Non-linear MHD simulations of the plasma instabilities by pellet injection in LHD plasma

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Introduction

The pellet injection is an experimentally proven method of plasma refueling in tokamaks [1, 2] and stellarators plasmas [3]. The pellet injection into the plasma is also used for plasma control, i.e. ELM (Edge Localized Mode) mitigation for tokamaks by means of the excitation of the Magnetohydrodynamic (MHD) activities. However, the plasma instabilities which are inimical phenomena via pellet injection are problems that have come into focus simultaneously. It is crucial to identify the complex physics mechanism between the plasma stability and the pellet ablation physics with non-linear MHD analysis.

In this work, the global MHD dynamics of the Large Helical Device (LHD), which is a large superconducting Heliotron in Japan, has been analyzed with MIPS code [4, 5] which solves the full MHD equations coupled with the pellet ablation model. The pellet ablation model which is based on neutral gas shielding model has been implemented in MIPS. The two important features are reflected in the implementation of the model into MIPS code in a similar manner with JOREK [6, 7]. The first feature is that the pellet is modelled as a localized adiabatic time-varying density source. The pellet density source is toroidally and poloidally localized. The second feature is that the pellet moves at fixed speed and the direction. The MHD modes excitation caused by the three-dimensionally localized pressure perturbation originated from the pellet injection has been observed. The dependence of the pellet injection condition on the MHD instabilities has been analyzed.

Model equations

The equilibrium of the LHD plasma which refers the shot of [8] is prepared by HINT2 code. The MIPS code computes the following full MHD equations starting from the initial equilibrium; In the magnetohydrodynamics approximation, plasma is modeled as a charge-neutral

electro-magnetic conducting fluid. In the incompressible description, the dynamics are given by

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \boldsymbol{v}), \tag{1}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} = -\rho(\boldsymbol{v} \cdot \nabla)\boldsymbol{v} - \nabla P + \boldsymbol{J} \times \boldsymbol{B} + \frac{3}{4}\nabla[\nu\rho(\nabla \cdot \boldsymbol{v})] - \nabla \times (\nu\rho\boldsymbol{\omega}), \tag{2}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E}, \tag{3}$$

$$\frac{\partial P}{\partial t} = -\nabla \cdot (P\boldsymbol{v}) - (\Gamma-1)P\nabla \cdot \boldsymbol{v} + \chi_\perp \nabla_\perp^2 (P-P_{eq}) + \chi_\parallel \nabla \cdot \left(\frac{\boldsymbol{B}}{B^2}\boldsymbol{B} \cdot \nabla P\right) + S_P, \tag{4}$$

$$\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B} + \eta(\boldsymbol{J} - \boldsymbol{J}_{eq}), \tag{5}$$

where is the vorticity $\boldsymbol{\omega} = \nabla \times \boldsymbol{v}$. Those equations are solved in the rectangular grids of the cylindrical coordinates (R, ϕ, Z). The resistivity η, the viscosity ν and the perpendicular and parallel heat conductivities $\chi_\perp$ and $\chi_\parallel$ which act as dissipation parameters are used in the equation. The system is normalizezd by $v_A R_{cnt}$, where v_A is the Alfvén speed and R_{cnt} is fixed as $R_{cnt} = 3.65\text{m}$. The resistivity and the perpendicular and parallel heat conductivities are assumed to be $\eta/\mu_0 = 10^{-6}$, $\chi_\perp = 10^{-6}$. The equilibrium current density is $\boldsymbol{J}_{eq}$ which corresponds to the Pfirsch-Schlüter current as net current equilibrium is not assumed in the model.

The neutral gas shielding (NGS) model of pellet ablation [9] is presently one of the widely compared model with experiment. The NGS model provides a simple relationship between the ablation rate, the pellet size, and plasma parameters by solving the hydrodynamic equations in steady state. In this way, the total hydrodynamic particle source by the pellet along its trajectory is given by

$$\frac{dN}{dt} = 4.12 \times 10^{16} \cdot r_p^{1.33} \cdot n_e^{0.33} \cdot T_e^{1.64}, \tag{6}$$

where dN/dt is the pellet ablation rate [particles/second], r_p is the pellet size (spherical size assumed) in [m], n_e is the electron density of the bulk plasma in [m^{-3}] and T_e is the electron temperature in [eV].

This pellet ablation model has been implemented in MIPS code in a similar way with JOREK [7]. The MIPS code models the MHD equations with the pressure evolution. The implementation of the ablated particles from the pellet is represented as the pressure perturbation, i.e. $S_P = \Delta N \cdot T$ where $\Delta N = (dN/dt)\Delta t$ which is the number of ablated particles per time step. Figure 1 shows the pressure perturbation caused by the pellet ablation. The model of the implemented pellet density (pressure) source is toroidally and poloidally localized.

