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Analysis of Behavior of Charged Particles in Cusp Type Direct Energy Converter for Advanced Fusion

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In order to convert kinetic energy of fusion-produced charged particles to electric power directly, separation of charged particles is necessary. A cusp type direct energy converter (CUSP-DEC) is expected to achieve this function. Some demonstration experiments using a small-scaled experimental device succeeded in efficient separation and direct energy conversion, and improvement of efficiency due to two-stage deceleration was proposed. In the present paper, orbit calculation of charged particles in the device was performed to analyze those experimental results theoretically for an application to an actual reactor. For electrons, those near the axis or with high energy go toward the point cusp and cannot be separated, and this is consistent with the experimental results. For ions, it is found that there are some particles unable to reach the additional electrode due to conditions on incident pitch angle and additional electrode bias voltage. Two cases of equivalent efficiency in a simple estimation were also examined and it was found that low voltage bias was desirable.

Keywords: advanced fusion, direct energy conversion, CUSP-DEC, orbit calculation, charge separation, two-stage deceleration

1. Introduction

In advanced fusion such as D-^{3}He fusion, neutrons are hardly created and most of produced energy is carried by charged particles, so direct energy conversion is expected. Momota at el, performed conceptual design of a power plant based on a D-^{3}He fusion reactor of field reversed configuration (FRC) with a pair of direct energy converters (DECs) [1]. One is a cusp type direct energy converter (CUSP-DEC), which separates charged particles into electrons, thermal ions, and fusion protons. The other is a traveling wave type direct energy converter (TWDEC), which recovers energy of the fusion protons.

The authors proposed use of slanted cusp in CUSP-DEC for efficient separation. A small-scaled experimental device was constructed and fundamental characteristics were examined using a low energy plasma source [2]. The characteristics for particles in keV order were also studied by connecting the device at the end of GAMMA 10, and efficient separation of electrons and ions and direct energy conversion were demonstrated [3]. According to the experimental results, efficient charge separation was achieved by an appropriately slanted cusp field. Considering the difference of orbits between electrons and ions, the study was developed into a proposition of multi-stage energy converter due to energy discrimination without grid electrodes in a CUSP-DEC configuration [4]. The proposition was partially confirmed with some experimental results [5]. These results should be referred by theoretical analysis as it is important for an application to an actual reactor.

In this paper, behavior of the charged particles in the CUSP-DEC device is discussed by comparing between experimental results and orbit calculation with theoretical consideration.

In the next section, the experimental device and experimental results are reviewed, and scenario of two-stage deceleration is explained. In Sec. 3, the results of orbit calculation are presented and the scenario of two-stage converter is discussed Conclusion is given in Sec. 4.

2. Review of experimental results and scenario of two-stage deceleration

2.1 CUSP-DEC experimental device

The CUSP-DEC experimental device is schematically shown in Fig. 1. The device has three magnetic coils, A, B, and C. The coil currents I_A and I_C have the same value and direction to create magnetic field, guiding charged particles to the cusp field. The coil current I_B is in opposite direction with I_A and I_C (I_{AC}, hereafter). By adjusting I_{AC} and I_B, the curvature of field line can be varied from normal to slanted cusp fields.

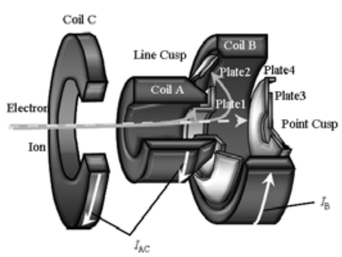

Fig. 1 CUSP-DEC experimental device.

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Fig. 2 shows the field lines in the device for $I_{\mathrm{AC}} = 30\mathrm{A}$ and $I_{\mathrm{B}} = 40\mathrm{A}$ as an example. The magnetic field strength at $(r, z) = (10\mathrm{cm}, 0\mathrm{cm})$ is about 246G. To detect the particle flux, four plane electrodes are settled as shown in Fig. 2, which locate at the entrance of line cusp (Plate1), the exit of line cusp (Plate2), the inner point cusp (Plate3), and the outer point cusp (Plate4). Electrons are deflected and guided along the field line to the line cusp, and reach Plate1 or Plate2, while ions can go straight to the point cusp and are collected by Plate3 or Plate4 because each Larmor radius is quite different.

