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

Shimpei Futatani¹ and Yasuhiro Suzuki^{2,3}

¹*Department of Physics, Universitat Politècnica de Catalunya (UPC),
Avinguda Diagonal 647, 08028 Barcelona, Spain*

²*National Institute for Fusion Science, National Institutes of Natural Sciences,
322-6 Oroshi-cho, Toki 509-5292, Japan*

³*SOKENDAI, The Graduate University for Advanced Studies, 322-6 Oroshi-cho,
Toki 509-5292, Japan*

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The effect of pellets on global MHD dynamics of the Large Helical Device (LHD), which is a large superconducting Heliotron in Japan, has been analyzed with the MIPS code. A pellet ablation model based on the neutral gas shielding (NGS) model has been implemented. Excitation of MHD modes by the three-dimensionally localized pressure perturbation caused by the pellet injection has been observed. The dependence of the MHD-instabilities on the pellet size has been analyzed.

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I. INTRODUCTION

The pellet injection is an experimentally proven method of plasma refueling in tokamaks^{1,2} and stellarators plasmas³. 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. Besides the benefit of pellet injection in terms of the ELM control, the plasma instabilities which are inimical phenomena via pellet injection are problems that have come into focus simultaneously. For instance, the pellet injection excites a resonant localized structure named ‘snake’^{4,5} that significantly changes the plasma character. Also, the pellet triggers neoclassical tearing modes (NTMs), one of macro-scale MHD responses which degrades the plasma confinement⁶. In the micro-scale, the density gradient driven instabilities are excited around the pellet deposition location⁷. 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 the MIPS-code^{8,9} which solves the full MHD equations coupled with a pellet ablation model. The pellet ablation model which is based on neutral gas shielding model has been implemented in MIPS. Two important features in our implementation of the model in the MIPS-code are similar to the implementation in JOREK^{10,11}. The first feature is that the pellet is modeled 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 direction. This paper reports about the initial study of the pellet-excited MHD dynamics in a stellarator plasma. An excitation of MHD modes by the three-dimensionally localized pressure perturbation originated from the pellet injection has been observed. The dependence on pellet size of the MHD instabilities has been analyzed.

II. MODEL EQUATIONS

The modeled equilibrium of a LHD plasma which refers to a plasma reported in a recent paper¹² has been prepared using the HINT code^{13,14}. The MIPS code computes the full MHD equations starting from the initial equilibrium; In the MHD-approximation, the plasma

is modeled as a charge-neutral electro-magnetic conducting fluid. In the incompressible description, the dynamics is given by

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

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

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \quad (3)$$

$$\frac{\partial P}{\partial t} = -\nabla \cdot (P \mathbf{v}) - (\Gamma - 1) P \nabla \cdot \mathbf{v} \quad (4)$$

$$\begin{aligned} & + \chi_{\perp} \nabla_{\perp}^2 (P - P_{eq}) + \chi_{\parallel} \nabla \cdot \left(\frac{\mathbf{B}}{B^2} \mathbf{B} \cdot \nabla P \right) + S_P, \\ \mathbf{E} = & -\mathbf{v} \times \mathbf{B} + \eta (\mathbf{J} - \mathbf{J}_{eq}), \end{aligned} \quad (5)$$

where $\boldsymbol{\omega} = \nabla \times \mathbf{v}$ is the vorticity, P is the pressure, and S_P is the source term. These equations are solved on a rectangular grid of the cylindrical coordinates (R, Z, ϕ) . The resistivity η , the viscosity ν and the perpendicular and parallel heat conductivities $\chi_{\perp}$ and $\chi_{\parallel}$ act as dissipation parameters in the equations. The system is normalized by $v_A R_{cnt}$, where v_A is the Alfvén speed and R_{cnt} is a major radius with $R_{cnt} = 3.65$ m. The resistivity and the perpendicular and parallel heat conductivities are assumed to be $\eta/\mu_0 = 10^{-6}$, $\chi_{\perp} = 10^{-6}$ and $\chi_{\parallel} = 0$. In the presented simulations, the pressure diffusion parallel to the magnetic field has been neglected by setting $\chi_{\parallel} = 0$. The equilibrium current density $\mathbf{J}_{eq}$ corresponds to Pfirsch-Schlüter (PS) current. The PS current paths are toroidally closed, and the direction of the flow is opposite between high field side and low field side. Therefore, the net current in toroidal direction is zero.

