# Gyrokinetic Simulation of Multiple-n Energetic Particle Driven Alfven Eigenmodes in ITER

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We have previously carried out linear simulations of two ITER equilibrium scenarios, one hybrid scenario and one steady state scenario, using the gyrokinetic ion/mass-less fluid electron hybrid model of GEM [1]. It is found that the hybrid scenario is stable for intermediate-n Alfvenic modes, and the steady state scenario is weakly unstable. Nonlinear simulations of single-n mode in the steady state scenario indicates significant redistribution of alpha particles. In this work we extend the nonlinear simulation to simultaneous excitation of multiple toroidal modes. We first describe the implementation of a kinetic electron closure to the gyrokinetic ion/fluid electron hybrid model in a radially global domain. This closure scheme has been previously implemented in the flux-tube geometry and shown to be efficient for Alfvenic waves such as the kinetic ballooning modes and the EP driven Alfven eigenmodes [2]. The closure scheme consists of kinetic calculation of the electron pressure terms in the electron continuity equation and the parallel Ohm's law. We then report simulations with GEM. The GEM code is particularly suited for such multiple-n simulations. It uses the field-aligned coordinates that naturally retain only the poloidal harmonics at each surface that scales with the local safety factor, i.e. $m \sim nq(r)$. The vorticity approach in GEM for obtaining the electric potential has proven to be numerically more robust than using the quasi-neutrality condition as usually done in gyrokinetic simulations. It is also more accurate, especially for the low-n modes. These algorithmic features will allow us to simultaneously simulate all the toroidal modes with $5<n<30$. Multiple ion species will be included, including both the alpha particles and beam particles. The alpha particles have a slowing-down distribution isontropic in velocity. The beam particles have a distribution anisotropic in velocity. Both species have been implemented in GEM. Energetic particle collisions in the form of slowing-down and pitch-angle scattering are included.

[1] G-Y Fu et. al., Final Report on DOE Fusion Theory Milestone Project
[2] Y. Chen, S. Parker, W. Wan and B. Bravenec, Physics of Plasmas 20, 092511 (2013)

## Facilities and Resources

### Intellectual Resources

The University of Colorado, Boulder campus provides a rich environment for research in basic plasma physics, the home of the Center for Integrated Plasma Studies, which has active research in theoretical and experimental plasma physics well supported by DOE, NSF and NASA. The plasma physics faculty includes five theorists (S. Parker, J. Cary, M. Horanyi, M. Goldman and D. Uzdensky) and two experimentalists (T. Munsat and S. Robertson). Prof. Munsat is an expert in fluctuation measurements in tokamaks and provides a valuable experimental contact and resource. Prof. Cary works in nonlinear dynamics applied to accelerators and transport in tokamaks and stellerators. Prof. Goldman does fundamental research in high-frequency nonlinear plasma turbulence in the ionosphere and magnetosphere. An important local resource is the Laboratory for Space Physics (LASP) and the Department of Astrophysical and Planetary Sciences which have many researchers very active in space and astrophysical plasma physics. Plasma physics research is also performed at NCAR, NIST and NOAA laboratories in Boulder. Researchers with expertise in plasma physics in Boulder, both on campus and at the institutes, include Drs. D. Baker, R. Ergun, T. Speiser, F. Bagenal, D. Newman, T. Onsager, G. Lu and H. Singer. In addition, fusion research is performed at Lodestar

Research Corporation and Tech-X Corporation, including research physicists Drs. D. D'Ippolito, J. Myra and S. Kruger.

**Computing Resources**

Kinetic simulation requires large-scale computing. We have excellent access and computer time allocations at both the National Center for Computational Sciences, Oak Ridge National Laboratory and the National Energy Research Supercomputer Center at Lawrence Berkeley Laboratory. The University of Colorado computing networks provide excellent access and bandwidth to the National computer centers across the country. Local computing resources include a broad mix of Unix workstations. The Center for Integrated Plasma studies has a rack-mount Linux cluster for in-house large-scale computation. We utilize Research Systems Interactive Data Language (IDL) and Open-DX for data analysis and stereoscopic visualization using low-cost high-performance Linux workstations.