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Simulation Study for New Diagnostic Method of Ion Energy Distribution in Edge Plasma

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Abstract

A new diagnostic method to measure the energy distribution of ions in the edge plasma using ion reflection on the solid surface is proposed. The major part of reflected particles is neutral, and they include the information of the energy distribution of the incident ions. Thus it is possible to obtain the energy distribution of the incident ions by measuring the energy distribution of the reflected particles. For this propose, the time-of-flight method (TOF) is suitable for its sensitivity in relatively low particle energy. The computer simulation for this measurement is performed by using Monte Carlo code TRIM.SP. including the effects of the gyro-motion and the sheath potential.

Keywords:

ion energy distribution, edge plasma, ion reflection, sheath potential, TRIM.SP. code, time-of-flight

1. Introduction

In fusion experimental devices, the edge plasma is believed to play important roles relating to the core plasma confinement. Therefore the edge plasma parameters, such as the density, the temperature, the electrostatic potential *etc.*, are necessary for understanding the physics of plasma confinement. In the edge plasma, the ion temperature is relatively low, and it is difficult to apply the ion temperature measurement technique used for the core region.

Ion reflection from plasma facing components is well known as one of the mechanisms of particle recycling. The reflection properties, such as the energy distribution of the reflected particles, depend on the incident ion species, energy, angle, the target material and so on [1]. It means that the energy distribution of the incident ions can be obtained from that of the reflected particles ideally if other parameters are known. Ion beam experiments show that several tens percent of the incident particles are reflected, and the state of the reflected particles is almost neutral in the incident energy range of less than 1 keV [2]. So the neutral energy analyzer using time-of-flight (TOF) method with relatively good sensitivity for low energy neutral particles (> 10 eV) [3] can be used to measure the energy distribution of the reflected particles.

Our proposal is to use the TOF method for measuring the energy distributions of the reflected particles from a small target plate installed in the edge plasma, and to obtain the energy distribution of the ions in that region. This method has fine spatial resolution corresponding to the size of installed small target, and is superior in getting the local ion energy

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distribution to usual TOF method which measures the charge exchange neutral particle from the core plasma.

For this method, the Monte Carlo simulation code TRIM.SP. [4] is utilized to obtain the energy distribution of the incident ions from that of the reflected particles. The effect of the gyro-motion of the ions and sheath potential are in consideration.

2. Computer Simulation

2.1 Modeling of incident ion distribution

The simple model for the calculation is shown in Fig. 1. The direction of magnetic field is assumed to be normal to the target plate. There are three regions in the model as follows; 1) the plasma region (hydrogen plasma), 2) the sheath region and 3) the target plate (tungsten target is assumed). To consider the simplest case, in the plasma region, the energy distribution of ions is assumed to be isotropic three- dimensional Maxwellian. In the sheath region, ions are accelerated by the sheath potential, and assumed to be collisionless. The target surface is considered to be flat and pure. The incident ion flux from the plasma to the sheath region can be expressed as below;

$$\Gamma(T_i) = \frac{1}{2\pi}\left(\frac{m_i}{kT_i}\right)^2 \int_{-\infty}^{\infty} \mathrm{d}v_\perp \int_0^{\infty} \mathrm{d}v_\parallel \, v_\parallel \exp\left(-\frac{m_i\,(v_\perp^2 + v_\parallel^2)}{2kT_i}\right) \quad (1)$$

where k is the Boltzmann's constant, m_i is the ion mass, $v_\parallel$ *and* $v_\perp$ is the parallel and perpendicular velocity, respectively. The azimuthal symmetry is assumed for the reflected particles. The normalized flux to the sheath region is below;

$$d\Gamma\,(E, \theta, T_i) = \frac{E}{(kT_i)^2}\sin 2\theta \exp\left(-\frac{E}{kT_i}\right)\mathrm{d}E\mathrm{d}\theta \quad (2)$$

