Comparison of Thomson scattering and Langmuir probe for electron property measurements in a DC magnetron plasma

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I. Introduction

Accurate and reliable electron property measurements are essential for understanding many different plasma phenomena, such as, particle collisions, reactions and plasma-surface interactions. Langmuir probes are widely used in low temperature plasma for electron temperature T_e and density n_e measurements because of the relative simplicity of the experimental technique, as well as, providing a localised measurement. However, there is no satisfactory theory for the case of magnetised plasma because cross-field transport mechanisms are poorly understood [1]. Consequently, there is difficulty modelling transport anisotropy and voltage drops consumed by plasma or sheath impedances outside of the probe sheath.

The current experimental approach is to align a probe with its surface-normal parallel to the magnetic field to reduce the electron current distortion, and sample only the high energy tail of the electron energy distribution for T_e measurements. This may not be representative of the bulk temperature for non-Maxwellian energy distributions but it ensures that the applied voltage sweep appears across the probe sheath [2].

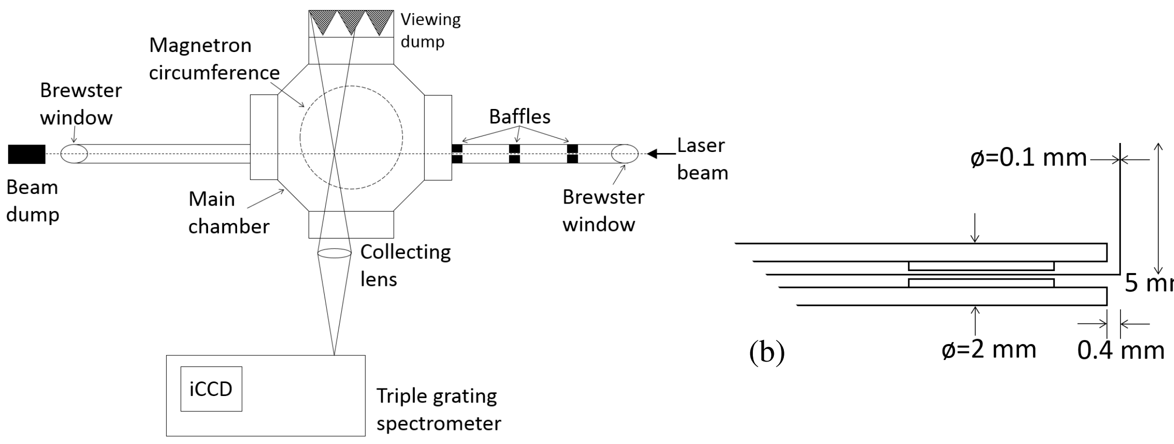
The aim of this research is to compare two routinely used techniques for measurement of electron properties, for the case of magnetised plasma. Non-simultaneous probe and Thomson scattering measurements have been performed above the racetrack of an argon DC magnetron discharge (7-36 mT), where electrons are the only magnetised species. The interpretation of the Thomson data is straightforward and is independent of magnetic field strength, hence the diagnostic provides reliable measurements of the bulk electron properties.

The following section, Sec II, contains a brief summary of the diagnostic methods and the experimental apparatus. The experimental results and discussion are presented in Sec III.

II. Apparatus and measurement techniques

A. Magnetron discharge system

A schematic of the experimental system is shown in figure 1(a). It consists of a VTech 150 series unbalanced magnetron (Gencoa Ltd, UK) mounted vertically above a grounded electrode in a 10 L aluminium vacuum chamber. The 150 mm diameter circular tungsten target (purity >99.95%) was surrounded by a ground shield and regulated dc power was supplied by a Pinnacle



(a)

Figure 1: (a) Cross-sectional view of the experimental apparatus. Brewster windows, baffles, and a viewing dump were used to minimise the effects of stray light. (b) Langmuir probe tip.

Plus power supply (Advanced Energy Inc.). A base pressure of 4×10^{-5} Torr was achieved using a turbomolecular pump backed by a rotary pump.

