Effects of Pellet ELM Pacing on Mitigation of Type-I ELM Energy Loss in KSTAR and ITER

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Abstract. Control of type-I ELMy H-mode by pellet injection has been numerically investigated in this work for KSTAR and ITER. A predictive transport modeling on ELMy H-mode in KSTAR reproduces consistent plasma dynamics compared with the experiments in other tokamaks, and provides a reasonable scaling between H-mode pedestal and ELM characteristics. The numerical simulation results of pellet ELM pacing in KSTAR show that the pellet induced ELMs release reduced energy bursts compared to spontaneous ELMs, which supports the necessity of high-frequency pellet injection for the mitigation of ELMs in tokamaks. A pellet-induced density perturbation model is applied to the ITER reference ELMy H-mode scenario so that the control of type-I ELMy H-mode by pellet injection can be demonstrated to check an availability of the pellet ELM pacing for mitigating ELM peaks in ITER. Even though the pellet ELM pacing is predicted to reduce the ELM peak by a factor of 2 compared to spontaneous ELMs in ITER, further enhancement of mitigation performance is required to satisfy engineering restrictions of PFCs for fully controlled ELMy H-mode plasmas. An ongoing MHD modeling on spontaneous and pellet-induced ELMs is introduced for better understanding of ELM physics and its control.

1. Introduction

Mitigation of Edge Localized Modes (ELMs) in H-mode discharges is a critical issue in fusion reactors to achieve high fusion powers without severe damages to plasma facing components (PFCs). Pellet injection is one of promising techniques for ELM mitigation, but the physics of ELM triggering mechanism by pellets has not been clearly understood so far owing to the complexity of ELM generation processes [1]. Most of pellet injection experiments in present day tokamaks have been conducted based on the experiences and assumptions. The transport of plasmas with injected pellets has not wholly examined yet. Numerical and theoretical studies with transport [2] and MHD [3] modeling on pellet-induced ELMs have recently started.

A pellet launching system from high field side (HFS) is planned to be installed for the KSTAR tokamak in the near future for a multipurpose task of core fueling, diagnosis, disruption mitigation, and ELM control. It is, however, uncertain how the injected pellets behave in plasmas and whether the pellets trigger ELMs in KSTAR. A preliminary study is, therefore, needed for the design of the pellet injection system and future experiments for KSTAR.

ITER may require more rigorous studies to guarantee a successful ELM control by pellet injection. ITER is planned to have two pellet launchers from HFS and low field side (LFS) for core fueling and ELM pacing. Novel pellet launching systems are under development to reach the engineering requirements [4]. Spontaneous ELM frequency and ELM energy loss in ITER were scaled to be about 1 - 5 Hz and ~ 20 MJ, respectively. But, the material limit of PFCs is only about 1 MJ [5], which means that the ELM energy loss should be reduced by a factor of 20 for undamaged PFCs. This is a challenging issue, but it is still questionable how the injected pellets affect ITER plasmas. Understanding of ELMs and their interactions with pellets must be progressed to satisfy the ITER requirements as well as the technology development of pellet injection systems.

This paper deals with the numerical investigation on the control of type-I ELMy H-mode using pellet injection in tokamak plasmas. Mainly the ELM mitigation performance is estimated and discussed for KSTAR and ITER, and additionally an ongoing MHD modeling on ELM mechanism is introduced.

2. Pellet ELM pacing simulation for KSTAR

Numerical modeling on ELMy H-mode and its control by pellet injection in KSTAR is carried out using a 1.5D core plasma transport code. The employed numerical code calculates self-consistently the continuity equation of electron density, the momentum equations of electron and ion, the current diffusion equation, and the toroidal momentum equation [6]. The simulation parameters are based on KSTAR baseline operation conditions: toroidal magnetic field 3.5 T, plasma current 2 MA, and neutral beam injection (NBI) power 8 MW. The thermal conductivities of electron and ion are calculated by linear combinations of neoclassical and anomalous transport components from ion temperature gradient, resistive ballooning, kinetic ballooning, and electron temperature gradient modes. General dynamics of the type-I ELMy H-mode plasmas in tokamaks are successfully reproduced, and the parametric analyses provide a reasonable scaling of H-mode pedestal and ELM characteristics. The inverse proportionality of ELM energy loss to the ELM frequency is confirmed [7] as seen in Figure 1.

