasing the total spectral range to 8–440 Å by adding a third spectrometer, dubbed the Metal Monitor and Lithium Spectrometer Assembly (MonaLisa), increasing time-resolution below 10 ms, and grouping the spectrometers together to view directly into the core of the plasma from one toroidal location. To expand coverage LoWEUS was moved to cover the range of 190–440 Å, up from the previous setting on NSTX that covered a maximum of 250 Å. This work provides data from these high resolution spectrometers of wavelengths greater than 250 Å and up to 440 Å for the first time.

The spectrometers will be used for monitoring, for example, low-Z Lyman-α (2p → 1s) transitions of carbon at 33.7 Å, oxygen at 18.9 Å, boron at 48.6 Å, and lithium at 134.9 Å. Possible metal impurities include copper, nickel, and iron whose L-shell lines predominately radiate between 8 and 20 Å and have M-shell lines that radiate throughout the covered spectral range. Future NSTX-U experiments will utilize high-Z PFCs made of molybdenum (Mo) and tungsten (W), both of which will have impurity line radiation captured including the region between 40 and 90 Å where Mo and W can radiate from different charge states from Mo XVI - XXIII and W XXVIII - XLIV. Given this ability to monitor nearly any impurity radiating from the plasma, the spectrometers will be a critical early detector of any problems that could develop within NSTX-U.

The spectrometers will offer an excellent opportunity to study impurity transport in NSTX-U, especially coupled with the planned laser-blow off (LBO) system that will be installed. The LBO system is based on a system[7] used at the Livermore Electron Beam Ion Trap (EBIT) facility and will be able to inject a controlled amount of atoms into the plasma at a given time. This will allow for the measure of impurity diffusivity, convective pinch velocity, and assess high-Z impurity transport at low collisionality and high-β regime.

II. SPECTROMETER SETTINGS

XEUS, MonaLisa, and LoWEUS are all flat-field grazing incident spectrometers[8] that provide high resolution in the EUV range. The grating used for all three spectrometers is based on the spherical Hitachi[9] design. XEUS employs a 2400 lines/mm grating, operates at an angle of incidence of 1.3°, provides a full width at half maximum (FWHM) of 0.1 Å, and a spectral coverage of 8–70 Å. MonaLisa employs a 1200 lines/mm grating, operates at an angle of incidence of 3.0°, provides a FWHM of 0.3 Å, and a spectral coverage of 50–220 Å. LoWEUS employs a 1200 lines/mm grating, operates at an angle of incidence of 3.0°, provides a FWHM

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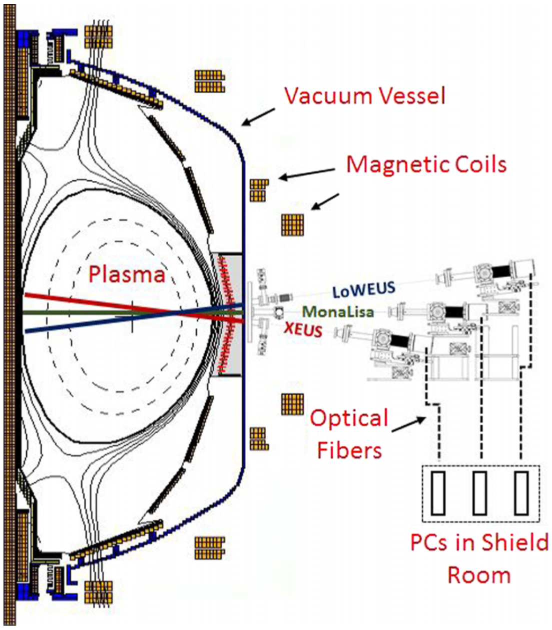

FIG. 1. EUV spectrometer locations with lines of sight for XEUS, MonaLisa, and LoWEUS shown in red, green, and blue, respectively. Also shown is a poloidal cross section of the NSTX-U vacuum vessel with a magnetic equilibrium reconstruction of shot 205079 at 0.70 s.

of 0.3 Å, and a spectral coverage of 190–440 Å. All three have 100 μm slits and the focal distance of approximately 23 cm.