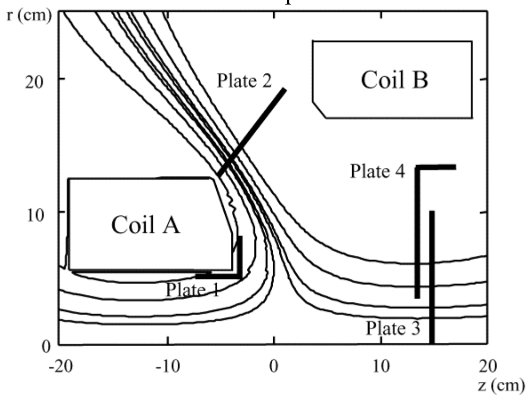


Fig. 2 Example of field lines of slanted cusp magnetic field.

2.2 Particle motion in the CUSP-DEC device

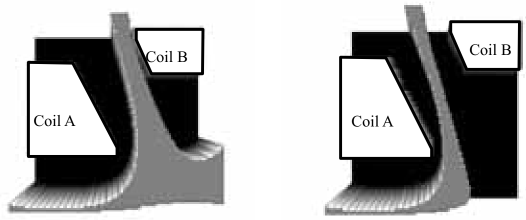
We consider movable region of incident particles in the CUSP-DEC device based on Störmer potential. In the device, not only magnetic field, but also electrostatic potential due to bias voltage of each electrode (denotes V_1, V_2, V_3, and V_4) the collectors affect particle motions. In an axi-symmetric system with a vector potential $A_\theta(r, z)$ and an electrostatic potential $\phi(r, z)$, the movable region of an incident particle with mass of m, charge of q, and initial velocity $v_0(r_0, z_0)$ where (r_0, z_0) is the incident point, is restricted to

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

Particle motions are discussed here under the positive bias on Plate3 and Plate4 (Plate3-4, hereafter), which are usually used for electrostatic energy conversion for ions.

Fig. 3 shows examples of calculated movable region for electrons under +1kV bias on Plate3-4 (V_{34}, hereafter). The incident electrons can move in the area indicated by gray. Fig. 3(a) and (b) are for $I_B = 10\mathrm{A}$ and 20A, respectively ($I_{\mathrm{AC}} = 30\mathrm{A}$ for both). In the case of gentle slant of (a), electrons can move in the point cusp region as well as in the line cusp region because of positive bias on Plate3-4. In the case of steep slant of (b), the region in the point cusp is excluded in the movable region. This means that steep slant cusp field can avoid electron inflow in the point cusp against the positive bias on Plate3-4. This characteristic was confirmed in the experiment showing the electron current decreased as I_B increased [2,3].

As for ions, those with high energy are flow into Plate3-4 and those with low energy are reflected. According to the estimation based on the experimental result, 62% and 28% of reflected ions flow into Plate1 and Plate2, respectively [4].



(a) (b)

Fig. 3 Examples of movable region for an electron of 2keV. Plate3 and Plate4 are biased with 1kV, and $I_{\mathrm{AC}} = 30\mathrm{A}$, and $I_{\mathrm{B}} = 10\mathrm{A}$ and 20A for (a) and (b), respectively.

2.3 Scenario of two-stage deceleration

When the electrodes are biased appropriately, they work as electrostatic energy converters. According to the conventional consideration, Plate1 and Plate2 are negatively biased for electrons, and Plate3-4 is positive for ions. However, ions with less energy than the potential energy on Plate3-4 cannot reach the electrodes. If the energy distribution of ions is large, energy of low energy ions cannot be recovered and conversion efficiency will not be high. The ion inflow to Plate1 or Plate2 cancels electron current and degrades those efficiencies. If the low energy ions are collected by another electrode biased positively, additionally converted energy can be obtained. This is a two-stage deceleration. Simultaneous inflow of electrons to the electrodes cancels ion current and degrades efficiency, so it should be avoided.

