First Confinement Time Evaluation for Particles Axially Injected into a Non-Adiabatic Trap

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This study presents the first detailed investigation of confinement times in non-adiabatic traps during the axial injection of thermal plasma from the mirror edge, using particle trajectory calculations. Plasma is supplied from a coaxially positioned plasma source through an orifice with a ring-shaped aperture. The results of the analysis show that the longest confinement time occurs when the ring radius of the aperture is approximately equal to the ion Larmor radius at the mirror region. Under these conditions, the confinement time is found to be approximately four times the time it takes for particles to traverse the device length at thermal velocity.

Keywords: non-adiabatic trap, stochastic motion, particle fueling, particle-tracking calculation, confinement

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The non-adiabatic trap is a magnetic confinement system composed of a solenoid and a Helmholtz coil positioned within the solenoid. The magnetic field generated by the solenoid is counteracted by the Helmholtz coil, creating a broad region with a weak magnetic field at the center of the device. The motion of particles within the trap is stochastic, as their trajectories in the weak-field region are significantly influenced by the gyro-phase of the plasma particles, particularly ions, upon entering this region [1, 2]. Leveraging this characteristic, Momota *et al.* theoretically demonstrated that the net particle confinement time scales approximately with the square of the number of traps when multiple non-adiabatic traps are connected axially [3]. Despite these findings, the confinement performance of a single trap remains unexplored. Therefore, it is crucial to evaluate the confinement time through simulations. This study aims to assess the confinement time when the plasma source is located at the edge of the mirror, with particles introduced from this boundary.

The coil arrangements for the non-adiabatic trap to be simulated are illustrated in Fig. 1. The contours of the magnetic flux generated by these coil configurations are depicted in Fig. 2. The vacuum vessel has a radius of 1 m and a confinement region length of 2 m. The Helmholtz coils are designed with a radius and spacing of 0.7 m. The solenoid is assumed to consist of 100 turns, with the coil current of 1 kA. The current in the Helmholtz coils is adjusted to precisely cancel the magnetic field generated by the solenoid along the central plane axis of the device (origin). Particles (deuterium ions) are injected from the left edge of the mirror end in a ring concentric with the confinement vessel. This setup simulates the inflow of thermalized plasma particles from a plasma source located at the left end of the non-adiabatic trap. An orifice is positioned between the plasma source and the confinement vessel, allowing plasma to be injected through the opening into the ring. The plasma ion temperature is set at 100 eV, with all velocity components assumed to follow Maxwellian distributions. These distributions are generated using normal random numbers via the Box-Muller method. However, only positive velocities are considered for the axial component. The particles are assumed to

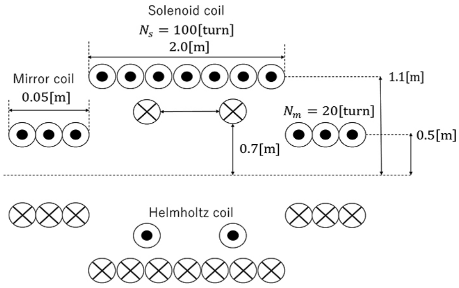

Fig. 1. Coil arrangement diagram in a non-adiabatic trap.

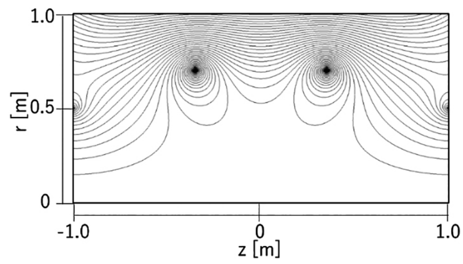

Fig. 2. Contour plot of poloidal magnetic flux.

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enter from the $z = -1$ m boundary and are constrained by the orifice on the ring. Consequently, the initial radial coordinate is determined by calculating the center position and the dispersion of the radial distribution. In this study, the trajectories of ions are analyzed under the assumption of charge quasi-neutrality. Consequently, an equal number of electrons are injected into the system to balance the ion charge. It is also assumed that the device initially contains no plasma and is in a vacuum state. Thus, the analysis focuses on the confinement characteristics at the stage when plasma begins to be supplied into the vacuum magnetic field.

