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ABSTRACT.

Ion temperatures, T_i, and velocity distributions, f(v), in the plasma edge of fusion devices are notoriously difficult to measure and thus rarely available but yet are important plasma boundary quantities. Though requiring the insertion of a material probe into the Scrape-Off Layer (SOL), the Retarding Field Analyser (RFA) is one experimental approach that can access the plasma ion or electron velocity distribution directly. By designing a "bi-directional" probe, ie. one which can intercept particles on both sides of a plane oriented perpendicular to the total field line direction at a particular location in the SOL, the device may also be used to simultaneously characterise any net flow that may be present there. In fact, according to recent theoretical work [1], it turns out that the presence of an external flow field should have a strong influence on the parallel field ion velocity distributions (and hence on the derived ion temperatures) at the upstream and downstream locations of any surfaces inserted into the flow. This contribution will offer the first experimental evidence for this effect, describing recent results obtained with an RFA in the JET plasma boundary.

1. RFA PRINCIPLE AND THE JET RFA

Figure 1(a) illustrates the well known [2, 3] basic principle of RFA operation. Charged particles are transmitted through a small aperture (width ~ λD , the Debye Length) and are analysed by retardation in the electric field established through bias potentials applied to a number of grids. Since the electron velocity distribution (and hence the electron temperature, T_e) can to some extent be measured by the simple single Langmuir probe, the primary focus of RFA application is often the ion velocity distribution. An appropriate electrode bias configuration for ion analysis is included in Fig.1(a), illustrating how the slit plate is normally negatively biased to repel all but the highest energy electrons. A positive voltage sweep, V_1, is applied to Grid 1 and a constant negative bias on Grid 2 at a value lower than that applied to the slit eliminates any remaining electrons. The collector at zero volts suppresses any ion induced secondary electrons. In tokamaks, the current-voltage characteristic thus obtained is often experimentally found to be closely consistent with that which would arise if the parallel ion velocity distribution were a Maxwellian shifted in velocity space by an amount equal to that gained by acceleration in the sheath and pre-sheath electric fields [2, 3]. In this case, for values of V_1 exceeding the voltage required to back-off this energy shift, the I-V characteristic can be written in the form: $I_c = I_i \exp)-Z_i V_1/T_i)$ where $I_i = AZ_iT_ie^2/m_i$, Z_i is the ion charge and T_i (in eV) is the ion temperature of the distribution.

A new RFA has recently been designed and successfully operated at JET using the fast reciprocating drive systems to insert the probe head several times into the edge plasma, whilst simultaneously employing a second probe to measure radial profiles of particle flux and T e for comparison with data from the RFA. The new probe head is illustrated in the form of a false colour solid model illustration in Figure 1(b). An extensive report on the technical design, construction and performance has recently been completed [4].

2. RESULTS - SOL FLOW AND T_i

An example of the kind of data produced by the diagnostic is given in Fig.2, from the ohmic phase of a low density, single null lower diverted equilibrium with I_p = 2.0MA and B_φ = 2.4T, both in the forward, or clockwise direction. The probe is inserted at a point on the upper, low-field-side of the poloidal cross-section and is designed such that the aperture slits (40µm wide, 3.0mm length) are aligned closely perpendicular to the total magnetic field direction at this point. For forward I_p, B_φ , the slit facing the ion drift direction (the ion, or i-side) intersects field lines spiralling upwards from the outer divertor whilst the electron, or e-side, slit faces the inner divertor. Figure 2(b) demonstrates that under certain conditions the RFA ion characteristics are clearly consistent with a shifted Maxwellian velocity distribution, though the magnitude of the shift in this case is not that of the true sheath potential fall since bias potentials and currents are measured with respect to the torus potential and not the local slit floating potential, V_f. The shift, V shift , can be appropriately corrected by floating the RFA slits and directly measuring V_f, but at the price of losing the simultaneous measurement of j_{sat} (Fig. 2(a)), the ion saturation current density to the plates (by applying a large negative bias, typically -150V).

It is already clear in Fig.1(a)) that the i-side/e-side j sat ratio considerably exceeds unity and thus that the RFA is immersed in a flowing SOL plasma. Such strong flow is regularly observed on JET for forward B_φ [5] and is usually estimated by employing a fit to the fluid model of Hutchinson [1,6] $M = 0.4\ln(j^u_{sat}/j^d_{sat})$ where M is the flow Mach No. (normalised to the isothermal sound speed, $c_s = (e(T^e + Z_iT_i)/m_i)^{1/2}$ (T_i, T_e in eV) and the superscripts u, d denote “upstream” and “downstream” with respect to the flow. The latter is defined as positive if it is directed towards the probe so that the i-side in Fig. 2(a) is the upstream side and the flow is directed along the total field from outer to inner divertor targets. The example RFA characteristics in Fig.2(b) already show that in addition to the j sat asymmetry, ratio where the superscripts i, e, now denote i-side and e-side.

