

T_e Measurements in the Cold Regions of Alcator C-Mod Divertor Plasmas

J.L. Terry, B. Lipschultz, C.J. Boswell, D.A. Pappas, A. Yu. Pigarov,
S.I. Krasheninnikov, and B. LaBombard

Plasma Science and Fusion Center, MIT, Cambridge, MA, 02139, USA

1 Introduction

There has been much interest in both diagnosing and understanding the role of neutrals, which is thought to be significant in the achievement of low temperature, high density, dissipative divertor plasmas. The research reported here deals with the measurement of the low electron temperatures, sometimes less than 1 eV, achieved in Alcator C-Mod divertor plasmas. The temperatures are determined from spectroscopic measurements which utilize emission from atomic deuterium or emission resulting from the formation of atomic deuterium, i.e. photo-recombination. Accurate measurement of divertor electron temperatures in this low range is important because in this range the balance between ions and neutrals varies strongly with T_e, because the experimental evaluations of the plasma source (ionization) and one of the plasma sinks (volume recombination) depend critically on the local temperature, and because it facilitates a more realistic comparison with the modelling of these plasmas.

A brief history of the observations of low divertor T_e begins with the measurement, using probes (e.g. [1]), of temperatures $\lesssim 5$ eV. Subsequently electron temperatures of $\lesssim 2$ eV were documented using Thomson scattering [2], and temperatures $\lesssim 1$ eV were observed spectroscopically [3–8]. The purpose of this work is to present the results and comparisons of four spectroscopic techniques used on Alcator C-Mod to measure T_e in the divertor.

2 Spectroscopic Techniques for Measurements of T_e < 1.5 eV

2.1 Using Photo-recombination Continuum Emission - $D^+ + e \rightarrow D_0^n + h\nu$

The continuum emission resulting from photo-recombination has a wavelength dependence of $I(\lambda, T_e, n) \propto g(\lambda, T_e, n)e^{(-hc/\lambda T_e)}$ for photon energies \geq the ionization energy from the n th quantum level. Here n is the principal quantum number of level into which the recombination occurs and $g(\lambda, T_e, n)$ is a weak function of both λ and T_e. For photo-recombination into the atomic ground state, $n=1$, the emission is at wavelengths $\lesssim 911$ Å (13.6 eV) and varies strongly with wavelength at low T_e. An experimental spectrum of this wavelength region measured along a single chord viewing the C-Mod divertor plasma is shown in Fig. 1. The smooth merging of the high- n Lyman lines into a photo-recombination continuum is clearly seen. Also shown is the spectrum *predicted* from a T_e = 0.82 eV, N_e=N_i = 1.02 × 10²¹ m⁻³ uniform plasma and 0.01 m path length. The agreement between the predicted spectrum and the measured continuum is excellent. Since the slope of the log of the intensity is directly related to the temperature, this measurement will be referred to as the “continuum slope” technique.

The chief advantage of this method for measurement of T_e is its strong sensitivity to temperature. The disadvantages are 1) the measurement is made in the vacuum ultraviolet where use of instrumentation and spectrometer calibration are difficult, and 2) the possible presence of impurity lines in this spectral region, making observation of this fairly weak

emission and determination of any additional background “continuum” emission difficult in some cases. In addition, this and the following techniques use chordal measurements viewing through regions of non-uniform plasma. Since the temperature determined is weighted by the emissivity along a chord, the emissivity must be known in order to make a local T_e measurement.

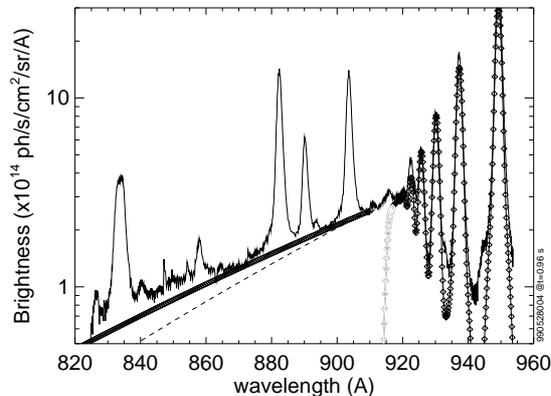


FIGURE 1. Measured spectrum showing the higher- n Lyman series lines and the photo-recombination continuum (thick solid line). Also shown is the predicted spectrum from a $T_e=0.82$ eV, $n_e = 1.0 \times 10^{21} \text{ m}^{-3}$ plasma (diamonds connected by a thin line). (The dashed line is the prediction for $T_e=0.67$ eV, showing the sensitivity to T_e .) Impurity line contamination is seen at 834, 883, 891, 904, and 920 Å.

