Computation of Neutral Gas Flow Generation From a CT Neutralization Fuel-Injector*)

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The feasibility of compact torus (CT) neutralization fuel injection method is studied by a simulation model using particle and MHD hybrid techniques. The neutralization process is simulated by using rate-coefficients. The magnetic and electric fields are found to respond sluggishly to the neutralization process. Slow ions generated by charge-exchange have been added to the model, although the CT neutralization process was not significantly affected by this. Finally, the minimum length for the CT neutralizer is proposed as 2 m from the simulation run time 10 μs at a CT injection speed of 200 km/s.

Keywords: compact torus, charge-exchange, hybrid simulation, plasma fuel-injection, slow ion, neutralization

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1. Introduction

"CT Neutralization Fuel Injection" is an expansion of the "CT Injection" method [1, 2]. The "CT Injection" method was proposed as a fuel-injection method for large-scale power generation plasmas such as the ITER. However, its feasibility is still unclear because of the difficulty concerning the translation process of a plasmoid across the vertical magnetic field of the fuel injection target. To solve this problem, the "CT Neutralization Fuel Injection" method has been proposed [3]. This method utilizes a neutralization cell which transforms the injection plasmoid into an ultra-fast neutral gas flow. It is expected to be faster than conventional methods such as the "Gas-Puff" or "Pellet Injection". Therefore, there is a high possibility of reaching the core of the fuel injection target.

In this study, we run a computer simulation on the neutralization process inside the "CT Neutralization Fuel Injection" device. A hybrid simulation model is used to take into account the electromagnetic behavior inside the neutralization cell. In particular, it should be clarified if the magnetic flux would decay with the plasma current and associated radial expansion of the plasma would cause the imbalance of the radial force, or not. We also study the influence of the axial electric field generated by the friction force between electrons in the moving plasmoid and slow ions.

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2. Simulation Model

2.1 Hybrid model

In our calculations, we focus on the plasmoid itself moving through the cell.

The CT plasmoid is treated as a stationary target with which the neutral gas particles of the cell collide and charge exchange, as shown in Fig. 1. The collision processes are simulated by using rate-coefficients. The calculation determines the plasmoid's degree of neutralization, and as a result minimum cell length is found.

In the hybrid model, ions in the CT are treated as particles, while the electrons are treated as a fluid. Initial ions are loaded into cells uniformly across the calculating area as 'super particles', which have statistical weights defined by the Maxwell distribution function,

$$f_{Mi} = n_i \left(\frac{m_i}{2\pi T_i}\right)^{3/2} \exp\left(-\frac{m_i v^2}{2T_i}\right), \quad (1)$$

where $v = \sqrt{v_r^2 + v_\theta^2 + v_z^2}$. Assuming that the initial CT plasma before penetrating the neutral gas region is in the Grad-Shafranov equilibrium, the necessary CT ion density

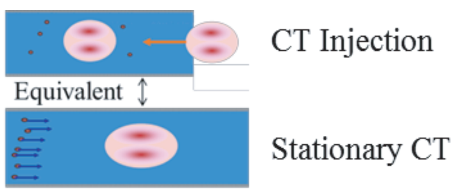

Fig. 1 Equivalent model between CT injection into a neutralization cell and axial neutral beam injection into a stationary CT.

profile for equation (1) is determined by solving the Grad–Shafranov equilibrium equation with a pressure profile for Spheromak like plasmoids, which results in a flux function shown in Fig. 2.

After loading about 10^8 ions as above mentioned 'super particles', particle motions are calculated using the equation of motion in magnetized plasmas [4],

$$m_\alpha \frac{d\boldsymbol{v}_\alpha}{dt} = q_\alpha (\boldsymbol{v}_\alpha \times \boldsymbol{B} + \boldsymbol{E}) - \sum_\beta m_\alpha \nu_{\alpha\beta} \left(\boldsymbol{v}_\alpha - \boldsymbol{u}_\beta\right), \tag{2}$$

where α is the test ion, β is the background electron, ν is the slowing-down collision frequency, $\boldsymbol{B}$ is the magnetic field, $\boldsymbol{E}$ is the electric field, and $\boldsymbol{u}$ is the background electron fluid velocity, respectively. The necessary initial magnetic field for equation (2) is obtained by,

$$B_r = -\frac{1}{r}\frac{\partial\psi}{\partial z}, \quad B_\theta = \frac{F}{r}, \quad B_z = \frac{1}{r}\frac{\partial\psi}{\partial r}, \tag{3}$$

while the electric field is calculated from the generalized Ohm's law,

$$\boldsymbol{E} = -\boldsymbol{u}_e \times \boldsymbol{B} + \frac{\boldsymbol{R}_{ei}}{en_e}, \tag{4}$$

where $\boldsymbol{R}$ is the resistive force between the ion particles and electron fluid, as will be mentioned later.

