# Trapping Efficiency of a Non-Adidabatic Confinement Device*)

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We performed trajectory analysis of beam ions in such a magnetic field structure having a weak magnetic field region over a wide range by canceling the magnetic field created by the solenoid coil with a Helmholtz coil. The rate at which the beam ions injected in the axial direction are trapped in the magnetic field structure is statistically examined. In addition, by adjusting the Helmholtz coil current, the position of the field-null point is changed, and the influence on the ion trapping rate is also investigated. As a result, it is found that the larger the beam dispersion, the higher the trapping rate, and the higher the energy, the lower the trapping rate. Furthermore, it is also found that in the case where the magnetic field is not completely canceled at the center of the device, there is an energy which extremely decreases the trapping rate.



Keywords: Helmholtz coil, non-adiabatic trap, particle separation, trajectory calculation, beam ion

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## 1. Introduction

Stochastic motion seen in charged particle motion brings engineering advantages and disadvantages. Takahashi *et al*. statistically examined adiabaticity breaking phenomena caused by the collisionless pitch angle scattering near the X-point in a field-reversed configuration (FRC) plasma [1]. It has been shown that the phenomena may promote the end-loss in the peripheral plasma. In addition, fast beam ions injected into the FRC as neutral beam particles and confined by the effect of the mirror magnetic field are also found to be end-lost due to collisionless pitch angle scattering at the magnetic field-null points [2, 3].

On the other hand, there is also a concept of confinement that positively utilizes stochastic charged particle motion. Momota *et al*. have proposed the concept of fusion plasma confinement combining non-adiabatic traps [4]. A non-adiabatic trap is a device that cancels the axial magnetic field generated by the solenoid coil with a Helmholtz coil and generates a zero magnetic field region in the center. Ions trapped in the device are subject to collisionless pitch angle scattering as a stochastic process, so the orbit is randomized. According to this property, in a unit in which multiple non-adiabatic traps are connected, the net particle confinement time is proportional to the square of the number of units. Therefore, it can be said that it is an attractive proposal as a concept of fusion reactor.

Particle separation plays an important role, for example, for direct energy conversion in ARTEMIS D-$^3$He nuclear fusion conceptual reactor [5]. For the realization of high efficiency direct energy conversion, the Kobe University group is conducting experimental research on particle separation using cusp magnetic field [6, 7].

Also, if particles can be selected by energy, various applications are possible. For example, in an electrostatic D-D beam confinement apparatus, it is possible to realize confinement of high-quality beam components if a particle separator capable of transmitting a beam component and excluding a thermal velocity component can be introduced. It is also possible to pave the way for the development of neutron sources for medical application [8, 9].

Therefore, in this simulation study, the purpose is to study whether the non-adiabatic trap proposed by Momota *et al.* [4] can be applied as a particle separation device.

## 2. Magnetic Field for Particle Separation

In the present study, we calculate the trajectory of charged particles in a device combining a solenoid coil and a Helmholtz coil. A schematic diagram of the device is shown in Fig. 1. Table 1 also shows the calculation area and the coil parameters. In this study, the current flowing in the Helmholtz coil is changed within the range of Table 1. If the magnetic field generated by the solenoid coil is set to be canceled, a region where the magnetic field becomes substantially zero spreads widely in the vicinity of the center of the device. The calculation is done under a two-dimensional cylindrical coordinate system.

A method of generating a magnetic field generated by the coil will be described. The vector potential $\mathbf{A}(r, z)$ generated by the circular current is expressed by the equation (1). First, we apply this formula to all the coils and

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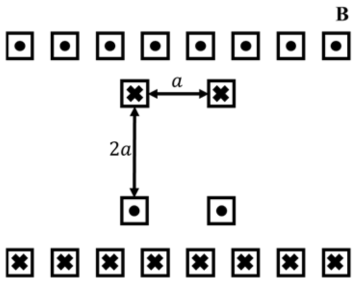


Fig. 1 Arrangement of coils for particle separation.

Table 1 Parameters of the coils and calculation region.

| | |
|---|---|
| Solenoid coil radius | 0.20 [m] |
| Solenoid coil turns | 100 [m$^{-1}$] |
| Solenoid coil current | 1.0 [kA] |
| Helmholtz coil radius | 0.15 [m] |
| Helmholtz coil current | 15~25 [kA] |
| Calculation region | $r$: 0.0 to 0.2 [m]<br>$z$: -0.25 to 0.25 [m] |

