Development of fast helium beam emission spectroscopy on MST

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Emission from an energetic neutral helium beam has been investigated as a potential localized diagnostic for the plasma parameters. A collisional-radiative model in atomic data and analysis structure was used to estimate evolutions of the atomic level populations in the beam and the beam emission intensities. It has been found that singlet lines are insensitive to the local metastable fraction and thus have been chosen to construct line ratios. The T_e and n_e dependences of the ratios were investigated and some have been found to be sensitive to the density, but no ratios show significant sensitivity to the temperature in the range of interest for Madison symmetric torus. The theoretically expected line ratios are compared with the experimental results. It is shown that local density measurements may be possible using the singlet line ratio technique. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2236279]

I. INTRODUCTION

The plasma temperature and density at the edge of tokamak and reversed-field pinch (RFP) plasmas may be accurately measured using thermal helium beam[1] or energetic lithium beam[2] diagnostics. However, both beams are limited to use in the plasma edge because of the small penetration depth of the injected neutral particles. Deuterium beam emission spectroscopy (BES) is widely used to measure density fluctuations in the core and edge region of tokamak plasmas.[3] A fast helium neutral beam has several potential advantages: a reduced beam halo, no fractional energy components, greater penetration than deuterium beams, and possibly more efficient charge exchange donation in certain energy regions. Helium is also being considered as the heating neutral beam species to minimize the activation of the vessel in future machines such as International Thermonuclear Experimental Reactor (ITER).[4] There have been several theoretical and experimental studies[5–7] with regard of the use of a helium beam as a diagnostic. However, the fundamental atomic data for fast helium beams have greater uncertainties and there is less experience in the use of helium beams. Among the factors affecting the local helium line emission is the existence of metastable atoms in the beam, ion impact effects, and the T_e, n_e, and Z_{eff} profiles. Fast helium BES has been investigated in the Madison symmetric torus (MST) for the potential as a local density and temperature diagnostic.

II. MODELING THE NEUTRAL HELIUM BEAM

A collisional-radiative (CR) model for fast helium beams has been developed by the atomic data and analysis structure (ADAS) group,[8] which takes into account electron and ion impact excitation, deexcitation, ionization, charge exchange between helium and fully stripped ions, and spontaneous emission from excited helium states (ADAS 311 and ADAS 313).

The local population density N_i of atoms in state i of a helium beam penetrating a plasma can be determined by stepwise solving the steady state statistical balance equations, represented in matrix form,

$$v_b \frac{dN_i}{dx} = \sum_j S_{ij} n_e N_j, \tag{1}$$

where S_{ij} is the CR matrix, which includes all the collisional and spontaneous emission contributions mentioned above, v_b is the beam velocity and dx is the distance along the beam path. The matrix elements S_{ij} are functions of electron and ion temperature (T_e, T_i), electron and ion density (n_e, n_i), and beam energy (E_b). ADAS 311 assembles the balance equations up to an arbitrary principal quantum number n. Levels up to an adjustable threshold n' are treated as *nlSL-resolved*, while levels with $n > n'$ are treated as *nS-resolved*, ie, levels with the same principal and spin quantum number are merged. In our calculations n' was chosen to be 5, the maximum principal quantum number n was 110. The excited states are treated as being in equilibrium with the ground state $(1\,^1S)$

and the two metastable states ($2\,^1S$ and $2\,^3S$). To calculate the beam attenuation and the nonequilibrium level populations, a set of cross coupled equations is constructed.[8] The cross coupling coefficients take into consideration the influence of stepwise atomic processes. The coupled equations are of the form,

$$v_b \frac{dN_{1\,^1S}}{dx} = - n_e S_{1\,^1S} N_{1\,^1S} + n_e S_{2\,^1S \to 1\,^1S} N_{2\,^1S} + n_e S_{2\,^3S \to 1\,^1S} N_{2\,^3S},$$

$$v_b \frac{dN_{2\,^1S}}{dx} = n_e S_{1\,^1S \to 2\,^1S} N_{1\,^1S} - n_e S_{2\,^1S} N_{2\,^1S} + n_e S_{2\,^3S \to 1\,^1S} N_{2\,^3S},$$

$$v_b \frac{dN_{2\,^1S}}{dx} = n_e S_{1\,^1S \to 2\,^1S} N_{1\,^1S} + n_e S_{2\,^1S} N_{2\,^1S} - n_e S_{2\,^3S} N_{2\,^3S}, \quad (2)$$

