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2D and 3D hybrid simulations of spheromak merging*

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Hybrid simulations of counter-helicity spheromak merging have been performed using the HYM code and compared with MHD and Hall-MHD simulations. The 2D hybrid simulations in the MHD-like regime, i.e. with relatively small thermal ion Larmor radius ρ_i/R_c~0.014 (R_c is the flux conserver radius), show remarkable difference compared to fluid results. It is found that for large resistivity (Lundquist number S~500), there are significant differences in reconnection rates and global spheromak dynamics. In particular, in the MHD runs, spheromaks move towards the midplane, and merge completely in about $10t_A$, whereas in hybrid simulations with the same plasma parameters, the spheromaks moved towards midplane initially, but then bounced back, and there was no complete reconnection. Unlike hybrid simulations, Hall-MHD simulations show global dynamics similar to that of MHD for these parameters. For lower resistivity with S~1500, the hybrid simulations show complete or nearly complete reconnection of spheromaks, and the FRC formation by t~$6t_A$, but the reconnection rates were much lower than in fluid runs. Comparison of results from hybrid simulations and MHD simulations shows thicker and shorter current layer in hybrid simulations. The hybrid simulations show an outward radial shift of the reconnection X-point which is related to generation of a quadrupole field, and has also been observed in 2D Hall-MHD simulations. Relatively large toroidal ion velocities up to V_φ~$2.5V_A$ are generated due to the 'sling-shot' effect both in fluid and kinetic simulations. Hybrid simulations also show much wider ion velocity profiles. Results of 2D and initial 3D hybrid simulations show that even in the MHD-like regime, there are significant differences between hybrid and MHD simulations of global reconnection, and demonstrate the need for a full kinetic description of plasma. These findings are in a sharp contrast with generally accepted paradigm that the inclusion of the Hall effects is sufficient to reproduce realistic reconnection rates of kinetic plasmas. Results of this study are also consistent with 2D full PIC and hybrid simulations of island coalescence, where it was found that fluid description including the Hall term does not describe reconnection in large systems correctly [1,2], unlike in the local current-sheet studies. It was shown that merging becomes increasingly ineffective for larger islands due to large gradients of the ion pressure tensor, broader ion diffusion region, and reduced outflow velocities [2], also demonstrating the importance of the kinetic ion description.

[1] H. Karimabadi, et al., PRL **107**, 025002 (2011); A. Stanier et al., PRL. **115**, 175004 (2015).
[2] J. Ng, et al., Phys. Plasmas **22**, 112104 (2015).

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