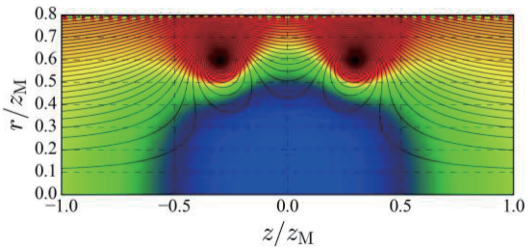


Fig. 2 Magnetic field in the chamber.

find the vector potential created by the solenoid coil and the Helmholtz coil. Then, by superimposing them, the vector potential generated by the two kinds of coils is found. By substituting this into equation (2), the magnetic field inside the device was determined.

$$A_\theta = \sum_i \frac{\mu_0 I_i}{4\pi} \int_0^{2\pi} \frac{\cos\chi \mathrm{d}\chi}{\sqrt{(z - z_i)^2 + r^2 + a^2 - 2ar\cos\chi}}, \tag{1}$$

$$\mathbf{B} = \mathrm{rot}\,\mathbf{A}. \tag{2}$$

Here, $\mu_0$ is the vacuum permittivity and $I_i$ is the current through the $i$-th circular coil. The magnetic lines of force and its strength of the generated magnetic field are shown in Fig. 2. In this study, the current of the Helmholtz coil was changed from 15 [kA] to 25 [kA], and the trapping condition of charged particles under each condition was investigated. In Fig. 2, the Helmholtz coil current is 19.3 [kA] and the center magnetic field by the solenoid coil

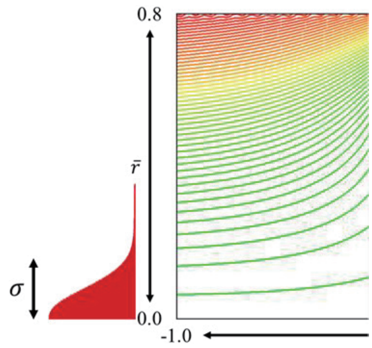


Fig. 3 Initial density distribution of particles.

is completely canceled.

## 3. Trajectory Calculation Procedure

An equation of motion represented by the following Eq. (3) is used for trajectory calculation of charged particles.

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \frac{q}{m}\mathbf{v} \times \mathbf{B}, \tag{3}$$

$$\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t} = \mathbf{v}. \tag{4}$$

Here, $\mathbf{v}$ is the velocity of the charged particle, $\mathbf{x}$ is the coordinates of the charged particle, $q$ is the charge of the charged particle, $m$ is the mass of the charged particle. We calculated the trajectory by solving this equation by simultaneous solving using Runge-Kutta method. The initial arrangement of the particles was carried out as follows assuming an ion beam. Regarding the $z$ coordinate, it was arranged at the left end of the device ($z = -0.25$ [m]) in all the particles. In addition, by generating normal random numbers, the ion beam was normally distributed in a plane perpendicular to the $z$ axis. The outline of the particle arrangement method is shown in Fig. 3 A constant energy is given to all the particles, the initial velocity in the $z$ direction is given using it, and the other velocity components are zero. In addition, the charged particles used are deuterium ions and the number of particles is 10,000.

## 4. Results and Discussion

In this section, the result of the trajectory analysis in the particle separator will be explained. The energy of the beam ion is set at 0.5 keV at the maximum.

The ion beam trajectory of 0.05 keV in the device is shown in Fig. 4. From the top of the figure the Helmholtz coil current is increased to 15 kA, 17 kA, 19.3 kA, and 25 kA. The beam ions are evenly distributed up to $r/z_{\mathrm{M}} = 0.4$ (where $z_{\mathrm{M}}$ is 0.25 m, which is half of the device length). Helmholtz coils are placed near $r/z_{\mathrm{M}} = 0.6$ where no beam ion trajectory is drawn. Since it is 19.3 kA to completely cancel the magnetic field of the solenoid coil, in the case of 15 kA or 17 kA, there is a point where there is a zero magnetic field between the position of the Helmholtz coil and

