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Two-Fluid and Resistive Nonlinear Simulations of Tokamak Equilibrium, Stability, and Reconnection

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The NIMROD[1] and M3D[2,3] codes now each have both a resistive MHD and a two-fluid (2F) capability including gyro-viscosity and Hall terms. We describe: (1) a new 3D verification and validation test in the resistive MHD regime using an applied loop voltage in which the two codes are in detailed agreement and they each match the experimental sawtooth period to within 10%, (2) new studies that illuminate the effect of 2F physics on spontaneous rotation in tokamaks and the effect on linear stability, and (3) nonlinear re-connection in regimes of relevance to fusion plasmas with reconnection rates that are in-dependent of the resistivity, and (4) linear two-fluid tearing mode calculations including electron mass that agree with analytic studies over a wide range of parameter regimes.
Sawtooth phenomena in a small ohmic tokamak: Both NIMROD and M3D have calculated the nonlinear evolution through three complete sawtooth cycles using the geometry and parameters of the CDX-U tokamak in the resistive MHD regime and find impressive agreement between the two codes in most all details of the simulation and with the experimental data: they match the sawtooth period to within 10%. In order to define this problem in a way that is accessible to other 3D simulation codes, the codes are initialized with a semi-analytic definition of a stationary equilibrium configuration that closely approximates the experimental conditions. This is done by specifying the pressures and densities as quadratic functions of the poloidal flux ψ, and giving a parametric form for the plasma boundary. Using the neo-classical resistivity and specifying a loop voltage V_{loop}, JSOLVER [4] is used to calculate a unique resistive stationary equilibrium that satisfies: $V_{loop} = 2\pi\eta < \mathbf{J}\cdot\mathbf{B} > / < \mathbf{B}\cdot\nabla\phi >$, where the brackets denote flux surface average. The perpendicular heat conduction profile is initialized self-consistently to provide steady state profiles: $\kappa_{\perp} = V_{loop} < \left|\nabla\psi\right|^2 / R^2 > / 2\pi\mu_0 T' < \left|\nabla\psi\right|^2 >$, where the prime denotes the derivative with respect to the poloidal flux function ψ. After the first sawtooth cycle, the code results become relatively independent of the initial conditions although the loop voltage remains as a boundary condition. For each crash, the n=1 component first becomes linearly unstable and drives the other toroidal modes with n>1 through nonlinear coupling. We find that substantial m>1 islands are formed during the crash, but these quickly re-heal during the ramp phase. Even though many surfaces breakup during the crash phase, the temperature does not completely flatten due to the presence of residual surfaces and cantori which form effective heat barriers [5]. These simulations are now being redone in the 2F regime.
2F equilibrium including flows: We present new numerical results of accurate axisymmetric free-boundary stationary states of a comprehensive two-fluid model of a high temperature model including self-consistent flow, gyroviscosity, and non-uniform, anisotropic thermal conduction. These solutions are true steady-states on all time scales. Results for large aspect-ratio, circular cross-section configurations, and realistic NSTX and ITER geometries and parameters are presented. Spontaneous rotation is observed to occur in the absence of external angular momentum injection, in accordance with

theoretical predictions [6]. For large aspect ratio circular plasmas, this rotation occurs even without the gyroviscous term included but is stabilized by sufficient density diffusion. For NSTX-like plasmas that have high-β, low aspect-ratio, and are elongated and diverted, the spontaneous rotation occurs only if gyroviscosity is included. The effect of these flows on the linear stability thresholds is presented.

Nonlinear 2F reconnection with an arbitrary guide field: We have extended the problem of nonlinear magnetic reconnection in a Harris current sheet to include a strong guide field to better approximate nonlinear reconnection in tokamaks and to obtain scaling relations and project resolution requirements to the ITER regime. Our interest is in the regime: $\delta \ll \rho_S \ll d_i$, $\beta \ll 1 \sim \beta_P$. Here, δ is the Sweet-Parker reconnection thickness, $\rho_S = \sqrt{\beta} d_i$ is the ion sound gyro-radius, $d_i = c/\omega_{Pi}$ is the ion skin depth. We find that for small enough resistivity, nonlinear reconnection rates are independent of the value of the resistivity. However, in the absence of electron inertia, all calculations require an effective hyper-resistivity λ_H proportional to d_i in order to resolve the singularity at the x-point.. The reconnection rate decreases with increasing λ_H, but asymptotes to a value independent of λ_H. The reconnection rate decreases with increasing guide field. If we include density evolution in the simulations, dependence of the growth rate on the guide field strength is even more dramatic. This can be partly explained by compressibility. Density depletes in the reconnection region for the zero or small guide field case, increasing the effective d_i, but not nearly as much when the guide field is increased. If density evolution is not included, we find that for fixed d_i, the guide field still reduces the rate of magnetic reconnection. This is more pronounced for larger d_i. We further find that increasing β increases the reconnection rate. These studies were done with a complete 8-field 2F model. In order to relate to some previous studies, we have repeated some of the calculations with the reduced 4-field model.[7] We find that the 4-field model does a fairly good job at reproducing the evolution at high guide field strengths, but not as good at low field strengths.

Two-fluid linear tearing in different parameter regimes: Linear slab-geometry two-fluid tearing-mode computations with the NIMROD code have been benchmarked with analytical results [8] in different large guide field regimes. Growth rates agree with the analytical results to within a half percent in the limit of small resistive layer width when using a 120x14 mesh of bicubic finite elements with packing at the rational surface. With the two-fluid model, the growth rate is 2.5 times larger than MHD at physically large values of sound gyroradius, and the computations converge to the MHD result in the small gyroradius limit. We have extended the large guide field theory to consider hyperbolic-tangent pressure profiles for verifying drift-tearing behavior in NIMROD and M3D.

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