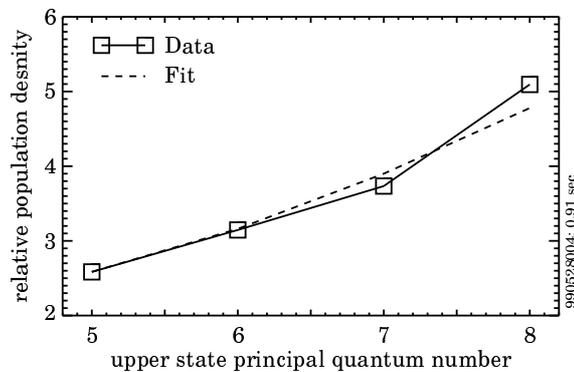


FIGURE 2. The relative population densities of the D_0 $n=5-8$ levels obtained from the relative intensities of the Balmer series lines. The dashed line shows the relative densities predicted by a Saha distribution with $T_e=0.92$ eV. This measurement is made at the same time, along the same line-of-sight, as the measurement illustrated in Fig. 1.

2.2 Using the relative population densities of high- n levels of D_0

A second technique, discussed in Ref. [6], uses the fact that above some level, n^* , the population densities of the excited levels of atomic deuterium are described by a Saha distribution. Thus for any set of levels with $n \geq n^*$, the ratio of population densities is $(n'^2/n''^2)e^{(IP_{n'}-IP_{n''})/T_e}$, where $IP_{n'}$ is the ionization potential from the n' level. The relative population densities are measured by detecting the relative intensities of the higher- n Balmer lines and dividing by the appropriate spontaneous emission coefficients. Such a spectrum is similar to that shown in Fig. 1, but for the Balmer series. The measured relative population densities and those predicted for a 0.92 eV temperature are shown in Fig. 2. This T_e determination was made at the same time, along the same view as that illustrated in Fig. 1, and similar temperatures are found. The chief advantage of this method, “Saha T_e ”, is that it is made in the visible/near-UV, which allows the use of fiber optics and visible spectrometers. This facilitates good spatial coverage of the divertor region. The disadvantages are 1) the assumption, at least in the case shown in Fig. 2, that n^* is ≤ 5 , so that there is no contribution to the $n \geq 5$ populations by electron-impact excitation from the D_0 ground state, and 2) relative insensitivity of the determination if $T_e \gtrsim 1.5$ eV, since $IP_{n'=5}=0.54$ eV.

2.3 Using the Line-to-Continuum Intensity Ratio

This technique is explained in detail in Ref. [9] and will be described here only briefly. The ratio of the intensity of a D_0 line with $n \geq n^*$ to the total continuum emission integrated over a wavelength band 5 nm to either side of the central wavelength of the line is a strong

function of T_e . The upper level of the line is populated according to the Saha distribution, while the underlying continuum is assumed to be due to *deuteron-electron bremsstrahlung (f-f) and deuteron photo-recombination (f-b) only*. The line used in this work is the $n=5$ to 2 Balmer line at 434 nm. The relationship between this ratio and the temperature is given in Fig. 11.5 of Ref. [9]. The advantages of this “Line-to-Continuum” technique are that it is made in the visible and that no sensitivity calibration is needed. The disadvantages are the possible violation of the assumption mentioned above, in addition to those of the “Saha T_e ” technique.

2.4 Using the Balmer Recombination “Edge”

Ref. [3] has a discussion of this measurement technique and a detailed analysis of the T_e determined on Alcator C-Mod. Briefly, it assumes, as does the “Line-to-Continuum” method, that the continuum emission is a result of hydrogenic f-f and f-b bremsstrahlung *only*. The measured, temperature sensitive intensity ratio is made on either side of the Balmer $n=2$ photo-recombination “edge” which occurs at $\lambda \approx 365$ nm. The measurement is made in the near-UV and has the same disadvantages as the “Line-to-Continuum” technique. In both methods any contaminating continuum emission will *raise* the inferred temperature.

3 Comparison of Electron Temperature Measurements

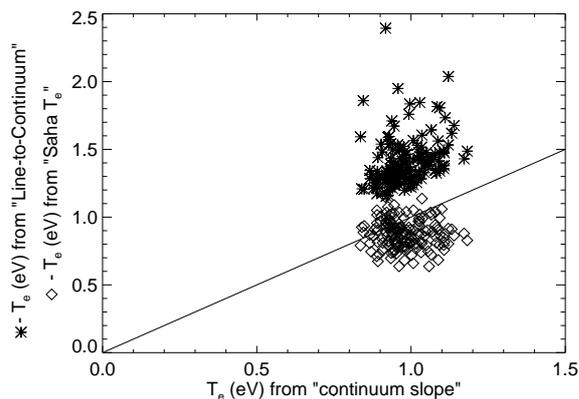


FIGURE 3. The comparison between the T_e s inferred from the “continuum slope” of the VUV emission, those using the “Saha- T_e ” method (diamonds) and those using the “Line-to-Continuum” method (asterisks). The measurements are made along a chord which views above the X-pt and ends ≈ 5 cm above the inner divertor strike point.

