Effect of neutral pressure on the He plasma flow measurement in a linear device

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1. Introduction

To understand the edge conditions and to control the impurities and power deposition of fusion plasmas, measurement of rotation and axial flow velocities is essential. To measure the plasma flow, a Mach probe has been used in various fusion devices such as JET [1], Tore Supra [2], DIII-D [3], ASDEX-U [4], Alcator C-Mod [5], HL-1 [6], CDX-U [7], CASTOR [8]. A typical Mach probe is composed of two directional electric probes, located in opposite directions and separated by an insulator. Therefore, one of the conductors collect charges from the upstream side and the other collects charges from the downstream side along the magnetic field lines [9].

In the strongly magnetized plasmas ($p_i << a$), such as in the fusion plasmas, gyro-radii of ions are much smaller (typically, $p_i = 0.1$ mm for $B = 1$ T, $T_i = 50$ eV and $D_a$) than that of the probe size (typically, $a = 20$ mm for most medium sized tokamaks), so magnetized Mach probe theory are to be applied to deduce the Mach numbers [10–15].

For the unmagnetized plasmas ($p_i > a$), several models have been developed for the analysis of torch plasmas including theories of Langmuir [16], Johnson and Murphree [17], Hudis [18] and Chung [19]. For the mirror plasmas, those of Chung [19] and Hutchinson [20] have been adopted. Without the prevailing theory of unmagnetized Mach probe, a new model has to be developed for a general geometry and conditions such as including collisional sheath of presheath. Choi and Chung [21] developed an unmagnetized collisional Mach probe theory including ionization, charge and momentum transfer of ions for high pressure argon plasmas (~10 Torr).

In this work, we have generated weakly collisional helium plasmas with pressures in the range of 2–35 mTorr. We also measured the ratios of ion saturation currents in the axial and azimuthal directions using a vector Mach probe and tried to deduce the Mach numbers using collisional theory for the axial and azimuthal directions.

2. Experiments

Experiments were performed in the NAGDIS-II (NAGoya Diver-tor Simulator-II) device, which is shown in Fig. 1 [22]. The water
cooled vacuum chamber is 2.5 m in length and 0.18 m in diameter and equipped with 21 solenoidal magnetic coils. The electromagnet assembly produces a steady-state axial magnetic flux up to 1000 G, while it was 300 G in current experiment, the NAGDIS-II device generates plasmas by a DC plasma source, which consists of LaB₆ disc cathode with a 108 mm diameter, an intermediate hollow stainless steel electrode and a hollow copper anode. It is directly heated by a graphite heater with up to 2.1 kW for a He plasma. Typical plasma densities are up to 10¹³ cm⁻³ for the He plasmas. External heating of the cathode keeps the discharge power at 4 kW in experiment. Through high differential pumping, the neutral pressure of the source region is maintained around 500–800 mTorr, while that of the divertor simulation region (test region) is 2–35 mTorr. Such experimental conditions are shown in Table 1.

For measurement of the plasma density and electron temperature, a single electric probe was used. A vector Mach probe was developed for the measurement of flow variation. All of the measurements were performed at z = 1.72 m (the “down” Langmuir probe position, close to the large turbo pump). Fig. 2 shows the schematic views of a single probe and a vector Mach probe. The probe tip was constructed by a cylindrical molybdenum wire of 2.5 mm in length and 0.5 mm in diameter, while the diameter of the probe holder is 2.7 mm. From these probe geometries, the range of probe tip velocities. Mach number at 15 mTorr becomes 0.71 increasing from 0.63 at Pₙ = 5 mTorr, which is a much bigger jump (13% increase) even if we consider the decrease of electron temperature Tₑ = 6.9 eV (Pₙ = 15 mTorr) from 7.6 eV (Pₙ = 5 mTorr). We expected 5% increase of Mach number due to electron temperature decrease, so we need a collisional model to see whether this jump of Mach numbers is due to an incorrect calibration factor for the deduction of Mach numbers, or not.

The unmagnetized collisional Mach probe model can be derived by taking the moments of the Boltzmann equation. Chung developed a collisionless unmagnetized Mach probe theory for a one-dimensional equation from the Boltzmann equation [19]. By assuming Boltzmann electrons and adding a collision term such as ionization and taking the moments, a collisional model can be written as [21]:

\[
\frac{dV}{dz} + \frac{dn}{dz} = n_2 n + \frac{V_a}{a} (n_0 - n),
\]

3. Analysis

To analyze the data of the current ratios, we need a model, which has been expressed as \( R = I_{down}/I_{up} = \exp[KM_u] \), where \( M_u = V_u/\sqrt{(T_u + T_i)/m_e} \) and \( K \) is the calibration factor depending upon the magnetic field, \( T_u/T_i \) and the collision parameters. If one utilizes existing collisionless theories [20,23,24], the axial Mach numbers are deduced as in Fig. 6 in radial direction, and in terms of neutral pressures. A sudden jump of Mach numbers occurs at the condition near 15 mTorr, which does not seem to be physical, since there is no extra mechanism such as energy input to increase the flow velocities. Mach number at \( P_n = 15 \) mTorr becomes 0.71 increasing from 0.63 at \( P_n = 5 \) mTorr, which is a much bigger jump (13% increase) even if we consider the decrease of electron temperature \( T_e = 6.9 \) eV (\( P_n = 15 \) mTorr) from 7.6 eV (\( P_n = 5 \) mTorr). We expected 5% increase of Mach number due to electron temperature decrease, so we need a collisional model to see whether this jump of Mach numbers is due to an incorrect calibration factor for the deduction of Mach numbers, or not.

