

## Utilizing M3D-C1 to understand triggering of ELMs in DIII-D pellet pacing experiments

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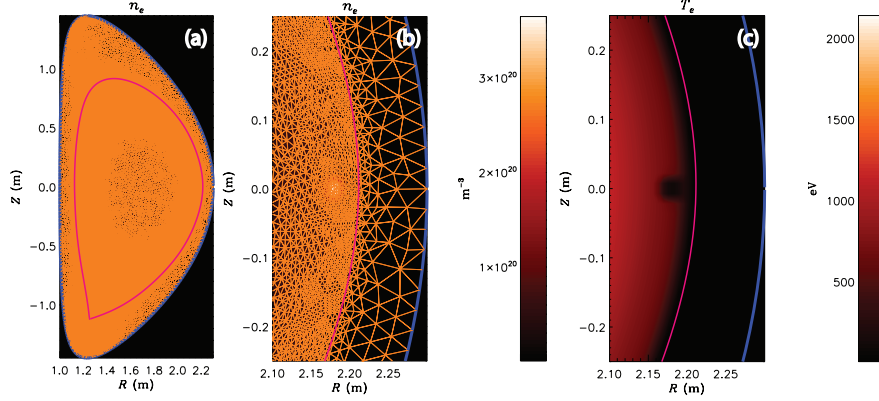
**Abstract** M3D-C1, a code for solving the linear and non-linear extended-MHD equations in toroidal geometry, is used to model pellet ELM triggering in DIII-D ITER-like plasmas. Understanding of the physical mechanisms of ELM triggering and improved modeling are required for confident extrapolation to ITER and beyond. M3D-C1 results run in linear 2D mode show that the localized perturbation is due to the pellet destabilizing peeling-ballooning modes. Calculations of linear peeling-ballooning stability as a function of pellet size suggest that a 2D pellet density ring underestimates the effects of the pellet.

**Introduction** ELMs<sup>[1]</sup> can lead to rapid (on the millisecond time-scale) loss of energy (up to 10 percent or more of stored energy in the plasma) and particles from the plasma edge. As such, mitigation of ELMs is critical for the success of ITER and other future burning plasma devices. Several methods to mitigate the negative effects of large ELMs on material and plasma confinement have been utilized<sup>[2][3][4]</sup>. This paper focuses on ELM pellet pacing. Experiments with hydrogenic pellet pacing have achieved an increase in the ELM frequency up to 12x above the natural ELM frequency<sup>[5]</sup>. As a result of these successful experiments, hydrogenic pellet ELM pacing is being implemented on ITER.

Modeling of ELM pacing from pellets and other triggering techniques is required to understand the triggering mechanisms and scale the results from current experiments to larger scale devices such as ITER and beyond. The work presented in this paper is focused on linear ELM stability in the presence of density perturbations and was modeled with M3D-C1, a resistive MHD code.

**1. Modeling Method** The M3D-C1 code<sup>[6][7]</sup> is used to model pellet ELM triggering in ITER-like DIII-D plasmas. M3D-C1 is a modern, implicit, high-order finite element 3D simulation code (either linear or nonlinear) for solving the two-fluid extended-MHD equations and is primarily designed for highly magnetized toroidal geometry. The code uses an unstructured triangular mesh that allows for adaptive zoning to capture the sharp gradients present in the pedestal edge of the plasma at the pellet deposition layer. This paper discusses 2D, linear, time-dependent, single-fluid MHD analysis on the effects of a 2D density ring perturbation on a DIII-D ITER-like plasma<sup>[8]</sup>. Recently, a pellet ablation model was incorporated into M3D-C1 and initial 3D, nonlinear results have been obtained but are not included in this paper.