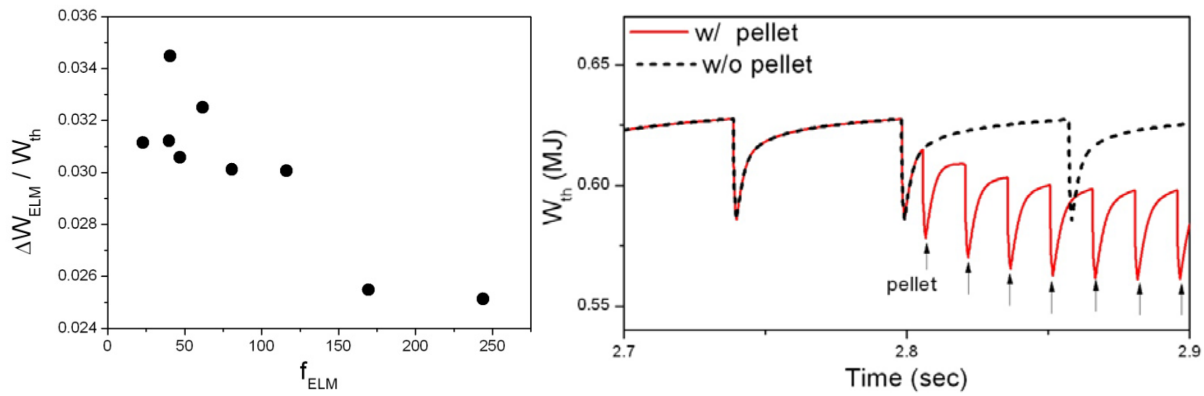

Fig. 1. Scaling of ELM energy loss normalized to total stored energy ($\Delta W_{ELM}/W_{th}$) as a function of spontaneous ELM frequency (f_{ELM}), and time evolution of total stored energy in type-I ELMy H-mode with and without pellet pacing in KSTAR

A neutral gas shielding (NGS) model [8] and a scaling model based on grad-B induced pellet drift [9] are applied to calculate the ablation rates and drift displacement of the ablated particles. The pellet injection model is integrated with the core transport code to simulate the plasma transport responding to pellet injection. The particle transport is described by the sum of diffusion and inward pinch terms [10]. The transport code coupled with the pellet injection model is benchmarked with a pellet fueling discharge at JET, which indicates that the particle transport is enhanced in the higher-density region after sequential pellet injections [2, 11].

For the description of ELM triggering by pellet injection, a pellet-induced density perturbation model, which is based on an assumption of ELM triggering by ballooning-like pressure perturbations induced after pellet injection, is proposed to carry out an ELM pacing transport simulation for KSTAR [2]. The transport enhancement factor at the edge pedestal and the ELM duration are fixed as 100 and 1 ms, respectively, for both spontaneous and pellet induced ELMs.

Evolutions of total stored energy according in type-I ELMy H-mode with and without pellet pacing in KSTAR are shown in Figure 1 (right). Pellets containing 10^{20} deuterium atoms are injected from HFS into the ELMy H-mode plasma with a spontaneous ELM frequency of f_{ELM} = 17 Hz. It is observed that the spontaneous ELM is completely paced to the pellet injection frequency so that $f_{ELM} = f_{Pel}$ = 66 Hz is achieved in the ELM pacing phase. The total energy stored in the plasma gradually decreases during a series of pellet injections to the slightly lower values than that without pellets. The energy loss of pellet-induced ELM normalized to total stored energy is considerably reduced compared with the spontaneous ELM, as appeared in Figure 2 where the ELM energy loss induced by pellets becomes significantly smaller at higher pellet injection frequency. The pellet-induced ELM energy loss decreases with increasing pellet injection frequency and an energy loss reduction of more than 50 % is obtainable at a pellet frequency of above 333 Hz. The pellet ELM pacing is successfully demonstrated by the transport modeling which strongly supports the necessity of high-frequency pellet injection for the mitigation of ELMs in tokamaks.

