Effect of recombination and ionization on the analysis of Mach and single probes in un-magnetized and magnetized plasmas of MAP-II and DiPS devices

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Abstract

For the analysis of atomic processes such as recombination and ionization in the divertor plasmas, we have developed a fast-scanning multiple probe system, which is composed of single, Mach and emissive probes along with Thomson scattering system at the material and plasma (MAP)-II divertor simulator with low magnetic field (about 200 G). Measured spatial variations of electron density, electron temperature, flow velocity and plasma potential will be given in comparison with those by Thomson scattering method. To analyze the data, a new fluid model on the ion collection to a probing object in un-magnetized plasmas is developed including electron–ion recombination, molecular activated recombination and ionization. This system is applied to another divertor simulator, divertor plasma simulator (DiPS), with higher magnetic field (up to 2 kG).

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1. Introduction

Edge conditions are important in influencing the characteristics of tokamak plasmas, and many problems such as detached plasmas, flow reversal and the strong heat flux limit are linked to the transport of momentum in the scrape-off layer. Although significant ion drift resulting from scrape-off flow plays an important role in impurity transport and fluctuation levels, it is difficult to accurately measure the flows [1]. Recombination processes in the fusion edge plasmas to achieve a detached plasma becomes a very promising scenario for the reduction of particle and heat fluxes onto the divertor targets. In addition to electron–ion recombination processes...
characterized by radiative and three-body recombination processes induced by the hydrogen or hydrocarbon \[\text{puffing}\] recently have shown the capability of contributing to the volume recombination. The conditions for each process to be effective strongly depend on electron temperature and electron density. Although basic plasma physics experiments in linear machines such as material and plasma (MAP)-II, divertor plasma simulator (DiPS), and other devices in the references therein, aimed at analyzing the magnetized presheath region of simulated tokamak edge plasmas, and have shifted toward the test of materials relevant to large fusion devices, they can still perform physics experiment related dust, radiation cooling and other atomic processes.

The goal of this paper is to analyze the effect of recombination and ionization on the analysis of Mach and single probes in un-magnetized and magnetized plasmas. With a fast-scanning probe and Thomson scattering (TS) systems, global change of density and electron temperature with neutral pressure and effect on the deduction of Mach numbers are to be analyzed by new one-dimensional fluid models along with existing two-dimensional fluid model.

2. Experimental setup

MAP-II device \[\text{generates plasmas by an arc discharge between a flat LaB6 cathode disk (diameter 30 mm) and an anode pipe in the source region, which consists of a plasma source and a dual chamber connected by a drift tube improving gas isolation. A core plasma stream about 5 cm in diameter is transmitted along a longitudinal magnetic field of about 200 G. The density of the plasmas in the first chamber (source chamber) is relatively high (3 \times 10^{13} \text{cm}^{-3}), while that in the second chamber (target chamber) is lower (2 \times 10^{12} \text{cm}^{-3}). \text{DiPS} \text{ is developed for analysis of electric probes with magnetic field effect, collision of charged particles and neutrals, probe shape and materials, and plasma and transport parameters, which is composed of three major parts: a divertor simulator with LaB6 DC plasma source (diameter = 100 mm, magnetic field up to 2 kG, } T_{i} \approx 0.2–0.7 \text{ eV}, \text{a material processing simulator with helicon plasma source, and a space simulator without magnetic field. The typical electron temperature and density are 2–3 \text{eV and up to } 10^{14} \text{cm}^{-3}\text{ for an Ar plasma and 5–10 \text{eV and up to } 10^{13} \text{cm}^{-3}\text{ for a He plasma.} \text{ Various electric probes (single, emissive, Mach) are installed on the fast-scanning probe systems, whose typical speed is about 1 m/sec and components are pneumatic cylinder, solenoid valves, optical limit switches, and bellows sectors. Total length of the probe assembly is about 100 cm and its stroke is 30 cm. \text{Fig. 1 shows the schematic views of a fast-scanning probe system and probe geometries in unmagnetized plasma MAP-II (} B = 200 \text{G}, \rho_{i} = 2.8(H) \sim 5.5(\text{He}), a_{p} = 1.4 \text{ mm, } P_{n} = 5–150 \text{mTorr} \text{ and magnetized plasma at DiPS (} B = 1.1 \text{kG}, \rho_{i} = 1.31(\text{He}), a_{p} = 3 \text{ mm, } P_{n} = 0.8–50 \text{mTorr}. \text{A TS [6] system is installed on MAP-II having a lens with a focal length of 1 m focuses the beam in the center of the plasma through a Brewster window and three baffle plates. A second harmonic Nd:YAG Laser (\leq 400–500 \text{mJ/pulse @ 532 nm, 7 ns, 10 Hz}) is used as the probe beam of the TS systems.} \text{3. Models} \text{ To see the effect on recombination on the axial profile of density, one may use an analytic solution in cylindrical geometry after separating the radial and axial components with classical diffusion in low magnetic field as in the Q-machine [7], then one can obtain the following equation for axial variation of plasma density from steady-state continuity and momentum equation assuming quasi-neutrality:}