The pellet is modeled as an axisymmetric density perturbation ring which was chosen as a first step in developing a pellet model to incorporate within M3D-C1. A fraction of the pellet was modeled assuming a cloud geometry based on output from the PRL code<sup>[9]</sup>. The PRL code was used to calculate the number of particles,  $3 \times 10^{19}$  particles, in an ionized ablation cloud produced by 1.3 mm by 0.9 mm deuterium pellet. A fraction of these particles,  $3.74 \times 10^{17}$ , representing the total number of particles in a normalized Gaussian distribution with 7 mm standard deviation in R and Z, was used



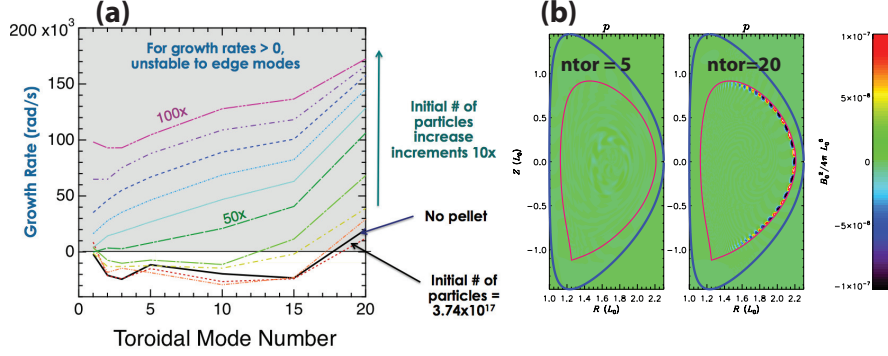
**Figure 1.** (a) A poloidal cross-section of the DIII-D plasma is shown for the M3D-C1 simulation. The red line is the last closed flux surface, LCFS, and the blue line is the computational boundary. The adaptive, triangular mesh elements (orange lines) are shown. A zoomed in portion of poloidal cross section in (b) showing the localized density perturbation and (c) the localized electron temperature at  $z = 0$ ,  $r = 2.18$  m.

to initiate the 2D density ring to simulate the pellet cloud.

Equilibrium data from a kinetic EFIT reconstruction of an ITER-like DIII-D discharge (147690) from an ELM pellet pacing experiment was chosen for these simulations. It is important to note that ELM pacing via hydrogenic pellet injection was successful for this DIII-D discharge. Central density and temperature were  $6 \times 10^{19}$  m<sup>-3</sup> and 2.1 keV, respectively, plasma current was 1.2 MA, major radius = 1.7 m, and a minor radius of 0.55 m. The measured rotation profile was also included in the simulation. The local electron temperature at the pellet location was calculated such that the total pressure remained constant when compared to the pressure profile from the kinetic EFIT equilibrium of the DIII-D plasma. The boundary conditions held the pressure, density and normal magnetic field constant at the boundary.

Initial modeling studies focused on a pellet perturbation located near the top of the density pedestal at a major radius of 2.18 m. Contours of the unstructured mesh used in the M3D-C1 simulation along with density and temperature data are shown in Fig. 1. The remainder of this paper will examine how the number of particles in the density perturbation and the location of the density perturbation affect MHD stability in the DIII-D ITER-like discharge.

**2. Effect of number of particles on MHD stability** The initial stability analysis simulated the pellet as a density ring with  $3.74 \times 10^{17}$  particles located at the edge of the density pedestal at a major radius of 2.18 m (Fig. 1). A plot of the kinetic energy growth rate as a function of the toroidal mode number,  $n_{\text{tor}}$  is shown in Fig. 2(a). It is evident in Fig. 2(a) that there is no appreciable difference in the kinetic energy growth rate when the density perturbation with  $3.74 \times 10^{17}$  particles is included in the simulation. These simulation results contradict the experimental observation as pellet pacing was successfully used to trigger ELMs in this particular DIII-D ITER-like discharge. This result suggests that the initial estimate of particle number in the 2D



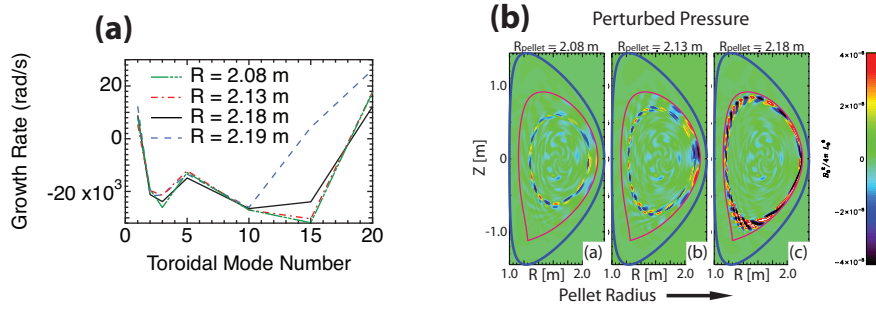
**Figure 2.** (a) Kinetic energy growth rate plotted vs. toroidal mode number for an initial number of particles ranging from  $3.74 \times 10^{17}$  to  $3.74 \times 10^{19}$ . (b) Contours of perturbed pressure are shown for  $n_{tor}=5$  and  $n_{tor}=20$  with  $3.74 \times 10^{17}$  initial particles.

density ring underestimates the effect of the pellet.

