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Large amplitude of electrostatic waves associated with magnetic field in divertor plasmas

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Abstract

The characteristics of divertor plasmas are investigated dynamically using a one-dimension-in-space and three-dimension-in-velocity particle-in-cell Monte Carlo collision simulation technique, and it is found that a strong magnetic field with a large incident angle of the magnetic field on the divertor plate gives rise to a hybrid electrostatic wave, which is made of waves with distinctive frequencies. These waves are then identified as being related, respectively, to the lower hybrid wave mode and electron Bernstein wave modes. The wave associated with the lower hybrid wave mode dominates the potential fluctuation, modulates the incident energy flux onto the divertor plate in a large magnitude and causes the wave-like variation of impurity production from the carbon-based divertor plate.

(Some figures in this article are in colour only in the electronic version)
Figure 1. Schematic of the simulation system. The magnetic field is incident on the divertor plate with an angle \( \theta \) against the surface normal. The spacing between the divertor plate and the plasma bulk is 3 mm.

have been carried out on the transition layer of nuclear fusion devices using a one-dimension-in-space and three-dimension-in-velocity (1d3v) PIC-MCC model [7–11].

We apply in this study a 1d3v PIC-MCC model [12] to investigate the effects of magnetic field on the characteristics of the plasma sheath next to the divertor plate. The aim of this study is to provide helpful physical information for researchers to design divertors. Our simulation results show that the magnetic field incident on the divertor plate gives rise to the formation of a hybrid electrostatic wave. The wave is a superposition of mainly two types of waves, which can be related to the lower hybrid mode and the electron Bernstein modes. The electrostatic wave modulates the energy flux of the incident ions onto the divertor plate, which has a direct influence on the impurity production.

In this study, the simulation tracks five types of charged macroparticles (representing, respectively, e, H+, H−, H_2^+ and H_3^+) while background neutrals—hydrogen molecules—are assumed to be temporally independent and spatially uniform for simplification. In the simulation we consider five types of collisions for electrons (elastic scattering, excitation, ionization, dissociation and recombination) and four types of collisions for ions (charge exchange, elastic scattering, vibrational excitation and mutual neutralization). Considering the high densities of electrons and ions in divertor plasmas, we also include the Coulomb collisions [13] of e–e, e–H+ and H+–H+ into the model. A total of 32 collision processes are considered in this study, for which the details can be seen in [10, 11, 14–16]. The Monte Carlo collision (MCC) technique is used to handle these collision processes.

The schematic of the simulation domain is given in figure 1. The divertor wall serving as one of the boundaries is electrically grounded, and the edge of the bulk plasma is located at the other side of the simulation domain. At the edge of the bulk plasma, a constant plasma density, a constant plasma temperature and electrical neutrality are always maintained. This boundary condition ensures that the bulk plasma potential is calculated self-consistently. The details of the technique that we have borrowed partially are explained in [17]. Another commonly used boundary condition, in which the electric potentials at both target and bulk plasma are fixed, is not employed. We start the simulation from a uniform distribution of electrons and protons \( n_p = 1.0 \times 10^{19} \, \text{m}^{-3} \). Their initial velocities are sampled from a Maxwellian distribution, with a temperature of 10 eV, and the gas pressure is 2.5 mTorr (around 0.3 Pa). The simulation time step is \( 2.0 \times 10^{-13} \, \text{s} \). The number of traced electrons and protons is at least \( 10^6 \), respectively, and the number of traced H−, H_2^+ and H_3^+ is about \( 2.0–3.0 \times 10^5 \), respectively. The spacing between the divertor plate and the boundary of the bulk plasma
is chosen to be 3 mm (the spacing is about 600 Debye lengths and each Debye length $\lambda_D$ is around 5 $\mu$m). The magnetic field line is oblique to the divertor plate, making an angle $\theta$ with the surface normal, and the magnetic strength is kept constant in the simulation domain. The divertor plate is assumed to be made of a carbon-based material, which is supposed to be the primary material for the divertor plate in ITER.