where E is the kinetic energy of particles, $E = m_i(v_\perp^2 + v_\parallel^2)/2$, and θ is the pitch angle in plasma region. In the sheath region, the energy distribution becomes shifted Maxwellian due to the acceleration by the sheath potential $q\Phi_s$, which is considered to include the presheath potential in this paper. The incident ion energy E_t to the target can be obtained by $E + q\Phi_s$. The incident angle Θ of ions to the target in this region can be obtained using the pitch angle θ, ion kinetic energy and sheath potential $q\Phi_s$ as below;

$$\tan\Theta = \frac{\sqrt{E}\sin\theta}{\sqrt{E\cos^2\theta + q\Phi_s}} \quad (3)$$

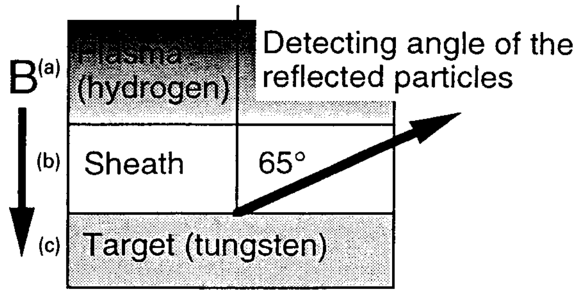

Fig. 1 Calculation model, made of three component; (a) plasma region, (b) sheath region, (c) target region.

The incident ion flux to the target can be obtained as below;

$$\mathrm{d}\Gamma\,(E_t, \theta, T_i, \Phi_s) = \begin{cases} \dfrac{E_t - q\Phi_s}{(kT_i)^2}\sin 2\theta \exp\left(-\dfrac{E_t - q\Phi_s}{kT_i}\right)\mathrm{d}E\mathrm{d}\theta & (E_t \geq q\Phi_s) \\ 0 & (E_t < q\Phi_s) \end{cases} \quad (4)$$

The incident angle and the ion energy flux of ions to the target are given by Eqs. (3) and (4), respectively. The larger sheath potential decreases grazing incident angle particles.

2.2 Calculation

Calculation of the energy and angular distribution of the reflected particles is done as follows; 1) The incident flux $d\Gamma\,(E_t, \theta, T_i, \Phi_s)$ from Eq.(4) is divided into rectangle whose width is 10 eV (E_t) and 5° (θ). 2) The energy and angular distributions of reflected particles are calculated for these rectangle considered to be mono energy, and one angle represented their center value. 3) The distribution of reflected particles and direction are reconstructed from the results of 2).

2.3 Results of Calculations for incident atomic ions

For the focus of this calculation in the edge plasma, the incident ion temperatures in this calculation are in the range of 30 to 90 eV. The sheath potential is varied from 0 to 3 kT_i. The energy distribution of the reflected hydrogen atoms for kT_i=50 eV and various sheath potential, and for mono energetic (E_0=150 eV) incident ions are also shown in Fig. 2 (a) where E_0 is the incident energy to the target. In the case of the mono energetic incident ions, the reflected atoms' energies, E_{ref}, are below incident ion energy (E_0) and have the peak close to E_0. On the other hand, in the

