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Comparison of Langmuir probe and Thomson scattering measurements in DIII-D

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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 nearly 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. © 2001 Elsevier Science B.V. All rights reserved.

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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]. 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 nearly 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

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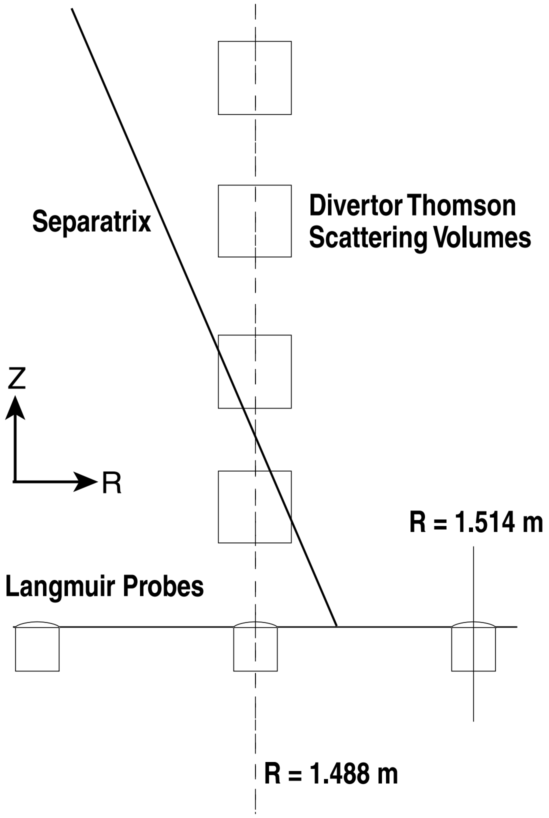

Fig. 1. The DTS measurement locations and the Langmuir probe location are shown with respect to the target plate in DIII-D. The laser path is vertical at $R = 1.488$ m and the scattering volume is approximately 1 cm^3.

$\sim$1 cm, is $\sim$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 non-trivial 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].

It is, therefore, advantageous to investigate discharges where the divertor is operated in the nearly sheath-limited regime, with the $T_e(s_\|)$ being almost flat (isothermal along **B**) and where, according to simple presheath theory [10], the density would be expected to drop by a factor of 2 between 'upstream' locations and the target surface. In this lower density, sheath-limited regime, all the DTS locations are upstream and the LP values of n_e should be about half of the DTS values while the LP T_e values should be about the same as 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.

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 in these cases are $n_{et} \approx 10^{19}$ m^{-3} and $T_{et} \approx 40$ eV. The parallel electron heat flux density to the target is given by

$$q_{\|et} = \gamma_e k T_{et} n_{et} c_{st}, \tag{1}$$

where $\gamma_e \approx 5$ is the electron sheath heat transmissions coefficient, and $c_{st} = (2kT_{et}/m_i)^{1/2}$ 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]

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

where the classical electron conductivity, $\kappa_{oe} \approx 2000$ (eV$^{7/2} - m/W$) for T in eV, s in m and q in W/m^2. Thus at $s_\| = 10$ m, T_e has only increased from 40 to <50 eV, which indicates near-isothermal conditions over this distance. Such ohmic discharges are therefore expected to be essentially 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: $\lambda_{ee}^{\mathrm{thermal}} \approx 10^{16} T_e^2$ (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 $3kT_e$. For these electrons, the e–e collision length is approximately 10× longer: $\lambda_{ee}^{\mathrm{tail}} \approx 10^{17} T_e^2/n_e$. The LP thus registers an electron temperature that is higher than that of the average thermal electrons at the target, roughly $T_e(s_\| = \lambda_{ee}^{\mathrm{tail}})$. We may estimate this value using the same simple model for $T_e(s_|)$: electron power carried entirely by classical parallel heat conduction. This model gives: $T_e(\lambda_{ee}^{\mathrm{tail}}) = T_{et}(1 + 7\gamma_e e c_{so} 10^{17}/2\kappa_{oe})^{2/7} = 1.28 T_{et}$, a small correction which is independent of T_{et} and n_{et} (c_{so} is the sound speed for $T_{et} = T_{it} = 1$ eV). Thus, in this model, all target LP values should be multiplied by 1/1.28 = 0.78. The smallness of the kinetic correction required at low density estimated by this very simple method is consistent with a more sophisticated kinetic analysis for higher density conditions reported at the last PSI conference [7], where no substantial kinetic effects were seen or predicted.