The spectrometers are all located at NSTX-U Bay E in the midplane (see Fig. 1). MonaLisa is mounted at a 0° angle with respect to the horizontal, while XEUS is mounted 7.0° below and LoWEUS is mounted 7.0° above the horizontal. XEUS is closer with the slit located approximately 1.5 m away from the center of the NSTX-U plasma core, followed by MonaLisa at 1.8 m and LoWEUS at 2.1 m. It is important to note that the spectrometers sit on the opposite side of the chamber as the two NBI, so contributions from charge exchange between ionized impurities and energetic neutrals are not expected to be measured in this setup.

The detectors used are Princeton Instruments PIXIS-XO 100B cameras, which consist of a 1340 × 100 pixel back-illuminated charge coupled device (CCD) designed for use with soft x-ray and EUV photons and have a 2 MHz digitization rate, allowing for fast readout times using the "full bin" mode (down to 1 pixel, 3 ms readout time). To allow for easy calibration and alignment of the detector, it is recommended to use the "full chip" mode (no pixels binned); however, this comes at the expense of time resolution (70 ms readout time). Currently the most optimal detector settings are being explored and tested on NSTX-U.

III. EXPERIMENTAL RESULTS

First results from the EUV spectrometers employed on NSTX-U are shown in Figs. 2-4. The spectra were taken from NSTX-U shot 205079 and were low confinement mode, 2-3 MW modulated NBI power (on from 0.25 to 1.06 s), 0.65 MA plasma current, and plasma lasted for just over 1 s. The peak electron temperature (T_e) was ~1.26 keV and peak electron density (n_e) was ~1.3×10^{19} m^{-3}.

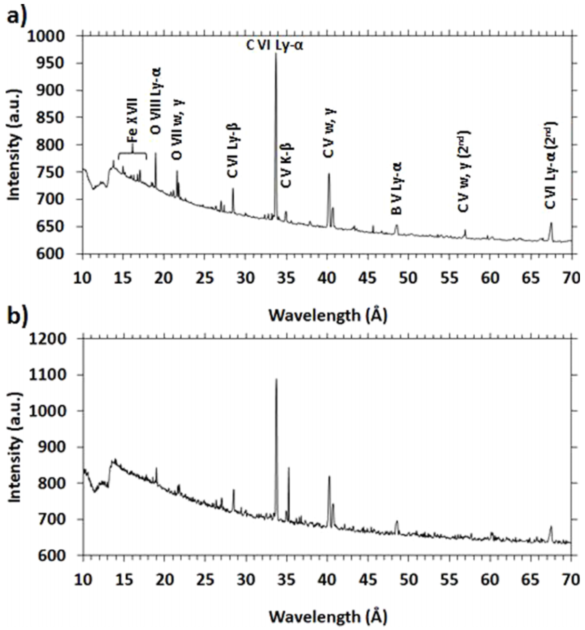

FIG. 2. Example of XEUS spectra taken from NSTX-U shot 205079 at (a) 0.17 s and (b) 0.73 s. Lines of B, C, O, and Fe are identified.

XEUS spectra in Fig. 2 are dominated by carbon throughout most of the shot, in particular, C VI Ly-α at 33.7 Å and C VI Ly-β at 28.5 Å. Other lines identified are C V *w* and *y* at 40.3 and 40.7 Å, respectively, O VIII Ly-α at 19.0 Å, O VII *w* and *y* at 21.6 and 20.8 Å, respectively, and B V Ly-α at 48.6 Å. Four lines of L-shell Fe XVII are at 15.0, 15.3, 16.8, and 17.1 Å are measured early on at 0.17 s (Fig. 2(a)) and disappear when NBI is turned on (Fig. 2(b)). Iron likely originates from stainless steel components as discussed later. Carbon, oxygen, and boron are expected to radiate within NSTX-U, so these spectra constitute a good example of a "clean" discharge; however, if the ratio of oxygen to carbon goes up (i.e., oxygen