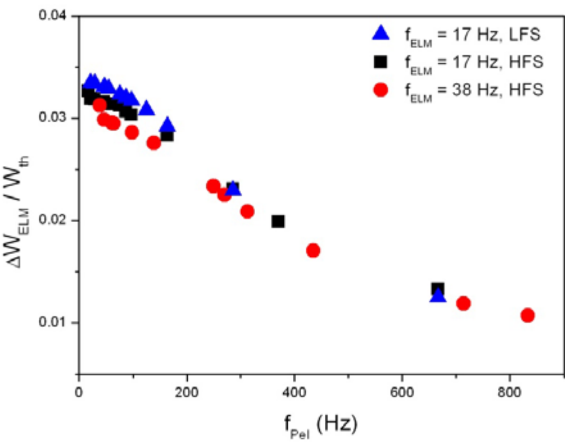

Fig. 2. Scaling of ELM energy loss normalized to total stored energy ($\Delta W_{ELM}/W_{th}$) as a function of pellet injection frequency (f_{Pel}) depending on pellet injection direction (LFS or HFS) and spontaneous ELM frequency (f_{ELM}) in KSTAR

3. Transport modeling of type-I ELMy H-mode in ITER

Extending the KSTAR simulation, the type-I ELMy H-mode scenario in ITER is numerically modeled by using the ASTRA code [12] on the basis of ITER design and operating parameters [13]. The major and minor radii of ITER are 6.2 m and 2.0 m, respectively. The toroidal magnetic field strength is 5.3 T, and the plasma current is 15 MA at a flat-top phase in the reference ELMy H-mode scenario. The elongation and triangularity of the plasma at 95 % of the last closed flux surface are 1.7 and 0.33, respectively. The volume-averaged electron density, $\langle n_e \rangle$ is set as 10.1 with $\langle n_e \rangle / n_G = 0.753$ where n_G is the Greenwald density limit. The injected external heating powers are limited to 33 MW for negative-ion based NBI [14] and 11.5 MW for prescribed ion cyclotron resonance heating (ICRH) [15]. A physics-based transport model, Multi-Mode Model (MMM) [16], is employed for anomalous transport calculations combined with neoclassical transport. Simulation starts at 100.0 s when the H-mode is established. The edge pedestal is formed by an assumption that the anomalous transport is fully suppressed outside the edge transport barrier at ρ = 0.95, therefore the edge transport barrier is governed by neoclassical transport. By the turbulence suppression outside the edge transport barrier, steep gradients of ion and electron temperatures at the pedestal are formed prior to an ELM crash as seen in Figure 3 (left). The radial profiles of external power deposition to electrons and ions from NBI, ICRH and alpha are shown in Figure 3 (right).

