GA–A23411

COMPARISON OF LANGMUIR PROBE AND THOMSON SCATTERING MEASUREMENTS IN DIII–D

by
J.G. WATKINS, P.C. STANGEBY, J.A. BOEDO, T.N. CARLSTROM,
C.J. LASNIER, R.A. MOYER, D.L. RUDAKOV, D.G. WHYTE

JULY 2000

DISCLAIMER

GA–A23411

COMPARISON OF LANGMUIR PROBE AND THOMSON SCATTERING MEASUREMENTS IN DIII–D

by
J.G. WATKINS,* P.C. STANGEBY,† J.A. BOEDO,‡ T.N. CARLSTROM,
C.J. LASNIER,◊ R.A. MOYER,‡ D.L. RUDAKOV,‡ D.G. WHYTE‡

This is a preprint of a paper presented at the 14th International Conference on Plasma Surface Interactions, May 22–26, 2000, Rosenheim, Germany to be published in the Proceedings.

*Sandia National Laboratory, Albuquerque, New Mexico.
†University of Toronto Institute for Aerospace Studies, Toronto, Canada.
‡University of California, San Diego, California.
◊Lawrence Livermore National Laboratory, Livermore, California.

Work supported by
the U.S. Department of Energy
under Contract Nos. DE-AC03-99ER54463, DE-AC04-94AL85000,
W-7405-ENG-48, and Grant No. DE-FG03-95ER54294

GA PROJECT 30033
MAY 2000

ABSTRACT

In this paper, we compare measurements of density and electron temperature made by target plate Langmuir probes (LP) and the divertor Thomson scattering (DTS) diagnostics in the DIII–D tokamak divertor. By examining low-density, ohmic ELM-free discharges, we can use the simple standard electron thermal conduction model (SETC) to relate the measurements at different but closely spaced locations. For this essentially sheath-limited regime, we have derived a correction factor of ~0.8 for local LP temperature values based on the SETC model. We have sorted the DTS measurements above the plate onto flux surfaces, calculated the connection length to the plate, and constructed parallel density and temperature profiles for comparisons along the magnetic field lines. Measurements from both diagnostics are consistent with the predictions of this very simple model.

1. INTRODUCTION

Over the past two decades, the study of the physics processes occurring in the edge of magnetic confinement devices such as tokamaks has been a major focus of most fusion energy projects and much progress has been achieved. Langmuir Probes, LPs, have played a central role in the edge studies on most tokamaks and therefore much of the understanding of the edge, which has been achieved over this period, is centrally dependant on the reliability of LP measurements made in strong magnetic fields. The interpretation of LPs, to extract values of n_e and T_e, from the voltage-current, IV, characteristics is well known to be subject to difficulty — particularly for the case of strong magnetic fields [1].

Further interpretive challenges are posed when the probes are flush-, or nearly flush-mounted in the solid surfaces of divertor targets or limiters. In the earliest applications of LPs to tokamak edge diagnosis, the probe collecting elements were perpendicular to **B**, making for a well-defined collection area. As tokamak heating powers and pulse lengths increased, it became necessary — at least for nonmoving probes — to go over to LP configurations involving glancing angles between the probe surface and **B**, in order to avoid probe over-heating. In such configurations, the definition of the probe's collecting area becomes more subject to difficulty. This puts in question the reliability not only of the probe value for n_e, but also its ion saturation current density, I_{sat}^{+}. The latter quantity is what is most directly and easily extracted from the IV characteristic and is of first importance and usefulness in its own right — for probes that are built in to divertor targets or limiters: for such probes, I_{sat}^{+} is simply the parallel particle flux density to the solid surface multiplied by the elemental charge. This particle flux largely sets the sputtering rate of the solid surface, the hydrogen recycling rate, the pumping rate, etc.

Interpretation of LP IV characteristics to extract T_e values is the most challenging aspect of probe interpretation and is already subject to difficulty when the collecting surface is normal to **B** [2]. Further questions arise for built-in, glancing-angle LPs [3].

It is, therefore, essential to establish the reliability of LPs — particularly for built-in, glancing-angle probes — in the tokamak environment. DIII–D is well suited to studies of this problem since, uniquely, it operates a divertor Thomson scattering, DTS system [4], which provides independent measurements of n_e and T_e quite near to the divertor targets and to the built-in DIII–D probes [5]. Earlier DIII–D studies of this matter have been published [6,7]. Here, the focus is specifically on comparisons of the DTS values and those of the built-in LPs — and for the simplest divertor operating regime — the sheath-limited, near-isothermal regime [8].

