Studies on the Effect of Radio Frequency Field in a Cusp-Type Charge Separation Device for Direct Energy Conversion[*)]

Masaki HAMABE, Hiroaki IZAWA, Hiromasa TAKENO, Satoshi NAKAMOTO,
Kazuya ICHIMURA[1)] and Yousuke NAKASHIMA[1)]

Department of Electrical and Electronic Engineering, Kobe University,
1-1 Rokkodai-cho, Nada-ku, Kobe 657-8501, Japan
[1)]*Plasma Research Center, University of Tsukuba, 1-1-1 Tennodai, Tsukuba 305-8577, Japan*

(Received 27 November 2015 / Accepted 1 February 2016)

In D-^{3}He fusion power generation, an application of direct energy conversion is expected in which separation of charged particles is necessary. A cusp-type direct energy converter (CuspDEC) was proposed as a charge separation device, but its performance was degraded for a high density plasma. The goal of the present study is to establish an additional method to assist charge separation by using a nonlinear effect of a radio frequency (rf) electric field. Following to the previous study, we experimentally examine the effect of an rf field to electron motion in a CuspDEC device. Two ring electrodes were newly installed in a CuspDEC simulator and the current flowing into the electron collector located in the line cusp region was measured on an rf field application. The significant variation in the current was found, and an improvement of the charge separation can be expected by using the phenomenon appropriately.

Keywords: direct energy conversion, CuspDEC, a radio frequency electric field, ponderomotive force

DOI: 10.1585/pfr.11.2405028

1. Introduction

In D-^{3}He fusion power generation, direct energy conversion can be applied and high efficiency can be expected because the produced energy in D-^{3}He reaction is kinetic energies of charged particles. Since harmful high energy neutrons are hardly generated, this power generation is expected as an excellent method in the environmental and economical aspects. For direct energy conversion, charged particles escaping from the reactor should be separated from each other in energy and electrical polarity. For this realization, using a cusp-type direct energy converter (CuspDEC) was proposed, which separated particles by using the difference of Larmor radii [1].

Previous studies show that CuspDEC is effective for charge separation of low density plasma [2]. The research for high-density plasma in the order of $10^{16}\ \mathrm{m^{-3}}$ was also performed, however, the separation performance degraded [3]. It was insufficient for highly efficient direct energy conversion and some additional methods to improve separation performance were required.

Using a radio frequency (rf) electric field was proposed as one of the additional methods. Ponderomotive force is known as a non-linear effect of high frequency electric field to the plasma [4]. The formula of the force to electrons $\boldsymbol{f}_{\mathrm{NL}}$ can be derived from the equation of electron motion and is represented as follows:

$$\boldsymbol{f}_{\mathrm{NL}} = -\frac{1}{2}\frac{e^2}{m\omega^2}\nabla\left\langle \boldsymbol{E}^2\right\rangle, \tag{1}$$

where e and m are charge and mass of electron, respectively, ω is the angular frequency of rf, and $\left\langle \boldsymbol{E}^2\right\rangle$ is time-averaged square of rf electric field. The force strength is proportional to gradient of square of electric field and is inversely proportional to electron mass. The force to ions can be derived in the same way and is inversely proportional to ion mass, so the force to electrons much stronger than that to ions. This characteristic is useful for charge separation, since rf electric field with a spatial gradient can give a strong force only for electrons. The rf electric field with the appropriate distribution can have a function to assist charge separation in a CuspDEC.

In the previous reports [5,6], we experimentally examined the effect of rf field in a CuspDEC simulator, and we found that the force showed a strong effect in the direction of static magnetic field. In this paper, a pair of ring-type electrodes were newly installed in the simulator and we experimentally examined the effect of rf field on electrons moving in the cusp magnetic field. We will observe variations in electron current due to rf field application, and will examine the result by comparing the theoretically expected ponderomotive effect.

As for the organization of the paper, the experimental device is explained in Sec. 2. The experimental results and discussion are presented in Sec. 3. The contents of the

---

author's e-mail: takeno@eedept.kobe-u.ac.jp

[*)] This article is based on the presentation at the 25th International Toki Conference (ITC25).

paper are summarized in Sec. 4.

2. Experimental Setup

Figure 1 schematically shows the CuspDEC experimental device. This device is composed of four magnetic coils, four plate electrodes, and two ring-type electrodes installed newly, which are placed coaxially. Argon plasma is generated by rf power application with a frequency of 13.56 MHz in a static magnetic field created by the current of Coil D. The rf power is provided by continuous pulse modulation. Coil C is for guide magnetic field, and Coil A and B are for a slanted cusp magnetic field. The current of Coil A and C (= I_{AC}) is supplied from a common power source, and that of Coil B (= I_B) is in the opposite direction from I_{AC} and has a different value. The field line curvature of the cusp magnetic field can be controlled by varying I_{AC} and I_B because the radii of Coil A and B are different from each other.