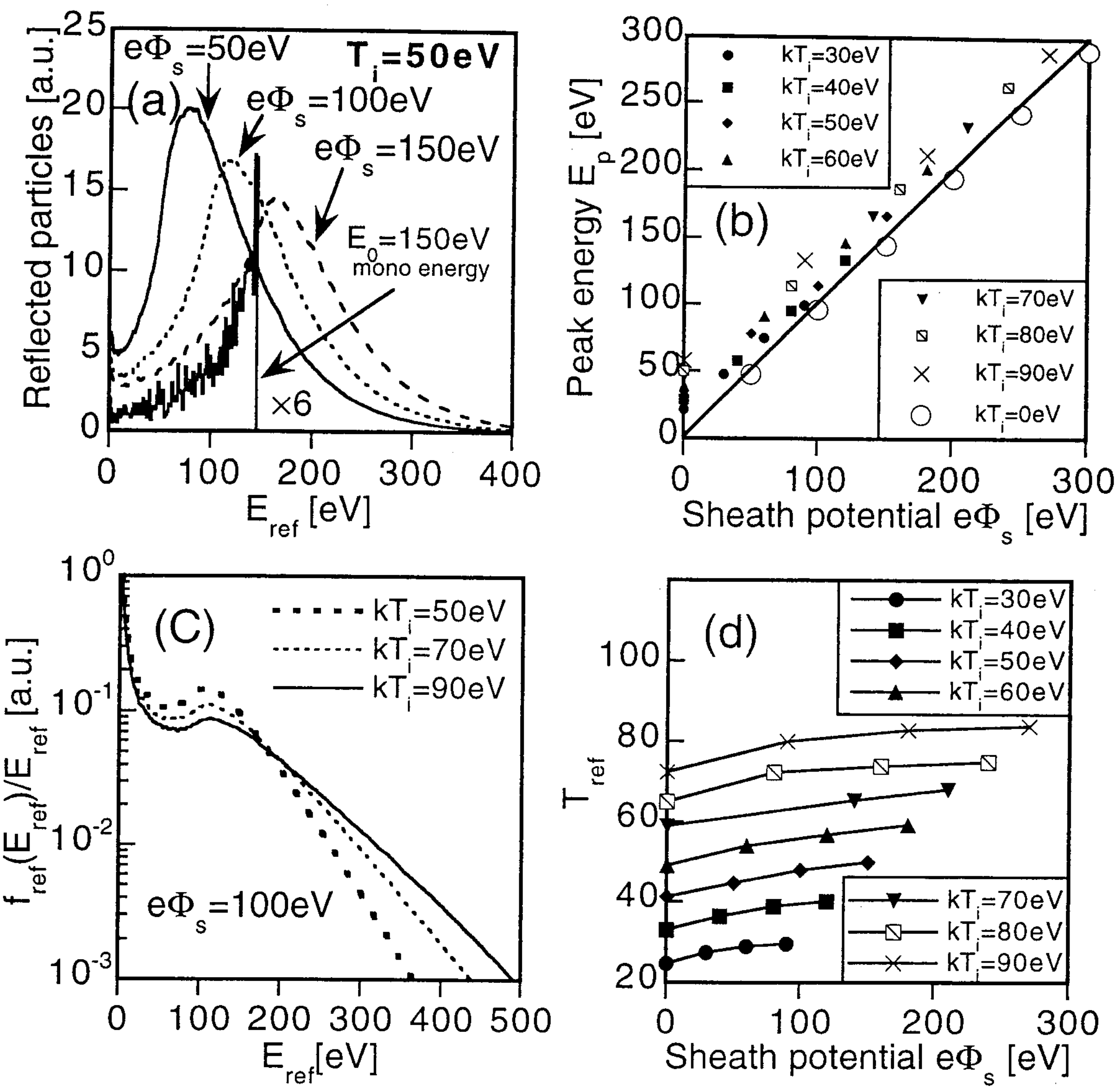

Fig. 2 (a) The energy distribution of the reflected hydrogen atom for various sheath potential, and mono energy case, (b) The peak energy, E_p, for various sheath potential, and the mono energy case, (c) dependence on T_{ref} for various sheath potential, (d) T_{ref} for various incident ion temperature kT_i and the sheath potential.

case of the finite kT_i, the energy distribution of reflected atoms spreads to higher energy region. The peak energy, E_p, in case of the finite kT_i shifts to higher with higher the sheath potential. The relation of E_p and sheath potential is shown in Fig. 2(b) with various kT_i. It is shown that E_p do not depend on kT_i and have linear dependence on the sheath potential. Therefore, the sheath potential can be obtained from the energy distribution of the reflected atoms.