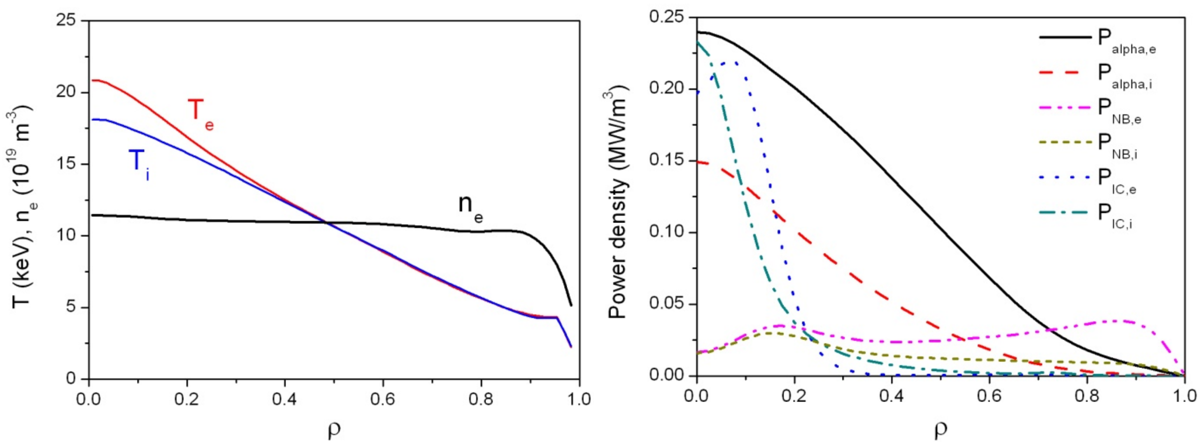

Fig. 3. Radial profiles of electron density (n_e), electron temperature (T_e), and ion temperature (T_i) (left), and power deposition to electrons and ions from NBI (P_{NB}), ICRH (P_{IC}), and alpha heating (P_{alpha}) (right) prior to ELM triggering in a type-I ELMy H-mode discharge of ITER

Analytic criteria for ballooning mode are applied to the triggering conditions of spontaneous ELM. Figure 4 illustrates the time evolutions of core and pedestal temperatures, volume-averaged electron density, alpha heating power, and total stored energy predicted from this modeling. It is obviously observed that the electron and ion temperatures at the pedestal top rapidly decrease by the ELM crashes. The electron density is also released by ELMs but sustained as almost constant level by gas puffing. It is clearly seen that the H-mode plasma transfers back to the L-mode due to the collapse of the edge pedestal by ELMs while the continuous external heating during the whole discharge leads to the re-transition to the H-mode, which results in the quasi-periodic oscillations of ELM crashes. Total stored energy, alpha power, and fusion power gain reach ~ 320 MJ, ~ 80 MW, and ~ 8, respectively. The resulting ELM energy loss is estimated to be ~ 25 MJ which is ~ 7.5 % of the total stored energy. Consequently, it is predicted that the type-I ELM in ITER will release an energy loss of 25 MJ to exceed the material limit of PFCs, which is required to be mitigated by external means. The present simulation predicts that T_{e0} ~ 23 keV, T_{i0} ~ 19 keV, and T_{ped} ~ 4.3 keV are achievable in stationary conditions from the type-I ELMy H-mode scenario in ITER.

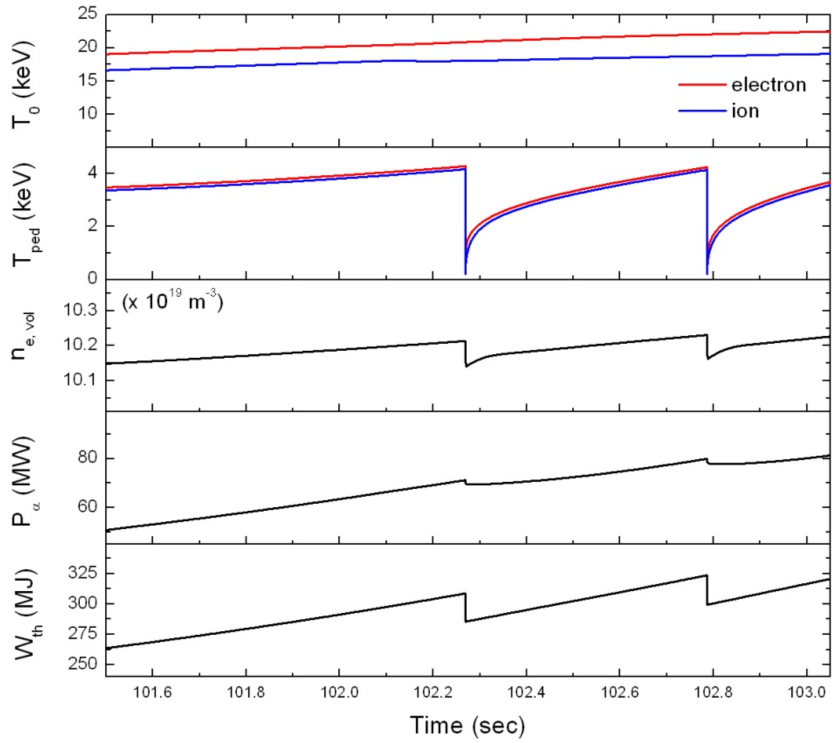

Fig. 4. Time evolutions of axis (T_0) and pedestal temperatures (T_{ped}), volume-averaged electron density ($n_{e,vol}$), alpha heating power (P_α), and total stored energy (W_{th}) in a type-I ELMy H-mode discharge of ITER