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 LP (1500 sweeps at 500 Hz) and the DTS 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 ms of the discharge during the sweep. A typical 65 × 65 EFIT grid was used and then further interpolated to a 1 × 1 mm^2 grid in the region of interest near the divertor plate and covering the eight divertor Thomson measurement locations. 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 from a probe near to the DTS measurement radius (probe number 3–3) were averaged to get the target value at $s_\parallel = 0$. 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.

5. Experimental measurements

5.1. Profiles across flux surfaces

Fig. 2 shows the temperature profiles obtained by combining the experimental measurements from the first four Thomson channels and the LP for two very low-density ohmic discharges. As expected, the T_e measurement from the target probe is slightly 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 model curve in Fig. 2. The density profiles are compared in Fig. 3. The target plate density has been multiplied by 2 in order to compare more easily with the upstream Thomson data. 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.

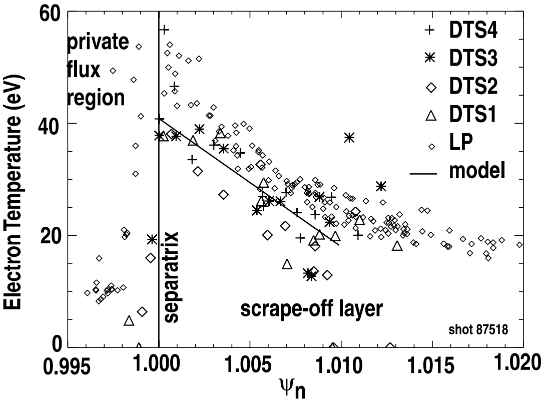

Fig. 2. The temperature profiles are shown versus ψ_n. These profiles show that the mean-free path averaged LP temperature is larger than the more local DTS measured temperature over the entire profile at all densities shown in Fig. 3. The mean-free path correction is shown as a solid curve on the temperature profile.

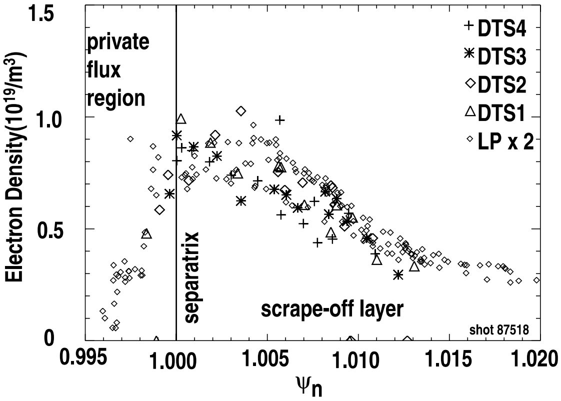

Fig. 3. The density profiles are shown versus ψ_n. These profiles show that the DTS measures about twice the target plate density at the edge of the presheath.

5.2. Parallel profiles

Fig. 4 shows the parallel temperature and density profiles obtained by the DTS system for five different flux surfaces. Langmuir probe measured values, as well as the reduced value from applying our correction factor, are shown on the far left of each figure (at $s_\parallel = 0$). Curves shown in the T_e plots are generated using Eq. (2), modified with our correction factor. The temperature

