Studies of Charge Separation Characteristics for Higher Density Plasma

in a Direct Energy Converter Using Slanted Cusp Magnetic Field

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(Received: 30 October 2009 / Accepted: 15 February 2010)

In an advanced fusion, fusion-produced charged particles must be separated from each other for converting their kinetic energy to electricity. The CUSPDEC performs this function of separation and direct energy conversion of thermal components. This paper summarizes experimental works by using a small scale experimental device and these results as charge separation characteristics by slanted cusp magnetic field. When the incident plasma is low-density, the dependences of the separation efficiency on magnetic field strength, energy of electrons, and gradient of the field line are explained by the theory based on a single particle motion. In high density plasma, however, this theory cannot always be applied due to a self-induced field. In the experiment, as plasma density became higher, separation capability of the charged particles became lower although the efficiency of separation was improved with some extent by using slanted cusp magnetic field. The modification of the theory applicable for high density plasma and the effective factor corresponding to separation efficiency was required in the following research.

Keywords: advanced fusion, direct energy conversion, CUSPDEC, charge separation, slanted cusp magnetic field, plasma density

1. Introduction

The D-³He fusion power generation is expected to be clean, sustainable, and high-efficiency power generation system: it has been reported that a large amount of ³He exists on the surface of the moon, and direct energy conversion can be applied as high energy neutrons are hardly created and most of the fusion energy is carried by charged particles in the reaction. Momota et al. proposed a conceptual design of a power plant of a D-³He fusion reactor based on a field reversed configuration (FRC) [1]. In the designed system, two types of direct energy converters were employed: cusp direct energy converter (CUSPDEC) and traveling wave direct energy converter (TWDEC). The main tasks of the CUSPDEC are separation of charged particles of the incident plasma and direct energy conversion of thermal ions. In the CUSPDEC, negatively biased grids for electron elimination are excluded, so the efficient charge separation can be achieved.

The authors proposed applying a slanted cusp magnetic field to CUSPDEC to separate charged particles more efficiently and a small scale experimental device was constructed. Low energy plasma from small plasma sources and end-loss flux of GAMMA 10 whose energies were from a few tens of eV to a few keV were used in the experiment, and efficient separation of charged particles and direct energy conversion were demonstrated [2, 3].

Orbit calculation of electrons and ions in the device was also performed to analyze those experimental results theoretically [4]. According to both experimental results and theoretical analyses, separation of the charged particles can be explained well by a single particle motion based on calculations of Störmer potential when the incident plasma is low-density [5]. In high density plasma, however, the motion of charged particles is expected to show collective behavior, so the applicability of the theory should be examined. In the previous experiments, the density of the objective plasma is in the order around 10^{12} m⁻³, and this is less than that expected in an actual reactor of 10^{16} m⁻³. The examination of charge separation in high density plasma is necessary for both experiments and theory.

In this paper, we describe the results of charge separation experiment using our experimental device by employing not only a microwave plasma source but also a helicon wave excited plasma source. Plasma density used in the experiment is from 10^{12} m⁻³ to 10^{15} m⁻³. The results are summarized and discussed as charge separation characteristics by slanted cusp magnetic field.

The organization of the paper is as follows. In Sec.2, the experimental device, the basic principle of the charge separation based on the single particle motion, and the way of evaluation of separation capability are explained. In Sec.3, experimental data of separation characteristics are presented and discussed with summarizing as a function of the scaling parameter by dividing into cases of low and high density plasmas. Conclusions are given in Sec.4.

2. Experimental setup

2.1. CUSPDEC experimental device

The CUSPDEC experimental device is schematically shown in Fig.1. The device consists of three magnetic coils, four particle collector plates, and a probe.

The coil currents I_A and I_C , which have the same direction and value (= I_{AC}), create a guide magnetic field. The coil current I_B is in opposite direction with I_{AC} and has a different value. A plasma source is settled in the left-hand side of the coil C, and charged particles are guided to the center of the device (between coil A and B) where a cusp field is created. The field line curvature can be varied from normal to slanted cusp fields by adjusting the coil currents of I_{AC} and I_{B} .