where $N_{n^{2S+1}L}$ is the population density of the nonequilibrium state specified by the quantum numbers n, S, and L. The CR cross coupling coefficients are represented by the symbol $S_{n^{2S+1}L \to n^{2S+1}L}$, where the subscripts specify the initial and final nonequilibrium levels. The cross coupling coefficients for which the subscript only specifies the initial state, e.g., $S_{n^{2S+1}L}$, refer to what can be described as the total loss coefficient from the level $n^{2S+1}L$. The total loss coefficient includes the CR ionization rate from the level $n^{2S+1}L$ as well as the contribution to populating the remaining levels. These nine coefficients are called "generalized collisional-radiative coefficients" (GCRCs). The ADAS code provides the GCRCs for a predefined list of plasma temperatures, densities, and beam energies. Furthermore, for emission lines of interest the so-called "effective beam emission coefficients" (EBECs) for each nonequilibrium level are calculated. These coefficients enable the deduction of the line intensity profiles from the population-density profiles of the nonequilibrium levels.

An analysis code package was developed to numerically solve Eq. (2) by using GCRCs and EBECs from ADAS. The code solves the coupled equations while moving in small increments along a spatial grid, while employing several ADAS library routines to implement the linear interpolation method to assemble the required coefficients at any point along the grid.

The T_e and n_e profiles are measured by the Thomson scattering and far infra-red (FIR) systems, respectively, in MST. The measured T_e and n_e profiles, approximated by the following functions, have been used in the modeling:

$$n_e(r) = [n_e(0) - n_e(a)]\left[1 - \left(\frac{r}{a}\right)^3\right] + n_e(a), \quad (3)$$

$$T_e(r) = [T_e(0) - T_e(a)]\left[1 - \left(\frac{r}{a}\right)^4\right] + T_e(a).$$

The $Z_{\rm eff}$ profile in MST is not yet reliably measured, and the constant profile of $Z_{\rm eff}=2$ is assumed for the calculation. This introduces errors in the calculated line emission intensity

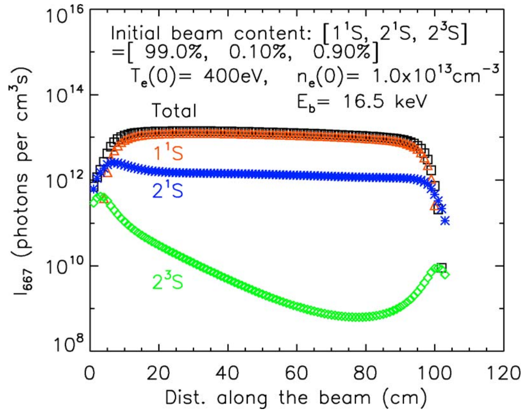

FIG. 1. (Color online) Evolution of the emission line intensities from each of the three non-equilibrium populations ($1\,^1S$, $2\,^1S$, and $2\,^3S$) for a singlet line (667.8 nm He I) along the helium beam path in a MST plasma: $T_e(0)=400$ eV, $n_e(0)=1.0\times10^{13}$ cm^{-3}, and $Z_{\rm eff}=2$. The beam content is assumed to consist of 99% of ground population and 1% of metastable population, among which 90% $2\,^3S$ and 10% $2\,^1S$ are assumed, on entry to the plasma.

(e.g., ~23% difference in the line ratio of 667.8 nm He I emission intensity to 492.2 nm intensity and ~8% difference in the ratio of 667.8 to 501.6 nm between $Z_{\rm eff}=2$ and $Z_{\rm eff}=4$ flat profile cases) and therefore the measurement of the actual $Z_{\rm eff}$ profile is desired for more accurate calculations in the future.

The evolution of the three nonequilibrium levels has been modeled for typical MST discharges with a beam energy of 16.5 keV. The line emission intensity profiles have also been calculated for He I lines in the wavelength region 318.8–728.1 nm, i.e., for six singlet and six triplet lines. Figure 1 shows the evolution of a singlet line intensity, 667.8 nm He I line, along the beam path. A separate investigation indicates that the contents of the beam on entry to the plasma consist of ~99% ground population and it was used for the modeling as an input.