The neutral gas shielding (NGS) model of pellet ablation¹⁵ is presently one of the models more widely compared with experiments. 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

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

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 the MIPS code in a similar way as in JOREK^{10,11}. The total particle source from the pellet is calculated from equation 6 using the local density and temperature and the radius of the real pellet (which reduces in time as the pellet ablates). The equivalent spherical radius of equation 6 is thus recalculated for the pellet at every time step. The position of the pellet changes in time along a given straight trajectory which the pellet is assumed to follow with a constant speed until its full ablation. The pellets deposit particles locally and adiabatically, producing strong local cooling. The local temperature drop is immediately reheated by the large parallel heat conductivity resulting in a pressure perturbation¹¹. The MIPS code models the MHD equations with the pressure evolution, not the equations of density and temperature separately, therefore the precise physics mechanism of the pressure perturbation is simplified assuming that the parallel heat conductivity is much faster than the parallel particle diffusivity since the main emphasis of the work is to understand the propagation of the pellet cloud in a stellarator plasma and the MHD response.

The code implementation models the ablated particles as a 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 source which is poloidally and toroidally localized (pellet location and radius).

FIG. 1. A zoom of the cross section of the toroidal and the poloidal plane of the pellet trajectory. The pellet location is indicated with the color contour plot.

This study adopts the neutral gas shielding (NGS) approximation, i.e. neglecting the additional shielding of the ionized part of the ablation cloud. The ablated pellet forms a cloud around the pellet with a few hundred nanoseconds time scale which is much faster

time scale of pellet ablation of a few hundred microseconds or MHD of a few milliseconds time scales. Plasma transport is longer time scale than MHD, that is in the order of a few hundred milliseconds. Therefore, the ionization process has been omitted in this work.

III. SIMULATION RESULTS

Initial MIPS-pellet-runs for non-linear MHD dynamics have been performed for a modeled LHD plasma. The numerical resolution which has been used for the study is $(N_R, N_Z, N_\phi) = (128, 128, 640)$ where N_R , N_Z and N_ϕ are the numbers of the grid points of the cylindrical coordinates (R, Z, ϕ) , respectively. The modeled LHD plasma has an edge electron pressure (P_e) of 1.1 kPa and P_e of the core region is 8.6 kPa. The electron temperature (T_e) at the edge is 0.55 keV and in the core it is 4.5 keV. The initial electron density (n_e) is constant with $1.1 \times 10^{19} [m^{-3}]$ for the entire domain. The pellet is injected from the outer-midplane of the LHD plasma as is the case in the LHD device³.

The pellet size has been varied from 1.0×10^{21} , 1.5×10^{21} and 2.0×10^{21} particles in a pellet, keeping the pellet injection velocity at 1000 m/s. The initial pellet injection location is $R = 4.70$ [m] which is outside of the plasma. The injected pellet enters the plasma and starts to ablate due to the plasma temperature according to the pellet ablation rate given by Eq. (6). Figure 2 shows the pellet ablation rate profiles versus time and versus plasma major radius R . The simulation shows a duration of the pellet ablation of typically 400-500 μs . The obtained time scale of the pellet ablation indicates that the ablation process is much faster than the ionization process of ablated particles from the pellet. The results of the pellet size dependence in the LHD plasmas show that the pellet penetration depth ranges for 0.4-0.6 m according to the pellet size. The simulation results compare reasonably well with values from experimental observations¹² with pellet sizes of 1.0×10^{21} [atoms/pellet] and injection velocities of 1000 m/s. The pellet ablation creates a pressure perturbation. After the pellet injection, the pellet cloud appears as toroidally and poloidally localized pressure perturbation. During the ablation process, the localized pellet cloud expands along the magnetic field lines as time evolves. In this simulation, the pellet cloud reached the toroidal equilibrium at the time of the maximum ablation. Figure 3 shows the pellet cloud profile at the maximum ablation rate for the pellet size of 2.0×10^{21} [particles/pellet]. The modeled plasma shows the $m/n = 1/1$ profile of the pellet cloud propagation. The configuration of