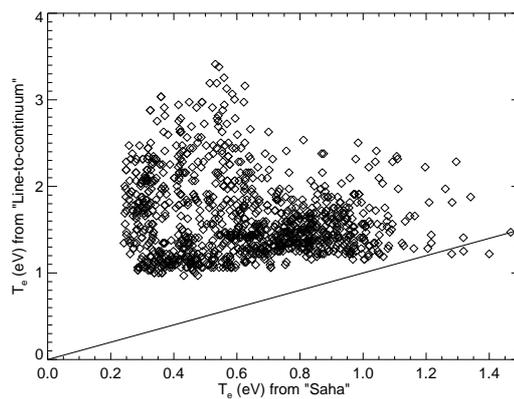


FIGURE 4. The comparison between the T_e s measured using the “Saha- T_e ” method and those using the “Line-to-Continuum” technique. The obvious disagreement at “Saha- T_e s” less than 1.5 eV implies that the lower temperature regions of the divertor emit continuum significantly greater than the f-f and f-b continuum.

In order to judge the accuracy and applicability of the techniques described above, a comparison of the T_e s inferred from each was made. Since the divertor plasma is not homogeneous, the comparisons must be made using measurements along nearly identical views. The “continuum slope” T_e is taken as the standard against which the others will be compared, since the modeling of the process giving rise to the emissions used in this technique assumes only that the process is photo-recombination of deuterons and electrons. Thus the accuracy of the inferred T_e is affected only by experimental errors in relative sensitivity calibration across the spectrum and in background continuum analysis. The absolute errors associated with this measurement are estimated to be $\approx \pm 0.15$ eV. The comparisons between the “continuum slope” T_e and those from the “Saha T_e ” and

“Line-to-Continuum” methods are shown in Fig. 3. Since the VUV spectrometer’s view of the divertor was limited, the range of measured T_e s was also limited. Nonetheless, general agreement is observed with the “Saha T_e ” values, while the “Line-to-Continuum” values are consistently higher by ≈ 0.4 eV. For this reason the “Saha T_e ” is also taken to be a reliable measure of temperature. Since the visible light views have far better divertor coverage, a more extensive comparison was made between the “Saha T_e ” and the “Line-to-Continuum” temperatures. This is shown in Fig. 4, where obvious disagreement is seen for “Saha T_e ” values $\lesssim 1.5$ eV. The clear implication is that the continuum emission in the 434 nm spectral region is significantly more than that predicted for f-f and f-b bremsstrahlung from a plasma with the “Saha” T_e . Other possible sources of continuum emission (especially at the low temperatures) involve neutrals and have been investigated theoretically using the atomic/molecular code CRAMD. Radiative formation of D_0^- and D_2^+ , as well as atom-electron and atom-ion bremsstrahlung require implausible atomic densities ($N_0 \gg N_e \sim 10^{21} \text{ m}^{-3}$) to account for the additional emission. However molecular processes can produce strong spurious continua from 3-body recombination of molecular ions, which produces many weak, unresolved lines. If this is the emission source, it may be possible to use it to estimate the D_2 density.

Because the “Balmer Recombination Edge” method makes the same assumption about f - f and f - b bremsstrahlung being the only continuum source, it too yields only temperatures $\gtrsim 1$ eV on C-Mod even along views with much lower “Saha- T_e ” values. For this reason it is believed to be inaccurate when attempting to measure temperatures $\lesssim 1$ eV on Alcator C-Mod.

4 Discussion and Summary

These results demonstrate, at least on Alcator C-Mod, the capability of T_e measurement in the ≈ 0.4 -1.5 eV range with an accuracy of approximately ± 0.25 eV. The reliable techniques on C-Mod are the “continuum slope” and the “Saha T_e ”. The methods which assume that the visible continuum emission is produced only by f-f and f-b bremsstrahlung were shown to overestimate the temperature, most probably because of emission from some other source. The ultimate goal of this work is to study the measured T_e s and the implications of these T_e s in understanding the dissipative divertor. A better understanding is possible if these chordal measurements can be used to give localized temperatures. Using the fact that the T_e measurements are weighted to the local emissivity along the chord, the temperatures can be made more local by measuring the 2-d distribution of recombination-associated emission. This is presently being done on C-Mod using CCD images of D_γ ($n = 5 \rightarrow 2$) emission from the divertor.

References

- [1] B. LaBombard et al., *Phys Plasmas* 2, p 2242 (1995)
- [2] S. L. Allen et al., *J. Nucl. Mater.* 241-243, p 595 (1997)
- [3] D Lumma et al., *Phys Plasmas* 4, p 2555 (1997)
- [4] B. Napiontek et al., *Proc. 24th EPS Conf. on CF and PP Vol 21A(IV)*, p 1413 (1997)
- [5] J.L. Terry et al., *Proc. 24th EPS Conf. on CF and PP Vol 21A(II)*, p 573 (1997)
- [6] B. Lipschultz et al., *Phys. Rev. Lett.* 81, p 1007 (1998)
- [7] J.L. Terry et al., *J. Nucl. Mater.* 266-269, p 30 (1999)
- [8] U. Wenzel et al., *J. Nucl. Mater.* 266-269, p 1252 (1999)
- [9] H.R. Griem, *Cambridge Univ Press*, p 293 (1997)