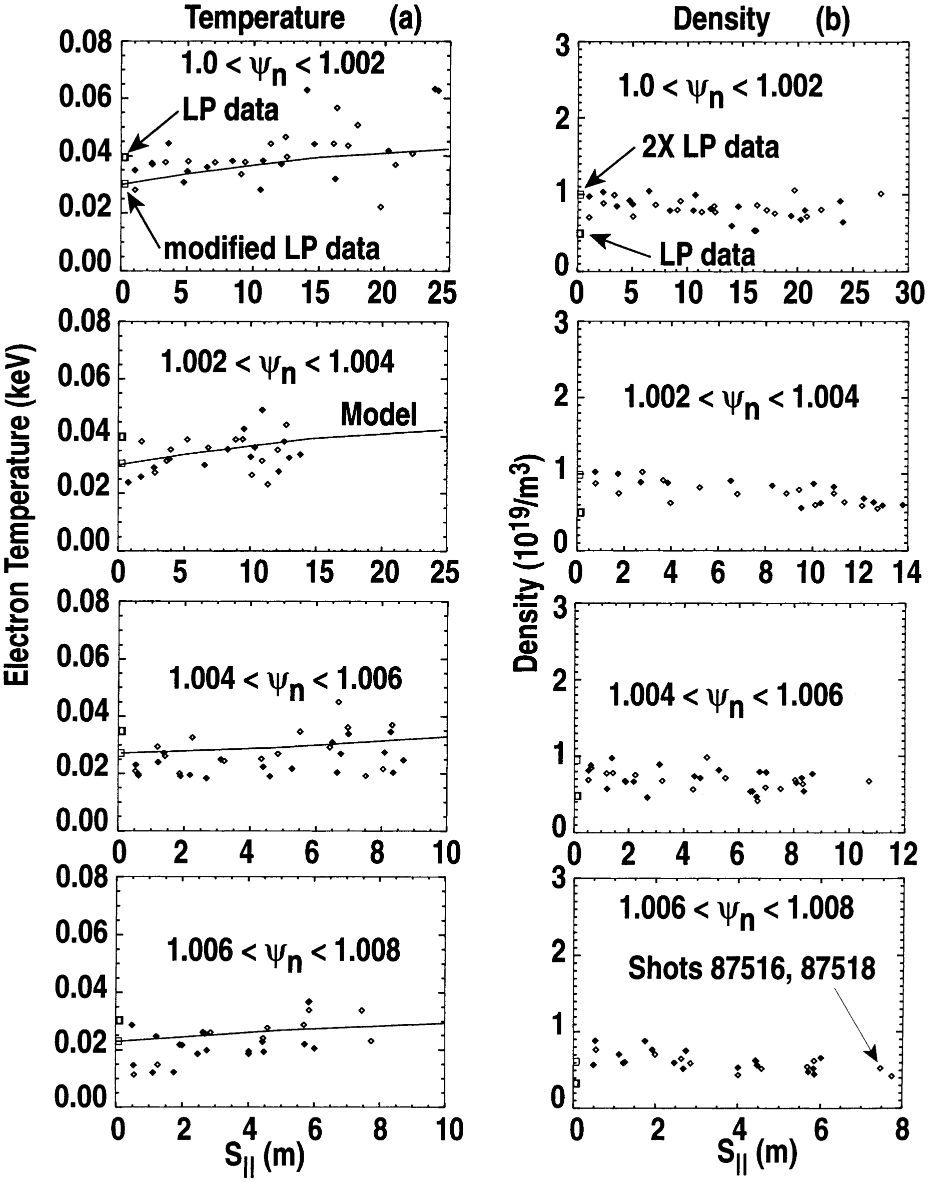

Fig. 4. The DTS measurements along a flux surface near the strike point and in the SOL on the outer divertor leg show (a) the temperature and (b) the density variations along the magnetic field above the divertor plate. The Langmuir probe values corresponding to this flux surface are shown against the left axis at $s_{\|} = 0$ as well as the corrected values as in Section 3. The model shown is from Eq. (2) using the corrected LP values. These plots are all compiled from accumulated data sorted by flux surface. Each graph represents ψ_n values in a 0.002 window.

profiles rise 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 ~1 m, indicating a parallel density scale-length still shorter, which would not be seen even by the first laser channel. Therefore, the density profile along the field is expected to be essentially 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 in T_e) are likely due to upstream $E \times B$ 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 constant density values shown.

7. Conclusions

We have compared measurements at different but close locations made by LP and the DTS 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 (SETC) 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 DTS 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 LPs 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.

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