Using Plate1 as the additional electrode, we can achieve the two-stage deceleration. Plate3-4 is biased positively and recovers the energy of high energy ions. Some electrons are drawn to the point cusp by electrostatic potential, but steep slant of the cusp magnetic field can reduce electron inflow towards the point cusp as previously mentioned. An appropriate setting of the slant can introduce electrons to Plate2 and cannot to Plate1. Ions are insensitive to magnetic field, so high energy ions flow into Plate3-4 and low energy ions are reflected to Plate1. When V_1 and V_{34} are selected according to the energy distribution of ions, high efficiency of the energy conversion will be achieved.

This scenario is examined by orbit calculation of charged particles in Sec. 3.

3. Orbit calculation in the CUSP-DEC device

3.1 Scheme of orbit calculation

The basic equation for orbit calculation is the motion of equation for a single particle:

$$m\frac{d\mathbf{v}}{dt} = q(\mathbf{v}\times\mathbf{B}+\mathbf{E}), \quad (2)$$

where m, q, and $\mathbf{v}$ are particle's mass, charge, and velocity, respectively. $\mathbf{B}$ and $\mathbf{E}$ are magnetic and electric fields, respectively, and t is time. Distribution of $\mathbf{B}$ is obtained by integration of the field due to small current according to Biot Savart's equation, and distribution of $\mathbf{E}$ is calculated by solving Laplace's equation due to a finite difference method. Eq. (2) is expressed in 2 dimensional cylindrical coordinate with axial symmetry, and the orbit is calculated by employing Runge-Kutta scheme. In the calculation of particle motion, walls, coils, and electrodes are not taken into account. Orbits in the following results are across those obstacles, but the particles will recombine and disappear at the first obstacle in the real situation.