The DTS system measures n_e and T_e at a number of locations *within* the plasma — not *at* the solid surface, as the LP does. In Fig. 1, the DTS measuring locations are shown. Even the location closest to the target, at a distance from the target in the poloidal plane of only ~1 cm, is ~1 m away from the target along **B**. In such a distance, significant changes in n_e and T_e can occur in the conduction-limited regime. It is, therefore, a nontrivial matter to relate the DTS and LP values for divertor plasmas in this regime and one has to resort to a more-or-less sophisticated analysis procedure in order to relate plasma quantities at these different locations. Such an undertaking, using onion-skin method (OSM) analysis, is reported elsewhere at this conference [9]. Adding to the problem is the fact that the very closest DTS location is suspect as to the reliability of the value of density that is returned from the DTS analysis, due to scattered and background light.

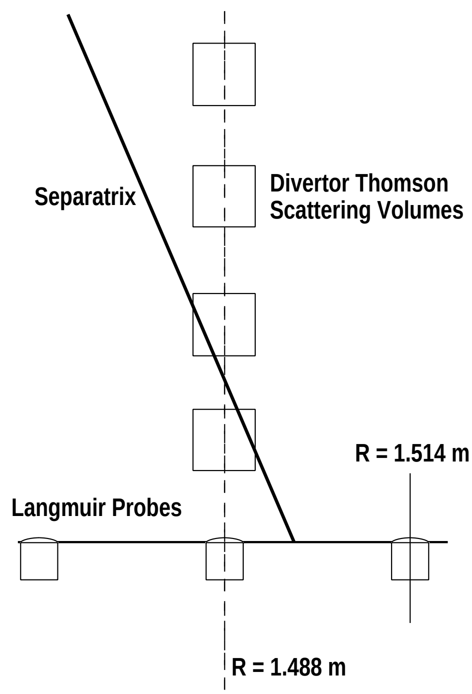

Fig. 1. The divertor Thomson scattering measurement locations and the Langmuir probe location are shown with respect to the target plate in DIII–D. The laser path is vertical at R = 149 cm and the scattering volume is approximately 1 cm^3.

It is, therefore, advantageous to investigate discharges where the divertor is operated in the sheath-limited regime, with the T_e ($s_{||}$) being flat (isothermal along **B**) and where, according to simple presheath theory [10], the density would be expected to drop by a factor of two between "upstream" locations and the target surface. Here "upstream" means a distance over which the recycling hydrogen is ionized (which corresponds to the distance over which the plasma is accelerated to the sound speed by the drop of the static pressure by a factor of 2 [10]). Typically, that distance is shorter than the distance to the (second closest) DTS measuring location and so in the sheath-limited regime it is expected that the LP value of n_e should be about half of the DTS values (for all of the DTS locations), while the LP T_e value should be about the same the DTS values. In this regime, therefore, it should be possible to almost directly compare the DTS and LP measurements, *i.e.*, with minimal invoking of any plasma theory or modeling.

Since systematic errors, and/or scatter, for each of these diagnostics techniques can approach or exceed factors of 2, a realistic objective for the present undertaking would be to seek to establish if, under sheath-limited conditions, the LP T_e values are about equal to the DTS ones and the LP n_e values are about equal to, or somewhat less than, the DTS ones.

2. DIII–D SHEATH-LIMITED DIVERTOR CONDITIONS

Ohmically heated discharges on DIII–D can involve plasma conditions at the outside divertor which would be expected to be in or near the sheath-limited regime. For example, conditions near the target outer strike point, $n_{et} \approx 10^{19}$ m^{-3} and $T_{et} \approx 40$ eV. The parallel electron heat flux density to the target is given by:

$$q_{||et} \; = \; \gamma_e \, kT_{et} \, n_{et} \, c_{st} \quad , \tag{1}$$

where $\gamma_e \approx 5$ is the electron sheath heat transmissions coefficient, and $c_{st} = (2\ kT_{et}/m_i)^{1/2}$, is the plasma sound speed, assuming $T_{it} = T_{et}$. For the above conditions, $q_{||et} \approx 2 \times 10^7$ W/m^2. Assuming that the parallel heat flux is carried entirely by electron heat conduction one has for the parallel temperature profile [10]:

$$T_e\,(s_{||}) \; = \; [\; T_{et}^{7/2} \; + \; 7\, q_{||et}\, s_{||}/(2\,\kappa_{oe})]^{2/7} \quad , \tag{2}$$

where $\kappa_{oe} \approx 2000$ for T (eV), s (m) and q (W/m^2). Thus at $s_{||} = 10$ m, T_e has only increased to <50 eV, which given the errors and scatter in both diagnostic, indicates effectively isothermal conditions over this distance, which is the typical spatial extent of the DTS locations. Such ohmic discharges are therefore expected to be in the sheath-limited regime, at least near the outer strike point.

