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Absolute wavelength calibration of a Doppler spectrometer with a custom Fabry-Perot optical system

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An Ion Doppler Spectrometer (IDS) is used for fast measurements of C VI line emission (343.4 nm) in the Madison Symmetric Torus. Absolutely calibrated flow measurements are difficult because the IDS records data within 0.25 nm of the line. Commercial calibration lamps do not produce lines in this narrow range. A light source using an ultraviolet LED and etalon was designed to provide a fiducial marker 0.08 nm wide. The light is coupled into the IDS at f/4, and a holographic diffuser increases homogeneity of the final image. Random and systematic errors in data analysis were assessed. The calibration is accurate to 0.003 nm, allowing for flow measurements accurate to 3 km/s. This calibration is superior to the previous method which used a time-averaged measurement along a chord believed to have zero net Doppler shift. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4955491]

I. INTRODUCTION

The Madison Symmetric Torus (MST) operates the Ion Doppler Spectrometer version II (IDS II)[1] for fast measurements of impurity ion emission. Charge exchange recombination spectroscopy (CHERS) at the C VI line near 343.4 nm is used to make localized ion measurements.[2] To this point, an absolute wavelength calibration has not been possible because the IDS II has a spectral range of only 0.5 nm. A fiducial marker would need to be less than 0.2 nm from the C VI line in order to be used for calibration, and there are no commercial sources which provide an emission line within this narrow range. A tunable laser could be used, but the cost of the laser would exceed that of the spectrometer itself. Other CHERS systems utilizing CCD detectors have been calibrated using gas discharge lamps, making repeated exposures of a neon lamp[3] or by measuring grating parameters and accounting for grating angle and atmospheric conditions.[4] However, these methods are not well suited to the IDS II which does not use a CCD.

In order to make an absolute wavelength calibration of the IDS II, a light source was designed to create a well-defined peak near 343 nm using a Fabry-Perot etalon and an ultraviolet (UV) LED. The etalon has a 0.08 nm wide transmission peak within the spectral range of the IDS II, as depicted in Figure 1(a). This technique is not commonly used, but Delabie *et al.* report the use of a similar setup in this issue of RSI.[5] A calibration accurate to 0.003 nm was achieved using this light source, which is equivalent to a flow uncertainty of 3 km/s. This is on the order of the random uncertainty of flow measurements in the MST. Poloidal flows in the MST are <10 km/s, whereas toroidal flows may be as large as 40 km/s.

II. LIGHT SOURCE

The optical train of the ultraviolet light source is diagrammed in Figure 2. First, an UV LED emits a 15 nm wide (FWHM) spectrum with maximum emission near 340 nm (model UVTOP335 from SETi). An aspheric lens with $f = 25$ mm collimates the LED light, which travels through an air-gap etalon from SLS Optics. The etalon transmits wavelengths with an integer number of half-wavelengths between the two mirrors, which were designed to have a separation of $d = 0.0998 \pm 0.0010$ mm. The $68\% \pm 4\%$ reflectivity of the etalon mirrors determines an effective finesse of 7.3, corresponding to a transmittance peak FWHM of 0.08 nm when the free spectral range is 0.6 nm. The lenses and etalon are made of fused silica and have AR coatings.

Spectrometer imaging is affected by the homogeneity and f/# of the entering light cone. A holographic diffuser from Edmund Optics diffuses the light exiting the etalon into a cone of angle 15°. 14.5 cm from the diffuser, a 2″ plano-convex lens with $f = 75$ mm focuses the light into the spectrometer fiber with f/4 to fill the IDS II optics. The final image magnification of 3 was chosen to cover the entire IDS II fiber bundle. Rotating the IDS II fiber within its mount changes the measured peak wavelength by 0.4 pm, demonstrating that the effect of remaining structure in the light cone is smaller than the desired calibration accuracy (~1 pm). The final component of the optical train is a 60/40 beamsplitter which allows data to simultaneously be analyzed by the IDS II and another calibrated spectrometer.

The mirror spacing is expected to be stable as the etalon spacer is made out of Schott ZERODUR glass with a coefficient of thermal expansion less than 10^{-8}/K near room temperature. The effective mirror spacing is increased by rotating the etalon; in order to move the transmission peak 0.001 nm, the etalon would need to be rotated 0.14° away from normal to the incoming light. This amount of movement is unlikely given the stiffness of the optical mounts.