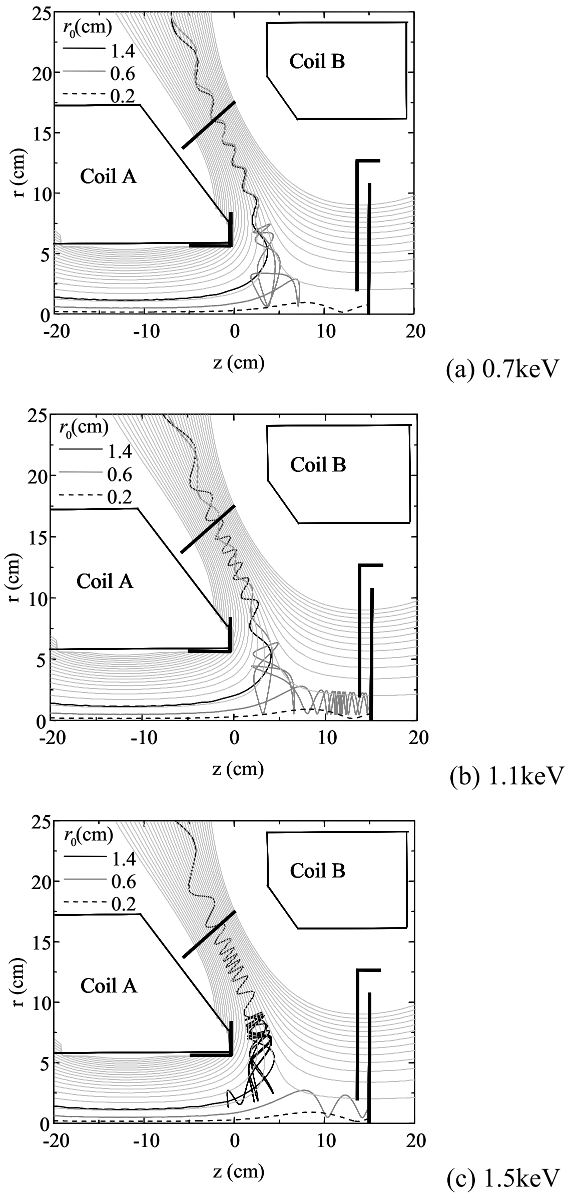


Fig. 4 Examples of electron orbit calculation. $I_{\mathrm{AC}} = 30\mathrm{A}$ and $I_{\mathrm{B}} = 20\mathrm{A}$ and $V_{34} = 1\mathrm{kV}$. Energy of incident electrons is 0.7, 1.1, and 1.5keV for (a), (b), and (c), respectively.

3.2 Orbit of electrons

In Sec. 2.2, the point cusp region is included in the movable region of electrons for some field condition. The orbit of electron is examined in this section.

Fig. 4 indicates examples of orbit calculation. $I_{\mathrm{AC}} = 30\mathrm{A}$ and $I_{\mathrm{B}} = 20\mathrm{A}$ and $V_{34} = 1\mathrm{kV}$. The difference of incident radial position can be examined in each figure, and electrons with outer incident radial position are guided in the line cusp and those near the axis go to the point cusp. The difference of electron energy can be compared between figures, and electrons with low incident energy are guided in the line cusp and those with high energy go to the point cusp. This is consistent with the experimental results that ratio of amount of electrons passing through the cusp field was large for a flux containing higher energy electrons [2,3].

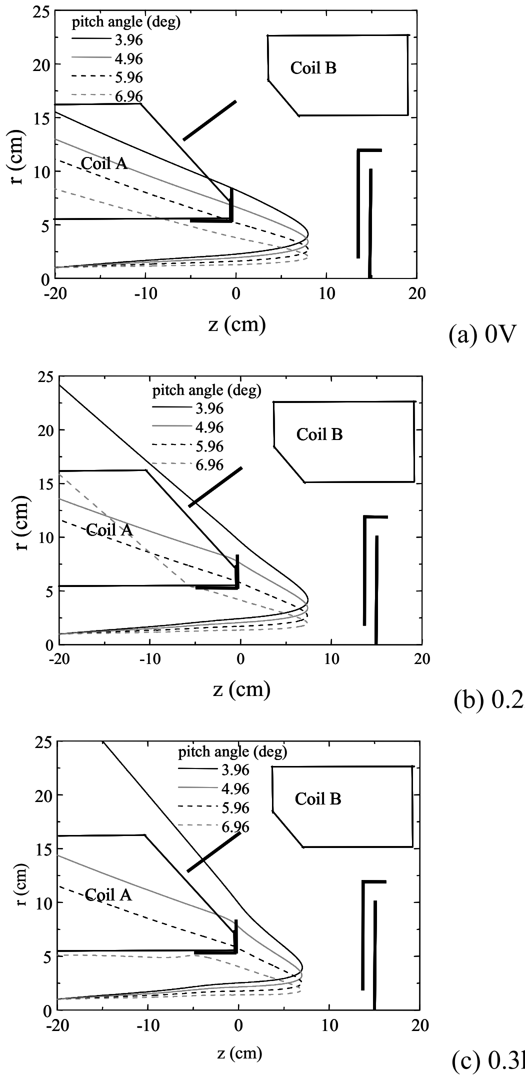


Fig. 5 Examples of ion orbit calculation. $I_{\mathrm{AC}} = 30\mathrm{A}$ and $I_{\mathrm{B}} = 20\mathrm{A}$ and $V_{34} = 1\mathrm{kV}$. Energy of ion is 0.5keV and incident position is $(r, z) = (1\mathrm{cm}, -20\mathrm{cm})$. V_1 is 0, 0.2, and 0.3kV for (a), (b), and (c), respectively.