3. MEAN-FREE PATH CORRECTION TO LANGMUIR PROBE T_E

The target LPs sample the electrons over a distance of λ_{ee} starting from the target. The e-e collisions length for the average ("thermal") electrons is: $\lambda_{ee}^{thermal} \approx 10^{16}\ T_e^2(eV)/n_e(10^{19}/m^3)$/The method of extracting T_e from the IV characteristic of LPs in strong magnetic fields involves use of the high-energy tail of the electron distribution, *i.e.*, the electrons with energy about 3 kT_e. For these electrons the e-e collision length is approximately 10× longer: $\lambda_{ee}^{tail} \approx 10^{17}\ T_e^2/n_e$. The LP thus registers an electron temperature that is higher than that of the average thermal electrons at the target. The LP registers $T_e(s_{||} = \lambda_{ee}^{tail})$, roughly. We may estimate this value using the same simple model for $T_e(s_{||})$: electron power carried entirely by classical parallel heat conduction; no convection; no volumetric losses; no e-i equipartition collisions; etc., which gives: $T_e(\lambda_{ee}^{tail}) = T_{et}(1 + 7\,\gamma_e\ ec_{so}\ 10^{17}/2\ \kappa_{oe})^{2/7} = 1.28\ T_{et}$, a rather modest "kinetic correction," and one independent of the absolute values of T_{et} and n_{et}. (c_{so} is the sound speed for $T_{et} = T_{it} = 1$ eV). Thus, all target LP values should be multiplied by 1/1.28 = 0.78 ~ 0.8, a rather small correction and smaller than the uncertainties, so perhaps one that is not worth making. For interest's sake, however, this correction is shown on Figs. 2 and 3. In reality, the complicating effects influence $T_e(s_{||})$, but in off-setting ways, with convection for example reducing the T-gradient and volumetric loss, such as P_{rad}, increasing it. The smallness of the kinetic correction required, estimated by this very simple method, complements and reinforces a much more sophisticated kinetic analysis for higher density ELMing H–mode and partially detached divertor conditions reported at the last PSI conference [7] where no significant kinetic effects were seen or predicted.

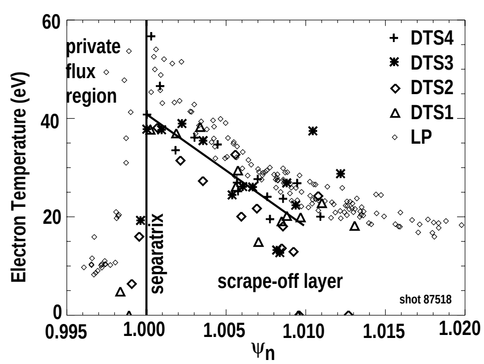

Fig. 2. The temperature profiles are shown versus ψ_n. These profiles show that the mean-free path averaged LP temperature is larger than the more local DTS measured temperature over the entire profile at all densities shown in Fig. 2. The mean-free path correction is shown as a solid curve on the temperature profile.