In the energy range of $E_{ref} > E_p + 2kT_i$, the energy distribution of reflected particles can be approximated below;

$$\frac{f_{ref}(E_{ref})}{E_{ref}} = A \exp\left(-\frac{E_{ref}}{T_{ref}}\right) \tag{5}$$

where f_{ref} is the distribution function of the reflected particles. A is a constant and T_{ref} is the constant representing f_{ref}. This is shown in Fig. 2(c). The straight line is obtained in the range of high energy. From this slope, the T_{ref} can be estimated. Figure 2(d) shows the T_{ref} value corresponding to kT_i=30 to 90 eV for various sheath potentials. They depend on the sheath potential weakly. It means that the incident ion temperature can be obtained from the T_{ref} value.

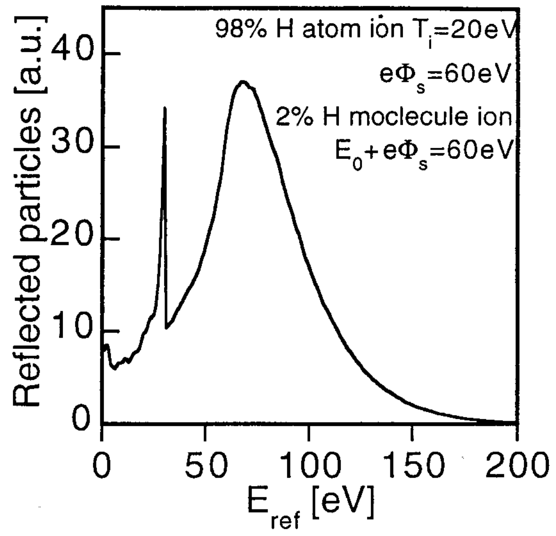

Fig. 3 The energy distribution of the reflected hydrogen atomic and molecular ion corresponding to kT_i=20 eV, $e\Phi_s$=60 eV and α=98%.

2.4 Results of calculation for incident atomic and molecular ions

In the high recycling divertor plasma, low electron temperature (~10 eV) is achieved. In such a plasma, the hydrogen molecular ions can be exist. Therefore, the energy distribution must be evaluated for mixed plasma (atomic and molecular ions). When neutral hydrogen molecule come into the plasma, and is ionized by the collision with electron. The molecular ion is dissociated by the collision with the electron in the short time. For example, kT_e=10 eV and $n_e=10^{19}$ m^{-3}, the life time as hydrogen molecular ions is ~1μs. Therefore, the ion temperature of the hydrogen molecular ion is low, and it can be assumed to be zero. Thus the molecular ions' energy is determined by the sheath potential. The incident angle to the target is normal. The mixing flux $\Gamma_{\rm she}$ to the sheath region is expressed below;

$$\Gamma_{\rm she} = \Gamma_{\rm atom} + \Gamma_{\rm mol} = \alpha\Gamma_{\rm she} + (1-\alpha)\Gamma_{\rm she} \quad (6)$$

where $\Gamma_{\rm atom}$ and $\Gamma_{\rm mol}$ are the incident flux of atomic and molecular ions and α is the mixing ratio of atomic ions, respectively. As the first approximation, the injection of a molecular ion corresponds to that of 2 atoms with half energy. The energy distribution of the reflected particle is shown in Fig. 3 in the case of kT_i=20 eV, $e\Phi_s$=60 eV and α=98%. The first peak in Fig. 3 is the contribution of the molecular ions. From this result, it is possible to separate the atomic and molecular ions' contribution easily. Thus, the estimation of E_p and $T_{\rm ref}$ discussed above is rarely varied even when the molecular ions are exist in edge plasma.

3. Summary

New diagnostic of the ion energy distribution using ion reflection on solid is proposed. The energy distribution of the reflected hydrogen atoms were calculated using Monte Carlo code TRIM.SP. taking the effects of the gyro-motion of the incident ions and the sheath potential into account. The results show that the sheath potential formed in front of the target and the incident energy distribution can be deduced from the energy distribution of the reflected atoms of incident ion. It means that electron and ion temperature can be obtained simultaneously by this diagnostic method. In the case of the hydrogen plasma which includes the molecular ions, it is possible to separate to each contribution.

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