The electrons from the plasma source move along the magnetic field lines, and are led to the line cusp area, and are collected by Plate 2. The ions go straight without too much the influence of the magnetic field and are collected by Plate 3 of the point cusp area. Plate 4 is a grid electrode and is disposed in front of the Plate 3.

Ring A and B are electrodes for creating an rf electric field. Figure 2 shows distribution of the field lines in the cusp magnetic field region on I_{AC}/I_B = 30/20 A. In this condition, the separatrix is just passing through the center of Plate 2 and electron current of Plate 2 is maximized. Two ring electrodes are installed on the same field lines in this field condition so that the dominant component of the created rf electric field becomes parallel to the magnetic field. An rf power source with a variable frequency can supply rf voltages on both electrodes. The phase difference between two voltages can be controlled with the same phase (in-phase) and the opposite phase to each other (out-of-phase).

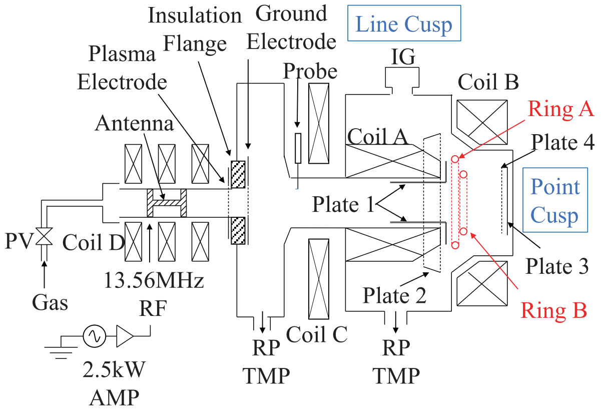


Fig. 1 CuspDEC experimental simulator.

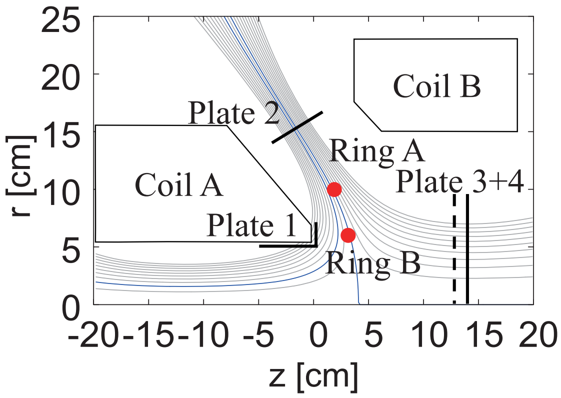


Fig. 2 Magnetic field lines in the cusp region.

3. Experimental Results

3.1 Evaluation of variation

Figure 3 shows a typical example of the waveform of electron current of Plate 2. Timing pulses with a solid line and a broken line indicated at the bottom of the figure mean pulse waveforms of plasma generation rf and rf voltage on ring electrodes, respectively. The former and the latter ones are supplied from 3 ms to 8.2 ms and from 4.5 ms to 6.2 ms, respectively. We evaluated current value with E (during application of rf voltage on ring electrodes) as the averaged current value of a fixed period in the region of the broken ellipse. As for that without E (no application of rf voltage on ring electrodes), the averaged value is taken between two averaged values corresponding to two regions of the solid ellipses.

3.2 Dependence on I_B

Figure 4 shows variation in electron current flowing into Plate 2 under the conditions of I_{AC} = 30 A and I_B = 10 ~ 35 A. The bias voltage on Plate 2 is 50 V and rf voltage on ring electrodes is 7 MHz and 60 V_{0p} with in-phase (subscript 0p denotes zero to peak). Closed and open circles are for with and without E, respectively.

According to Fig. 4, almost no current is found on some conditions regardless of rf voltage application. As incident electrons are along field lines, the region of electron flow in the line cusp is limited to a narrow channel between

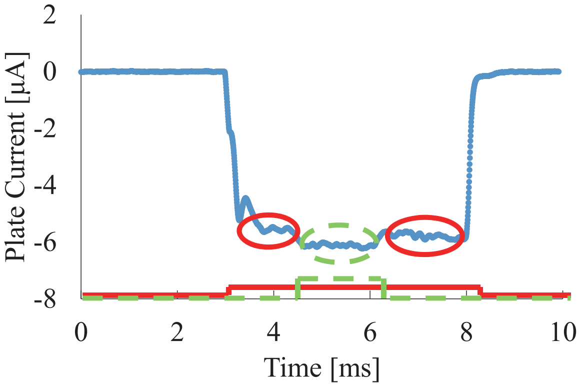


Fig. 3 An example of waveform of electron current.