4. ELM pacing simulation by pellet injection in ITER

4. 1. HFS pellet injection

A Simplified Mass Ablation and Relocation Treatment (SMART) model [17] is used to calculate the pellet mass deposition profile for pellet ELM pacing simulation in ITER. The SMART model, which consists of pellet ablation [18], cloud formation [19], and mass relocation [20] modules, calculates the plasma temperature and density profiles after pellet injection. Typical radial profiles before and after pellet injection in the ITER ELMy H-mode scenario are illustrated in Figure 5 (left). A cylindrical pellet of 2 mm in diameter is injected at a velocity of 200 m/s from HFS into the H-mode plasma. The pellet parameters are selected to deliver pellet mass to the pedestal region escaping from gross perturbations on the core confinement during the pellet ELM pacing phase. This figure shows local increment in volume-averaged electron density and decrements in temperatures after pellet injection while the pressure profile does not change due to the adiabatic process.

A density perturbation model [2] is employed to determine the ELM triggering condition in ITER, as used in KSTAR modeling. The ELM energy losses in pellet-induced ELMs are scaled in Figure 5 (right) throughout the simulations repeated by changing the pellet injection frequency from 2 Hz to 4 Hz for a fixed pellet size. It is found that the ELM energy loss decreases from 25 MJ in a spontaneous ELM to 12 MJ in a 4 Hz pellet injection from HFS. The energy loss fraction normalized to total stored energy decreases down to 4.2 % at 4 Hz which is much less than 7.6 % of the spontaneous ELM. This indicates that ELM can be significantly mitigated by HFS pellet injection in ITER, but the energy loss still exceeds the material limits. Unfortunately pellets at the frequency higher than 4 Hz cannot activate an ELM with the density perturbation model due to relatively low plasma pressure caused by too frequent pellet injections. Additional analysis is required to check an availability of higher frequency pellet injection in ITER.

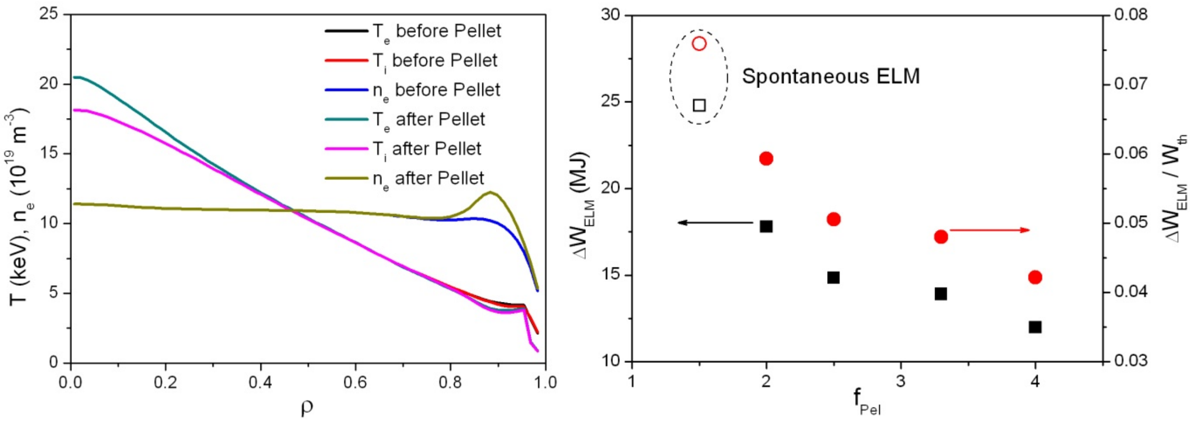

Fig. 5. Density and temperature profiles of electron and ion before and after HFS pellet injection (left), and ELM energy loss (ΔW_{ELM}) and ELM energy loss normalized to total stored energy ($\Delta W_{ELM}/W_{th}$) as a function of pellet injection frequency (f_{Pel}) (right)