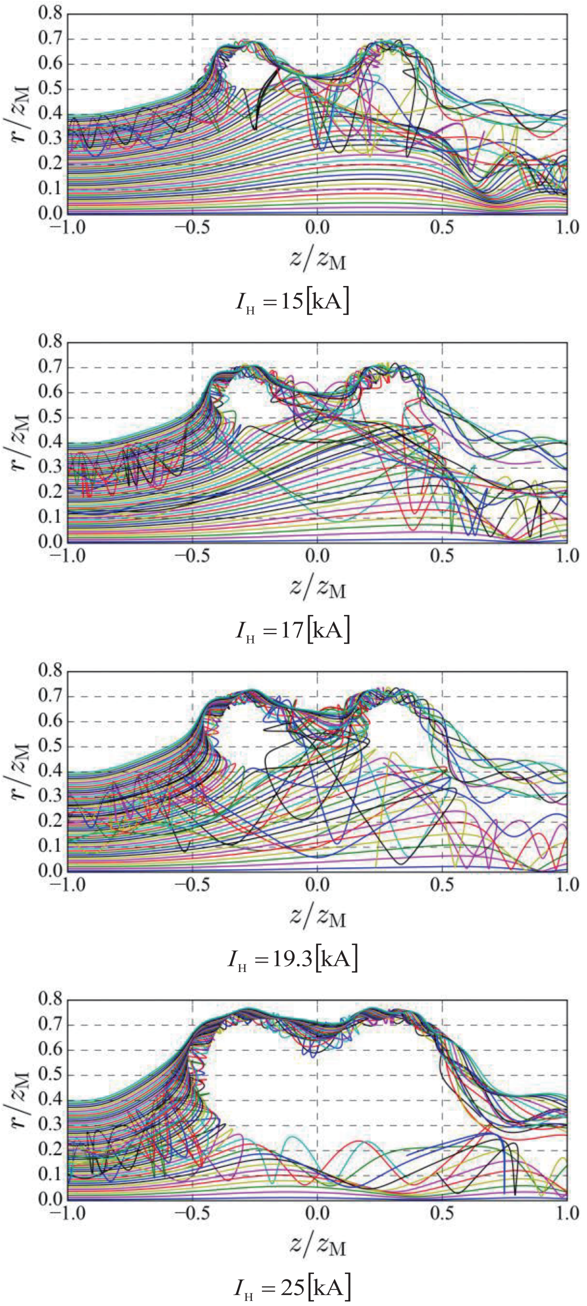


Fig. 4 Deuterium ion orbit (0.05 [keV]).

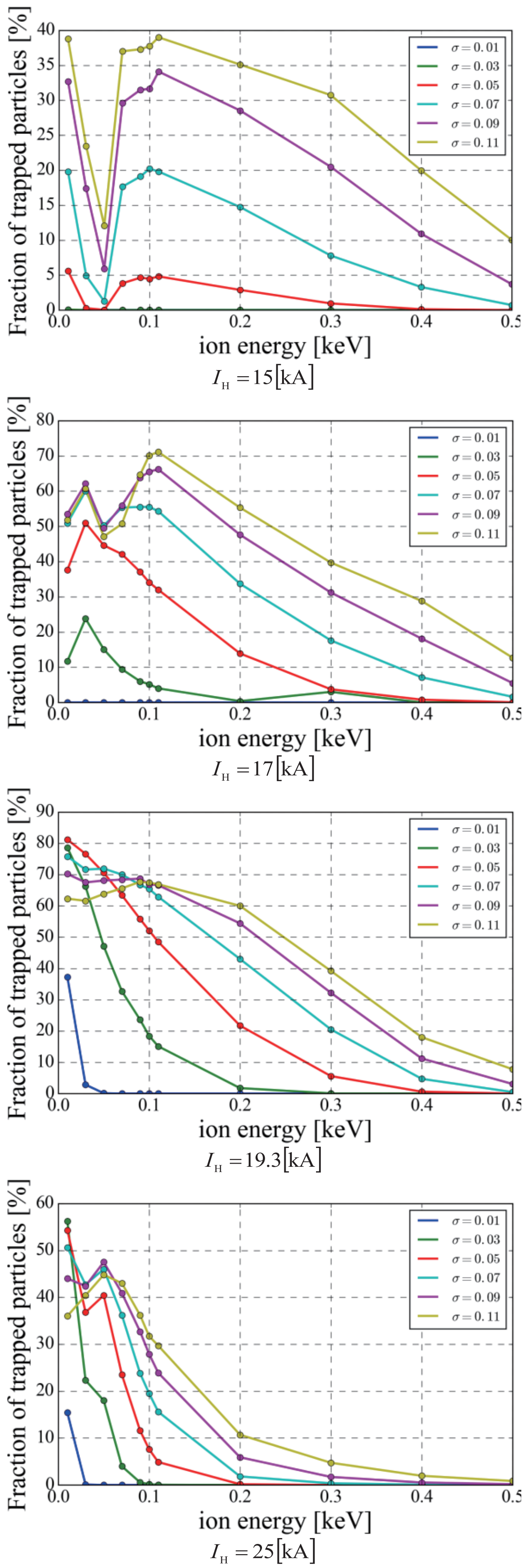


Fig. 5 Magnetic field in the chamber.

the $z$ axis. Therefore, when passing through this area, collisionless pitch angle scattering occurs and it can be seen that the beam ion trajectory is greatly disturbed.