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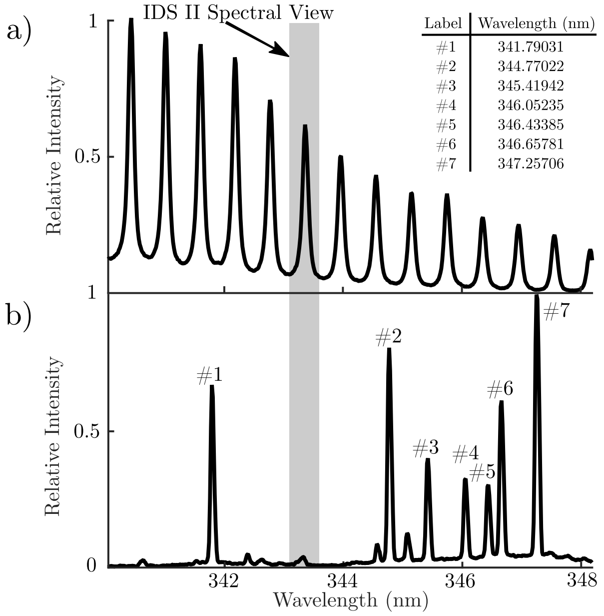

FIG. 1. Spectra for (a) custom ultraviolet light source and (b) neon lamp. Neon emission lines are labelled, and their wavelengths are given in the table inset.

III. CALIBRATION DATA ANALYSIS

There are two parallel processes to calibrate the IDS II: the measurement of the wavelength of an etalon transmission peak and the determination of the location of that peak in the IDS II. Each must be accurate on the order of a thousandth of a nanometer in order to reduce systematic error in velocity measurements below their random uncertainty.

A second calibrated spectrometer is necessary to measure the wavelength of a transmission peak. Typical spectra are shown in Figure 1 for a spectrometer with 8 nm wide spectral coverage and a CCD detector. A neon discharge lamp was used to calibrate the CCD spectrometer, but even neon calibrations can easily be subject to systematic errors greater than 0.001 nm, which corresponds to a few hundredths of a pixel for the spectrometers used in this work. We explored errors related to how the peak location is determined using Monte Carlo analysis and multiple peak-finding strategies.

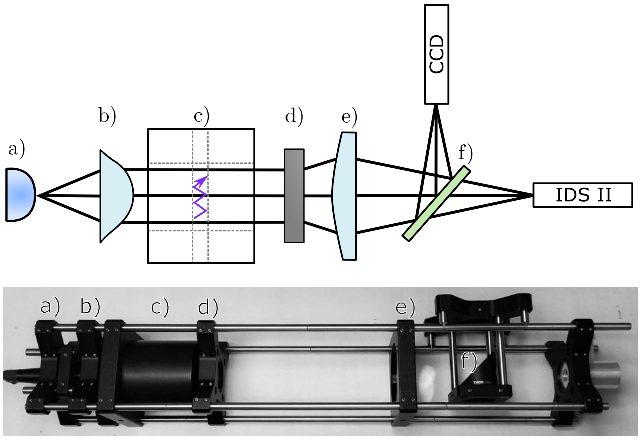

FIG. 2. Diagram and photograph of the ultraviolet light source designed to create a fiducial marker for the IDS II. The components are (a) UV LED, (b) aspheric lens, (c) air-gap etalon, (d) holographic diffuser, (e) plano-convex lens, and (f) beamsplitter.

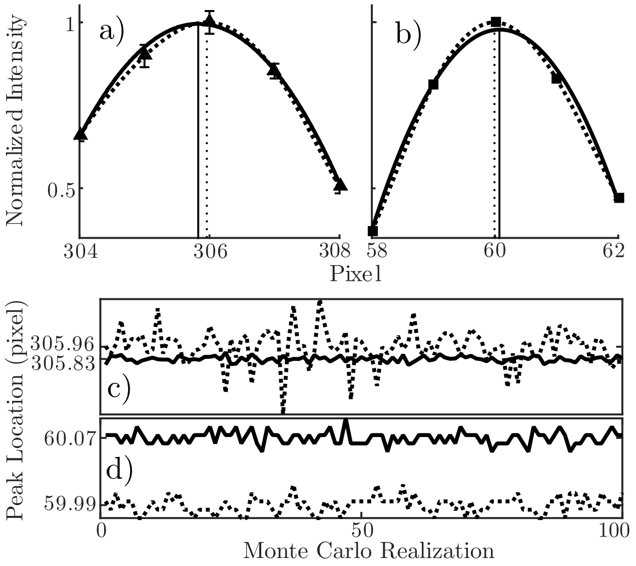

FIG. 3. One (a) ultraviolet light source peak and (b) neon lamp emission line are plotted with spline interpolation (dotted) and parabolic least-squares fit (solid). Error bars are shown which represent the variation in sequential spectra. The neon error bars are smaller than the marker size. Monte Carlo analysis returned the peak locations in (c) for the UV light source and (d) for a neon line.