4. 2. LFS pellet injection

The deposition depth of pellet is much shallower in LFS pellet injection than HFS in ITER. In the LFS case regardless of pellet size and velocity, most ablation occur outside the edge transport barrier before the pellet penetrates into the deep core region due to the high pedestal pressures of H-mode plasmas. Furthermore, the toroidally outward drift motion of the pellet is so strong that most pellet masses are predicted to drift toward the boundary region. This causes the surface-averaged profiles of plasma density and temperature to be practically unchanged after LFS pellet injection in ITER. The density perturbation model hardly works in the LFS case to determine the ELM triggering by pellet injection.

Nevertheless, it is assumed that the pellet from LFS also triggers ELMs with its perturbation caused by ablation though its ELM triggering physics has not been clarified so far. In Figure 6 (left), the radial profiles of the electron density perturbations provided by LFS pellet ablation for various pellet sizes are drawn along with those of background electron temperature and density. The injection velocity is fixed as 200 m/s. In this figure, all the pellet masses ablated are considered to be expelled to the boundary so that the temperature and density profiles virtually do not change. However, the peak of electron density perturbations by LFS injection appears to be able to reach the pedestal top position for a large pellet of 5 mm or at least the half-width position of the pedestal for a small pellet of 2 mm. As discussed in References [1] and [21], the pellets reaching the half-width position of the pedestal were observed to trigger artificial ELMs. Therefore, the perturbations from LFS pellets predicted in this simulation are expected to be applicable to trigger ELMs in ITER.

ELM pacing simulations are performed based on the assumption that LFS pellets can trigger ELMs in ITER. Figure 6 (right) shows the scaling of ELM energy loss and ELM energy loss normalized to total stored energy as a function of pellet injection frequency. They decrease down to 13.7 MJ and 4.8 % at 4 Hz of injection frequency, respectively. The LFS pellet injection is expected to reduce the ELM energy loss by a factor of 2 as well as the HFS, but its mitigation performance would be slightly weaker compared to the HFS at the same frequency. It is predicted that the injection at 5 Hz mitigates ELMs down to 11.6 MJ and 4.1 %. However, the ELM mitigation performance is still insufficient to achieve fully controlled ELMs in the ITER ELMy H-mode scenario.

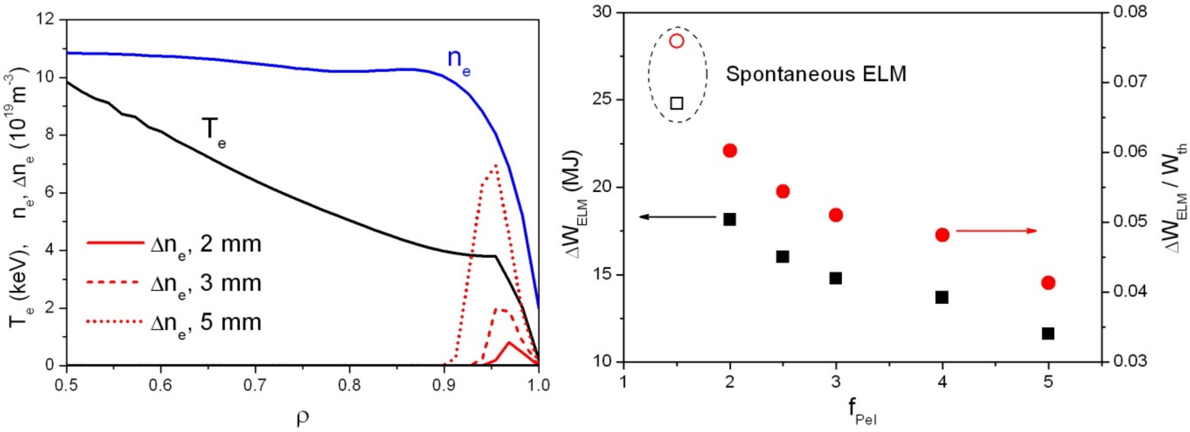

Fig. 6. Radial profiles of pellet perturbations ($\mathbf{\Delta n_e}$) to an H-mode plasma ($\mathbf{n_e}$, $\mathbf{T_e}$) in LFS injections with different sizes (left), and ELM energy loss (ΔW_{ELM}) and ELM energy loss normalized to stored energy ($\Delta W_{ELM}/W_{th}$) as a function of pellet injection frequency (f_{Pel}) (right)