Modeling indicates that the emission intensity of a triplet line (e.g., 587.6 nm He I) is strongly affected by the fraction of metastable atoms. Therefore, the metastable fraction is necessary to calculate the emission intensity of a triplet line but it is only possible by solving statistical balance equations, which requires T_e, n_e, and $Z_{\rm eff}$ profiles as inputs. This means that the theoretical estimate of the local line ratio between triplet line intensities is not possible unless there is another way to evaluate local metastable fractions. Triplet line intensities are thus not usable for local plasma parameter measurement such as T_e and n_e.

On the other hand, it is seen that the total emission intensity of a singlet line in the plasma core comes mostly (>90%) from the contribution of the ground state atoms (see Fig. 1). If the small contribution from the metastable atoms to the total intensity is ignored, one does not need to know the metastable fraction to estimate total emission intensity of a singlet line. The T_e and n_e dependences of a number of ratios between He I singlet lines have been investigated. It is identified that the ratio of 667.8–492.2 nm He I lines (I_{667}/I_{492}) would be good for the local density measurement as this ratio is sensitive to the density variation and

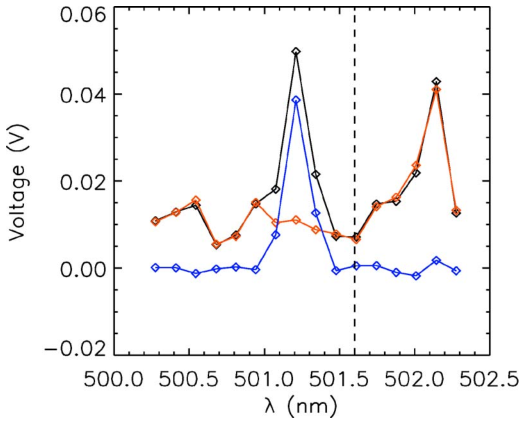

FIG. 2. (Color online) Doppler shifted 501.6 nm He I beam emission line; net beam contribution is represented by the blue line, which is the result when the background channel (red) is subtracted from the beam channel (black). The vertical line represents the wavelength of the non-Doppler shifted 501.6 nm He I line.

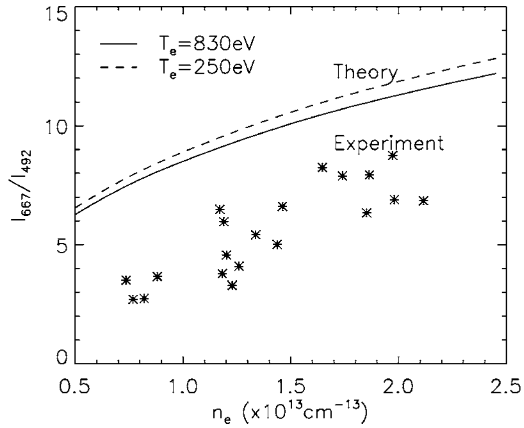

FIG. 3. Dependence of I_{667}/I_{492} on the local electron density. The theoretical line ratio was calculated for the upper and lower bounds of the experimentally measured T_e values. The theoretically anticipated insensitivity of the ratio to the electron temperature could not be confirmed due to the lack of experimental data.

very independent of the temperature variation. Unfortunately, no excellent ratio for the local temperature measurement has been identified. All ratios out of six singlet lines in the ADAS database are expected to have weak temperature dependence.

