Responsivity Calibration of the LoWEUS Spectrometer[a)]

J. K. Lepson,[1, b)] P. Beiersdorfer,[2] R. Kaita,[3] R. Majeski,[3] and D. Boyle[3]

[1)] *Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA*

[2)] *Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

[3)] *Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA*

(Dated: 27 July 2016)

We performed an *in situ* calibration of the relative responsivity function of the Long-Wavelength Extreme Ultraviolet Spectrometer (LoWEUS), while operating on the Lithium Tokamak Experiment (LTX) at Princeton Plasma Physics Laboratory. The calibration was accomplished by measuring oxygen lines, which are typically present in LTX plasmas.The measured spectral line intensities of each oxygen charge state were then compared to the calculated emission strengths given in the CHIANTI atomic database. Normalizing the strongest line in each charge state to the CHIANTI predictions, we obtained the differences between the measured and predicted values for the relative strengths of the other lines of a given charge state. We find that a 3rd degree polynomial function provides a good fit to the data points. Our measurements show that the responsivity between about 120 and 300 Å varies by factor of ∼30.

PACS numbers: 52.55.Fa, 52.25.Vy, 52.70.Kz

I. INTRODUCTION

The extreme ultraviolet (EUV) region is rich in emission lines that provide important diagnostic information on the plasma conditions. In laboratory settings, such as those produced in magnetic fusion devices, this region is investigated spectroscopically mainly in order to diagnose the plasma impurity content[1]. In addition, EUV emission lines also may provide plasma parameters, such as electron temperature and density, ion temperature, and bulk ion velocity[2]. Oxygen is a prominent component in most fusion plasmas. Because of its ubiquity, it can be a useful diagnostic and our measurement in the following utilize the presence of oxygen lines in the LTX tokamak.

An accurate responsivity function is important in order to determine absolute or relative intensities of emission lines from various plasma impurities, and thus to determine relative impurity concentrations. Measurements of the responsivity function may be performed with a reference source, in particular synchotrons, such as the Advanced Light Source[3]. Although accurate, it is labor-intensive and requires the movement of the spectrometer between different locations. Here we demonstrate an *in situ* calibration of the spectral responsivity function.

II. METHODS AND RESULTS

Plasma emission on the Lithium Torus Experiment at PPPL was measured with the LoWEUS spectrometer. LoWEUS is a varied-line-spacing flat-field grating spectrometer with a mean spacing of 1200 lines/mm and an instrumental resolution of 0.3 ; data are collected with a cryogenically cooled CCD camera and an image size of 1300 x 1340 pixels[4]. Emission in the EUV region we studied (115-325 Å) is typically dominated by lines of lithium and oxygen, but extrinsic impurities, such as aluminum, are seen in some shots. A typical spectrum obtained on LTX is shown in Fig. 1. The dominant lines observed in this spectrum include helium-like Li II, hydrogenic Li III, boron-like O IV, lithium-like O V, and helium-like O VI.

Oxygen emission lines were identified with the aid of the CHIANTI database. The CHIANTI atomic database has been developed and refined over the past 20 years[5,6]. Although there are some deficiencies in the atomic data for the more esoteric elements found in astrophysical plasmas[7,8], CHIANTI's atomic modeling is mature and is well tested for the commoner elements with low atomic number, such as oxygen, and is used extensively in solar physics. Oxygen emission lines predicted by the CHIANTI model are therefore well suited as reference standards for the calibration of an EUV spectrometer.

For our calibration, we used spectral emissivity calculations from CHIANTI for electron densities $N_e = 10^{10}\mathrm{cm}^{-3}$ and $N_e = 10^{15}\mathrm{cm}^{-3}$, which bracket the density of LTX plasmas. CHIANTI calculations show that there are very few oxygen lines in this region that exhibit a strong density dependence. In fact, most lines show no density dependence, and the density dependence of those that do is minor given that the density differs by five orders of magnitude. In the following, we exclude the few lines that showed a signficant density dependence.

We produced a synthetic spectrum for each oxygen charge state, based on the CHIANTI data, as indicated by the red, blue, and green traces in Fig. 1, representing the emission of O IV, O V, and O VI. The calculated intensity of the strongest line for each charge state was normalized to its measured intensity. In Fig. 2 we plot the ratios of the measured to calculated intensities for each of the three oxygen charge states. Data are plotted for a density of both $N_e = 10^{10}\mathrm{cm}^{-3}$ and $N_e = 10^{15}\mathrm{cm}^{-3}$,

[a)]Contributed paper published as part of the Proceedings of the 21st Topical Conference on High-Temperature Plasma Diagnostics (HTPD 2016) in Madison, Wisconsin, USA.