\[ n(z) \propto \exp[-m(Sn_{c}z)^{2}/4T], \]

where \( S, n_{c}, m, T \) are effective volume recombination rate (\( \langle \sigma v \rangle_{\text{rec}} \), plasma density at \( z = 0 \), ion mass and plasma temperature, respectively. Assuming the uniform plasma source profile, the overall ambipolar diffusion and radial classical diffusion, the radial density profile in the cylindrical plasma has the form of

\[ \frac{n(s)^{2}}{n_{0}^{2}} \equiv N_{1}(s) = b + cI_{0}(s) \quad (0 \leq s \leq s_{1}), \]

\[ N_{2}(s) = dI_{0}(s) + eK_{0}(s) \quad (s_{1} \leq s \leq s_{2}), \]

where \( b, c, d, e \) are constants to be determined by the boundary conditions \( (N_{1}(0) = 1, \ N_{1}(s_{1}) = N_{2}(s_{1}), \ N_{2}(s_{2}) = 0, \ s_{1} = \text{source radius, } s_{2} = \text{wall radius}) \), \( s = r/R_{0} \), \( n_{0} \) density at \( r = 0 \), and the relaxation length \( R_{0} = (\eta T/B_{0}^{2})^{1/2} \). Here \( I_{0}, K_{0}, \eta, B_{0} \) are the zeroth order modified Bessel functions of the
first and second kind, resistivity, external magnetic field, respectively, and the radial diffusion would be assumed to be classical to fit the radial profile in terms of recombination rate ($S$).

Using the Mach probe, composed of two opposite directional probes, the ratio ($R$) of ion saturation currents are measured in the upstream and downstream directions with strongly negative bias modes (e.g., $V_b = -150 \text{ V}$), then the relevant Mach numbers ($M$), is deduced using appropriate theories of recombinating and ionizing plasmas in the unmagnetized and magnetized plasmas. For this, consider a Boltzmann transport equation of ions

$$\frac{\partial f}{\partial z} + \frac{q}{m} E_z \frac{\partial f}{\partial v} = S_i(v,z) + \frac{G_{ne}(z)}{n_e(z)} f_n(v) - S_n e(z) f_s(z,v),$$