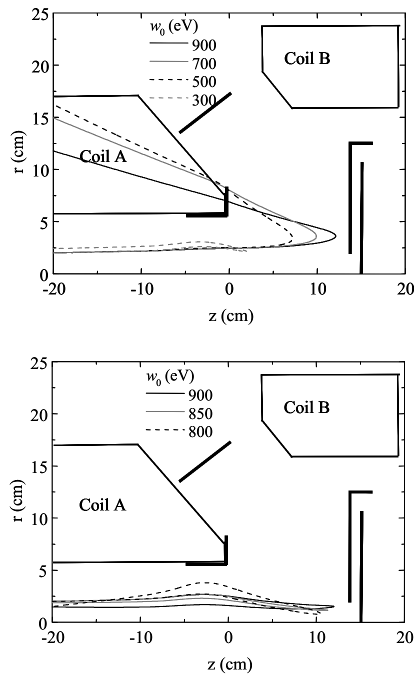
3.3 Orbit of ions

The large amount of ions reflected by the electrostatic potential go toward Plate1. When the Plate1 is biased positively for direct energy conversion, a part of ions toward Plate1 may not be able to reach Plate1. Orbit calculation can reveal the characteristics.

Fig. 5 shows examples of ion orbit calculation. From $(r,z)=(1\text{cm},-20\text{cm})$, ions with energy of 0.5keV and several pitch angles come into the device where $V_{34}=1\text{kV}$ and V_1 is varied. The pitch angles are defined by the angle to the field line which has -2.96 degree to the axial direction at the incident point.

In Fig. 5(b), each orbit is found to be extended in the radial direction compared with Fig. 5(a), and one of the ions goes to Plate2. This may be because ions slowing down due to electrostatic field by Plate1 spend more time in the region with radial electric field. According to Fig. 5(c), the ion with pitch angle of 6.96 degrees is deflected just before Plate1 and does not reach the electrode although it has enough initial energy (0.5keV) compared with the bias potential (0.3kV). This is because most of the kinetic energy of the ion is in the azimuthal direction. As shown above, some of the reflected ions toward Plate1 cannot reach Plate1 in the view point of pitch angle and azimuthal velocity.

By assuming the energy distribution of ions, the conversion efficiency with two stages can be calculated for a pair of (V_1, V_{34}). In some cases, there are two values of V_1 for the same V_{34} and efficiency[5], however, examination of the orbit clarifies the difference of the real efficiencies.



(a) 0.26kV

(b) 0.72kV

Fig. 6 Examples of ion orbit calculation for two-stage deceleration. $I_{AC}=22.5A$ and $I_B=20\text{A}$ and $V_{34}=1\text{kV}$. Here, (a) and (b) are for $V_1=0.26\text{kV}$ and 0.72kV.

Fig. 6 shows examples of orbits for two-stage deceleration. $V_{34}=1\text{kV}$ and V_1 is determined by the condition that total efficiency is expected to be 70% on ion temperature $T=0.55\text{keV}$ and when the energy distribution function of ions is proportional to $T^{-1.5}E^{0.5}\exp(-E/T)$, where E is ion energy in eV.

In the case of (a) $V_1=0.26\text{kV}$, the ion with incident energy of 300eV is reflected to the entrance, but other ions with higher incident energy can reach the Plate1. On one hand, in the case of (b) $V_1=0.72\text{kV}$, all the ions with different incident energy are reflected to the entrance and cannot reach Plate1. Thus, even if the same efficiency was obtained in a simple estimation, the actual efficiency in the case of (a) will be much higher than that in the case of (b). The lower V_1 provides better result.

4. Conclusion

Orbit calculations of charged particles in the CUSP-DEC device were performed to analyze previous experimental results and to examine new proposal of two-stage deceleration for an application to an actual reactor.

For electrons, those near the axis or with high energy go toward the point cusp and cannot be separated, which is consistent with the experimental results. For ions, it is found that there are some particles unable to reach the additional electrode due to conditions on incident pitch angle and additional electrode bias voltage. Two cases of equivalent efficiency in a simple estimation were also examined and it was found that low voltage bias was desirable.

Construction of a generalized theory is expected through additional calculations and experimental verifications.

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