B. Incoherent Thomson scattering system

A frequency-doubled Nd:YAG laser (10 Hz, pulse energy 200 mJ, pulse duration 5 ns, beam divergence 0.5 mrad, 532 nm) injected electromagnetic radiation into the plasma and the scattered light was directed into a triple grating spectrometer in the double subtraction configuration (focal length 640 mm, third grating reciprocal dispersion 0.7 nm/mm) by a lens (diameter 75 mm, focal length 200 mm, detection solid angle 0.05 sr). The spectrometer entrance slit (effective aperture 6 mm $\times$ 0.30 mm) was parallel to the direction of the laser beam propagation and an iCCD camera recorded the spectra. A notch filter was placed between the first and second gratings to attenuate the signal in the range 531.5-532.5 nm to avoid saturation of the iCCD camera by the stray light/ Rayleigh scattering signal at the laser wavelength.

Data accumulation from 6000 laser pulses was used to obtain a satisfactory signal-to-noise ratio. To isolate the Thomson signal, a plasma emission spectrum was recorded for each measurement and subtracted from the laser-plasma spectrum. Measurements were averaged over the entrance slit width, which gives a spatial resolution of 2.7 mm with the beam waist $\sim$ 0.5 mm. Absolute electron densities were calibrated using Rayleigh scattering from room temperature argon gas in the pressure range 0.1-5 Torr after each Thomson measurement.

C. Langmuir probe measurement system

A schematic of the tungsten-wire Langmuir probe tip (radius $r_p = 0.05$ mm, length 5 mm) used is shown in figure 1(b). The probe was inserted radially into the vacuum chamber with the tungsten wire pointing towards the magnetron target so that the tip length was perpendicular to