In modern fusion devices, the divertor plates are commonly designed to make them easily form a large angle with the magnetic field to reduce the peak heat flux onto the divertor plate. Hence, we are mainly interested in the cases for the large incident $\theta$. Figure 2 displays how the densities of electrons and ions vary with the distance from the divertor plate with the magnetic field incident at an angle 85° and its strength being 1.5 T. As seen, either electron density or $H^+$ density is overwhelmingly higher than that of $H_2^+$ or $H^-$ ($H_3^+$ density is even much lower, we ignore it in figure 2). The whole sheath region is usually divided into the Debye sheath (DS) and the magnetic presheath (MP). The former is the region directly next to the wall where the net space charge exists, while the latter linking the former contains negligible net charge, i.e. the quasi-neutrality condition holds. The boundary between the MP and the bulk plasma is arbitrarily defined as the location where the potential is equal to 95% of the potential in the bulk plasma. Thus, we can estimate from the information provided in figure 2 that the thicknesses of DS and MP are roughly 24 $\mu$m and 1.2 mm, respectively. Compared with the MP sheath, the DS is very narrow, about 5$\lambda_D$. The major part of potential fall drops on the MP. These simulation results are in agreement with theoretical predictions [18].

The temporal variation of the potential at a distance of 1.5 mm from the divertor plate is shown in figure 3(a), with the same parameters in figure 2. Clearly, distinct electrostatic waves exist in the simulation domain. We filter out the high frequency components and draw the low frequency components as shown in figure 3(a). It can be seen that the low frequency components are a relatively smooth wave packet, accounting for a major percentage of the
Figure 3. (a) Evolution of the plasma potential being measured at 1.5 mm away from the divertor plate. (b) Result after applying fast Fourier transform to the data of (a). The magnetic field is incident on the divertor plate at an angle $\theta = 85^\circ$, and its strength is 1.5 T.

The original potential wave, and the maximal amplitude of the waves is about 150 V. To analyze the component of the waves in depth, we apply the Fourier transform to the time-dependent wave, and present the corresponding result in figure 3(b). The result indicates that the wave is made of waves of different ranges of frequencies. The low frequency component is also a superposition of waves of different frequencies, which center on the frequency 2.3 GHz (we refer to the frequency as $F_L$). In contrast to the peak of the spectrum magnitude at the frequency $F_L$, there are a series of small spectrum peaks in the high frequency region. To see them clearly, we present a zoom of these peaks in the inset graph of figure 3(b). The first three wave packets in the high frequency region center on the frequencies of 69 GHz, 128 GHz and 189 GHz, respectively. (We name these peak frequencies for convenience as $F_{1H}$, $F_{2H}$ and $F_{3H}$. See the legends in the inset graph of figure 3(b).)

To characterize the wave in the low frequency $F_L$, we examine the variations of its peak frequency values by varying the incident angle and the strength of the magnetic field. Figure 4(a) shows the curve of the frequency value $F_L$ versus the incident angle of the magnetic field when the magnetic strength is fixed at 1.5 T. We can see that the frequency $F_L$ decreases as the angle $\theta$ increases, and approaches a value of 0.60 GHz when the angle approaches 90°. When the magnetic field is perpendicular to the electric field, the frequency of the ‘lower hybrid wave’ is given theoretically by [19]

$$F_{lh} = \frac{1}{2\pi} \sqrt{\frac{1}{\omega_{ci}^2 + \omega_{pe}^2} + \frac{1}{\omega_{ce} \omega_{ci}}}^{-1},$$  \hspace{1cm} (1)$$

where $\omega_{ci}$ and $\omega_{ce}$ are the ion cyclotron angular frequency and the electron cyclotron angular frequency, respectively, and $\omega_{pi}$ is the ion plasma angular frequency. With the parameters used in the simulation, we obtain $F_{lh} \approx 0.55$ GHz from equation (1), while the value of $F_L$ from
the simulation at $\theta = 90^\circ$ is 0.60 GHz. To further verify the argument, we evaluate the value of $F_L$ as a function of magnetic field from the simulation when the angle $\theta$ is 90°, and the corresponding value from equation (1), which are shown in figure 4(b). The simulated results are in very good agreement with theoretical results. We can firmly relate the $F_L$ to the lower hybrid frequency.

