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Motion of the ablation cloud in torus plasmas

RYUICHI ISHIZAKI,[1]
N. NAKAJIMA,[1] M. OKAMOTO[1] and P. B. PARKS[2]
[1]National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan
[2]General Atomics, San Diego, CA 92186-5608, USA

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Abstract. The motion of an ablation cloud is investigated in a tokamak by using ideal magnetohydrodynamic equations with ablation processes. The cloud quickly expands along the magnetic field and simultaneously drifts to the lower field side due to a tire tube force and $1/R$ force. It is found that the acceleration of the cloud increases and subsequently decreases due to the energy deposit from the bulk plasma and, finally, the cloud is stopped due to the poloidal field.

1. Introduction

Injecting small pellets of frozen hydrogen into torus plasmas is a proven method of fueling. Experimentally, it is known that the density distribution, after the pellet is ablated by encountering the high-temperature plasma, is not consistent with the distribution inferred from assuming that the ablated material remains on the flux surfaces where the ablation occurred [1]. In addition, it is observed that the plasmoids are intermittently created [1]. The physical processes are divided into the following two stages. The first stage is the ablation of mass at the pellet surface due to the high-temperature bulk plasma which the pellet encounters. The neutral gas produced by the ablation is rapidly heated by electrons and ionized to form a high-density and low-temperature plasma, namely a plasmoid. The second stage is the redistribution of the plasmoid by free streaming along the magnetic field lines and by magnetohydrodynamic (MHD) processes which cause mass flow across flux surfaces. The former stage is well-understood by an analytic method [2] and numerical simulation [3]. Although each of the drift motion and intermittent creation of the plasmoid have been investigated in the latter stage [4, 5], physics including both of them have not been clarified yet. Since the intermittent creation is considered to be closely related to the former stage, the purpose of the study is to understand the drift motion and intermittent creation of the plasmoid comprehensively by carrying out the simulation including both stages. As a first trial, the drift motion of the plasmoid is investigated in a tokamak. It is found that the motion to the lower field side is induced by a tire tube force due to the plasmoid pressure and $1/R$ force due to the magnetic field.

2. Basic equations

Since the plasmoid is such a large perturbation that the linear theory cannot be applied, a nonlinear simulation is required to clarify the behavior of the plasmoid. The drift motion is considered to be a MHD behavior because the drift speed obtained from experimental data [1] is about 0.01–1.0v_A, where v_A is an Alfvén

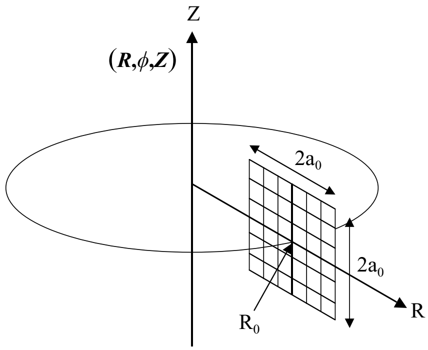


Figure 1. Coordinate system used in the CAP code.

velocity. Thus, the three-dimensional MHD code including the ablation processes has been developed by extending the pellet ablation code (CAP) [3]. The equations used in the code are

$$\frac{d\rho}{dt} = -\rho\nabla\cdot\mathbf{u}, \tag{2.1a}$$

$$\rho\frac{d\mathbf{u}}{dt} = -\frac{\beta}{2}\nabla p + (\nabla\times\mathbf{B})\times\mathbf{B}, \tag{2.1b}$$

$$\frac{dp}{dt} = -\gamma p\nabla\cdot\mathbf{u} + H, \tag{2.1c}$$

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{u}\times\mathbf{B}) \tag{2.1d}$$

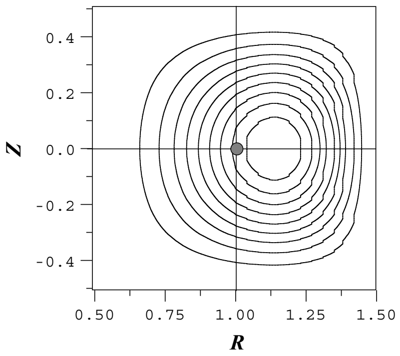
All variables except time and length are normalized by those at the magnetic axis, ρ_0, p_0, B_0 and v_A, where $v_A = B_0/\sqrt{\mu_0\rho_0}$. Length and time are normalized by the major radius at the center of the poloidal surface, R_0, and Alfvén transit time, $\tau_A = R_0/v_A$, respectively. γ and $\beta = 2\mu_0 p_0/B_0^2$ are the ratio of the specific heats and plasma beta, respectively. The heat source H is given by

$$H = \frac{dq_+}{dl} + \frac{dq_-}{dl}. \tag{2.2a}$$

where $q_\pm$ is the heat flux dependent on electron density and temperature in the bulk plasma and the plasmoid density. l is the distance along the field line. The subscript + (−) refers to the right (left)-going electrons. Then, the heat source can be calculated on each field line. Assuming Maxwellian electrons incident to the plasmoid, a kinetic treatment using a collisional stopping power formula leads to the heat flux model, $q_\pm$ [3], which is used in the construction of one of the ablation models [2]. The cylindrical coordinates (R, ϕ, Z) are used in the code as shown in Fig. 1. R and ϕ are a major radius and toroidal angle, respectively, and the R–Z plane is a poloidal surface. a_0 is a minor radius. The boundary is assumed to be a perfect conductor. The *cubic interpolated pseudoparticle* (CIP) method is used in the code as a numerical scheme [6].