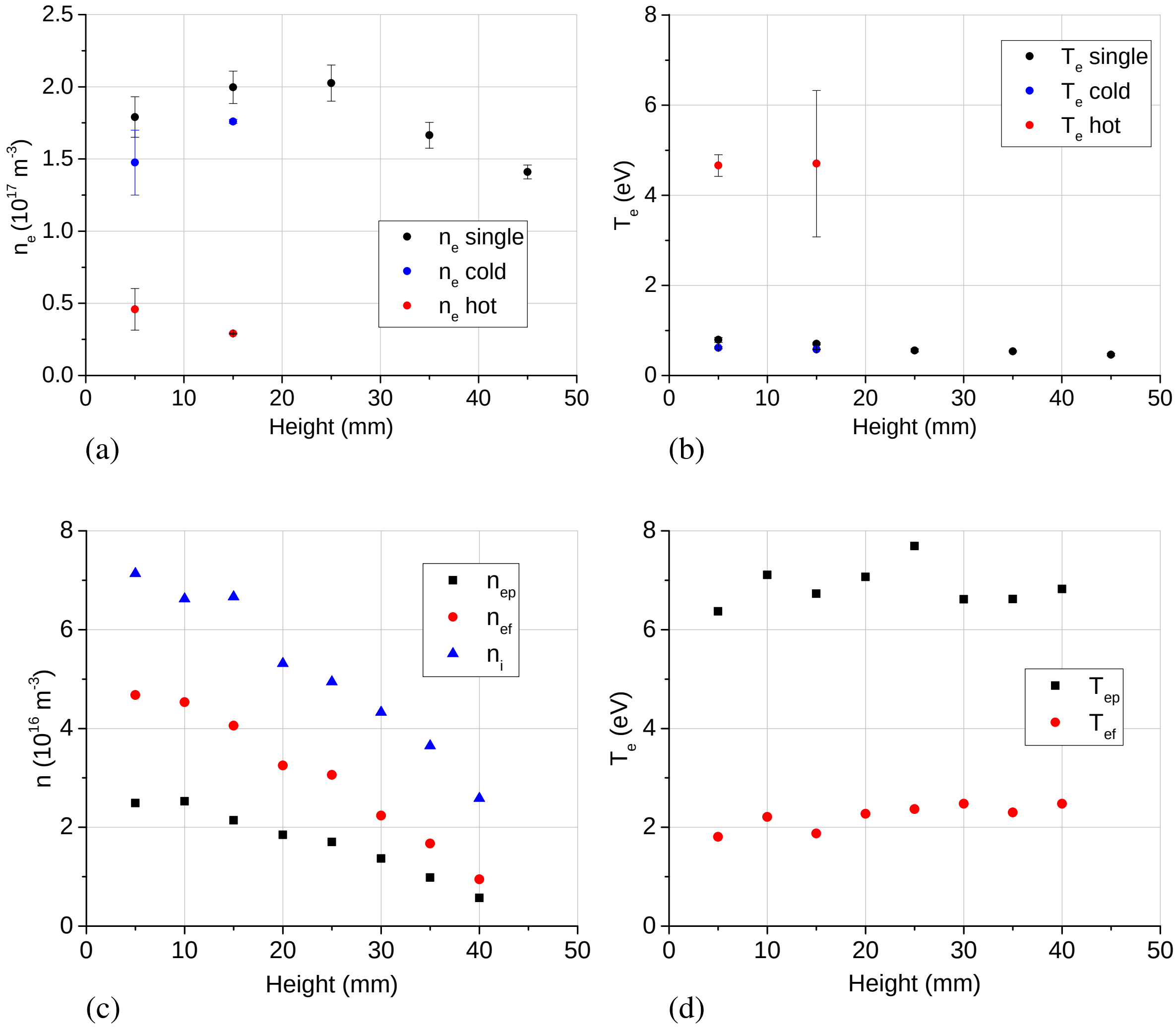


Figure 2: Thomson scattering n_e (a) and T_e (b) as a function of height above the magnetron racetrack. Langmuir probe data plotted separately in (c) and (d). Terms described in text.

the magnetic field. A -110 to 20 V bias with respect to the grounded chamber was applied to the probe using a saw-tooth ramp (period 192 ms). Probe current was calculated by measuring the voltage drop across a high (power supply) side 68.3 Ω resistor. Measurements were averaged over 50 cycles using an oscilloscope.

Standard analysis techniques [3] were used to determine the plasma potential V_p, ion density n_i, n_e, and T_e. These were: maximum in the first derivative of the probe IV gives location of V_p; n_i calculated from orbital motion limited (OML) theory; n_e from equating the current at V_p to the electron thermal flux and T_e from the gradient of the electron retardation region.

III. Results and discussion

Measurements were performed at a fixed 41 mm radial position from the centre of the magnetron and the axial height to the target surface was varied by adjusting the magnetron mount.

The magnetron was operated at a constant power of 100 W with argon gas pressure 12 mTorr. The target voltage drifted between -320 to -295 V.

Figures 2(a)(b) show Thomson scattering n_e and T_e profiles. The error bars represent standard deviation from several measurements. Density overestimation caused by the transmission of the collection window decreasing during plasma operation is less than 10%. A single Maxwellian velocity distribution ($T_{e\ \mathrm{single}} \sim 0.6$ eV) provided a good fit to the Thomson spectra $\geqslant 25$ mm from the target surface, but closer to the target, a bi-Maxwellian fit was applied because there was evidence of a hot electron component $T_{e\ \mathrm{hot}} \sim 5$ eV with relative density <25 % and $T_{e\ \mathrm{cold}} \approx T_{e\ \mathrm{single}}$.

Given that the ions are unmagnetised, it is surprising that n_i from the probe was up to a factor 5 lower than the Thomson n_e. For this reason the probe density measurements have been plotted separately; shown in figure 2(c). The OML theory applied to the ion current assumes cold collisionless ions in the probe sheath, $r_p/$ Debye length < 3 and ion gyroradius $\gg r_p$. These assumptions have been verified by calculating ion mean free path from cross-section data [4], taking measurements at lower pressure (not shown) and using the Thomson measurements to calculate the Debye length.

The electron retardation region of the probe IV was non-exponential so a single temperature could not be assigned to each probe characteristic. Electron temperature was calculated using the gradient tangent to the IV curve at the plasma and floating potential separately; T_{ep} and T_{ef} (figure 2(d)). These values were then used to calculate electron density n_{ep} and n_{ef}. Both electron densities were consistently lower than the ion density, with n_{ef} larger than n_{ep} because $T_{ef} < T_{ep}$. The probe electron temperature has better agreement with the Thomson hot component suggesting that the probe analysis method is insensitive to the cold population.

The discrepancy between the ion and Thomson density needs to be resolved before the effect of electron magnetisation can be understood. This is currently being investigated.

References

[1] P.C. Stangeby, Plasma Phys. Control. Fusion **37**, 1337-1347 (1995)

[2] R.A. Pitts and P.C. Stangeby, Plasma Phys. Control. Fusion **32**, 1237 (1990)

[3] J.D. Swift and M.J.R. Schwar, Electrical Probes for Plasma Diagnostics (Elsevier, New York, 1969)

[4] M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing (Wiley, New Jersey, 2005)