At the line cusp side, electron collectors Plate 1 and 2 are settled, and ions collectors Plate 3 and 4, which are usually parallel-connected electrically, are located at the point cusp end. A Langmuir probe located at the entrance is to measure electron density and temperature of the incident plasma.



Fig.1 CUSPDEC experimental device.

The typical particle motion is explained in Fig.2. The field lines for $I_{AC} = 30$ A and $I_B = 20$ A are shown together with cross sections of coils A, B and particle collector plates 1-4.

The incident plasma comes from $z \le -20$ cm. The electrons are deflected along the field line to the line cusp. These electrons are collected by the particle collectors located at the entrance line cusp (Plate1) and the exit of line cusp (Plate2). On the other hand, thermal ions are slightly deflected and separated from electrons. They reach the electrodes located at the inner point cusp (Plate3) and the outer point cusp (Plate4). This is because the Larmor radius of ions is far larger compared with that of electrons. The radii of coils A and B are different from each other, change of relative coil currents $I_{\rm B} / I_{\rm AC}$ varies the gradient of the field line, resulted in formation of a

slanted cusp field. The effect of this to particle motion is explained in the next section.

Biasing a positive and negative voltage on Plate 3,4 and 1,2, respectively, the kinetic energies of ions and electrons are converted into electricity, thus the direct energy conversion is achieved.



Fig.2 The main part of CUSPDEC with the example of the field line and routes of electrons and ions.

2.2. Störmer potential

The charge separation using slanted cusp magnetic field can be explained by movable region of incident particles based on Störmer potential. The Störmer potential F(r, z) for particles with a canonical angular momentum p_{θ} in a system of an axisymmetric magnetic field given by the vector potential $A_{\theta}(r, z)$ is represented by

$$F(r,z) = \frac{m}{2} \left(\frac{p_{\theta} - qA_{\theta}(r,z)r}{mr} \right)^2, \qquad (1)$$

where q is the charge, m is the mass, and $p_{\theta} = mr^2\theta + qA_{\theta}r$, which is conserved. When initial kinetic energy of the incident particle is $W = mv_0^2/2$ and no electric field is applied, the particle in a magnetic field can move the only region satisfying $F(r, z) \le W$. When the incident point of the particle is $(r_0, z_0) = A_0$, and azimuthal component of initial velocity $v_{\theta}(r_0, z_0) = 0$, this inequality expression is represented by

$$\left|\frac{qA_0}{mv_0}\right| \cdot \frac{r_0}{r} \cdot \left|1 - \frac{rA_\theta}{r_0A_0}\right| \le 1.$$
 (2)

In general, the value of $|qA_0|/mv_0$ of electrons is large and the value of r_0/r is on the order of 1, so $|1-rA_{\theta}/r_0A_0|$ is close to 0 and the value of rA_{θ} is constant which is an equation of field line. So the electrons strictly follow the magnetic field line in CUSPDEC. On the other hand, the ions don't necessarily follow the magnetic field line as the value of $|qA_0|/mv_0$ of ions is much smaller than that of electrons. This is the basic principle underlying the method of charge separation by the cusp magnetic field. The value of $|qA_0|/mv_0$ is regarded as the parameter which has an influence on charge separation. This parameter is effective as a scaling parameter of charge separation by slanted cusp magnetic field.

If the electrostatic potential $\phi(r, z)$ is present, the particle trajectory is restricted to

$$\left(\frac{qA_0}{mv_0}\right)^2 \left[\left(\frac{r_0}{r}\right)^2 \left(1 - \frac{rA_\theta}{r_0 A_0}\right)^2 + \frac{2m\phi}{qA_0^2} \right] \le 1$$
(3)

instead of Eq. (2). When direct energy conversion is performed, Plate3 and Plate4 have a positive potential. In this case, charge separation should be considered by using this equation.

2.3. Effect of slanted cusp magnetic field and evaluation of separation efficiency

We further discuss the effect of slanted cusp magnetic field. The motion of electrons is along magnetic field lines, the orbit directly varies with the curvature of the field lines and they reach any particle collectors according to the curvature. The orbit of ions is not sensitive with the curvature and large part of them reaches Plate3+4 (connected in parallel), so we evaluate the efficiency of charge separation by the amount of electrons arriving at Plate3+4. We define transmission ratio of electrons \Re_e by the number of electrons arriving at Plate3+4 divided by the number of incident electrons.