A complete analysis of M, T_i^i, T_i^e, for the probe reciprocation of Fig.2 is compiled in Fig.3, along with data (black triangles) from a second reciprcocating probe head which was inserted at approximately the same time in the discharge at the same poloidal location (but at a different toroidal position) and from which a scanned Langmuir probe provides data for j_{sat}, T_e and V_f on the upstream side only. Unfortunately, there is a good deal of uncertainty with regard to absolute probe positions with respect to the separatrix, due both to errors in knowledge of the absolute probe location in space and in the equilibrium reconstruction. In Fig.3, separatrix distances have been estimated by first using electron pressure balance between outer divertor target Langmuir probe measurements (whose positions are known rather accurately) and those obtained upstream and then by radially shifting the RFA i-side j_{sat} profile (Fig. 3(b)) until the profile shapes are in reasonable agreement. The use of pressure balance in this case is particularly appropriate in view of the low density, ohmic conditions which provide a reasonably simple SOL with weak parallel temperature gradients and a low recycling divertor. At the strike points, T_e ~ 20eV, $n_e \sim 3\times10^{19}$ m^{-3} at both the inner and outer divertors and both divertor plasmas are well attached. A further multiplicative factor of ~2 is also generally required on the RFA j sat to match absolute magnitudes. The origin of this is not understood, but may be due to reduction in current when ions are lost to the side walls of the chamfered edges in the probe end cap bordering the entrance aperture plates.

Although the RFA data are rather scattered, Fig.3 illustrates that $T_i^i > T_i^e$, $(T_i^i + T_i^e)/2 > T_e$ and $M > 0$ throughout most of the profile (the smoothed, mean ion/electron-side T_i is plotted as the dashed line in Fig.3(a). Error bars have been omitted for clarity, but are generally of order 5% when RFA collector currents are high, becoming more significant at lower currents (and hence further out in the SOL in the case of Fig. 3(a). Concerning the general observation that $T_i > T_e$, this is qualitatively expected in the low density SOL in which these measurements have been obtained. The SOL collisionality parameter, $\nu^*_{SOL} = L_c / l_i^i \approx 10^{-16}\, n_e L_c / T_i^2 \sim 1$ (L_c is the probe to target connection length of ~ 40m) on a flux surface at the point of closest approach to the separatrix in Fig.3 and so the temperature equilibration time is very much longer than the effective SOL energy confinement time.

Regarding the strong i-side, e-side T_i asymmetry, the data would appear to be the first qualitative experimental demonstration of the recent theoretical assertion [1] that such an effect should be observed by an RFA immersed in a strong plasma flow. This is due to the perturbing effect of the probe itself which depletes ions preferentially on the downstream side, generating strong electric fields and modifying the ion velocity distribution. According to this theory, the real T_i in the plasma cannot be measured by a single-sided RFA in a flowing plasma, but is given rather accurately by the mean value of i-side to e-side values provided the drift is not too strong. Figure 4(a), extracted from ref. [1], plots the expected ratio of aln (T_i^i/T_i^e) as a function of normalised, cold ion plasma drift speed, U_0, for varying $\tau = T_i / T_e$. As shown in Fig.3(d), U_0 is related to the measured M by the multiplying factor $\sqrt{1+\tau}$. In the theory, the ratio T_i^i/T_i^e increases with U_0 and decreases with τ. In Fig. 4(d), the measured quantity ln (T_i^i/T_i^e) is plotted against the measured flow speed, whilst Fig. 4c) gives the measured τ for reference. At the flow maximum (corresponding to the position of maximum insertion for this discharge), $\tau \sim 2.5$, $M \sim 4$, $U_0 \sim 0.8$ and the RFA yields ln (T_i^i/T_i^e) ~ 0.5-0.8. This should be compared with the expected value, read crudely from the curve in Fig.4(a) of ln (T_i^i/T_i^e) ~0.4. Experimentally, deeper in the SOL, where U_0 decreases, τ also decreases and the T_i ratio is approximately constant, though the data are very scattered. Such behaviour is also qualitatively consistent with the theory, though absolute magnitudes do not agree. The theory also predicts a reasonably strong variation of the expected upstream- downstream pre-sheath potential difference (Fig.4(b)). This is more difficult to assess experimentally from the noisy RFA data, which itself must be corrected for the (unmeasured) local value of V_f. For the measured values of M and τ near the separatrix in Fig.3, the expected theoretical difference would be $\sim T_e$ volts favouring the upstream (i-side) and as such should be observable. This does not appear to be the case for the V shift data in Fig.3(b).