The unmagnetized collisional Mach probe model can be derived by taking the moments of the Boltzmann equation. Chung developed a collisionless unmagnetized Mach probe theory for a one-dimensional equation from the Boltzmann equation [19]. By assuming Boltzmann electrons and adding a collision term such as ionization and taking the moments, a collisional fluid model is expanded from Chung’s kinetic model. The collisional fluid model obtains a relation between the flow velocity and the ratio of the ion sheath current densities. The equations of the unmagnetized collisional fluid model can be written as [21]:

\[
\frac{dV}{dz} + \frac{dn}{dz} = n_2 n + \frac{V_a}{a} (n_0 - n),
\]
Fig. 2. Schematic view of probes (left: Single electric probe, right: Mach probe).

Fig. 3. Ion gyro-radii of He gas plasma for given pressures.

Fig. 4. Electron density and temperature for given pressures.

Fig. 5. Ratio of $J_{up}/J_{dn}$ for the axial and azimuthal direction, where each of $J_{up}$ and $J_{dn}$ are ion saturation currents at the upstream region and downstream region.
\[ \frac{dN}{dx} = M_0 - 2M - \sigma N(M_0 - 2M) + \rho N(M_0 - M). \]  
\[ \frac{dM}{dx} = \frac{(M^* + 1)\tau^* + \sigma (M^* + 1) + \rho M^*}{(1 - M^2)N^* + 1 - M^2}. \]

where \( \tau^* = (1 - N)\tau \) and \( M^* = M_2 - M_0M \). If the collision terms in Eqs. (6) and (7) are not neglected, the solutions of \( N(x) \) and \( M(x) \) cannot be analytical. However, \( N(M) \) can be given as Stangeby did [11] in his magnetized fluid theory like the following:

\[ \frac{dN}{dx} = \frac{(M_0 - 2M)N\tau + \sigma N^2(M_0 - 2M) + \rho N^2(M_0 - M)}{(M^* + 1)\tau + \sigma N(M^* + 1) + \rho NM^*}. \]  

4. Results and discussion

The numerical result of Eq. (8) is shown in Fig. 7, which is the relation between the calibration factor \((K)\) and the collision parameters such as \( \sigma \) (normalized ionization collision frequency) and \( \rho \) (normalized momentum collision frequency). One of \( \sigma \) and \( \rho \) were fixed and when the other value varies as in Fig. 7, the variation of \( K \) with \( \rho \) is bigger than the case of \( \sigma \), which indicates that the collisional
The effect of $r$ is more dominant than $\sigma$. Fig. 8 shows the variation of $K$ in terms of neutral pressures, neutral temperatures and ion temperatures. At higher neutral pressure, at more than 15 mTorr, $r$ is bigger than 0.03 and the effect of $r$ is dominant as in the case of Fig. 7. Therefore, in deduction of the Mach numbers, ionization does not have as much of an effect as the momentum collision in unmagnetized plasma. This indicates that ion-neutral collision is more important than electron-neutral collision (say, ionization).

Utilizing the results of Fig. 8, we deduce the radial variations of the axial Mach numbers with pressure, as shown in Fig. 9. We even check the same case as Fig. 6 with inclusion of collisional effect, which produces different results from Fig. 10. The result indicates that the rate ($\Delta M$) of overestimation using the collisionless model compared to those using the collisional model is about 120%, where $\Delta M(\%) = (M_{CL} - M_C) / M_C \times 100$, where $M_{CL}$ and $M_C$ are the Mach numbers of collisionless and collisional models, respectively. In applying the collisional model, one cannot see the sudden jump of the axial Mach number with pressure. If we calculate the absolute velocity by considering the electron temperatures, the change of the velocity drop would be more severe, so that the curve would be smoother with $r$. These results demonstrate the non-physical prediction of the collisionless model and the necessity of inclusion of the collisional effect to the analysis of Mach number in collisional flowing plasmas.

Azimuthal Mach numbers are also deduced using the present collisional model, which is shown in Fig. 11. These Mach numbers are not only very small, but also do not show consistent behavior which needs further future analysis due to abnormal behavior at the edge plasma. However, the azimuthal flows near the center seem to decrease around the center.
plasmas. Flow reversal is shown in higher pressure plasma. Although ion-neutral collision and ionization would produce reasonable Mach numbers for the higher pressure plasma, we may need other atomic processes such as charge exchange and recombination in detached plasmas.

5. Conclusion

Two Mach probes (one for the axial flow and the other for the azimuthal flow) have been used for the measurement of flow variation, and the ratio of upstream to downstream currents are measured by changing the neutral pressure for the deduction of flow velocity in a linear divertor simulator, NAGDIS-II (NAgoya Divertor Simulator-II). Helium plasma has been generated with flow velocity in a linear divertor simulator, NAGDIS-II (NAGoya Divertor Simulator-II). Helium plasma has been generated with a magnetic flux of 300 G by the pressure of 2.35 mTorr. Variation of azimuthal Mach numbers with pressure. Besides the effect of collisionality, we also observed that the flow reversal for $r > r_0$, $r_0$ is a radius of the plasma column at the edge plasma in the axial direction at higher neutral pressure, although the actual implications of this abnormal behavior should be discussed at a separate place in near future.

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