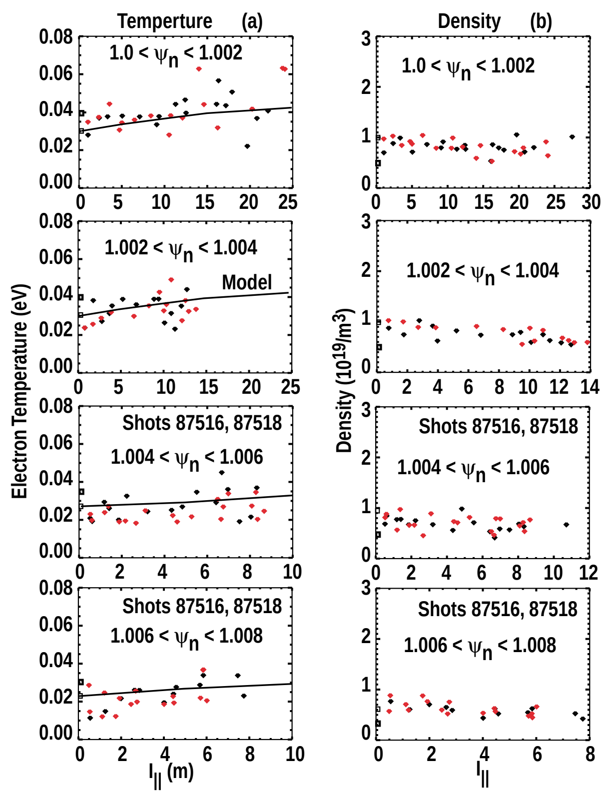

Fig. 3. The DTS measurements along a flux surface near the strike point and in the SOL on the outer divertor leg show the (a) temperature and (b) density variations along the magnetic field above the divertor plate. The Langmuir probe values corresponding to this flux surface are shown against the left axis at $s_{||} = 0$. These plots are all compiled from accumulated data sorted by flux surface. Each graph represents ψ_n values in a 0.002 window.

4. TECHNIQUE USED FOR THE MEASUREMENT COMPARISON

During a slow strike point sweep of two low power ohmic heated DIII–D tokamak discharges, simultaneous measurements were acquired with the target plate Langmuir probes (1500 sweeps at 500 Hz) and the divertor Thomson scattering system (30 pulses at 20 Hz). The core plasma conditions were observed to be constant during the sweep. EFIT equilibria were generated for each laser time using the "default" boundary conditions which set the separatrix current to zero as is often assumed for ohmic and L–mode discharges. For the probe mapping, EFIT equilibria were generated for every 10 milliseconds of the discharge during the sweep. A 65×65 EFIT grid was used to give better spatial definition of the calculated flux surfaces. The EFIT grid was then further interpolated to a 1×1 mm grid in the region of interest near the divertor plate and covering the eight divertor Thomson measurement locations. The parallel lengths along the magnetic field line from each Thomson location to the target were calculated from this interpolated grid for each laser pulse. The measurements were sorted by ψ_n value (ψ_n is the normalized flux surface coordinate; $\psi_n = 1$ on the separatrix; $\psi_n > 1$ in the SOL; $\psi_n < 1$ in the private flux zone plasmas) and were assigned to flux "surfaces" for each ψ_n window of 0.002. LP values in this same ψ_n window and from a probe near to the DTS measurement location (probe number 3–3) were averaged to get the target value at $s_{||} = 0$. As is always the case with flux surface mapping, this technique is subject to error due to uncertainties in the particular boundary condition on the current profile. A different EFIT solution could cause the flux surfaces to move and redistribute some of the points.

It is possible that conditions, especially in the divertor, can change as the strike point is swept and it is best to compare measurements from as similar a geometry as possible. For this reason, the probe nearest the Thomson location is chosen for the comparison so that the least amount of strike point variation is needed and, therefore, the angle of incidence and the flux compression are nearly constant over this part of the sweep.

5. EXPERIMENTAL MEASUREMENTS

5.1. Profiles across flux surfaces

Figure 2 shows the temperature profiles obtained by combining the experimental measurements from the first four Thomson channels and the Langmuir probes for two very low density ohmic discharges. As expected, the T_e measurement from the target probe is higher than the Thomson local T_e measurement over the entire profile for this case. The target plate T_e, as estimated from our mean-free-path correction to the probe measurement, is also shown as the curve in Fig. 2. The density profiles are compared in Fig. 4. The target plate density has been multiplied by a factor of 2 in order to more easily compare with the upstream Thomson. The correction factor of 0.8 to the probe T_e results in a very small density correction of only 1.1 or 10% since deriving the density from the saturation current only involves the square root of the temperature.

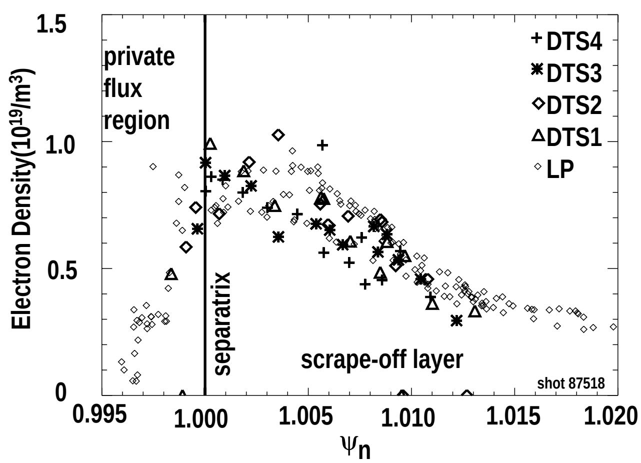

Fig. 4. The density profiles are shown versus ψ_n. These profiles show that the DTS measures about twice the target plate density at the edge of the presheath.