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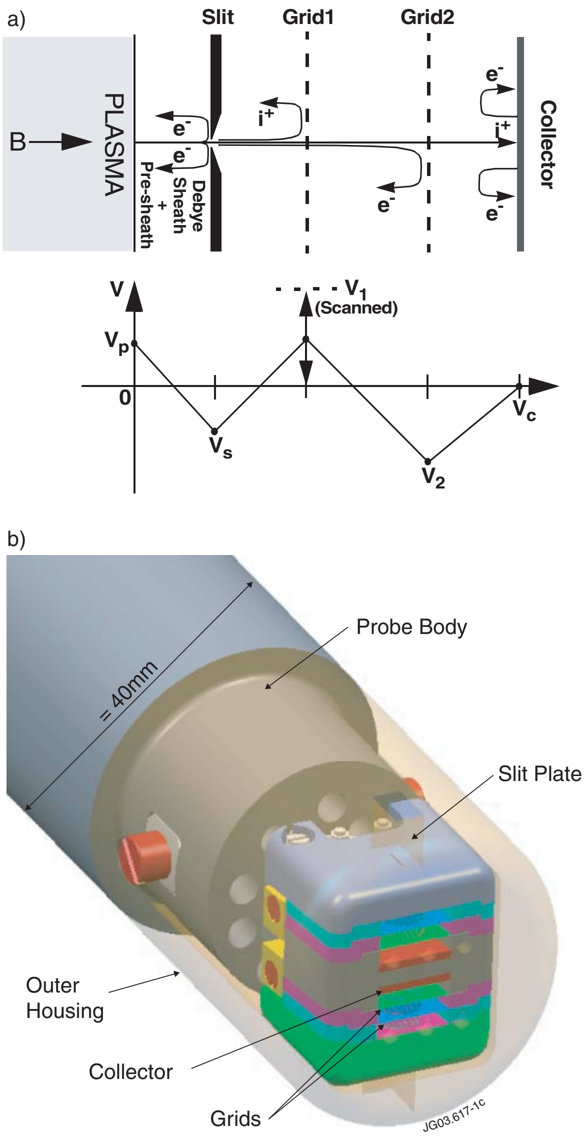

Figure 1: (a) Illustrating the RFA principle and bias potential arrangement for ion analysis and (b) showing the engineering and assembly of the JET RFA probe head.

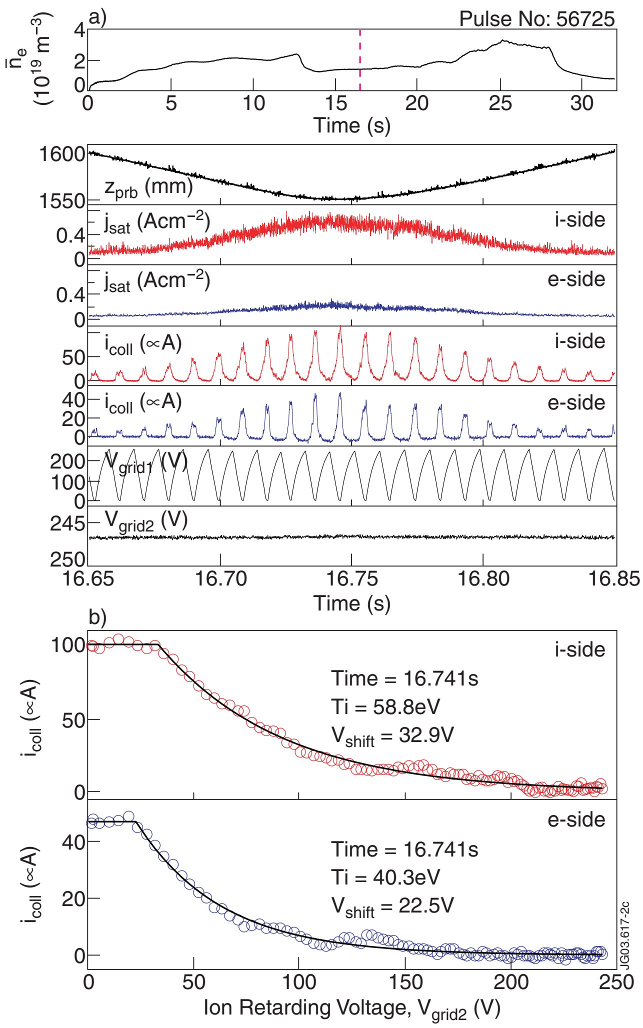

Figure 2: (a) Time sequence of RFA data for a single reciprocation into a low density, ohmic discharge. (b) example RFA characteristics and their fits for a single time in (a). Red: ion-side, blue: electron-side