In the analysis of particle supply, ΔN superparticles are introduced at time intervals of Δt [s]. Given a particle supply rate S [s^{-1}], the weight w of a single superparticle is defined as $w = S\Delta t/\Delta N$. In this study, the particle supply rate is set to = 10^{20} s^{-1}, and the time interval $\Delta t = 1.24 \times 10^{-8}$ s corresponds to the gyration period of particles in the magnetic field at the midplane and device wall.

Deuterium ions move within the magnetic field configuration depicted in Fig. 2. Some ions follow trajectories around the magnetic field lines near the Helmholtz coil, others are trapped in regions of weak magnetic fields, and some are lost through the mirror end. Let $N(t)$ represent the total number of ions in the confinement region at time t, and τ_p denote the particle confinement time. The relationship is expressed as: $N(t) = S\tau_\mathrm{p}(1 - \exp(-t/\tau_\mathrm{p}))$ where τ_p is the confinement time of the particles in the system.

In this study, the confinement time τ_p is determined by incrementally introducing superparticles from the edge of the computational domain and fitting the time-dependent number of particles $N(t)$ in the confinement region to the functional form of Eq. (1) using the least squares method.

Figure 3 illustrates the accumulation of particles in the confinement region as a result of particle supply. The figure shows the particle distribution 124 μs after the initiation of particle supply. A relatively large number of particles are concentrated in the weak magnetic field region near the device axis. These particles exhibit non-adiabatic motion, are reflected within the cusp-shaped magnetic field region, and remain in the trap for extended periods.

Conversely, some particles are confined along the magnetic field lines outside the Helmholtz coil. The motion of these particles is regular, and their residence time within the trap is relatively short.

The relationship between the ring radius r_inj, where particles are injected along the axial direction, and the confinement time τ_p is illustrated in Fig. 4. In this figure, the Larmor radius of a particle with thermal velocity at the mirror edge is indicated by the red vertical dashed line. The ratio $\tau_\mathrm{p}/\tau_\parallel$, representing the confinement time τ_p to the axial travel time $\tau_\parallel$ (calculated by dividing the device length by the thermal velocity), is shown on the right vertical axis. The solid orange horizontal line corresponds to a ratio of 1.

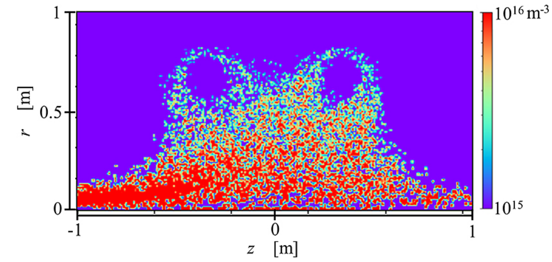

Fig. 3. Color contour of ion density 124 μs after particle supply. Here, $r_\mathrm{inj} = 0.05$ m.

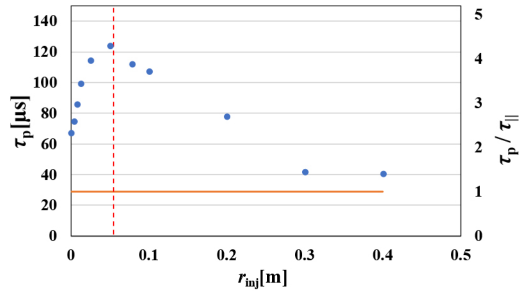

Fig. 4. Particle confinement time τ_p (left vertical axis) and its ratio to axial travel time $\tau_\parallel$ (right vertical axis) versus ring injection position r_inj.

For injections occurring closer to the device axis than the Larmor radius, the confinement time is relatively short. This is due to the spiral motion of the particles as they wrap around the magnetic field lines near the device center, which leads to a loss of particles from the opposite end of the injection position due to axial momentum after traversing the weak magnetic field region.

When the injection ring radius equals the Larmor radius, the particles no longer exhibit spiral motion around the device axis. Upon reaching the weak field region, their motion becomes more complex, influenced by the magnetic field lines near the Helmholtz coil. This results in the longest confinement time, as the particles undergo a reciprocating motion within the device.

If the injection ring radius exceeds the Larmor radius, the particles predominantly follow magnetic field lines that pass outside the Helmholtz coil. The motion becomes adiabatic, and the confinement time is reduced due to increased edge losses.

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