5.2. Parallel profiles

Figure 3 shows the parallel temperature and density profiles for five different flux surfaces. The left axis shows the Langmuir probe measured value as well as the reduced value from applying our correction factor. The temperature profiles are rising slowly going away from the plate. As we move out in ψ_n, the field lines move away from the plate slightly faster due to the steeper angle at the plate. For this near-isothermal case at 40 eV, the ionization length of neutrals coming off the plate is estimated to be of order 1 m, indicating a parallel density scale-length still shorter, which would not be seen even by the first laser channel and, therefore, the density profile along the field is expected to be flat as observed.

6. DISCUSSION

Typical target plate densities in DIII–D are an order of magnitude larger than shown here. By examining the low density case, we have accentuated the differences in localization of the measurements, but at the same time, greatly simplified the model needed for comparison. The temperature measurements show that the case under study is, in fact, near-isothermal and that the probe value is the same as that expected from the upstream values measured by the Thomson. The density is approximately one-half the upstream value which is also consistent with expectations for sound speed ion collection at the plate in the isothermal, sheath-limited regime. The estimated density drop to one-half the upstream value happens extremely close to the target ($\lesssim$1 m along the field). The fluctuations seen in the data (mostly the T_e) are likely due to upstream E×B turbulence known to be present in ohmic and L–mode conditions. The upstream T_e fluctuations would only contribute to the density through sqrt(T_e) and this is evident in the more stable density values shown.

The electrons in this regime behave essentially one-dimensionally whereas the neutrals are inherently three-dimensional. Since the mean-free path for ionization is very short at 40 eV for these neutrals, we would expect most ionization to occur near the plate. Our estimates of $\lesssim$1 m along the field for the density profile to flatten out would mean that the first Thomson channel would not be expected to see any of the gradient in front of the plate. The flat density profile seen along the field verifies that the neutrals are contributing little to the complexity of the problem in this regime, thus permitting the particularly simple interpretation used here.

7. CONCLUSIONS

We have compared measurements at different but close locations made by Langmuir probes and the divertor Thomson scattering diagnostic in DIII–D for a particularly simple case, requiring minimal plasma modeling. By sorting the measurements onto flux surfaces, parallel profiles were obtained that confirm the case under study is in the near-isothermal, sheath-limited regime. Using the standard electron thermal conduction model and a correction for mean-free path effects on the local plate temperature in this regime, we have shown that the target plate Langmuir probe measurements are consistent with the upstream measured Thomson scattering values. The density and particle flux density to the target, as measured by the built-in target LPs, are also in excellent agreement with the Thomson measurements. The divertor Thomson scattering diagnostic has proven to be a very useful diagnostic measurement for verification of the conditions above the target plate along the field line where the probes are sampling. Built-in target Langmuir probes remain a valuable and reliable diagnostic with many advantages (ease of placement, low cost, good spatial and temporal resolution) and can be expected to continue to provide much useful information, especially as divertor geometry becomes more closed and diagnostic access becomes more difficult.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy under Contract Nos. DE-AC03-99ER54463, DE-AC04-94AL85000, W-7405-ENG-48 and Grant No. DE-FG03-95ER54294.

REFERENCES

[1] P. Stangeby, G.M. McCracken, Nucl. Fusion **30**, 1225 (1990).

[2] P. Stangeby, G.M. McCracken, S. Erents, *et al.*, J. Vac. Sci. Technol. A, **2**, 702 (1984).

[3] Th. Daube, K.-U. Riemann, H. Schmitz, Contrib. Plasma Phys. **38**, (1998) S, 145

[4] T.N. Carlstrom, Rev. Sci. Instrum. **68**, 1195 (1997).

[5] D. Buchenauer *et al.*, Rev. Sci. Instrum. **61**, 2873 (1990).

[6] J.G. Watkins *et al.*, J. Nucl. Mater. **241–243**, 645 (1997).

[7] J.G. Watkins *et al.*, J. Nucl. Mater. **266-269**, 980 (1999).

[8] P.C. Stangeby, “The Plasma Boundary of Magnetic Fusion Devices,” (Institute of Physics Publishing, Bristol, 2000).

[9] P.C. Stangeby *et al.*, “Onion Skin Method analysis of DIII–D edge measurements,” to be presented at 14th Int. Conf. on Plasma Surfaces Interactions, May 22–26, 2000, Rosenheim, Germany, to be published in proceedings.

[10] See references in “The Plasma Boundary of Magnetic Fusion Devices,” P.C. Stangeby (Institute of Physics Publishing, Bristol, 2000).