NON-IDEAL AND SHAPING EFFECTS IN EXTENDED-MHD SIMULATIONS OF ELM-FREE TOKAMAK PLASMAS

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Free energy provided by steep gradients in the edge region of fusion plasmas can trigger Edge Localized Modes (ELMs) instabilities leading to quasi-periodic eruptive events that cause severe heat loads on plasma facing components (PFCs), and significantly impacting reactor availability, lifespan, and overall costs. Addressing ELMs in burning plasmas is essential for the success of fusion reactors. Different approaches to ELM suppression during high-confinement H-mode have been investigated; however, the ideal solution would be to operate in an intrinsically ELM-free regime. Here, we employ nonlinear simulations to investigate three ELM-free regimes. In particular, we use the NIMROD[1] code to study instabilities in DIII-D discharges with negative triangularity (NT) plasma shaping[2], and the impact of plasma impurities, specifically carbon, on Quiescent H-mode (QH-mode)[3] discharges. We perform a full nonlinear benchmark between extended MHD codes M3D-C1[4] and NIMROD for enhanced pedestal scenarios in NSTX[5]. Our focus here is experimental validation as well as code benchmark. We model the entire plasma, including the core, edge, SOL and vacuum regions. Our main results are as follows: 1) With a 2-fluid model, we find a persistent reconnecting edge n=1 mode for strongly shaped NT plasmas (delta =-0.54) in DIII-D. 2) QH-mode simulations show large pedestal localized n=4 and 5 electron temperature perturbations, while the magnetic energy is dominated by the n=1 and 2 perturbations. 3) In the presence of equilibrium rotation, M3D-C1 and NIMROD simulations of enhanced pedestal H-mode discharges show low-n (n=4-6) modes with relatively low growth rates, and both codes show similar nonlinear saturation amplitudes.

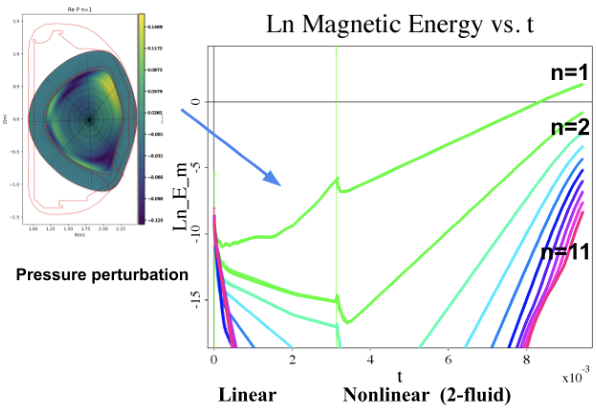

FIG. 1: Time histories of magnetic mode energies for case 193754 during two-fluid simulations. Mode structure shows n=1 mode (m=3) concentrated in the edge.

ELM-free negative triangularity regimes in DIII-D: Recent developments of ELM-free NT regimes via plasma shaping have exhibited interesting edge MHD dynamics [6]. Here, we have performed global simulations for two strongly shaped NT DIII-D discharges with low and high beta, discharges 193754 and 193843, respectively. Our two-fluid NIMROD simulations are consistent with experiments and show no ELM activity. Only slow-growing n=1 fluctuations are observed in the simulations. For the high beta case, a core n=1 hybrid pressure/current driven mode is found; while, for the low beta case a slow-growing tearing mode n=1, m=3 localized in the edge region is obtained. Simulations are performed at high-resolution with 22 toroidal modes. Figure 1 shows magnetic energy evolution and the dominant mode structures (both linear and early nonlinear). In these simulations we start with linearly evolving toroidal modes, and at around 3ms we start the nonlinear evolution. To eliminate the stabilizing effect of an artificially close wall, we have used a conforming wall (with extension of 54% beyond the closed-flux region) and included the SOL region. Unlike in ELMing DIII-D positive trangularity (PT) simulations, where the nonlinear mode coupling of intermediate-n PB modes causes reconnection-mediated ELM crash [7], here consistent with the experiment[6], we obtain ELM-free NT states with only slow-growing n=1 fluctuations.

ELM-free Quiescent H-mode regimes in DIII-D: We have performed nonlinear MHD simulations of a Wide Pedestal QH-mode (WPQH) DIII-D plasma with the extended-MHD NIMROD code. The WPQH-mode DIII-D analyzed in this work, discharge 184971, uses a nonstandard configuration for QH-mode access, normal Ip and normal Bt for DIII-D, and has been chosen for diagnostic magnetic-field alignment and availability. The simulations include two-fluid/Finite Larmor Radius (FLR) effects and full-Braginskii collisionality with the impurity collisionality effects from carbon and anisotropic closures. Using this model, the simulations indicate the appearance of field-aligned pedestal tearing modes and electrostatic modes. The dominant modes are n = 1-5, which is expected for a QH-mode plasma. Comparison between simulation results and experimental observations will be discussed.

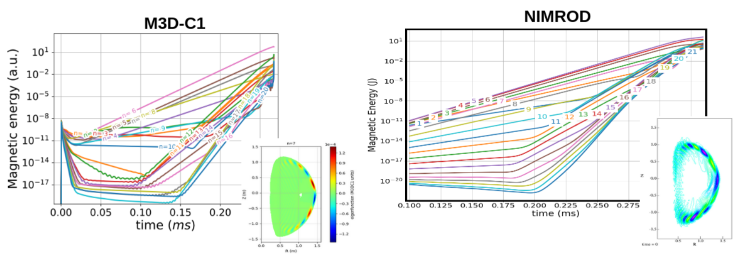

FIG. 2: The magnetic energy for different toroidal modes calculated with M3D-C1 and NIMROD is shown together with the mode structure calculated by the two codes.

ELM-free regimes in spherical tokamaks: ELM-free H-mode regimes were found in NSTX using enhanced pedestal scenarios [5]. M3D-C1 [4] has been extensively used to investigate the effect of resistivity on edge stability of ELMing plasmas in NSTX [8]. In this paper, full extended MHD studies are conducted for ELM-free enhanced pedestal (EP) H-mode in discharges 132588 and 141133 using the M3D-C1 and NIMROD codes in order to investigate the edge stability in these plasmas. We have performed extensive linear simulations with both codes and found a similar mode spectrum. Linear and nonlinear M3D-C1 and NIMROD simulations of NSTX ELM-free discharges show good agreement. In particular for the EP H-mode regime, we obtain slow-growing low-n edge modes in the nonlinear simulations with M3D-C1 and NIMROD as shown in Figure 2. These simulations would also help with optimization of ELM-free regimes for ST reactor design [9]. The role of accurate flow profiles in the extended MHD simulations is investigated. ELM-free pulses in MAST-U have been identified and non-linear simulations are being performed to analyze potential edge modes and their nonlinear stability behavior.

Our extended MHD analysis, presented here, aims to validate and explain the MHD nonlinear dynamics for the plasma edge region. Plasma shaping, in particular, shows a very pronounced effect on P-B mode activities in our global extended MHD model. Unlike in ELMing DIII-D PT simulations, where the nonlinear mode coupling of intermediate-n PB modes causes reconnection-mediated ELM crash [7], here consistent with the experiment[6], we obtain ELM-free NT states with only reconnecting edge n=1 fluctuations. ELM-free scenarios in both conventional as well as spherical tokamaks are demonstrated in our MHD/2-fluid nonlinear simulations.

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