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MHD simulation of tilt instability during the dynamic FRC magnetic compression process

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The field reversed configuration (FRC) is a compact toroid primarily sustained by the poloidal magnetic field. The magnetic compression has been demonstrated as an effective heating method for FRCs in experiments[1]. However, the gross magnetohydrodynamic (MHD) instabilities remain a critical challenge for the pulsed FRC system, with the potential of tilt instability being the most dangerous.

The FRC stability to the tilt mode has been confirmed in the low-$\bar{s}$ kinetic regime, where $\bar{s}$ is the averaged gyroradius between the magnetic axis and the separatrix[2]. However, the empirical confinement scalings suggest that practical fusion reactors need to operate within the MHD regime above a minimum $\bar{s}$ of 10-20[3]. Whereas it is promising to extend the reactor potential of FRC to the large-$\bar{s}$ MHD regime in steady state[3], the stability of FRC during a dynamic compression against tilt mode remains unclear.

In this work, we perform nonlinear MHD simulations of the tilt mode during dynamic FRC magnetic compression using the NIMROD code[4]. The effects of the magnetic field ramping rate and the toroidal flow on tilt instability are also examined. As can be seen in figure 1, the tilt instability grows on the Alfvén timescale and disrupts the FRC in the early stage of the magnetic compression process. The tilt mode causes notable deformation during the linear growth phase, which is followed by complete disruption of the FRC in the nonlinear phase. There is no evidence of dynamic nonlinear stabilization. The linear growth rate of the tilt mode increases with the compression field ramping rate and approaches an asymptotic value. Enhanced compression dynamics also induce larger velocity displacements outside the separatrix. Toroidal flow can reduce both the linear growth rate and the nonlinear saturation amplitude of the tilt mode. Higher initial rotation rates produce stronger stabilizing effects. In addition, the stabilizing effect of rotation is enhanced as the compression field ramping rate increases due to the enhanced flow shear and toroidal field generation during dynamic compression, as shown in figure 2. Although the tilt mode remains unstable with a toroidal rotation Mach number close to 0.5, the onset of tilt distortion can be delayed, allowing a magnetic compression ratio up to 5.3 before the compression heating terminates.

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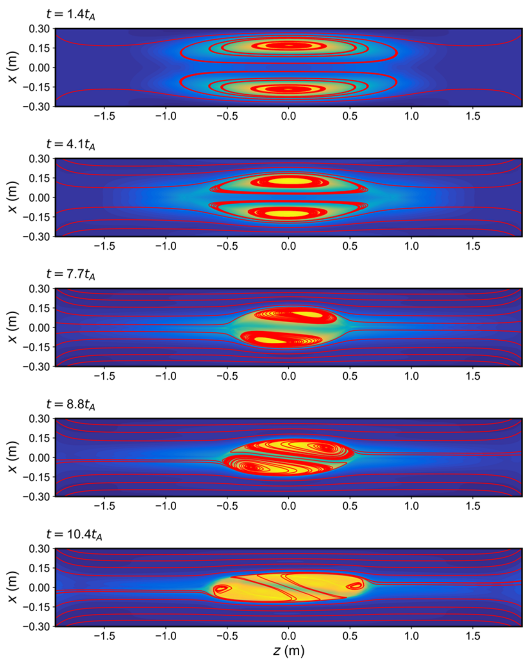

Figure 1. Temporal evolution of magnetic field lines (red) and pressure contours (colored) in the poloidal plane for the case with a compression field ramping rate of $0.12B_{\mathrm{w0}}/\mu\mathrm{s}$.

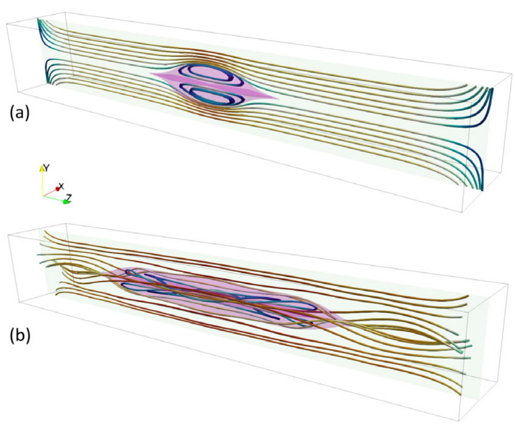

Figure 2. The 3D pressure contours and magnetic field lines for the cases (a) without initial toroidal flow at $5.2t_A$ and (b) with initial toroidal rotation at $6.1t_A$ under a compression field ramping rate of $0.18B_{\mathrm{w0}}/\mu\mathrm{s}$.

References

[1] D.J. Rej *et al.*, Phys. Fluids B: Plasma Phys., **4**, 1909 (1992)

[2] E.V. Belova *et al.*, Phys. Plasmas **11**, 2523 (2004)

[3] J.T. Slough *et al.*, Phys. Rev. Lett. **69**, 2212 (1992)

[4] C.R. Sovinec *et al.*, J. Comput. Phys. **195**, 355 (2004)