Now we characterize the peak frequency values in the high frequency regime as shown in the inset graph of figure 3(b). First we may note that the frequencies $F_{1H}$, $F_{2H}$, $F_{3H}$, ... $F_{nH}$ approximately form an arithmetic sequence. Recalling the electron Bernstein modes when the wave propagates perpendicularly to the magnetic field, we have the following dispersion relation from the linear kinetic theory [19]:

$$1 - \frac{2\alpha_e^2}{k^2 \lambda_D^2} \sum_{n=1}^{\infty} \frac{n^2 I_n(\lambda)}{(\omega^2 - n^2 \omega_{ce}^2)} = 0,$$

where $\omega$ is the electron Bernstein angular frequency, $k$ is the wave vector, $\lambda_D$ is the Debye length, $I_n$ is the modified Bessel function and $\lambda$ equals $k^2 k_B T / m \omega_{ce}^2$ ($m$ is the mass of electron.
and $T$ is the temperature). From equation (2), we can compute the dispersion curves for electron Bernstein modes. In figure 5(a), the asterisks represent the results obtained from the simulation, and the inset graph shows the Bernstein mode’s theoretical results. In figure 5(b), we present the simulated values of $\omega/\omega_{ce}$ as a function of the magnetic field strength, and the corresponding theoretical results from equation (2) in the inset graph. Figure 5 indicates that the simulated results are in qualitative agreement with those from the linear kinetic theory for electron Bernstein modes. However, discrepancies between simulated and theoretical results exist. Roughly, our calculated values are at most 50% larger than the corresponding values predicted by the theory in the whole range of $\lambda$. These discrepancies may have resulted from the linear approximation used in the theory.

Now we look at what effects these electrostatic waves have on the erosion of divertor plates. As shown in figure 3(a), we can see that the amplitude of the electrostatic wave is approximately 150 V at the magnetic field strength of 1.5 T. This implies that the electrostatic wave can modulate the incident energy flux onto the divertor surface in a large magnitude (against the average kinetic energy of initial ions of 15 eV). As shown in figure 6(a), the energy flux of ions striking the divertor plate therefore has wave characteristics. This finding has a very important bearing on the erosion of the divertor plate since the energy and density of the incident ions directly determine the impurity production. To give a qualitative estimation, we assess the extent to which the electrostatic wave affects the erosion yield of a carbon-based divertor plate by the energetic ions. Taking the analytical formulae of physical sputtering and chemical erosion [20], we incorporate a surface-emitted impurity module in the PIC-MCC model. The corresponding results are presented in figure 6(b). We can see that the net erosion rate also has wave characteristics—when the energy flux is high, the erosion yield of impurity is high. This suggests that the erosion yield is not temporally uniform. The implication of these
results may be important for a fusion device: the impurity production has a certain pattern, which will then have an influence on the impurity migration and plasma characteristics.

In summary, we employ the PIC-MCC simulation to analyze the effects of magnetic field on divertor plasmas. Simulated results show that the existence of a magnetic field in the divertor plasmas gives rise to a hybrid electrostatic wave. The hybrid electrostatic wave is the superposition of a series of waves of different frequencies. We can categorize them into two types of wave modes—the lower hybrid wave mode and the electron Bernstein wave modes. The plasma density and velocity distribution fluctuations in the magnetized plasma are highly likely to be the main driving mechanism of exciting the waves. Similar results on waves in divertor plasmas, to the best of the authors’ knowledge, have not been reported. The variation of potential next to the divertor plate due to the electrostatic wave modulates the energy flux of the incident ions onto the divertor plate. Variations in the energy flux of incident ions directly affect the impurity production of the carbon-based divertor plates. These findings may be significant for divertor plasma characteristics and impurity migration.

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