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A General Analysis of Electric Probes: Deduction of Mach Number and Plasma Density in Complex Plasmas.

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A single electric probe is used to deduce the electron temperature and plasma density, and a Mach probe (MP) is for the deduction of Mach number. However, the deduced plasma density or Mach numbers would be severely different from those by collisionless models if plasma were in the complex conditions with magnetic field, various atomic processes would be necessary by including these parameters. A typical MP is composed of two directional electric probes located at opposite sides of an insulator, which is mostly used as a parallel MP, but there are other MP's such as perpendicular MP (PMP), rotating (Mach) probe (RP), Gundestrup probe (GP), and visco-MP (VMP), depending upon the shape of the probe holder, location of different probes, or the way of collecting ions. Existing theories of parallel Mach probes in un-magnetized and magnetized flowing plasmas are introduced in terms of kinetic, fluid and particle-in-cell models along with key physics and comments. Experimental evidences of relevant models are shown along with validity of related theories, which have been partially performed in the linear divertor simulators. Deduced data of tokamak experiments are to be re-evaluated especially for the collisional cases. Error analysis is to be given. For the probes other than the typical parallel Mach probe (MP), the relation between the ratio of ion saturation currents and normalized drift velocity ($M_\infty = v_d/\sqrt{T_e/m_i}$) can be expressed as a combination of the functional forms: Exponential and/or polynomial form of $M_\infty = v_d/\sqrt{T_e/m_i}$ for PMP; Incident angle of magnetic field, cross-field flow velocity and ratio(R) of ion saturation currents of MP for RP and GP; Two R's of separate two MP's for VMP. Collisions of ion/electron/neutrals, asymmetries of ion temperatures and existence of hyper-thermal electrons, existence of ion beam, supersonic flow and negative ions can affect the deduction of the flow velocities by MP.

1.Introduction

Although the current issue of fusion science is to check the engineering feasibility of fusion energy via ITER (International Tokamak Experiment Reactor), the basic scientific problems are still to be understood, among which the problems of plasma-material interactions via the edge localized modes (ELM) and flow related phenomena, and these are very similar to the analyses of the various electric probes.

Generally using collisionless probe theories, a single electric probe is used to deduce the electron temperature and plasma density, and a Mach probe is for the deduction of Mach number. However, the deduced Mach numbers or density would be severely different from those by collisionless models if plasma were in the complex conditions with magnetic field, various atomic processes would be necessary by including these parameters.

A Mach probe (MP) is an electric probe system to deduce the plasma flow velocity from the ratio of the ion saturation currents. Generally, a typical MP is composed of two directional electric probes located at opposite sides of an insulator, which is mostly used as a parallel MP, but there are other MP's such as perpendicular MP (PMP), Gundestrup probe (GP) or rotational probe (RP), and visco-MP (VMP), depending upon the shape of the probe holder, location of different probes, or the way of collecting ions.

From this brief review, existing models for the deduction of flow velocity and density are to be summarized in the collisional plasmas and compared with those in the collisionless ones. Experiments in the simulated divertor devices will be given using not only electric probes but alos laser-aided diagnostics.

2.Models

For the parallel MP, the relation between the ratio of the upstream ion saturation current density (J_{up}) to the downstream (J_{dn}) and the normalized drift velocity ($M_\infty = v_d/\sqrt{T_e/m_i}$) of plasma has generally been fitted into an exponential form ($R = J_{up}/J_{dn} \approx \exp[KM_\infty]$). For the GP or RP, with oblique ion collection, $R = \exp[K(M_\parallel - M_\perp \cot\theta)]$, where K is a calibration factor ~ 2.4, $M_{\parallel} = M_{\infty}$, $M_{\perp}$ is normalized perpendicular flow to the magnetic field, and θ is the angle between the magnetic field and probe surface. Normalized drift velocity of the flowing plasmas is deduced from the ratio (R_m) measured by an MP as $M_{\infty} = \ln[R_m]/K$. Existing theories of Mach probes in un-magnetized and magnetized flowing plasmas are introduced in terms of kinetic, fluid and particle-in-cell models or self- and self-similar methods along with key physics and comments. For the probes other than the typical parallel Mach probe (MP), the relation between the ratio of ion saturation currents and M_{∞} can be expressed as a combination of the functional forms: Exponential and/or polynomial form of M_{∞} for PMP; Two R 's of separate two MP's for VMP. Collisions of ion/electron/neutrals, asymmetries of ion temperatures and existence of hyperthermal electrons, existence of ion beam, supersonic flow and negative ions can affect the deduction of the flow velocities by MP. Since the ion saturation current density is dependent upon the magnetic field, collisionality and charge states of the plasmas, the deduced density of the unperturbed plasmas should be changed accordingly, if one-directional electric probe is used. If one uses a spherical, cylindrical or planar probe exposing two sides (or all sides) of the probe to the plasma, flow effect could be canceled while other effects is still valid.

3. Experiment

To establish and confirm the method of deduction of Mach numbers and densities, one needs not only to develop the physical model but also to verify the model by the independent diagnostics such as laser-induced fluorescence (LIF) and laser Thomson scattering (LTS) methods. Proper provision of electron temperature is the sufficient condition for the deduction of absolute flow velocity for all flow measurement, especially for the case of collisional plasmas, since almost all the existing probe theories are for the case of collisionless and stationary plasmas. To resolve these complex problems, LIF and LTS methods are to be introduced with electric probe measurement for the measurement of plasma flow and plasma parameters in the weakly magnetized collisonal plasmas generated at the Divertor Plasma Simulator (DiPS). Plasma is generated by LaB6 cathode discharge with magnetic field of 500 - 2000 Gauss. For the wide range of collisionality, plasma density $(n_e = 10^{11} \sim 10^{14}\ cm^{-3})$ and electron temperature $(T_e = 2 \sim 9\ eV)$ are measured by a single electric probe using a conventional collisionless probe theory. To check the effect of collisionality and magnetic field on the flow, density and temperature, various electric probes (single, triple and Mach probes) and laser (LIF and LTS) systems have been installed. Based upon previous modeling of the neutral effect, ion-neutral collision is considered as most dominant effect on the change of ion momentum among various atomic effects such as recombination and ionization. Variations of Mach number and plasma density with collisionless models are to be compared with those by collisonal models for different pressures which indicates that the Mach numbers by the collisionless model are overestimated by 50 % - 100 %. Data of Mach probe has been compared to those by LIF and those of SP are compared to those by LTS, and data of various linear divertor simulators such as MAP-2 of University of Tokyo and NAGDIS-2 of Nagoya University have been shown to compare with those of DiPS. Deduced plasma densities with flow and pressure are also to be presented.

4.Summary

Single probe and Mach probes(Parallel Mach probe(MP), perpendicular MP, rotating Mach probe, Gundestrup probe, and visco-MP) are analyzed by comparing existing theories in un-magnetized and magnetized flowing plasmas in terms of kinetic, fluid and particle-in-cell models along with key physics and comments. Experimental evidences of relevant models are shown along with validity of related theories. Deduced data of tokamak experiments are re-evaluated for the collisional edge conditions.

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