High-Resolution Grazing-Incidence Spectrometer for Temperature Measurements of Low-Z Ions Emitting in the 100 Å – 300 Å Spectral Band*

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We have constructed a high-resolution grazing-incidence spectrometer designed for measuring the ion temperature of low-Z elements, such as Li^+ or Li^{2+}, which radiate near 199 Å and 135 Å, respectively. Based on measurements at the Livermore Electron Beam Ion Trap we have shown that the instrumental resolution is better than 0.034 Å at the 200 Å setting and better than 0.028 Å for the 135-Å range. Such a high spectral resolution corresponds to an instrumental limit for line-width based temperature measurements of about 35 eV for the 199 Å Li^+ and 50 eV for the 135 Å Li^{2+} lines. Recently obtained survey spectra from the Lithium Tokamak Experiment at the Princeton Plasma Physics Laboratory show the presence of these lithium emission lines and the expected core ion temperature of approximately 70 eV is sufficiently high to demonstrate the feasibility of utilizing our high-resolution spectrometer as an ion-temperature diagnostic.

I. INTRODUCTION

High-resolution x-ray spectroscopy has proved to be a very successful tool for diagnosing a wide variety of plasmas, from astrophysical sources to laboratory plasmas both of low and high densities and temperatures.[1-3] For example, spectroscopy can be used to determine the ion temperature by measuring the width of the emission line.[4] Three basic ingredients are required for a successful application of this technique. First, the Doppler broadening due to the thermal motion has to be the dominant broadening mechanism for the emission line and, thus, this approach of the temperature diagnostic favors low-density plasmas where Stark broadening and opacity effects are small contributors to the line profile. Second, the observed emission line has to be spectrally isolated, i.e., not a blend of many different lines. Emission spectra of few-electron systems such as H-like, He-like ions are very well suited because of their relatively simple and well known line emission structure. However, if one would limit the use of the spectroscopic ion temperature diagnostics to these two ion species, then for each element there would be a natural lower limit of diagnosable temperature, i.e., the temperature at which He-like ions are starting to be generated and an upper limit when the temperature is high enough to fully strip the ion of all its electrons and the characteristic line emission disappears. Third, the resolving power of the spectrometer has to be sufficiently high in order to resolve the line profile and determine the line width. High-resolution grazing incidence spectrometers recently constructed at the Lawrence Livermore National Laboratory will extend the application of high-resolution spectroscopy to the extreme ultraviolet (EUV) range.[5] The high spectral density of lines in the EUV band requires the use of high-resolution spectrometers for quantitative studies.[6] A detailed discussion of the Livermore high-resolution EUV spectrometer design and the determination of the spectral resolution are found in sections II and III. The application for measuring the temperature of low-Z ions is discussed in Section IV.

II. DESIGN AND IMPLEMENTATION

The design of the high-resolution grazing incidence grating spectrometer is based on a curved, variable-spaced grating. The grating is 5 cm by 10 cm in size and has a radius of curvature of 44.3 m. The groove spacing in the center of the grating is 2400 lines/mm and the variation in groove spacing provides the capability to focus the diffracted rays along a plane nearly perpendicular to the diffracted rays instead of the Rowland circle, allowing one to use planar detectors such as CCD chips.[7] The angle of incidence onto the grating is 2° and due to the large radius of curvature, the distance between the source or slit and the grating should be close to 150 cm in order to optimize the focusing capability over a large spectral range. Likewise, the distance between the grating and the detector should be of similar size yielding an overall length of the instrument of about 3 m. The detector mount has been designed to move along an arc pivoting around the center of the grating and additional adjustments for the distance of the detector to the grating have been put in place. The x rays are detected with a thinned back-illuminated charge coupled device (CCD) designed for use with soft x-ray and EUV photons. The CCD array of 1300 x 1340 pixels is a little over one square inch in size, each individual pixel measures 20μm by 20μm.[8] For this high-resolution spectrometer, the width of one pixel is equivalent to 12.5 mÅ in the short wavelength range, i.e., at 100 Å, and 21 mÅ at 300 Å. The CCD is cooled with liquid nitrogen and the signal processing includes a special low-noise analog-to-digital converter. Minimizing the accumulation of noise is key for utilizing this instrument on facilities with very low flux where exposure times of several minutes up to an hour are required. Long exposure times also require exquisite mechanical stability and isolation from vibrational sources in order to maintain the high spectral resolution.

The calibration effort includes measurements of the spectral reflectivity of the grating, the determination of the dispersion, and the quantum efficiency of the detector. The majority of these calibration measurements have been performed at the Livermore Electron Beam Ion Trap (EBIT).[9,10] This high-resolution grazing incidence grating spectrometer design has been successfully utilized for a variety of measurements, in particular, at EBIT and also at laser produced plasma sources.[11,12] Currently, two nearly identical spectrometers are in operation, one at EBIT and one - named HIGS - was recently moved from Lawrence Livermore National Laboratory (LLNL) to the Lithium Tokamak Experiment (LTX) at the Princeton Plasma Physics Laboratory (PPPL).