3. Simulation results in a tokamak

MHD simulation has been carried out to clarify drift motion of the plasmoid in a tokamak plasma with $\beta = 0.01$, $R_0/a_0 = 2$ and $\gamma = 5/3$ as shown in Fig. 2. In an



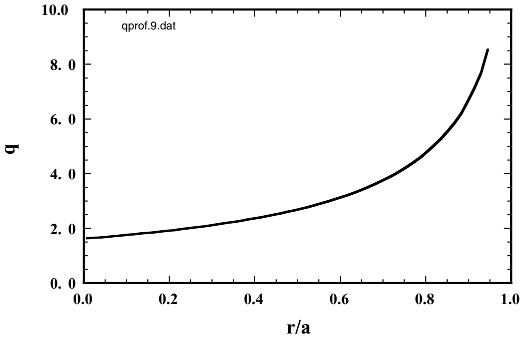


Figure 2. (a) Initial position of the plasmoid on the poloidal surface in the tokamak, where magnetic surfaces are shown by contour lines. (b) Equilibrium q-profile in the tokamak.

initial condition, the plasmoid is stationary at $R = R_0$, and peak values of density and temperature of the plasmoid are 1000 times density and 1/1000 times temperature of the bulk plasma at the magnetic axis, respectively. The plasmoid, whose half width is $0.03R_0$, encounters the electrons with fixed temperature 2 keV and density 10^{20} m^{-3}. Figures 3(a) and (b) show density contours in the equatorial plane at $t = 1.0\tau_A$ and $6.0\tau_A$, respectively. The plasmoid is found to expand in the toroidal direction and simultaneously drifts to the lower field side. Figure 3(c) shows temporal evolution of peak values of the plasmoid pressure and density. The pressure reaches more than 150 times the bulk plasma pressure due to heating. On the other hand, the density decreases because the plasmoid expands along the magnetic field. Since a decrease in the density reduces the energy deposit to the plasmoid, the pressure decreases after it reaches a peak value. In addition, the pressure and density have oscillation with a period of about $1.0\tau_A$ induced by the fast compressional Alfvén wave. The drift motion is considered to be induced by a tire tube force coming from the plasmoid with an extremely large pressure disturbance and by a $1/R$ force stemming from the toroidal magnetic field with a gradient and curvature. Figure 3(d) shows the temporal evolution of the displacement of the plasmoid from the initial position, ΔR. Solid and dashed lines show ΔR in the tokamak plasma and in a uniform plasma with the toroidal magnetic field, respectively. Although the plasmoid in the toroidal magnetic field can reach near the boundary, $\Delta R = 0.5$, that in the tokamak is stopped at $\Delta R = 0.34$ because compression of the poloidal field suppresses the motion. Since the pressure increases and subsequently decreases as shown in Fig. 3(c), the acceleration also increases and subsequently decreases in both cases. The maximum drift speed in the tokamak is about $0.05v_A$ which corresponds to 10^5 m s^{-1} with the parameters $B_0 = 1$ T, $\rho_0/m_p = 10^{20}$ m^{-3} and $R_0 = 1$ m where m_p is the mass of a proton. This value is roughly the same order as experimental data [1].

4. Summary and future work

The motion of the plasmoid in the tokamak is investigated by using the ideal MHD equations including the heat flux model. It is found that the drift motion to the lower field side is induced by a tire tube force due to the plasmoid pressure and $1/R$ force due to the magnetic field. The pressure of the plasmoid increases due to heating

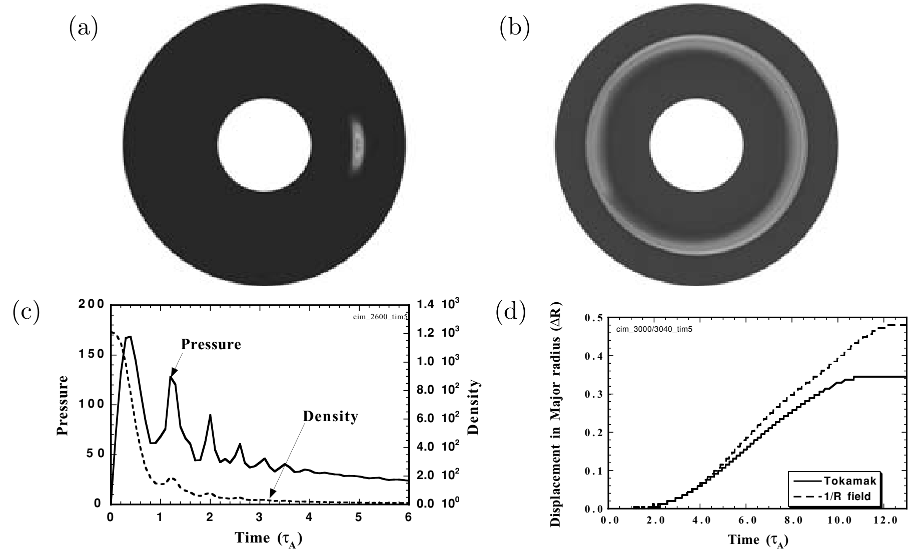


Figure 3. Density contours in the equatorial plane in the tokamak plasma at (a) $t = 1.0\tau_A$ and (b) $t = 6.0\tau_A$. (c) Peak values of pressure (solid curve) and density (dashed curve) of the plasmoid versus time. (d) Displacements of the peak density of the plasmoid in the tokamak plasma (solid curve) and in a uniform plasma with the toroidal magnetic field (dashed curve) versus time.

from the bulk plasma, and subsequently decreases because the energy deposit to the plasmoid is reduced by decrease in the density. Thus, the acceleration of the plasmoid increases and subsequently decreases. Finally, the plasmoid is stopped because compression of the poloidal field suppresses the motion. In addition, the pressure and density have oscillation induced by the fast compressional Alfvén wave. A comprehensive simulation including the creation of the plasmoid with resistivity and atomic processes will be carried out as future work.

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