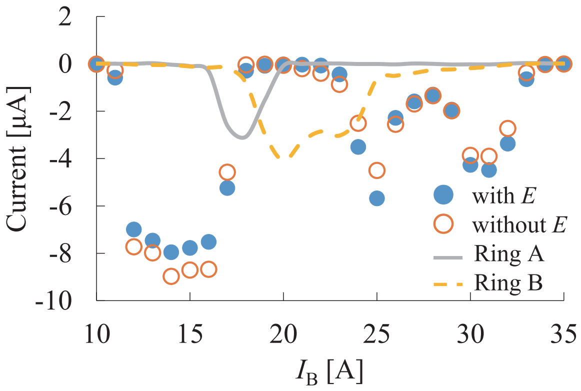
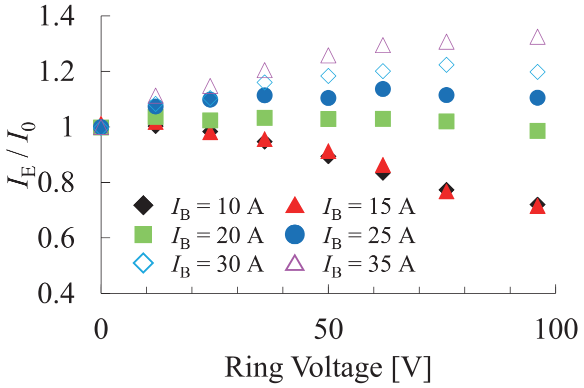
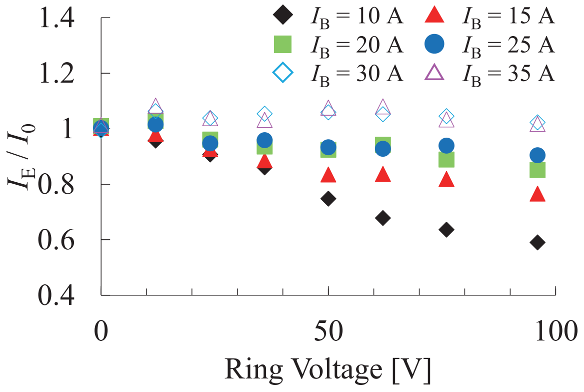


Fig. 4 Electron current versus current of Coil B.



(a) in-phase



(b) out-of-phase

Fig. 5 The dependence of I_E/I_0 on magnetic field strength.

the field line corresponding to incident radial position of $(r, z) = (2\,\text{cm}, -20\,\text{cm})$ and the separatrix (Fig. 2). As I_B is changed, the angle of the channel to the axis changes, and the channel does not pass through Plate 2 in the conditions of $I_B \leq 11$ A or $34\,\text{A} \leq I_B$. In the condition of $17\,\text{A} \leq I_B \leq 24$ A, Ring A and B become a shade of electron flow, which is confirmed by solid and broken curves in Fig. 4 showing measured electron current of Ring A and B.

In the condition of $12\,\text{A} \leq I_B \leq 16$ A, electron current with E is smaller than that without E, while that with E is larger for $I_B = 25$ A or $30\,\text{A} \leq I_B \leq 32$ A.

3.3 Change in electron current on constant magnetic field

The dependence of electron current on rf ring voltage was examined. Figure 5 shows the measured results of rf ring voltage dependence for several kinds of magnetic field strengths. The current I_B is as in the figure, and I_{AC} is also varied by keeping the same current ratio of $I_{AC}/I_B = 30/25$ A. In this condition, the shape of the cusp magnetic field is the same and the degree of inclination of the field is constant, so the variation of magnetic field in Fig. 5 is purely for its strength. The bias voltage on Plate 2 is 50 V. The frequency of the ring voltages is 7 MHz.

Figure 5 (a) shows results for in-phase application. In the figure, I_E and I_0 denote electron current with E and that without E, respectively (thus, I_0 is I_E on zero ring voltages). The relative electron current I_E/I_0 is taken for ordinate, so the value greater than 1 means increase of electron current due to rf application. According to Fig. 5 (a), electron current increases as ring voltage increases when 25 A $\leq I_B$, while it decreases with ring voltage on $I_B \leq 15$ A. It is almost constant on $I_B = 20$ A, and the increase factor to ring voltage increases with magnetic field strength.

On the other hand, in the case of out-of-phase showing in Fig. 5 (b), electron current decreases on $I_B \leq 25$ A and it is almost constant on $I_B = 30$ and 35 A. The increase factor also increases with magnetic field, but we cannot find increasing cases in the phasing with out-of-phase.

The increase of electron current ($1 \leq I_E/I_0$) of Plate 2 in the case of in-phase is quite significant. As Plate 2 is a collector for electrons, the result shows some possibility that it means an enhancement of charge separation. The mechanism of the phenomenon can be considered as follows.