(3)

where $v \equiv v_z$, and the transport sources for the unmagnetized (I: $\rho_i > a$) and magnetized (II: $\rho_i < a$) cases are given as

$$S_i \approx \frac{v_i}{a} \left(1 - \frac{n_i}{n_{\infty}}\right) f_{\infty}(I), \quad \frac{D_{\perp}}{a^2} \left[\alpha(f_{\infty} - f_i) + (1 - \alpha)\left(1 - \frac{n_i}{n_{\infty}}\right) f_{\infty}\right] (II),$$

with $G = \langle \sigma v \rangle_{\text{ion}}$, $S = \langle \sigma v \rangle_{\text{eir}} + (1 - \delta)\langle \sigma v \rangle_{\text{dr}}$, $\delta = \langle \sigma v \rangle_{\text{eirn}(H^+)} / \langle \sigma v \rangle_{\text{drn}(AH^+)}$, and the subscripts ion, eir, dr, ic mean by ionization, electron–ion recombination, dissociative recombination, and ion conversion, respectively. Here $D_{\perp}$ is the anomalous cross-field diffusivity, $a = a_p$ is the probe radius (or size), and $\alpha(\equiv n_{\perp} / n_m D_{\perp})$ is the normalized shear viscosity. $f_{\infty}$ is a shifted Maxwellian with ion temperature, $T_i$, and $f_s$ is a Maxwellian with neutral temperature, $T_n$. For mono-atomic particles $\delta$ is almost unity excluding molecular activated recombination ($\text{mar} \approx ic + dr$). With quasi-neutrality, $n_e = Zn_i$, and Boltzmann electrons, taking the zeroth and first moments lead to the following equations for both the unmagnetized ($\rho_i > a$) and magnetized plasmas ($\rho_i < a$), separately:

$$\frac{dn}{dM} = \frac{n}{n_i} \frac{\left[\tau(1 - n)(M_{\infty} - 2M) - 2\sigma_i n M + \rho_i n^2 M\right]}{(1 - n)(1 - M_{\infty} M + M^2) + \sigma_i n(1 + M^2) - \rho_i n^2},$$

(4)

$$\frac{dn}{dM} = \frac{n}{n_i} \frac{\left[\eta(1 - M_{\infty} M - M) - (1 - x) n M_{\infty} - M + 2\sigma_i n M - \rho_i n^2 M\right]}{(1 - n)(1 - M_{\infty} M - M)(1 - (1 - x)n) + \sigma_i n(1 + M^2) - \rho_i n^2},$$

(5)

where the following dimensionless variables are used: $M \equiv V_d/C_s$, $M_{\infty} \equiv V_d/C_s$, $n \equiv n_i/n_{\infty}$, $\eta \equiv z/a$ (for $\rho_i > a$), $z/L$ (for $\rho_i < a$), $L \equiv a^2 C_s D_{\perp}$, $\tau \equiv v_i/
$C_s = [T_i/(T_i+ZT_e)]^{0.5}$, $\sigma_1 = G\alpha n_0/C_s$, $\sigma_2 = (G\alpha n_0/C_s)(L/a)$, $\rho_1 = S\alpha n_\infty/C_s$, $\rho_2 = (S\alpha n_\infty/C_s)(L/a)$, and $C_i \equiv [(T_i + ZT_e)/m_i]^{0.5}$. Although these equations may produce values larger than $n = 1$ for $z = 0$ [8,9], the sheath values ($n_s = n (M = -1)$) for various $M_\infty$ do not change for $z \neq 0$ and non-zero values of $\rho_{1,2}$ and $\sigma_{1,2}$. This is shown by getting non-singular solutions of $n(y)$ and $M(y)$ including small ionization and charge-exchange in solving $dn/dy$ and $dM/dy$, separately, and calculate the sheath values [10].

4. Result and analysis

Both MAP-II (un-magnetized) and DiPS (magnetized) plasmas are usually generated at pressure of several mTorr. Fig. 2 shows the variations of plasma density and electron temperature measured by a single probe comparing with those by TS. Both electron temperature and plasma density measured by electric probe seem to agree well with those by TS within experimental error. Electron temperatures deduced from the floating and plasma potentials measured by an emissive probe are also added, and they are smaller than those by electric probe and TS methods.