FIG. 2. Pellet ablation rate profile (top) versus time and (bottom) versus plasma major radius R .

the three-dimensional pellet cloud profile reflects the location of the flux tube along which the pellet cloud expands. In a longer time-scale, the pellet cloud will be distributed over the poloidal direction due to transport process.

Once released from the pellet, that density cloud expands along the field line of the flux tube at the sound speed of the ions. Simultaneously with this expansion, the cloud is being heated by electrons along the field lines at a much higher speed dictated by the parallel thermal diffusion. This results in a local pressure cloud formation that expands along the field line^{11,16}. Figure 4 shows the time evolution of the pressure perturbation at the pellet location respect for the plasma equilibrium. Simulations show that the pressure perturbation is 8-13 % respected to the equilibrium depending the injected pellet size. The MIPS code solves the pressure evolution assuming that the parallel heat conductivity is fast and the local drop of the temperature is not considered. Therefore, the pressure perturbation is

FIG. 3. The pellet cloud profile at the maximum ablation for the pellet size of 2.0×10^{21} [particles/pellet].

proportional to the particle deposition.

The 3D profile of the pellet cloud depends on the magnetic configuration. The pellet simulation of different equilibrium which is based on different magnetic configuration as shown in Fig.5. The pellet cloud shows the profile of $m/n = 2/1$ is different from Fig.3 which is reconstructed equilibrium based on the experiment data. It indicates that 3D profile of the extension of pellet cloud strongly depends on the configuration of magnetic field, especially in stellarators which consist of complex magnetic configuration. The scan

FIG. 4. The time evolution of the pressure perturbation at the pellet location respect for the plasma equilibrium for the pellet sizes of 1.0×10^{21} , 1.5×10^{21} and 2.0×10^{21} [atoms/pellet].

FIG. 5. The pellet cloud which is induced by the injection of large pellet, 2.0×10^{21} [particles/pellet] in the plasma of different magnetic configuration.

and the detail analysis of the dependence of magnetic configurations will be carried out for future work.

Figure 6 shows the time evolution of magnetic energies for two cases; without pellet injection and the injection of the 2.0×10^{21} [atoms/pellet] pellet. The spectra are computed up to $m = 96$ and $n = 48$. In order to distinguish the lines, only the combinations of $m = 1 - 3$ and $n = 1 - 3$ which are the dominant modes are plotted. The time evolution of the magnetic energies in the absence of the pellet injection is very stable and decaying.

FIG. 6. Time evolution of the magnetic energies of (top) without pellet injection and (bottom) the injection of 2.0×10^{21} [particles/pellet] pellet.

However, the pellet with 2.0×10^{21} [particles/pellet] excites all modes, especially the ones with higher m numbers, $m/n = 3/1$, $m/n = 3/2$ and $m/n = 3/3$ at $t = 150 \mu s$. The magnetic energies are excited during the pellet ablation process. After the full pellet ablation, the pressure perturbation decays and is redistributed via plasma transport processes. Therefore, the MHD excitation starts to relax when the pellet reaches the full ablation, at $t = 480 \mu s$.

Figure 7 shows the time evolution of the magnetic energies for the cases with no pellet and pellet sizes of 1.0×10^{21} , 1.5×10^{21} , and 2.0×10^{21} . The modes of $m/n = 2/1$, $m/n = 2/2$, $m/n = 2/3$ are plotted with solid lines, dashed lines and dotted lines, respectively. The amplitude of the excited MHD energies is proportional to the size of the injected pellet, larger pellets result in larger amplitudes of the excited MHD activity.