In the path from the incident position to Plate 2, electrons are passing through an rf field region created by two ring electrodes. We consider the region by dividing into three zones. The first zone is before Ring B, where rf field strength increases as electron approaches Ring B. Thus, the gradient of rf field strength is positive in the moving direction of electrons, so the ponderomotive force becomes negative. In the second zone between Ring B and Ring A, the rf field is different according to phasing of rf voltages. The rf field is so weak in the case of in-phase, while it is quite strong in the case of out-of-phase. For both phasing, the spatial distribution of the field is rather uniform, thus the ponderomotive force is not so large. The situation in the third zone after Ring A is opposite to that in the first zone, and the ponderomotive force becomes positive.

When we consider the electron path according to Fig. 2, the corresponding second and third zones are quite near the electrodes and the field strength is large, while the first zone is rather far because the magnetic field line is bending near Ring B. Totally, the ponderomotive effect in the third zone provides positive force in the direction

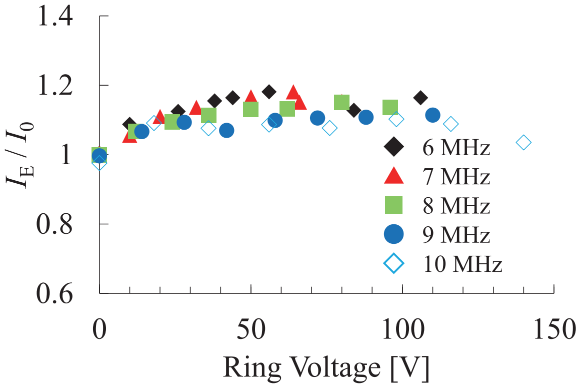


Fig. 6 The dependence of I_E/I_0 on frequency of rf field.

of electron motion, which may result enhancement of the electron current.

As for decrease of electron current, which is remarkable in the case of out-of-phase, it may be caused by an extremely intense rf field in the second zone. In the period that the rf field in the second zone is in the co-directional to electron motion, some of the electrons may be reflected by the field, and this reduces electron current of Plate 2. Possibility of other mechanism is also remained. For example, acceleration and deceleration by a linear electric force cannot be canceled during an rf period for electrons running in the region without uniformity. The results in Fig. 5 also show that the amount of decrease depends on strength of magnetic field. Although we cannot obtain a clear reason for this dependence, an effect of ponderomotive force perpendicular to magnetic field may be possible, which depends on electron cyclotron frequency.

3.4 Dependence on frequency of rf field

From Eq. (1), pondermotive force depends on the frequency of rf field. We also conducted the current measurement by varying the frequency of the voltage on the ring electrodes.

Figure 6 shows the results of the measurement for in-phase application. The field condition is $I_{AC}/I_B = 30/25$ A, and bias voltage on Plate 2 is 50 V. According to the figure, the increase of electron current due to increase of rf voltage is found for all frequency range performed (6 - 10 MHz). The amount of increase has a dependence on the frequency, and it is smaller for higher frequency. This characteristic is also confirmed for $I_B \geq 20$ A with the same field line configuration. The ponderomotive force by Eq. (1) is inversely proportional to the square of the frequency, so the experimental results do not contradict the ponderomotive theory qualitatively. The quantitative evaluation and the reason of decreasing tendency of I_E/I_0 over 100 V_{0p}, however, are not clear.

4. Summary

Setting a goal on improvement of charge separation performance of CuspDEC by nonlinear effect of rf electric field, we newly installed two ring electrodes in CuspDEC experimental device, and examined the effect of rf field application. As a result, we observed changes in the electron collector current by an application of an rf electric field. The result suggesting enhancement of charge separation was also found, and its mechanism can be qualitatively explained by spatial arrangement of electrodes in the magnetic field structure. A quite primitive effect was found in the study, then the complete clarification of the mechanism should be followed. After that, appropriate applications should be developed in future.

Acknowledgememt

The authors acknowledge valuable discussions with Drs. J. Miyazawa and T. Goto. This work was supported in part by a Grant-in-Aid for Scientific Research (C) (25420255) from Japan Society for the Promotion of Science. This work was also supported in part by the bilateral coordinated research between Plasma Research Center, University of Tsukuba, National Institute for Fusion Science, and Kobe University (NIFS13KUGM082).

[1] H. Momota *et al.*, Proc. 14th IAEA **3**, 319 (1993).
[2] Y. Yasaka *et al.*, Nucl. Fusion **49**, 075009 (2009).
[3] Y. Munakata *et al.*, Plasma Fusion Res. **7**, 2405071 (2012).
[4] F.F. Chen, *Introduction to Plasma Physics and Controlled Fusion, 2nd Ed.* **1** (Plenum Press, 1984) p.305.
[5] H. Takeno *et al.*, 23rd ITC (2013) P1-53.
[6] H. Takeno *et al.*, PLASMA2014 (2014) 18PB-031.