III. EXPERIMENTAL RESULTS AND COMPARISON WITH THEORY

The helium neutral beam was fired into MST plasmas, and the emission light from interactions with plasma particles was observed at a particular spatial point, i.e., at $r/a=0.115$ above the magnetic axis. Figure 2 shows the schematic overview of the diagnostic system. Two optical heads, with viewing angles of 45° and 105°, collect light from the beam as well as background. This allowed simultaneous measurement of the Doppler-shifted (i.e., redshifted for 45° and blueshifted for 105° viewing angles) helium beam emission light at two wavelengths, enabling continuous (data acquisition frequency of 1 MHz and preamplifier bandwidth of 200 kHz) local line ratio measurements such as I_{667}/I_{492} during the beam duration time. Each optical head consists of two measurements; one for the emission light from the beam and the other for the background light. The background light is subtracted from the beam emission light to yield the net beam contribution. The first wavelength (e.g., 667.8 nm He I) is monitored by two grating monochromators with a photo-multiplier tube (PMT) detector at the exit slit. One monochromator is an $f/8.6$ Czerny-Turner design with 500 mm focal length (Jarrell-Ash, 1.6 nm/mm dispersion with 1180 g/mm grating). The other is also an $f/6.5$ Czerny-Turner layout with 500 mm focal length (Acton Research, 0.75 nm/mm dispersion with 1800 g/mm grating). The second wavelength (e.g., 492.2 or 501.6 nm) is monitored by the ion dynamics spectrometer (IDS) system,[9] an $f/10$ Czerny-Turner design with 1000 mm focal length (Jarrell-Ash, 0.33 nm/mm dispersion with 1180 g/mm grating). It has two input channels and an array of two 16 output subchannels, each with a PMT detector, to cover a ~2 nm wavelength window. As a result, a total of four channels are employed to simultaneously monitor beam emission and background intensities for two wavelengths of interest. Figure 2 shows an example of Doppler shifted 501.6 nm He I beam emission line. One important advantage of using the line ratio technique is that it does not require an absolute value of line intensity and naturally cancels out the contribution of electron density to the line intensity of each wavelength. The relative calibration of the whole emission detection system was performed with respect to the wavelengths of interest to ensure proper calibration of the detector sensitivity to those wavelengths.

The dependence of various line ratios on local T_e and n_e was investigated using data provided by Thomson scattering and FIR systems. Figure 3 shows an experimental line ratio (I_{667}/I_{492}) along with the theoretically predicted ratio for comparison as a function of electron density. The general pattern of the density dependence of the ratio is well reproduced by experiment but the absolute values do not match exactly. This is possibly due to an error in the atomic data associated with the line intensity calculation. Of particular concern is any error in the ion impact excitation cross sections. The error propagation analysis is currently under way by the ADAS group.[10] However, experimental data to check the theoretically expected temperature insensitivity of the ratio I_{667}/I_{492} is yet to be established. An experimental campaign to investigate the temperature dependence is to be carried out in the near future.

The measured density dependence of the ratio I_{667}/I_{492} is strong enough (from ~3 to ~8 for $n_e \sim 0.7$ to $\sim 2.0 \times 10^{13}$ cm^{-3}), while the theoretically expected temperature dependence is weak enough (<5% for $T_e \sim 250$ to ~830 eV), to be used for the local density measurement. However, the theoretical modeling needs to be improved to better match the experimental result. There has been no singlet ratio identified to have strong enough temperature sensitivity to be used for the local temperature measurement.

IV. SUMMARY AND DISCUSSIONS

The widely used line ratio technique such as in the thermal helium beam diagnostic cannot be simply reapplied to the high energy neutral helium beam diagnostic due to the complication caused by the presence of metastable atoms. This problem can be effectively solved by using singlet line ratios, for which most ($>90\%$) contributions come from the ground atoms. The theoretically anticipated line ratio pattern agrees with experimental results with some discrepancy of the absolute values. The ratio I_{667}/I_{492} alone could be used for the local density measurements with the confirmation of its insensitivity to the temperature, for which an experimental investigation is currently under way.

[1] B. Schweer, M. Brix, and M. Mehnen, J. Nucl. Mater. **266–269**, 673 (1999).
[2] E. Wolfrum, F. Aumayr, D. Wutte, H. P. Winter, E. Hintz, D. Rusbuldt, and R. P. Schorn, Rev. Sci. Instrum. **64**, 2285 (1993).
[3] G. McKee *et al.*, Rev. Sci. Instrum. **70**, 913 (1999).
[4] M. G. O'Mullane *et al.*, *Advanced Diagnostics for Magnetic and Inertial Fusion*, edited by P. Stott *et al.* (Kluwer Academic, New York, 2002).
[5] F. M. Levinton, Rev. Sci. Instrum. **57**, 1834 (1986).
[6] H. Evensen, D. Brouchous, D. Diebold, M. Doczy, R. J. Fonck, and D. Nolan, Rev. Sci. Instrum. **63**, 4928 (1992).
[7] T. Thorson, R. Fonck, and B. Lewicki, Rev. Sci. Instrum. **70**, 902 (1999).
[8] H. P. Summers *et al.*, JET Internal Report No. JET-IR (94)06 (JET Joint Undertaking, UK, 1994).
[9] D. J. Den Hartog and R. J. Fonck, Rev. Sci. Instrum. **65**, 3238 (1994).
[10] M. Proschek (private communication).