[b)]Electronic mail: lepson@ssl.berkeley.edu

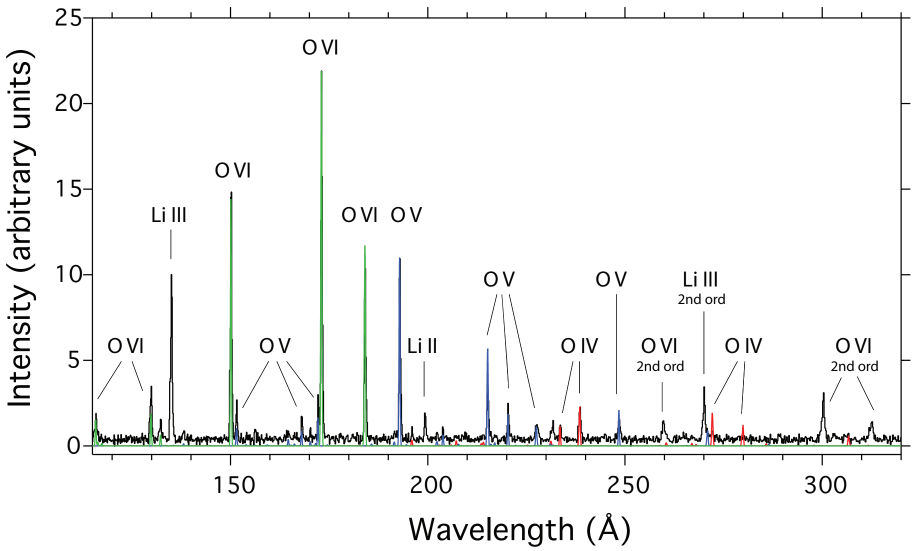

FIG. 1. Synthetic spectrum of oxygen emission derived from the CHIANTI database (colored by charge state) overlaid onto LoWEUS spectrum of LTX (black, sum of 16 shots taken on 21 Feb 2014.

which shows there is a relatively minor variation between the two densities assumed in the calculations. Although there is no strong dependence on the density, there is, however, rather large line to line variation in the ratio of calculated and measured intensities. The large variation in the ratios and their deviation from the fit may appear discouraging. However, we note that our previous calibrations on synchrotrons of the types of gratings we use in our instrument showed that the relative grating reflectivity varies smoothly[3]. In fact, our synchrotron calibrations showed a monotonically diminishing reflectivity as the wavelength was increased; it showed none of the abrupt changes as a function of wavelength implied by the line to line variations in Fig. 2. We therefore conclude that this variation reflects problems in the atomic data used by CHIANTI. In addition, the lines of O IV were quite weak, which increases the measurement error. Because our data set includes a very large number of lines (a total of 30), we may expect that these problems diminish or even vanish in the average. Note that this is reliant upon having a large number of lines to compare; the smaller the data set the more likely it is to deviate from the actual value simply due to chance.

The ratios plotted in Fig. 2 were fitted with a polynomial. The best fit was described by a 3rd order polynomial. A 2nd order fit, based on the χ^2 residuals, was not as good, while higher order fits were unrealistically complex without increasing the accuracy. The fit shows that the responsivity varies by about a factor of 30 between about 120 and 300 Å, which is primarily due to the lower responsivity as one moves away from the blaze angle of the grating. This degree of variation is also not unreasonable based on our earlier synchrotron calibration of such gratings[3].

III. DISCUSSION

In order to test the reliability of the instrumental response function displayed in Fig. 2, we examined the emission of Al V, which has lines near 130 Å, as well as near 280 Å. Our response function indicates that the measured intensities need to be multiplied by a factor of 22. Indeed, after doing so, the measured intensities match those calculated, validating the responsivity function we derived from the measured and predicted oxygen spectra.

Oxygen emission is not confined to LTX plasmas, but is nearly ubiquitous in fusion plasmas. As a result, *in situ* calibration of the response function of an EUV spectrometer is possible at essentially any magnetic fusion device. Spectrometers similar to LoWEUS are in place also on the National Spherical Torus Experiment Upgrade (NSTX-U) at the Princeton Plasma Physica Laboratory and Alcator C-Mod at the Massachussetts Institute of Technology, and one has just been installed at the DIII-D tokamak at General Atomics[9–11].