We evaluate \Re_e experimentally as follows: most of the field lines at the entrance connects to Plate3+4 under $I_{\rm B} / I_{\rm AC} = 0$, and the electron current at Plate1 and Plate2 are not detected. Thus, the value of the electron current of Plate3+4 corresponds to the number of incident electrons. In the experiment that the value of $I_{\rm B} / I_{\rm AC}$ is varied, the efficiency of charge separation is evaluated by

$$\mathfrak{R}_e = \frac{I_{es}(I_B \neq 0)}{I_{es}(I_B = 0)},\tag{4}$$

where I_{es} is the electron saturation current at Plate3+4.

3. Experimental results and discussion with a scaling parameter

3.1. Charge separation characteristics for low density plasma

In the experiment, helium or argon is used as a material gas of the plasma. Microwave-generated plasma

whose density is from 10^{12} m⁻³ to 10^{13} m⁻³ and helicon wave excited plasma whose density is from 10^{13} m⁻³ to 10^{15} m⁻³ are used. Their electron temperature is around 10 eV. Here, electron density and temperature are not those of produced plasma itself, but those measured by the probe shown in Fig.1, and there is an aperture between plasma production region and the probe.

In order to examine the factor of $|qA_0|/mv_0$, the electron transmission ratio \Re_e is measured as a function of the magnetic field intensity. Fig.3 shows the variation of \Re_e as a function of coil currents. The abscissa indicates the value of I_{AC} and I_B was settled to keep $I_B / I_{AC} = 1.17$, in which the minimum value of \Re_e is obtained. According to Fig. 3, \Re_e decreases as I_{AC} increases, that is, the magnetic field intensity increases. This is so natural result because the decrease of \Re_e means strong restriction of electron motion to the field lines. In the view point of the factor of $|qA_0|/mv_0$, this is also consistent as large intensity of magnetic field means large value of A_0 , and hence, the larger factor results strong restriction of electron motion.



Fig.3 The dependence of electron transmission ratio on the magnetic field intensity under $I_{\rm B} / I_{\rm AC} = 1.17$.

As for the dependence of v_0 in the factor, the former report, which including results of the experiment using end-loss flux of GAMMA 10, provides adequate results [5]. The electron transmission ratio was examined as a dependence on field line curvature for plasma flux with high-energy electrons whose energy is a few keV. In the case of high electron energy, \Re_e became large. This is also consistent that higher energy means the small factor of $|qA_0|/mv_0$, and weak restriction of electron motion.

The data of electron transmission ratio for low density (from 10^{12} m⁻³ to 10^{13} m⁻³) helium plasma are summarized in Fig.4 as a function of $|qA_0|/mv_0$. The open triangles represent measured data and the curved surface is a response surface which is created by the kriging method, one of the interpolation methods [6]. These results were obtained under the condition of I_B / I_{AC}

= 1.1 ~ 1.4. The value of the factor $|qA_0|/mv_0$ is evaluated by assuming that the incident particle starts at $(r_0, z_0) = (1, -20)$ cm in the cusp magnetic field.



Fig.4 Charge separation characteristics by using slanted cusp magnetic field. The incident plasma is low density.

According to Fig.4, as the value of $|qA_0|/mv_0$ becomes larger, the electron transmission ratio is reduced. Electron transmission ratio is less than 0.1 when the value of $|qA_0|/mv_0$ is more than 15. On one hand, the electron transmission ratio increases as the plasma density increases. As the density of plasma increases, interaction between charged particles becomes strong. In general, this interaction brings collective behavior of electrons and ions, that means to separate them becomes difficult. The experimental results are consistent with this consideration.

3.2. Dependence of separation capability on plasma density

As found in Fig.4, electron transmission ratio increases in case of higher density plasma. It means that the behavior of them cannot be regarded as a single particle motion because high density plasma behaves collective motion. In the theory of charge separation based on Störmer potential, the error becomes large, so modification of the theory is necessary. This paper presents experimental data and summarizes them as charge separation characteristics to modify the theory of charge separation for high density plasma.