In each time step, after the ion's motion is calculated, the ion velocity is calculated by the PIC method. The electron velocity is given by the definition of current density,

$$\boldsymbol{j} = en_e (\boldsymbol{u}_i - \boldsymbol{u}_e), \tag{5}$$

where the electron density is assumed to be equal to the ion density obtained from the PIC method to fulfill the quasi-neutrality. Finally, by integrating Faraday's law,

$$-\frac{\partial\boldsymbol{B}}{\partial t} = \nabla \times \boldsymbol{E}, \tag{6}$$

we obtain the magnetic field needed for the next time step.

In plasma, the ion's motion is changed by collisions and the electric field is also affected. In our calculations, slowing-down collisions and pitch-angle scattering are considered. Slowing-down collisions are the ion's drag against electrons, causing deceleration. This term is used in the equation of motion by means of the slowing-down collision frequency, which is obtained from the Vlasov equations [4]. Next, pitch-angle scattering is the effect of the ions colliding with each other. The total energy of colliding ions remains unchanged, while the velocities are changed by the collision. The base pitch-angle is calculated and the collision frequency is used to determine the effective pitch-angle for each collision [5].

2.2 Neutralization calculations

The charge exchange effect of the ions is simulated by reducing the weight of each 'super particle' using the charge exchange rate coefficient,

$$\frac{dW_i(t)}{dt} = -W_i(t)\, n_n \langle\sigma v\rangle, \tag{7}$$

$$W_i(t + \Delta t) = W_i(t)\,(1 - n_n \langle\sigma v\rangle \Delta t), \tag{8}$$

where W_i is the weight, n_n is the neutral fluid density, and $\langle\sigma v\rangle$ is the charge exchange rate coefficient, respectively.

During the neutralization process, slow ions are generated by charge exchange in the neutralization cell. They are 'slow' in that the ions are lower in temperature than the CT, meaning lower energy. The slow ions are expected to 'pull (decelerate)' the CT by the friction force between electrons in the moving plasmoid and will create an axial electric field.

3. Results and Discussions

At first, the hybrid simulation without considering the slow ions has been carried out. The Grad-Shafranov equilibrium of a CT in a 'flux-conserved' container was used for the initial CT state. The parameters listed in Table 1 were assumed in the simulation.

The simulation results are summarized in Fig. 3. These results are reasonable, since the front-end of the CT becomes neutralized faster than the rear sections in accordance with the typical reaction time $1/(n_n \langle\sigma v\rangle)$, which is about 1 µs. Also, the simulation run time 10 µs at a CT injection speed of 200 km/s corresponds to a neutralizer penetration length of about 2 m.

However, axial electric field generation and radial expansion of the plasma were not observed in significant levels in this result. By adding slow ions to our simulation, we expect the electric field to intensify and cause current decay.

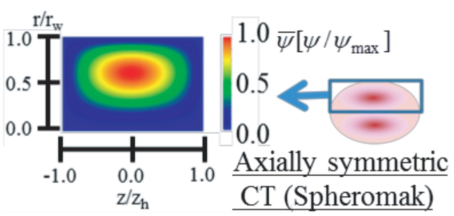

Fig. 2 Normalized poloidal flux function in the Grad-Shafranov equilibrium state.

Table 1 CT parameters.

Max Ion Density	7.0×10^{21}	[m^{-3}]
Ion Temperature	10	[eV]
CT Radius	5.0	[cm]
CT Length	7.5	[cm]
CT Elongation	1.5	[-]
CT Magnetic Field	0.2	[T]

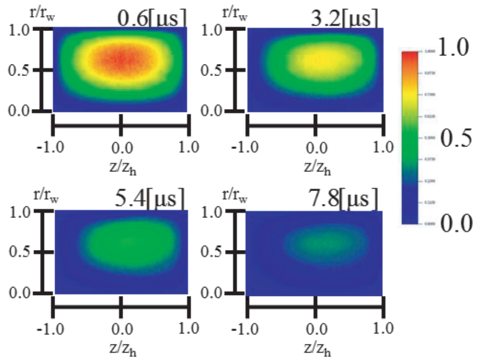

Fig. 3 Time evolution of CT ion density. The colors indicate the remaining density normalized to the initial maximum ion density parameter $7.0 \times 10^{21}\ \mathrm{m}^{-3}$. The neutral gas pressure is at 1.0×10^{-3} Torr and the CT injection velocity is at 200 km/s.