A simulation study increasing the particle number in the 2D density ring by factors of 10 is shown in Fig. 2(a). As the number of particles is increased, there is an observable difference in the kinetic energy growth rate. The kinetic energy growth rate increases above zero with increasing particle number, indicating the modes become unstable and suggests that the density perturbation will be more effective at triggering ELMs. The equilibrium is always unstable for  $n_{tor}=20$  (Fig. 2(b)), however, by increasing the number of particles in the density perturbation by a factor of 50, from  $3.74 \times 10^{17}$  to  $1.87 \times 10^{19}$ , the density perturbation leads to all toroidal mode numbers being unstable (Fig. 2(a)). The ELM pellet pacing experiments show that the introduction of frozen deuterium pellets induce ELMs; therefore, initial pellet modeling suggests that  $3.74 \times 10^{17}$  particles underestimates the pellet effectiveness at triggering ELMs.

A comparison of the perturbed pressure contours is shown in Fig. 2(b) for density perturbation of  $3.74 \times 10^{17}$  particles for  $n_{tor}=5$  stable case and  $n_{tor}=20$  unstable case. For  $n_{tor}=5$  there is no noticeable pressure perturbation and the mode is stable. However, for higher  $n_{tor}$  of 20 in cases with  $>30x$  initial particles, the mode is unstable and the pressure profile is perturbed near the location of the 2D density ring, suggesting the pellet will lead to ELM triggering at higher mode numbers. As the particle number is increased, the pressure is perturbed at the density ring location for lower toroidal mode numbers, the kinetic energy growth rate increases above zero, indicating the ELM is triggered (not shown in this paper).

**3. Effect of density perturbation location on MHD stability** The previous cases placed the density perturbation at the top of the edge density pedestal,  $R = 2.18$  m. The density perturbation location was scanned to assess the impact of pellet location on MHD stability. With the initial density perturbation of  $3.74 \times 10^{17}$ , there is no effect on the instability growth rate by varying the location of the initial density perturbation. When the initial number of particles is increased by a factor of 10 to  $3.74 \times 10^{18}$  particles, changes in the kinetic energy growth rate are observed due to varying density perturbation location (Fig. 3(a)). The strongest effect in increasing the kinetic



**Figure 3.** (a) Kinetic energy growth rate vs.  $n_{\text{tor}}$  for 4 density perturbation locations with  $3.74 \times 10^{18}$  particles. (b) Initial density perturbation with  $1.5 \times 10^{19}$  initial particles located at major radius of (a) 2.08 m, (b) 2.13 m, and (c) 2.18 m.

energy growth rate occurs for a density perturbation placed at a major radius of 2.19 m. Significant increases in the mode growth rate were observed for cases with  $n_{\text{tor}} > 10$ .

Details in the contours of the perturbed pressure reveal that an edge mode was triggered at the pellet ablation location for all cases with an initial number of particles  $= 1.496 \times 10^{19}$ . Four locations for the density perturbation were explored for this study at major radius of: 2.08 m, 2.13 m, 2.18 m (Fig. 3(b)) and 2.19 m (contour not shown). The perturbation amplitude was similar for a pellet located at major radius of 2.08 m, 2.13 m, and 2.18 m. The pressure perturbation amplitude was a factor of 50 greater when the pellet was placed at a major radius of 2.19 m.

**Conclusion** M3D-C1 has been used to investigate how pellet injection triggers ELMs in DIII-D. The pellet was modeled as a density perturbation in 2D geometry and the total pressure was held constant. The number of particles and pellet location was varied for single-fluid, time-dependent simulations. The simple pellet density perturbations were shown to destabilize high- $n$  modes in the pedestal region. It was observed that high  $n_{\text{tor}}$  mode numbers were the most unstable. By increasing the number of particles to  $1 \times 10^{19}$ , unstable edge modes were observed at the pellet ablation location, which suggests that the 2D 'pellet' density ring underestimates the effects of the pellet.

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