III. DETERMINATION OF THE INSTRUMENTAL RESOLUTION

While thorough calibration of the spectrometer is important for an accurate quantitative analysis of the spectra, it is the precise alignment that allows one to reach the highest possible spectral resolution of the instrument. Using the identical high-resolution grazing-incidence spectrometer at the Livermore EBIT, the optimization of the alignment was achieved by performing a series of measurement where the line width was determined as a function of the distance between the detector and the grating. By repeating this “focus scan” at various spectral ranges we were able to map out the best detector alignment at a given wavelength. An example of such a focus scan is displayed in Figure 1.

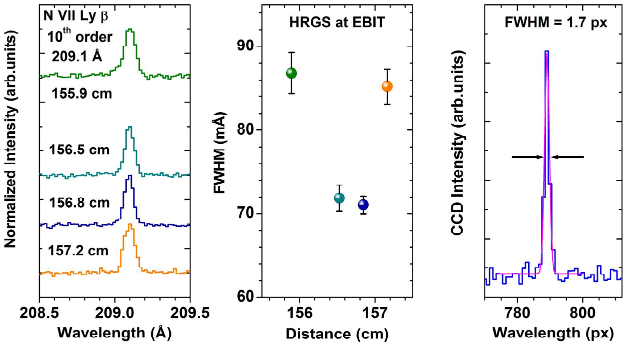

FIG. 1. Example of a focal scan of the high-resolution grazing incidence spectrometer at the Livermore EBIT. The left panel (a) shows a series of spectra taken at different detector-to-grating distances and the extracted line widths (FWHM) are plotted in the center panel (b). The right panel (c) shows the narrowest line profile that has been observed after optimizing the spectrometer alignment.

In particular, Fig. 1a shows a comparison of the observed line profiles – in this case the N VII Ly-β line in 10th order - as a function of detector-to-grating distance and the extracted line width (FWHM of the Gaussian fit) is plotted in Fig. 1b. The width of the narrowest line we observed during various calibration measurements was from the $1s2p^1P_1$ - $1s^2$ $^1S_0$ transition in He-like N^{5+}, commonly referred to as line w, measured in 10th order. The FWHM of the Gaussian fit was 1.7 pixels. The line profile is shown in Fig. 1c. The measured line width is a convolution of the instrumental broadening, the source size and the temperature of the emitting ions, respectively. Without further differentiation between the various mechanisms that cause line broadening, we can extract an upper bound for the instrumental width using the observed FWHM of 2 pixels (rounded up for providing a more conservative estimate) which corresponds to 25 mÅ at the 100-Å location, and to 42 mÅ when the detector is placed to measure the 300-Å spectral range. The derived range for the lower limit of the instrumental resolving power stretches from 4000 for the 100-Å region to 7000 at the 300-Å setting, respectively. Technically, these results apply only to the high-resolution grazing-incidence spectrometer at the Livermore EBIT. Although, the spectrometer design is identical to HIGS which is fielded at LTX at PPPL, there are minor differences that may impact the resolution of the instrument. First, the performance of the gratings may vary slightly due to their exposure to different environments at different facilities over the years. Second, no slit is being used when operating the spectrometer at EBIT because the source itself is a narrow line of about 50μm diameter. The exact shape of the source of emission at EBIT depends on the operating parameters of the ion trap, mainly trap potential, beam current, and magnetic field strength.[13] However, one can certainly expect a similar spectral resolution from HIGS when using a slit of 50μm width or less. Hence, the expected resolving power for HIGS is approximately 4700 near the 135-Å Li III line.

IV. ION TEMPERATURE DIAGNOSTICS

The temperature broadened Gaussian profile of an emission line shows a simple relation between the line width and the ion temperature:

$$\Delta E = 2\, E_0 \sqrt{2\ln(2)\frac{E_{T_{ion}}}{E_{m_{ion}}}} \quad (1).$$

Where ΔE is the full width at half maximum (FWHM), E_0 is the energy of the centroid of the emission line, $E_{T.ion}$ is the thermal energy of the ion (E_{Tion} = kT_{ion}), and $E_{m.ion}$ is the energy equivalent to the ion rest mass ($E_{m.ion}$ = $m_{ion}c^2$). The relation expressed in Eq. 1 shows that for a given wavelength, emission from lighter elements will have a wider profile at the same temperature than their heavier counterparts. For example, if both the oxygen and lithium ions in the LTX plasma have the same ion temperature then the broadening of the lithium lines will be 50% larger than that of the oxygen lines. Eq.1 can be re-arranged such that one obtains a relation between the resolving power and ion temperature, i.e.,

$$\frac{E_0}{\Delta E} = \sqrt{\frac{E_{m_{ion}}}{E_{T_{ion}}}}\ \frac{1}{\sqrt{8\ln(2)}} \quad (2).$$

Eq. 2 is useful for calculating the lowest required resolving power of the spectrometer in order to measure the temperature broadened line width. Since the resolving power of our instrument increases with wavelength, the sensitivity to an observable line broadening due to the ion temperature is highest at the long-wavelength limit.