From the MAP-II data, consider the ionizing case (mode 0) at the center ($Z = 1$ and $T_i \approx T_e = 0.1T_c$ are assumed): $B = 200$ G, $a = 1.35 \times 10^{-3}$ m, $P_n = 5.5$ mTorr, $T_e = 6$ eV, $n_\infty = 1.5 \times 10^{19}$ m$^{-3}$, then the relevant numbers for helium become as $C_s = 1.199 \times 10^4$ m/sec, $\lambda_D = 4.699 \times 10^{-6}$ m, $\rho_i = 7.9 \times 10^{-3}$ m, $n_n \approx 7.63 \times 10^{18}$ m$^{-3}$, $\tau = 0.3$, $\sigma_1 = 2.2 \times 10^{-4}$, $\rho_1 = 1.7 \times 10^{-7}$. Then the recombinant case (mode 4) at the center ($Z = 1$ and $T_i \approx T_e = 0.1$, $T_c$ is assumed): $B = 200$ G, $a = 1.35 \times 10^{-3}$ m, $P_n = 112$ mTorr, $T_e = 1$ eV, $n_\infty = 7 \times 10^{18}$ m$^{-3}$, then the relevant numbers for helium become as $C_s = 4.895 \times 10^3$ m/sec, $\lambda_D = 2.808 \times 10^{-6}$ m, $\rho_1 = 3.226 \times 10^{-3}$ m, $n_n \approx 9.32 \times 10^{19}$ m$^{-3}$, $\tau = 0.3$, $\sigma_1 = 6 \times 10^{-8}$, $\rho_1 = 2 \times 10^{-6}$.

In DiPS device, we obtain the data for the following pressure modes: $P_n = 0.8$ (mode 1), 4.8 (mode 2), 27 (mode 3), and 53 (mode 4) mTorr. For the reaction rates in DiPS, they are increased by a factor of $L/a$, which is ~10 for the following conditions: $B_0 = 1100$ G, $n_e = 3.5 \times 10^{12}$ cm$^{-3}$, $T_e = 8.5$ eV (mode 1), $n_e = 9 \times 10^{12}$ cm$^{-3}$, $T_e = 3$ eV (mode 4). Then the normalized transport ($\tau$), ionization ($\sigma_2$) and recombination ($\rho_2$) rates for modes (1, 4) are (0.3, 0.3), (7 $\times 10^{-3}$, 2 $\times 10^{-3}$) and (2 $\times 10^{-9}$, 2 $\times 10^{-9}$), respectively.

Since the contribution from ionization and volume recombination in both MAP-II (unmagnetized) and DiPS (magnetized) is too small ($\sigma_1 = 6 \times 10^{-6}$–2.2 $\times 10^{-4}$, $\rho_1 = 1.7 \times 10^{-7}$–2 $\times 10^{-6}$, $\sigma_2 = 7 \times 10^{-4}$–2 $\times 10^{-3}$, $\rho_2 = 2 \times 10^{-9}$–2 $\times 10^{-6}$), comparing with that from transport ($\tau = 0.3$), the relation between the flow velocity with the ion current density ratio is almost the same as that without these contribution of atomic processes, i.e., the maximum change in ratio ($R$) with drift velocity ($M_\infty$) is about 0.4% for recombination case, and less than 2% for ionization case, which results less difference in the flow velocity in the logarithm form. So one can use analytic formulae of collisionless models for the un-magnetized (Eq. (4) with $\sigma_1 = 0 = \rho_1$) and magnetized cases (Eq. (5) with $\sigma_2 = 0 = \rho_2$ or [11]) such as $M_\infty = 2 (R - 1)/(R + 1)$, $\rho_i > a_p$, and $M_\infty = \ln(R/K)$, $\rho_i < a_p$, where $K = (2 + 2z)/(2 + z)$ + $z$ arctan(1 + $z$)$^{0.5})/(1 + $z$)^{0.5}$.

