Multi-species extended MHD simulations of ELM-free negative triangularity DIII-D plasmas

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The ELM-free Negative Triangularity (NT) plasma shaping regime has revealed a robust ELM-free edge while achieving H-mode equivalent core performance. Recent DIII-D ELM-free strongly shaped NT plasmas have exhibited edge MHD dynamics with pronounced magnetic fluctuations[1]. Understanding and predicting the onset and saturation of these edge magnetic fluctuations within the MHD framework is crucial for assessing the viability of NT plasma shaping for fusion power plants (FPP). Here, we have carried out global extended MHD simulations of strongly shaped (with average triangularity δ = -0.54) plasmas at both low (β_N =1.36) and high beta (β_N =2.65), as well as weakly shaped (δ =-0.01) NT DIII-D discharges. The extended MHD NIMROD model includes two-fluid, electron inertia, ion gyroviscosity, and multispecies collisionality via Spitzer resistivity and heat conductivities from Braginskii closures. We model the entire plasma, including the core, edge, SOL and vacuum regions. The multispecies corrections, in particular due to enhanced resistivity when carbon species are included, provide realistic diffusivities for the onset of edge instabilities. Unlike in ELMing DIII-D PT simulations, where the nonlinear mode coupling of intermediate-n Peeling-Ballooning modes causes reconnection-mediated ELM crash, here we obtain ELM-free NT states for strongly shaped discharges. Consistent with the experimental observations,[1] we find pronounced global n=1 edge MHD mode activities in all these NT DIII-D discharges. By performing a systematic Lundquist number (S) scaling and including multispecies collisionality, we first uncover a strong S scaling ($\propto S^{-0.6-0.7}$) of tearing-like nature for strongly-shaped NT plasmas while a rather weaker S scaling ($\propto S^{-0.4}$) of interchange pressure-driven nature is obtained for the weakly-shaped NT discharge (both during ELMing and ELM free phases). The strong S scaling of the reconnecting n = 1 edge mode in strongly shaped NT plasmas, at both high and low beta, indicates a favorable suppression of edge tearing mode activity as S increases, particularly toward the FPP projection. Resistive interchange-like activities could be more persistent for weaker NT plasmas. Second, we have also extended our two-fluid simulations into the nonlinear regime, and confirmed the reconnecting nature of the n=1 mode showing good agreement with experimental measurements obtained via electron cyclotron emission imaging (ECE-I) mode structure and electron temperature perturbations from the NIMROD simulation. Some highlights of nonlinear results, including relaxation of plasma current via a two-fluid core dynamo effect in the high beta NT plasma, will also be discussed. This work was supported by the DOE SciDAC program and Award Numbers DE-AC02-09CH11466, DE-FC02-04ER54698, DE-SC0023500, DE-SC0022270 and DE-SC0024592.

[1]T Cote, G Yu, AO Nelson, N Leuthold, N Richner, S Stewart, F Khabanov, Y Zhu, F Ebrahimi, J King, C Paz-Soldan, L Schmitz, KE Thome, ME Austin, F Scotti, "First observations of edge instabilities in strongly shaped negative triangularity plasmas on DIII-D", Plasma Physics and Controlled Fusion 67 (2025) 035033.