FINAL TECHNICAL REPORT

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MIT participation in the Center for Extended Magnetohydrodynamics Modeling

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This researcher participated in the DOE-funded Center for Extended Magnetohydrodynamics Modeling (CEMM), a multi-institutional collaboration led by the Princeton Plasma Physics Laboratory with Dr. Stephen Jardin as the overall Principal Investigator. This project developed advanced simulation tools to study the non-linear macroscopic dynamics of magnetically confined plasmas. The collaborative effort focused on the development of two large numerical simulation codes, M3D-C1 and NIMROD, and their application to a wide variety of problems. Dr. Ramos was responsible for theoretical aspects of the project, deriving consistent sets of model equations applicable to weakly collisional plasmas and devising test problems for verification of the numerical codes. This activity was funded for twelve years.

The main scientific achievements pertaining to this MIT-based task are reported in the 16 refereed publications listed below. In addition, 23 oral presentations posted online at the CEMM web page http://w3.pppl.gov/cemm/workshops.html, were given by Dr. Ramos at the semiannual workshops organized by the CEMM team. A major contribution has been the novel formulation of the finite-Larmor-radius drift-kinetic equation that uses as reference frame the rest frame of the macroscopic flow and guarantees the consistency with the particle, momentum and energy conservation laws expressed by fluid equations. This formulation has been implemented in two new neoclassical codes (NIES and DK4D) developed by B. Lyons and S. Jardin, and a new kinetic module of the NIMROD code developed by E. Held. The code development

and neoclassical simulations of NIES and DK4D were the subject of B. Lyons' doctoral dissertation at Princeton University, co-directed as part of this project by Drs. Jardin and Ramos.

CEMM-supported publications

[1] J.J. Ramos, "General expression of the gyroviscous force", Phys. Plasmas **12**, 112301 (2005).

[2] J.J. Ramos, "Fluid theory of magnetized plasma dynamics at low collisionality", Phys. Plasmas **14**, 052506 (2007).

[3] J.J. Ramos, "Finite-Larmor-radius kinetic theory of a magnetized plasma in the macroscopic flow reference frame", Phys. Plasmas **15**, 082106 (2008).

[4] S. Jardin, C. Sovinec, J. Breslau, N. Ferraro, S. Hudson, J. King, S. Kruger, J. Ramos and D. Schnack, "Two-fluid and resistive nonlinear simulations of tokamak equilibrium, stability and reconnection", 22nd IAEA Fusion Energy Conference, Geneva, Switzerland, 2008. IAEA-CN-165/TH/P9-29.

[5] E. Ahedo and J.J. Ramos, "Parametric analysis of the two-fluid tearing instability", Plasma. Phys. Control. Fusion **51**, 055018 (2009).

[6] J.J. Ramos, "Fluid and drift-kinetic description of a magnetized plasma with low collisionality and slow dynamics orderings. I. Electron theory", Phys. Plasmas **17**, 082502 (2010).

[7] J.J. Ramos, "Fluid and drift-kinetic description of a magnetized plasma with low collisionality and slow dynamics orderings. II. Ion theory", Phys. Plasmas **18**, 102506 (2011).

[8] E. Ahedo and J.J. Ramos, "Supersonic regime of the Hall-magnetohydrodynamics resistive tearing instability", Phys. Plasmas **19**, 072519 (2012).

[9] B.C. Lyons, S.C. Jardin and J.J. Ramos, "Numerical calculation of neoclassical distribution functions and current profiles in low collisionality, axisymmetric plasmas", Phys. Plasmas **19**, 082515 (2012).

[10] S.E. Kruger, T.G. Jenkins, E.D. Held, J.J. Ramos, J. King, D.D. Schnack and R.W. Harvey, "Coupled simulations of RF effects on tearing modes", 24nd IAEA Fusion Energy Conference, San Diego, California, 2012. IAEA-CN-197/TH/P3-11.

[11] J.J. Ramos, "Quasineutrality and parallel force balance in kinetic magnetohydrodynamics", J. Plasma Phys. **81**, 905810111 (2015).

[12]B.C. Lyons, S.C. Jardin and J.J. Ramos, "Steady-state benchmarks of DK4D: A time-dependent, axisymmetric drift-kinetic equation solver", Phys. Plasmas **22**, 056103 (2015).

[13]J.J. Ramos, "On the normal-mode frequency spectrum of kinetic magnetohydrodynamics", J. Plasma Phys. **81**, 905810325 (2015).

[14]J.J. Ramos, "New regime of low ion collisionality in the neoclassical equilibrium of tokamak plasmas", Phys. Plasmas **22**, 070702 (2015). Erratum: Phys. Plasmas **22**, 119902 (2015).

[15]J.J. Ramos, "On stability criteria for kinetic magnetohydrodynamics", J. Plasma Phys. **82**, 905820607 (2016).

[16]A. Ito and J.J. Ramos, "Two-fluid tearing mode instability in cylindrical geometry", submitted to Phys. Plasmas (2017).