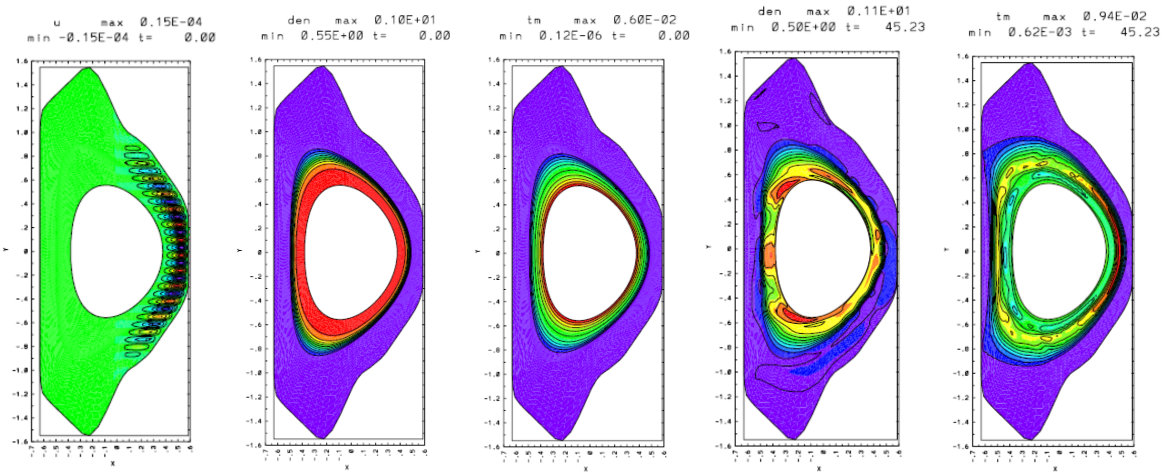

Fig. 7. Preliminary results of M3D modeling on spontaneous ELMs. (From left to right) Velocity stream function, initial density and temperature distributions at $t/\tau_A = 0.0$, density and temperature distributions at $t/\tau_A = 45.23$ where $\tau_A = R_0/v_A$ and $v_A = B_0/(\mu_0\rho_0)^{1/2}$, Alfvén speed.

5. Discussion

The simulation results of the ITER ELMy H-mode show that the spontaneous ELM energy loss will severely damage the PFCs including divertor target plates, but can be mitigated with high-frequency pellet injections. The pellet ELM pacing analyzed at various injection locations and frequencies is predicted to reduce the ELM energy loss by a factor of 2 at a frequency over 4 Hz, but this is insufficient yet for the stable and sustainable operation without severe damages to PFCs in ITER. Pellet injection is evidently advantageous to mitigate ELM peaks. However, other options, such as combined operation of pellet pacing with divertor control techniques, would be worth considering in order to obtain the fully controlled ELMy H-mode plasmas in ITER and fusion reactors. As an intermediate step, the global picture suggested by this transport modeling provides a prediction on ELM pacing performance in the future pellet injection experiments.

A 3D MHD modeling using the M3D code [22] is presently ongoing on the spontaneous and pellet-induced ELMs for better understanding of their triggering mechanisms. Velocity stream function and pellet-like density perturbation are intentionally introduced to the plasma in a marginally stable equilibrium state as free energy sources destabilizing the spontaneous and triggered ELMs, respectively. The M3D code calculates plasma evolutions responding to the artificial perturbations. Preliminary simulation results are presented in Figure 7, which describes the spontaneous ELM crash destabilized by the inserted velocity stream function. Similarities and differences in triggering phenomena between spontaneous and pellet-induced ELMs will be analyzed throughout the MHD approach. Accompanying the transport modeling, the 3D MHD approach could shed light on ELM physics and its control in magnetic fusion devices.

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