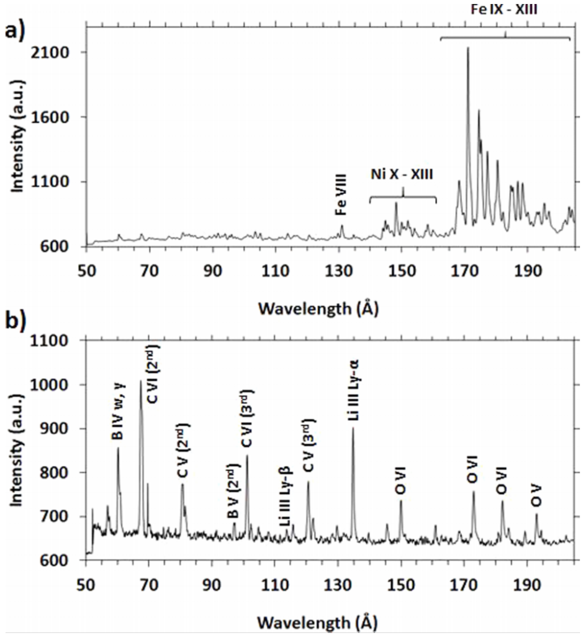

FIG. 3. Example of MonaLisa spectra taken from NSTX-U shot 205079 at (a) 0.03 s and (b) 0.73 s. Lines of B, C, O, Ni, and Fe are identified.

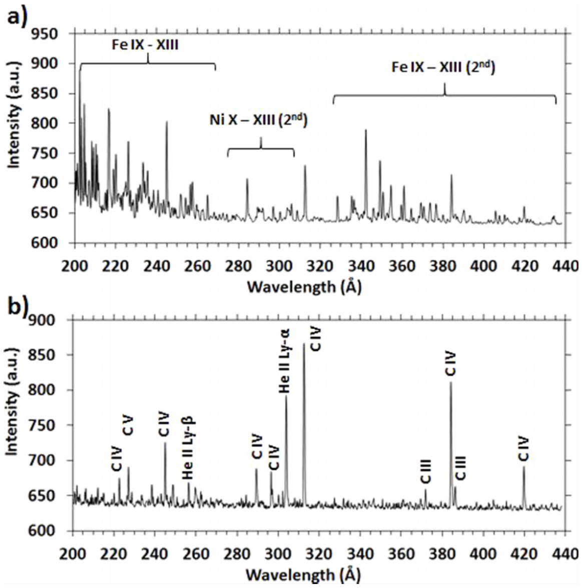

FIG. 4. Example of LoWEUS spectra taken from NSTX-U shot 205079 at (a) 0.03 s and (b) 0.73 s. Lines of He, C, Ni, and Fe are identified.

increases) in consequential shots, it could be a sign that wall conditioning, such as a boronization, is in order.

MonaLisa spectra are shown if Fig. 3. The position of the detector with respect to the focal plane is still being adjusted for MonaLisa; however, information about the plasma can still be gathered. For instance, in the first 100 ms of the shot, before the NBI is turned on, the spectrum is dominated by M-shell lines of Fe and Ni, two components of stainless steel, as shown in Fig. 3(a). This phenomenon of stainless steel radiating early before the NBI heating was also seen in Ref. 3 on NSTX and it is confirmed to occur in NSTX-U. After M-shell of Fe and Ni is "burned out," the spectra are dominated by carbon, oxygen, and lithium lines, as shown in Fig. 3(b). The overlap section between 50 and 70 Å of XEUS and MonaLisa in Figs. 2(b) and 3(b) at 0.73 ms shows an important difference in, for example, second order of C VI Ly-α at 66.5 Å, which is much more intense on MonaLisa than it is on XEUS. The difference in intensity is possibly caused by differences in grating used or also viewing the plasma from different angles.