Fig. 2. Measurement of plasma density and electron temperature via single probe (SP), emissive probe (EP) and Thomson scattering (TS) at ionizing plasma ($P_n = 5.5$ mTorr). (a) Plasma density, (b) electron temperature. $M0 = $ mode 0, $M4 = $ mode 4.
Fig. 3. Normalized radial density profile of MAP-II (Solid legends) and DiPS (Open legends). Plasma size \((r_e \text{ (mm)})\) of MAP-II is 25 and for DiPS 15. First legends \(M\) means by magnetized and \(U\) by un-magnetized, the second \(Mx\) indicates mode \(x\).

Fig. 3 shows the variations of normalized plasma densities of MAP-II and DiPS. The peak density varies as \(1.8 \times 10^{13} \text{ cm}^{-3} \sim 4 \times 10^{12} \text{ cm}^{-3}\) with pressure. Decay of central density may be fitted into Eq. (1) as \(n_0/n_i = \exp[-(S_0^2/T_0 - S_i^2/T_i)mn_i^2z^2_p/4] \approx 4\), where \(z_p\) is the position where the fast-scanning probe is inserted (\(\approx 25\) cm), 0 and 4 indicate the normal mode (mode 0) and mode 4. Here \(T_e, T_i, n_{\infty}, n_i\) of two modes are given as \((6, 1 \text{ eV}), (0.6, 0.1 \text{ eV}), \ (1.5 \times 10^{13}, 7 \times 10^{12} \text{ cm}^{-3}), \ (7.7 \times 10^{12} \text{ cm}^{-3}, \ 6.2 \times 10^{13} \text{ cm}^{-3}\). This is a fitting if \(n_e\) is assumed to be \(\approx 10^{16} - 10^{17} \text{ cm}^{-3}\), which is the density at the surface of LaB6. From the normalized profiles, we can calculate the e-folding lengths \((r_e)\) approximately as 23 (mode 0), 25 (mode 1), 30, 44, and 58 mm (mode 4), which are inversely dependent upon the relaxation length \((R_0 = (\eta T/B_e^2z)^{1/2})\) in Eq. (2). Since \(\eta \propto T_e^{-3/2}, \ R_0 \propto \sqrt{\eta} T_e^{-3/4}\) for fixed \(B_0\). Because \(R_0\) is the relaxation length of \(N(\equiv n_e/n_0)\), it would be better use \(r_e(4)/r_e(0) = \sqrt{[R_0(0)/R_0(4)]}^{0.5}\). From given experimental data, \(r_e(4)/r_e(0) = 48/23 = 2.09\) and \([R_0(0)/R_0(4)]^{0.5}\) is as 1.36, and there seems to be a large difference. However, if we take the humped profile of mode 4 into consideration, the ratio of \(r_e\) becomes 1.43, which is close to the inverse of relaxation length. Radial density profile becomes broader with neutral pressure, indicating that the recombination makes the profile broader, or ionization does the profile steeper, which is consistent with the simple planar diffusion model [12]. The humped profiles at higher pressures in both devices are yet to be explained.

5. Conclusion

The overall change of density profile has been explained by a two-dimensional fluid model with uniform source in terms of volume recombination. To deduce the flow velocity from the Mach probe measurement, we introduced a new one-dimensional fluid model including ionization and recombination in addition to the transport source which reflects the two-dimensional effect both in the un-magnetized and magnetized flowing plasmas.

Recombination with neutral pressure affects the overall change of plasma density \((n_{\infty})\) and electron temperature \((T_e)\), yet it does not give large impact on the deduction of the local Mach numbers \((M(r))\) due to small values of both reaction rates. However, the absolute magnitude of flow velocity decreases with recombination (or neutral pressure) due to reduction of electron temperature. If neutral
pressure is very high as in the private regions or larger connection length of the flux tube ($L$) of existing and future toroidal divertor machines, contribution from recombination would become larger due to strong magnetic field ($L/a \gg 1$) and neutral pressure (strong $i-n$ collision) comparing linear machines, then it will affect the deduction of the Mach numbers, which is often calculated as supersonic, yet it might be subsonic in reality.

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