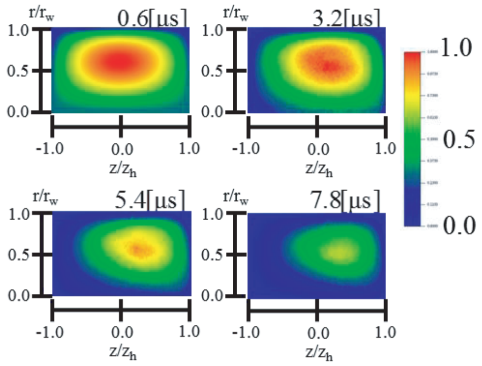

Fig. 4 Time evolution of CT ion density combined with the slow ion density. The color bar normalization, gas pressure, and injection velocity are the same as Fig. 3.

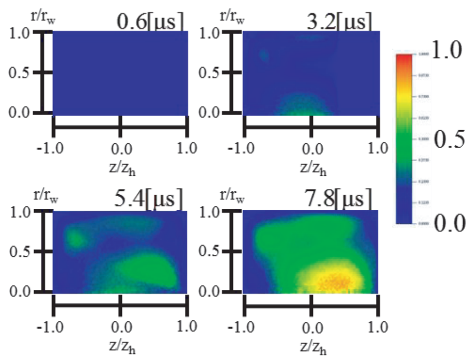

Fig. 5 Time evolution of slow ion density. The color bar normalization, gas pressure, and injection velocity are the same as Fig. 3.

We now show the results of a hybrid simulation on CT plasma with slow ions included in the model. The plasma was calculated with the same parameters as before.

Figure 4 is the combined ion density time evolution result of our simulation and Fig. 5 is the result with only slow ion density. As shown, a fraction of the slow ions are trapped by the CT magnetic field, with the slow ion's trajectory being almost the same as the CT ions. Also, the combined ion density shows that the CT neutralization process is not affected much by the slow ion's emergence.

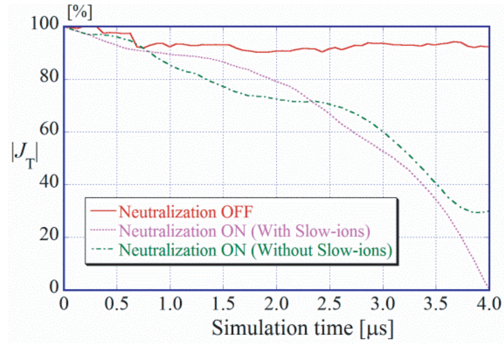

Fig. 6 Time evolution of normalized toroidal current at initial maximum current position.

Now, we follow up on the topic of the effects of neutralization. We expected that magnetic flux decay and the associated radial expansion of the plasma would occur from the toroidal plasma current reduction, which in turn is caused by the neutralization process. To check the validity of current decay in our results, we first determined the L/R time of toroidal current decay estimated from the toroidal inductance and Spitzer resistivity.

The spheromak inductance L and the plasma resistivity R was determined by using the plasma major radius R_0 for simplicity,

$$L \approx \mu_0 R_0, \tag{9}$$

$$R = \eta \frac{\ell}{S} = \eta \frac{2\pi R_0}{S}, \tag{10}$$

where S is the plasma cross section and η is Spitzer resistivity, which is calculated by,

$$\eta = 1.03 \times 10^{-2} \times Z_{\mathrm{eff}} \ln \Lambda\, T^{-3/2}\ [\Omega \cdot \mathrm{cm}] \tag{11}$$

where Z_{eff} is the effective charge number, T is the plasma temperature in eV, and $\ln \Lambda$ is the Coulomb logarithm. In our hydrogen CT plasma, the effective charge number is 1.0 and temperature is at 10 eV, resulting in $\eta \approx 3 \times 10^{-5}\ \Omega \cdot \mathrm{m}$. Therefore, the L/R time is determined as $\tau \approx 50\ \mu\mathrm{s}$ using formula (9), (10), and parameters from Table 1.

From the L/R time above, some natural toroidal current decay is expected, but not at significant levels. Now we show the actual toroidal current time evolution result in Fig. 6. From this result, we can determine that abnormal current decay is being caused by the neutralization.

4. Summary

From our results, the CT neutralization process is not affected overall from slow ions. Therefore, the CT was neutralized in a run length that collates to a neutral gas cell length of about 2 m.

However, there are a lot of elements not considered yet in our simulation; such as electric field electron pressure gradients, charge re-exchanges, and also problems associated with numerical oscillation persists. Therefore, we plan to add and solve the above factors and improve our simulation to achieve a more accurate representation of the CT neutralization process.

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