Transmission ratio of electrons in two types of the incident plasma, low density in the order of 10^{12} m⁻³ and high density in the order of 10^{15} m⁻³, is plotted in Fig.5 as a function of $I_{\rm B} / I_{\rm AC}$ where $I_{\rm AC} = 30$ A. According to this figure, as the value of $I_{\rm B} / I_{\rm AC}$ increases, electron transmission ratio decreases and becomes small enough over $I_{\rm B} / I_{\rm AC} \sim 1$ in the case of low density plasma. This is the typical same result as before and it can be explained by using calculations of Störmer potential of electrons. In the case of high density plasma, the value of transmission ratio becomes large. The value is larger for all measured

condition of $I_{\rm B}$ / $I_{\rm AC}$ compared with that of low density and the value for high $I_{\rm B}$ / $I_{\rm AC}$ condition is around 0.5 and separation efficiency is degraded.



Fig.5 The dependence of electron transmission ratio on gradient of the field line.

The degradation of separation efficiency was examined as a dependence on plasma density. Fig.6 focuses on the condition of $I_{\rm B} / I_{\rm AC} = 1.17$ and shows the dependence of electron transmission ratio on plasma density. The gradient of the field line in this condition provides the most efficient separation of charged particles in the case of low-density plasma.



Fig.6 The dependence of electron transmission ratio on plasma density under $I_{\rm B}$ / $I_{\rm AC}$ = 1.17.

According to this figure, the efficiency of charge separation becomes worse as the density of the incident plasma increases. Electron transmission ratio is less than 0.1 for $10^{12} \sim 10^{13}$ m⁻³, while that becomes around 0.5 for 10^{15} m⁻³. According to Fig.6, a criterion of good separation is that the plasma density is less than around 10^{14} m⁻³. This can be considered by the relation between the Debye length and the size of the incident plasma. The Debye length for the electron density of 10^{14} m⁻³ is a few millimeters when the electron temperature is 10 eV. The

radius of the incident plasma is around a centimeter, thus the self induced field between separated electrons and ions could be shielded by collective behavior of the plasma when the electron density is over 10^{14} m⁻³. As the charged particles change their orbit to shield the field, charge separation becomes difficult resulted in the degradation of separation efficiency.

For high density plasma, the charge separation characteristics corresponding to Fig.4 was examined. In Fig.7, transmission ratio of electrons for high density plasma is shown as a function of $|qA_0|/mv_0$ and plasma density. The open triangles and the curved surface are the same meaning as those in Fig.4. These data were obtained in the experiment of argon plasma beam with densities from 10^{14} m⁻³ to 10^{15} m⁻³.



Fig.7 Charge separation characteristics by using slanted cusp magnetic field. The incident plasma is higher density.

According to Fig.7, the electron transmission ratio becomes worse as the plasma density increases. As for the dependence on the factor of $|qA_0|/mv_0$, it is different from that found in Fig.4, and large $|qA_0|/mv_0$ does not necessarily mean efficient charge separation. The theory of charge separation should be modified and effective factor corresponding to separation efficiency should be found.

4. Conclusion

The characteristics of charge separation by slanted cusp magnetic field were studied, especially about the dependence on plasma density.

The efficiency of charge separation, which is evaluated by transmission ratio of electrons to the point cusp, is changed by various parameters of the device and plasmas. The factor of $|qA_0|/mv_0$ was examined employing both experimental results of dependence on magnetic field and electron energy and theory of Störmer potential. The electron transmission ratio has a good correlation with the factor in the low density. The

experimental results are summarized as a function of a scaling parameter of $|qA_0|/mv_0$ and plasma density.

In high density plasma, however, the transmission ratio of electrons becomes worse. The efficiency of charge separation degrades as the density increases. This is because increase of self-induced field in high density plasma. The estimation of Debye length of dense plasma with degraded efficiency well corresponds to the size of incident plasma. The charge separation characteristics using a scaling parameter for high density plasma was also obtained, but the modification of the theory and the effective factor corresponding to separation efficiency was required in the following research.

Acknowledgment

The authors acknowledge valuable discussions with Drs. Y. Tomita, M. Ishikawa, and Y. Nakashima. This work was supported in part by the bilateral coordinated research between Plasma Research Center, Univ. Tsukuba, National Institute for Fusion Science, and Kobe University.

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