Novel Algorithms for the Accurate and Fast Solution of the Two-Fluid MHD Equations

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The study of magnetically confined fusion involves complex physics that spans disparate time and length scales, requiring diverse simulation strategies ranging from magnetohydrodynamics (MHD) to particle-based models. While single-fluid MHD simulations are computationally efficient, they fail to capture critical phenomena at smaller scales. Conversely, particle-based methods, though accurate, are computationally prohibitive for full-domain simulations. The two-fluid MHD model provides a middle ground, significantly reducing computational complexity while preserving essential physical details lost in standard MHD models.

This work introduces novel algorithms for solving the two-fluid MHD equations using a finite volume approach, with a focus on enhancing simulation efficiency. Key innovations include relaxing the time step restrictions imposed by the speed of light constraint through an implicit Maxwell solver, and the use of a locally implicit treatment for stiff source terms. These advancements allow for larger time steps and reduced computational costs without sacrificing accuracy.

Additionally, this study extends the multi-physics approach to capture plasma-wall interactions using a rigid body ghost fluid method, enabling the simultaneous simulation of plasma and material interactions within a unified computational domain. The implemented algorithms are highly parallelized and validated against established benchmarks, including shock-capturing problems, magnetic reconnection scenarios, and the demonstration of two-fluid effects. The results show a reduction in computational time compared to traditional fully explicit methods.

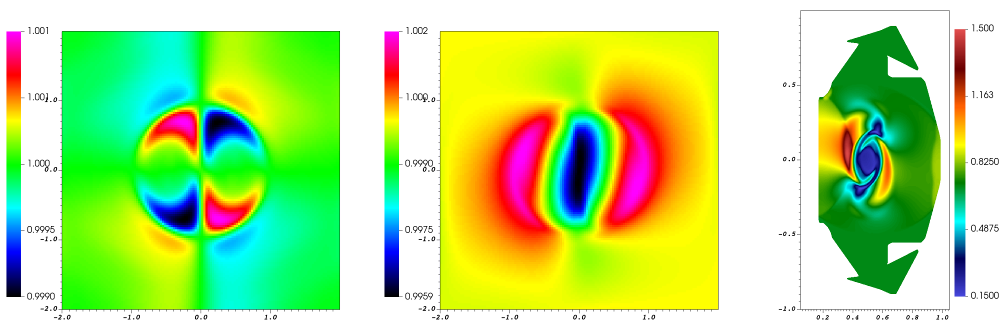

Figure 1: *Validation test cases from left to right - ideal MHD and two-fluid tilting cylinder, and MHD rotor in a tokamak geometry.*