Simulation results

Initial MIPS-Pellet runs for non-linear MHD dynamics have been performed. The modelled LHD plasma has the edge electron pressure (P_e) of 2.4kPa and P_e of the core region is 6.9 kPa.
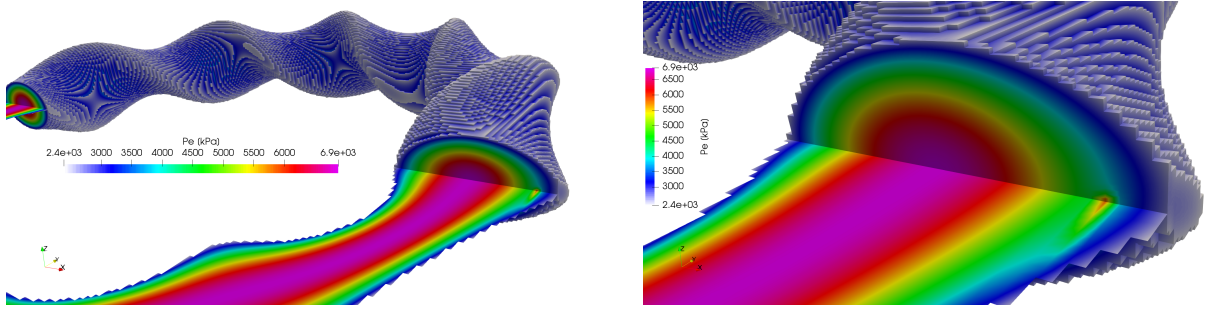
Figure 1: (Left panel) The global picture of the pressure perturbation caused by the pellet ablation and (Right panel) the zoom of the cross section of the toroidal plane of the pellet trajectory.
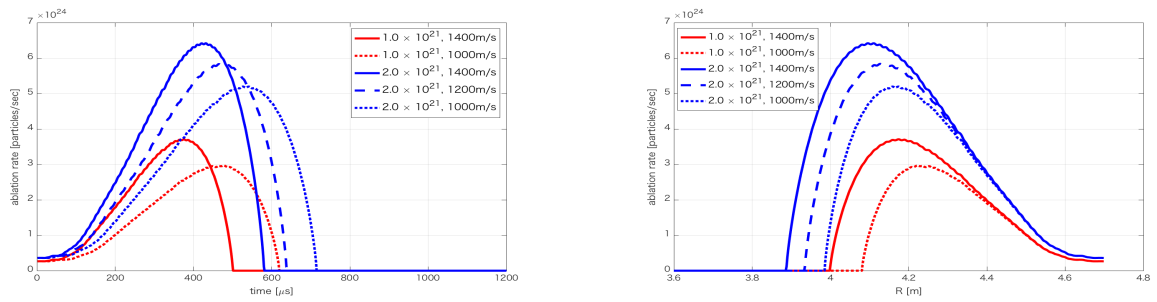

Figure 2: Pellet ablation rate profile (left) versus time and (right) versus plasma major radius R.

The electron temperature (T_e) at the edge is 1.4 keV and the core is 3.9 keV. The initial electron density (n_e) is constant with $1.1 \times 10^{19} [m^{-3}]$ for whole domain.

The pellet is injected from the outer-midplane of the LHD plasma (See Fig. 1). The pellet size has been varied for 1.0×10^{21}, 1.5×10^{21} and 2.0×10^{21} particles in a pellet. The injection velocity also has been varied for 1000m/s, 1200m/s and 1400m/s. Figure 2 shows the pellet ablation rate profiles versus time and versus plasma major radius R. The simulation shows the duration of the pellet ablation is typically 400-600 μs. The results of the pellet size dependence in the LHD plasmas show that the pellet penetration depth ranges for 0.5-0.7 m according to the pellet size. The simulation result is reasonably comparable values with the experiment observation [8] which is the case of the pellet size of 1.0×10^{21} within injection velocity of 1000m/s.

The pellet ablation creates the pressure perturbation. The pellet cloud propagates along the magnetic field lines. Figure 3(a) shows the pellet cloud profile at the maximum ablation of the pellet size of 2.0×10^{21} [particles/pellet]. The profile of the pellet cloud propagation profile
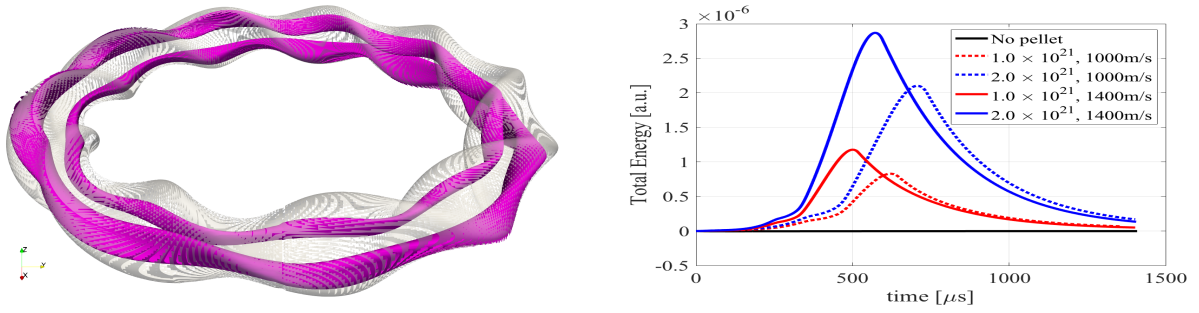
Figure 3: (Left panel) The pellet cloud profile at the maximum ablation of the pellet size of 2.0×10^{21} [particles/pellet]. (Right panel) Time evolution of the total energy for several pellet injection conditions.

depends on the magnetic configuration. The three-dimensionally localized pressure perturbation excites the MHD modes. Figure 3(b) shows the total energies for three cases, without pellet injection, 1.0×10^{21} and 2.0×10^{21} pellet sizes. The plasma is very stable therefore the energy growth is not observed when the pellet is not injected. However, the injection of the pellet excites the plasma energy and the energy growth is proportional to the injected pellet size.

Conclusions and perspectives

In the present work it is shown that the first approach of the pellet simulations for LHD plasma using MIPS code. This pellet ablation based on neutral gas shielding model has been implemented in MIPS code in a similar way with JOREK code. The pellet density (pressure) source is localized in toroidally and poloidally. The pellet ablation profiles are compared with the experiment data and the reasonable comparison has been observed which confirms the validity of the model and the implementation. The growth of the MHD modes caused the pellet injection has been observed for several pellet conditions. In the future work, the MHD physics model will be improved, for example, by splitting the pressure into density and temperature. Simulation results of MHD instabilities in LHD plasma will be compared with experiment.

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