Measurements with the Livermore Long Wavelength Extreme Ultraviolet Spectrometer (LoWEUS) on LTX have shown that the main emission in the 100-300 Å range comes from Li and O.[14] Thus, our best candidates for measuring the ion temperature are the 199 Å Li^+ and the 135 Å Li^{2+} lines. Fortuitously, there are also oxygen emission lines in the vicinity of the Li lines, close enough that the lines from both ions can be measured simultaneously. Our initial operational qualification of HIGS on LTX with a large slit of 100µm confirmed the capability to capture the oxygen and lithium emission lines simultaneously and comparison with the LoWEUS spectra provided unambiguous line identification as shown in an example in Fig. 2. We have started optimizing our alignment using a 40µm slit width and looking at the 135Å Li Ly-alpha line. Although it is not a single line but a blend of Li Ly-$\alpha_{1,2}$, it would require a cold plasma of less than 2 eV temperature to be able to resolve the two lines, provided one has a spectrometer with sufficient resolving power, of course. The nearby O VI line at 150 Å is also a blend but the separation is 0.036 Å and we should be able to resolve the doublet when the alignment is optimized unless the ion temperature exceeds 150 eV.

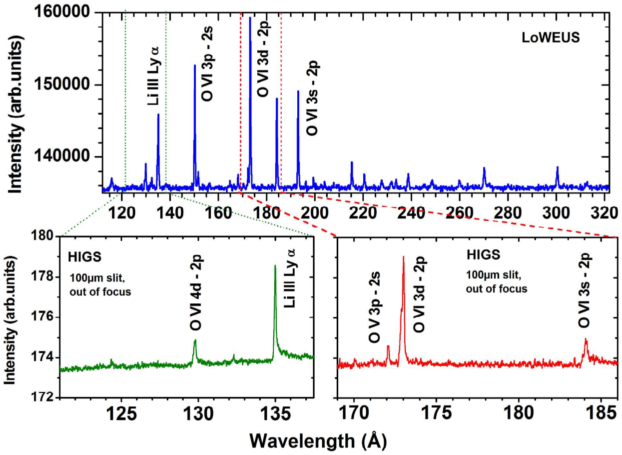

FIG. 2. Comparison of LoWEUS and HIGS spectra. The HIGS spectra were recorded with a wide slit and without fine alignment of the detector position. The main goal of this series of shots was the unambiguous identification of the spectral location and range of HIGS at LTX.

Fig.3 shows the current status of our optimization process. The measured line width of the Li III line is 0.053 Å (FWHM). While the alignment has not been finished, we can already put some upper limits on the temperature of the H-like Li ions. Assuming that the measured line width is solely due to the ion temperature and none of the broadening is due to the instrument provides a very conservative upper limit for the ion temperature of 180 eV. A refined estimate for the upper limit of the ion temperature can be obtained by using the instrumental resolution that we have obtained from our measurements at EBIT, i.e., 0.028 Å. Deconvolving the observed width with this instrumental resolution yields a line width of 0.045 Å which would give us an upper limit of 130 eV for the temperature of the Li ions in the LTX plasma. However, we are clearly not yet at best focus and the fact that the width of the oxygen lines is not smaller than the width of the Li lines indicates that the width is not dominated by the ion temperature but by the instrument instead. We expect further improvement on the spectral resolution when measurements with HIGS at LTX will resume.

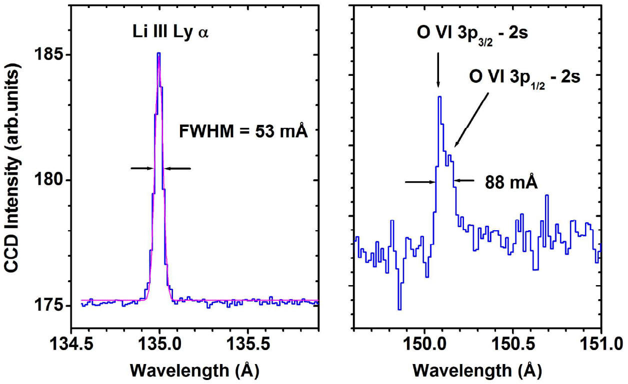

FIG. 3. Current status of the instrumental resolution of the HIGS at LTX. The measured width (FWHM) of the Li Ly-α line is 53 mÅ. This is only an intermediate result since the optimization process has not been finished, yet. However, even at this intermediate alignment state HIGS can already resolve the finestructure of the O VI 2p – 2s transitions at 150 Å, i.e., the separation of the $2p_{3/2}$ and $2p_{1/2}$ levels.

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