

Kinetic Stability of the Field Reversed Configuration

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New computational results are presented which advance the understanding of the stability properties of the Field-Reversed Configuration (FRC). The FRC is an innovative confinement approach that offers a unique fusion reactor potential because of its compact and simple geometry, translation properties, and high plasma beta. One of the most important issues is FRC stability with respect to low- n (toroidal mode number) MHD modes. There is a clear discrepancy between the predictions of standard MHD theory that many modes should be unstable on the MHD time scale, and the observed macroscopic resilience of FRCs in experiments.

We have developed a 3D nonlinear hybrid and MHD simulation code (HYM) [1] to investigate a variety of non-ideal MHD effects, including plasma flow and kinetic effects on FRC stability properties, particularly with respect to the $n = 1$ tilt mode. Previous calculations demonstrated a significant reduction in the linear growth rates in prolate FRCs with $E \gtrsim 4$ due to kinetic effects [1,2], and a nonlinear saturation of instabilities for $\bar{s} \lesssim 2$ [3], where E is the separatrix elongation, and \bar{s} is a kinetic parameter which measures the number of thermal ion gyro-radii in the configuration. No absolute linear stability was found even in the highly kinetic regime ($\bar{s} < 1$) [1]. We present new results of hybrid and two-fluid (Hall-MHD) simulations of prolate FRCs with $E = 4 - 8$ and $\bar{s} = 1 - 8$. The instability mechanisms at low \bar{s} and the nonlinear evolution of unstable modes for larger values of \bar{s} are investigated, as well as the effects of the particle loss along the open field lines, and Hall stabilization.

Analysis of particle trajectories for small \bar{s} demonstrates the existence of a significant fraction of the regular-orbit-ions. These ions can be in betatron resonance [4] with MHD modes, in particular with the $n=1$ mode, maintaining the tilt instability in the large gyroradius regime, beyond the FLR stabilization threshold. Simulation results for $\bar{s}=0.8$ racetrack separatrix shape and $E=7$ (Fig. 1) show that a relatively small fraction (about 4%) of resonant particles contributes significantly to the energy balance, and is important for the instability

drive. The unstable mode is a negative energy wave, which propagates in the direction opposite to the equilibrium current (in the ion frame) with the phase velocity smaller than the ion diamagnetic velocity. It is also found that the fraction of regular orbits versus stochastic orbits in FRC depends strongly on the separatrix shape and elongation.

The nonlinear saturation, observed at low \bar{s} [3], occurs due to the nonlinear deviation of the ion distribution function from a local Maxwellian. The unstable configuration evolves nonlinearly into a new equilibrium with smaller \bar{s} , larger E and the increased separatrix beta. The nonlinear stabilization of the $n = 1$ tilt mode explains the observation in the low \bar{s} experiments of initial $n = 1$ tilt motion that does not result in total loss of confinement. However, the reported FRC stability for larger values of \bar{s} ($\bar{s} \gtrsim 4$) has not been explained so far.

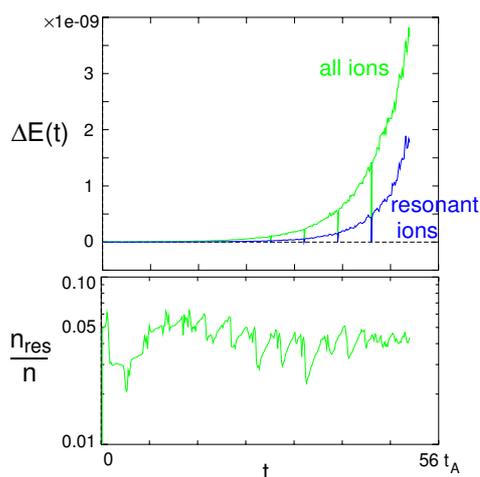


Figure 1: Kinetic energy (a), and fraction of resonant ions (b) from simulations of $n = 1$ tilt mode with $E=7$ and $\bar{s}=0.8$.

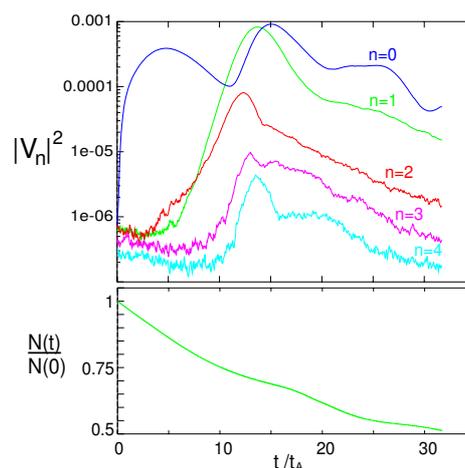


Figure 2: Energy plots for $n=0-4$ modes (a), and total number of particles (b) from simulations with $E=4$ and $\bar{s}=7.4$.

Our hybrid simulations with loss boundary conditions (Fig. 2) and larger values of \bar{s} (small gyroradius regime) show a significant loss of particles (about 30 %) during linear phase of the instability. Particle loss along the open field lines has a destabilizing effect on the $n = 1$ tilt mode, increasing the linear growth rate by $\approx 10\%$ compared to simulations with periodic boundary conditions. The increase in the growth rate is related to the reduction of the separatrix beta and the plasma pressure outside the separatrix.