FIG. 7. Time evolution of the magnetic energies for the case of absence of the pellet, 1.0×10^{21} (green lines), 2.0×10^{21} (blue lines), 2.0×10^{21} (red lines). The pellet injection velocity is 1000 m/s for all cases. The modes of $m/n = 2/1$, $m/n = 2/2$, $m/n = 2/3$ are plotted in the solid lines, dashed lines and dotted lines, respectively.

IV. CONCLUSIONS AND PERSPECTIVES

The present work showed the first usage of the MIPS-code to investigate the effect of pellet ablation on MHD-behavior of stellarator plasmas. The modelling of the pellet ablation with the neutral gas shielding has been implemented in the MIPS code in a similar way as in JOREK. The pellet density (pressure) source is localized toroidally and poloidally and the source moves at fixed speed and direction. The duration of the pellet ablation which has been observed in the simulations is 400-500 μ s which is a typical time scale of the pellet ablation in fusion plasmas. The pellet ablation profile has been compared with experimental data which is shown in Fig. 4(b) of Ref [12]. The reasonable agreement was found for the depth of the pellet deposition which gives confidence in the validity of the model and its implementation. The growth of the MHD modes caused by pellet injection has been studied via a scan of the pellet size.

In future work, the MHD physics model and the pellet model will be improved, for example, by splitting the pressure into density and temperature. It is important to solve the precise physics, i.e. the pressure perturbation is excited by the ablated particles of the pellet and also the recovery of the local temperature drop via large parallel heat conductivity. Regarding the pellet model, the present pellet cloud modelling assumes the ablated pellet

particles are directly converted to the plasma particles. In order to understand the precise physics phenomenon due to the pellet in the fusion plasma, the model will be improved to consider the neutrals modelling, i.e. the ablated pellet particles are converted to the neutrals particles, then the neutrals particles will be converted to the plasma particles in a self-consistent way which considers the local temperature etc. Simulation results of MHD instabilities in LHD plasma will be compared with experimental results for different scenarios, including the dependence of magnetic configurations.

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Appendix A: Appendix: Parallelization performance of MIPS code

The MIPS code is the extraction of the MHD interface from the MEGA code which is a unique code for modeling 3D Kinetic-MHD hybrid simulations⁸. It allows to treat the different time-scales of the perturbations for the analysis of the plasma. The advantage and the novelty of the MIPS and MEGA codes is that the simulation geometry can be chosen arbitrarily as the code works in three-dimensional Cartesian grids. The simulation geometry depends, therefore, on the implementation of the magnetic field configuration, i.e. the implementation of X-point geometry in tokamaks or stellarators which have helical shaped magnetic configurations. The MPI parallelization is performed by cutting the three-dimensional Cartesian grids into equal pieces of cubes according to the number of cores to

FIG. 8. The time consumes for MIPS performance versus number of cores of MPI parallelization.

be used. The performance of the parallelization has been analyzed using MareNostrum IV which is the most powerful supercomputer in Barcelona, Spain. The numerical resolution of the simulation domain for the test case is $128 \times 128 \times 256$, while for the production run $128 \times 128 \times 640$ was used. The number of cores has been varied for 16, 32, 64, 128, 256, 512, 1024, 2048, 4096, 8192, 16384 cores. The speed of the MPI computing increases linearly according to the number of cores until 4096 cores as shown in Fig. 8. Numbers of cores larger than 8192 do not profit from the parallelization. The parallelization scaling might be limited to show the saturation between 4096 to 8192 cores due to the problem size. The communication overhead increases with the number of cores and the workload they have to do. It is reasonable to observe the saturation of the scaling between 4096 and 8192 cores using the resolution of the problem size.

The pellet simulation can not take advantage of a toroidal periodicity but needs to treat the full torus and therefore it requires a large resolution in toroidal direction. One production run requires 48 hours of wall-time using 256 cores.

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