LoWEUS data in the covering 190–440 Å are shown for the first time in Fig. 4. Early on in the shot, as in MonaLisa data, M-shell Fe lines are seen, which last until the NBI is turned on after 100 ms. Second order M-shell Fe lines can be seen after 340 Å. After the NBI is turned on M-shell Fe quickly goes away and after the spectra are dominated by carbon and helium. Helium is present from both He-glow discharge cleaning between shots, and the occasional experiments run with He-gas. Detailed spectra of both early time (Fig. 4(a)) and late time (Fig. 4(b)) are provided. Lines identified to help with calibration are C IV lines at 222.8, 244.9, 289.2, 296.9, 312.4, 384.1, and 419.6 Å. A few He lines that have been identified are He II at 303.8 and 256.3 Å.

Fig. 5(a) shows time histories of n_e, T_e, plasma current, and NBI power while Fig. 5(b) highlights an example of line intensities as a function of time for Ly-α lines of B V, C VI, and O VIII from NSTX-U shot 205079. As expected, carbon dominates oxygen through the duration of the shot. The sudden spike in intensity just after 0.9 s correlates to the NBI power jumping from 2 MJ to 3 MJ and n_e going from ~1.0 to 1.3 $\times 10^{19}$ m^{-3}. As mentioned above, studying line intensities and ratios as functions of time (during the course of one experiment and also many experiments) will be crucial in assessing wall conditions and wall conditioning techniques.

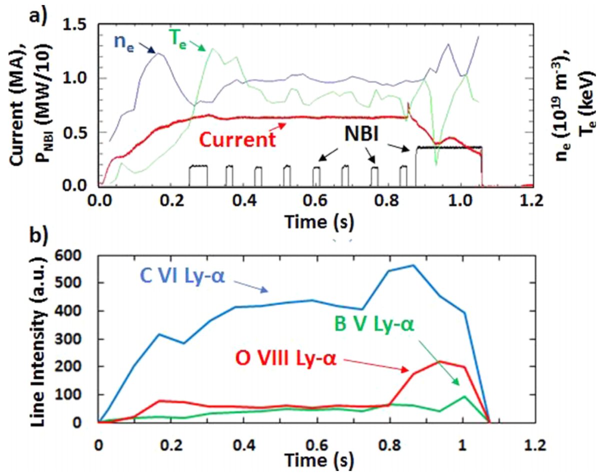

FIG. 5. (a) Signals from NSTX-U shot 205079 and (b) line intensities of B V, C VI, and O VIII Lyman-α as a function of time.

IV. CONCLUSIONS

NSTX-U results of EUV spectra covering the spectral range of 8–440 Å have been shown for the first time. In particular data from LoWEUS covered the spectral range greater than 250 Å which has never before been covered with this setup. The radiation was shown to be dominated by M-shell Fe and Ni lines before NBI heating and then dominated by C, followed by He, Li, O, and B lines. Work continues on finalizing the positions and settings of the detectors. Once finished future work will include gathering trend information to assess wall conditioning techniques. Studying particular line ratios with knowledge of electron temperature and density from Thomson scattering will also be able to provide key benchmarks to atomic codes (see Ref. 4 for examples). Finally, once the planned LBO system is installed, the EUV spectrometers will provide invaluable information on impurity transport.

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[1] J. E. Menard *et al.*, Nucl. Fusion **52**, 083015 (2012).
[2] P. Beiersdorfer *et al.*, Rev. Sci. Instrum. **79**, 10E318 (2008).
[3] J. K. Lepson *et al.*, Rev. Sci. Instrum. **83**, 10D520 (2012).
[4] J. K. Lepson *et al.*, J. Phys. B **43**, 144018 (2010).
[5] M. L. Reinke *et al.*, Rev. Sci. Instrum. **81**, 10D736 (2010).
[6] M. E. Weller *et al.*, Rev. Sci. Instrum. **83**, 10E101 (2012).
[7] A. M. Niles *et al.*, Rev. Sci. Instrum. **77**, 10F106 (2006).
[8] N. Nakano *et al.*, Appl. Opt. **23**, 2386 (1984).
[9] T. Kita *et al.*, Appl. Opt. **22**, 512 (1983).