Figure 3 compares parabolic least-squares and cubic interpolation methods near the maxima of ultraviolet light source and neon peaks. Typically, least-squares fits are used to find the centroids of lineshapes, but these rely on an accurate model of the lineshape. Slit curvature in the image plane of Czerny-Turner spectrometers causes the transfer function to be asymmetric and vary across the image plane. This asymmetry results in a mismatch between symmetric model functions (e.g., parabola or Gaussian) and narrow features like neon lines. However, the broad etalon transmission peak is described by a parabola within its error bars. In contrast, a cubic spline interpolation results in large random error (∼0.2 pixels) for a transmission peak while the sharper neon line has random error similar to parabolic fits. The magnitude of the difference between parabolic and interpolated peak locations is similar for neon and light source peaks.

After determining peak locations, the CCD data were fit to a quadratic curve to convert the horizontal axis from pixels to nanometers. While Figure 1 shows many neon lines in the view of the spectrometer, the lines labelled #1, #2, #6, and #7 were used to weight each wavelength region evenly. The systematic error of the neon calibration was determined by measuring the wavelengths of lines which were *not* used in the calibration and comparing these values to reference values.[6] Table I has the measured and reference wavelengths of these neon lines, showing that the neon calibration is accurate to better than 1 pm.

The total calibration error was measured by focusing the IDS II on neon emission lines near 343 nm and calibrating it using the light source. Figure 4 shows the light source and neon emission for a region near the 345 nm neon line. Spline interpolation of data is overlaid. This was done for three neon

TABLE I. Neon calibration measures independent neon emission lines to better than 1 pm.

Line	Measured λ (nm)	NIST λ (nm)	Discrepancy (pm)	Lines used in calibration
#2	344.770 41	344.770 22	0.2	#1,#3,#6,#7
#3	345.419 28	345.419 42	−0.2	#1,#2,#6,#7
#4	346.051 82	346.052 35	−0.5	#1,#2,#6,#7
#5	346.433 79	346.433 85	−0.05	#1,#2,#6,#7

lines, and the IDS II measured neon wavelengths accurate to 0.003 nm, providing a measure of the absolute calibration uncertainty that includes all sources of error.

When measuring Doppler shifts in plasma emission with the IDS II, there are additional sources of error related to uncertainties in the model of the atomic lineshape. For example, there is also an O VI emission line 0.01 nm from the C VI line, and the relative emission from these impurities affects the model lineshape.[2] In the past, the central chord of the MST has been used to calibrate the IDS II based on the assumption that the chord bisecting the poloidal plane should measure no net Doppler shift and that the background emission is primarily O VI. Indeed, the newly calibrated spectrometer measured the wavelength of background emission to be more consistent with the O VI line than the C VI line. Interestingly, passive measurements on this central chord often show variations in the line centroid on the order of several thousandths of a nanometer over several plasma discharges. This movement is not likely to be an instrumental effect as performing the light source calibration of the spectrometer at the beginning and end of one such series of plasma shots showed no change in the wavelength calibration of the spectrometer. (The light source calibration of the spectrometer is easily performed multiple times per run day.) More likely, the relative contributions of O VI and C VI are varying throughout the day.

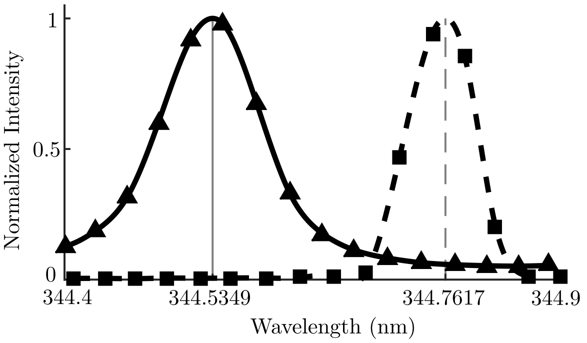

FIG. 4. IDS II measurements of an etalon transmission peak (triangles) and neon emission line (squares) near 345 nm. Error bars are smaller than data marker size.

IV. SUMMARY

An absolute wavelength calibration of the IDS II spectrometer was made using a custom ultraviolet light source. The design uses a Fabry-Perot etalon to create transmission peaks in the spectrum of an ultraviolet LED. Careful analysis was done to measure the wavelength of an etalon transmission peak with an accuracy on the order of 0.001 nm. Random and systematic errors in the analysis method were explored. Calibrating the IDS II at neon lines near the region of interest showed the final calibration has an accuracy of 0.003 nm, which allows ion velocity measurements to be made with an error of 3 km/s. This absolute calibration will be used with CHERS to make fast localized measurements of ion velocity in the near future.

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