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, by Princeton Plasma Physics Laboratory under Contract DE-AC02-09CH11466, and supported by the U.S. De-

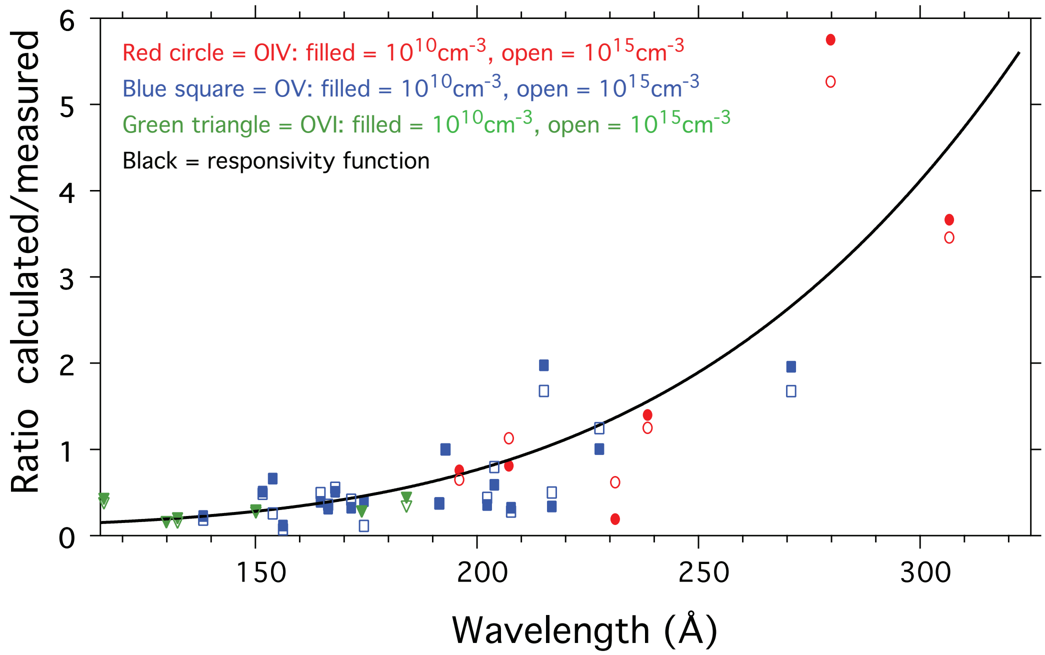

FIG. 2. Ratio of calculated (CHIANTI) to measured line strengths for oxygen emission lines on LTX with the derived responsivity function. Charge states are colored as in Fig. 1. Only first-order lines were used.

partment of Energy Basic Plasma Science Program.

[1]B. C. Stratton, M. Bitter, K. W. Hill, D. L. Hillis, and J. T. Hogan, Fusion Sci. Techn. **53**, 431 (2008).
[2]J. Lepson, P. Beiersdorfer, M. Bitter, and S. M. Kahn, Can. J. Phys. **86**, 175 (2008).
[3]M. May, J. Lepson, P. Beiersdorfer, D. Thorn, H. Chen, D. Hey, & A. Smith, RSI **74**, 2011 (2003).
[4]J. Lepson, P. Beiersdorfer, J. Clementson, M. F. Gu, M. Bitter, L. Roquemore, R. Kaita, P. G. Cox, and A. S. Safronova, J. Phys. B **43**, 144018 (2010).
[5]K. P. Dere, E. Landi, H. E. Mason, B. C. Monsignori Fossi, & P. R. Young, A&AS **125**, 149 (1997).
[6]E. Landi, P. R. Young, K. P. Dere, G. Del Zanna, H. E. Mason, ApJ **763**, 86. (2013).
[7]J. K. Lepson, P. Beiersdorfer, E. Behar, & S. M. Kahn, ApJ **590**, 604 (2003).
[8]J. K. Lepson, P. Beiersdorfer, E. Behar, & S M. Kahn, ApJ **625**, 1045 (2005).
[9]J. Lepson, P. Beiersdorfer, J. Clementson, M. Bitter, K. W. Hill, R. Kaita, L. Roquemore, & G. Zimmer, RSI **83**, 10D520 (2012).
[10]M. L. Reinke, P. Beiersdorfer, N. T. Howard, E. W. Magee, Y. Podpaly, J. E. Rice, & J. L. Terry, RSI **81**, 10D736 (2010).
[11]P. Beiersdorfer,, G. V. Brown, J. B.Camp, E. W. Magee, J. K. Lepson, Y. Podpaly, & M. L. Reinke, Can. J. Phys. **89**, 653 (2011).