In the large \bar{s} simulations, the linear growth rate of the $n = 1$ tilt mode is very close to that of the MHD with $\gamma \gtrsim 0.9\gamma_{mhd}$, and the nonlinear saturation does not occur. However, the observed nonlinear evolution is considerably slower than that in the MHD simulations. Thus, despite the loss of about half of the particles, a field reversal of $B_z \approx -0.5B_{ext}$ is still present by $t = 32t_A$ in the simulations shown in Fig. 2. Significant ion spin up in toroidal (diamagnetic) direction is also observed at $t > 20t_A$ with $V_i \approx 0.3v_A$, which agrees well with experiments. The slow nonlinear evolution found in the kinetic simulations is probably related to the reduction of the effective value of \bar{s} during the nonlinear phase on the instability, after a significant fraction of internal flux is lost. Both the reduction of \bar{s} and the ion spin-up can have a stabilizing effect on the instability, extending the FRC life-time to $t \gtrsim 30t_A$. In contrast, the MHD simulations show a rapid FRC disruption in about $\approx 10t_A$. Since end mirror coils are likely to improve particle confinement and further slow down the nonlinear evolution, our large- \bar{s} nonlinear results potentially can provide an explanation of the observed FRC behavior for $\bar{s} > 4$ cases.

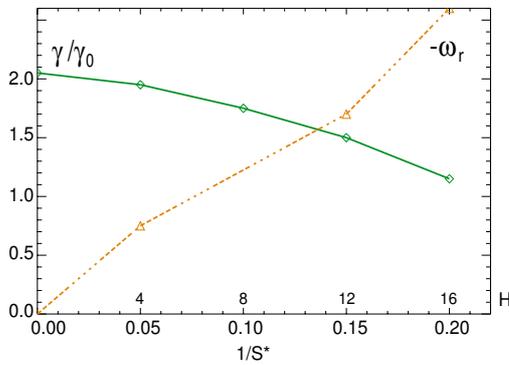


Figure 3: Growth rate and real frequency of the tilt mode from Hall-MHD simulations with $E=6$.

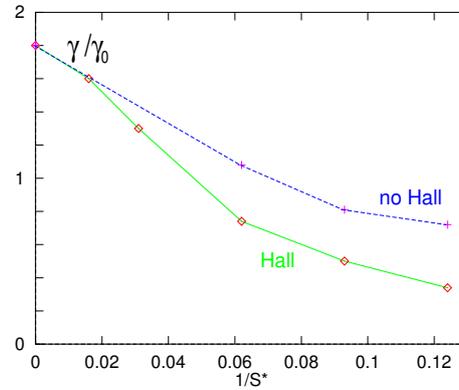


Figure 4: Growth rate of the tilt mode from hybrid simulations with Hall term (solid line) and without Hall term (dashed line) for $E=4$.

In order to assess the importance of different stabilizing factors on the FRC stability properties, we have performed two-fluid (Hall-MHD) simulations of the $n = 1$ tilt mode. The MHD version of HYM code has been modified to include the Hall term in the Ohm's law, and sub-cycling in the induction equation has been used to insure the numerical stabil-

ity. Calculations with $E=6$ and elliptical separatrix shape show a reduction of the tilt mode growth rate for small \bar{s} (Fig. 3) and a significant change in the mode structure (Fig. 5). The unstable mode has a negative real frequency, and propagates in the direction opposite to that of the equilibrium current. The reduction in the linear growth rate by a factor of two for $S^*/E \sim 1$ ($S^* \approx 5-8 \bar{s}$) due to Hall stabilization is not sufficient to explain the stability, and therefore, finite Larmor radius and other kinetic effects are also important.

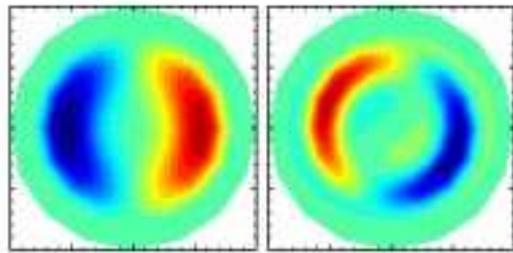


Figure 5: Linear mode structure from (a) MHD, and (b) Hall-MHD simulations with $S^*=5$ and $E=6$.

In addition, we have performed hybrid simulations for $E=4$ and elliptic separatrix shape both including Hall term in the Ohm's law, and without it. A similar reduction in the linear growth rate due to Hall effect has been found (Fig. 4). A comparison of the results of the Hall-MHD and hybrid simulations with and without Hall term have shown that the Hall term is responsible for the mode rotation in the negative direction and the change in the linear mode structure, however, the reduction in the growth rate is mostly due to finite Larmor radius effects. Our numerical simulations have demonstrated that a combination of kinetic and nonlinear effects is essential for explaining the experimentally observed FRC behavior.

References

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This work is supported by US DOE.