The results of the trajectory analysis are collected statistically, and Fig. 5 shows the relationship between the trapping rate and energy. It is regarded as trapped when the traveling length of the beam ion exceeds the sum of the device length (2.0 normalized length) and the Helmholtz coil diameter (1.2 normalized length). Therefore, the traveling length of trapped particles exceeds $3.2z_M$. In Fig. 5, $\sigma$ is the standard deviation of beam dispersion. Since $\sigma$ is normalized by $z_M$, 99.7% of the beam ions exist when $\sigma = 0.05$ up to $r/z_M = 0.15 = 3\sigma$ in Fig. 4.

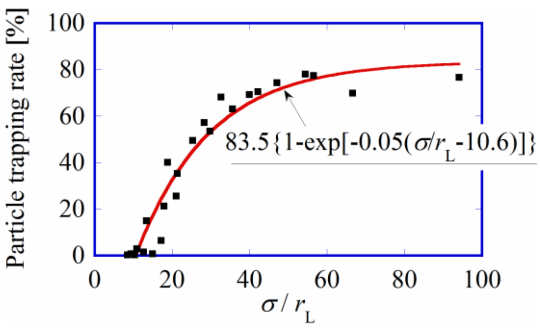


Fig. 6 Fitting curve of particle trapping rate vs. $\sigma/r_L$.

According to Fig. 4, when the energy is higher than 0.1 keV regardless of the Helmholtz coil current $I_H$, the trapping rate decreases as the energy increases. Also, it can be seen that when the beam dispersion is large, the trapping rate is high. As shown in Fig. 2, it can be seen that a part of the magnetic line of force extending from the end of the device exists so as to wind around the Helmholtz coil. When the beam dispersion is large, the number of beam ions far from the device axis at the injection position relatively increases, the magnetic field becomes stronger as it goes away from the device axis, so that the beam ions are easily caught by the magnetic force lines wrapping around the Helmholtz coil.

However, in the case of $I_H = 15$ kA, a peculiar trend is obtained in the figure. It is found that the trapping rate decreases from 0.01 keV to 0.05 keV at the beam ion energy and the trapping rate increases to 0.1 keV after reaching the minimum at 0.05 keV. For this interesting property, further analysis, such as investigating the degree of stochasticity of beam ion motion using Lyapunov exponent, is necessary. Also, when $I_H = 19.3$ kA which canceled the central magnetic field, it shows that the trapping rate is the highest.

Figure 6 shows the relation between the trapping rate and the abscissa as $\sigma/r_L$ ($r_L$ is the Larmor radius of the beam ion evaluated by solenoid magnetic field) when $I_H = 19.3$ kA canceling the central magnetic field. In Fig. 6, all the results of various energies and beam dispersion are aggregated, and the trapping rate can be expressed as a function of one expression $\sigma/r_L$. Since the $r_L$ increases as the high energy beam ion is used, $\sigma/r_L$ becomes small. Also, the smaller the beam dispersion, the more it can be injected along the device axis, the smaller the trapping rate becomes. From Fig. 6, it is found that the particles passing through the apparatus should be $\sigma/r_L < 10$. Although complete trapping is impossible, it is found that the condition $\sigma/r_L > 40$ is desirable to obtain a trapping rate of about 80%.

# 5. Concluding Remarks

In this research, we have analyzed the trajectory of beam ions in a magnetic field structure with a weak magnetic field region over a wide range by canceling the magnetic field created by the solenoid coil with a Helmholtz coil. This magnetic field structure is essentially the same as the non-adiabatic trap proposed by Momota [4], but here we also considered the magnetic field structure with the Helmholtz coil current as a parameter and the position of the field-null point changed.

Here, the rate at which the beam ions injected in the axial direction from the end of the device is trapped in the magnetic field structure was statistically examined. As a result, it was found that the larger the beam dispersion, the higher the trapping rate, and the higher the energy, the lower the trapping rate. Furthermore, in the case where the magnetic field is not completely canceled at the center of the device, it was also found that there is energy which extremely minimizes the trapping rate. We will quantitatively investigate the stochasticity of the beam ion motion at energy minimizing the trapping rate by statistically investigating the jump of the magnetic moment and further analysis of this tendency will be a future subject. In this study, results based on single particle trajectory calculation have been shown. However, when the plasma density increases in the weak magnetic field region at the center of the device, there is a possibility that the magnetic field structure changes due to the diamagnetic plasma current. At this time, there is also a possibility that the weak magnetic field region disappears and the non-adiabatic property in the plasma ion motion is lost. Also, since the proposed device has strong non-uniformity of the magnetic field including the weak magnetic field region, it is expected that a large difference will be generated between electron and ion orbit. For this reason, the influence of the electric field due to the two-fluid effect is considered to increase, and it is necessary to clarify these in future research.

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