Hybrid Approach for Plasma Simulation: Integrating data-driven ML model with traditional Fluid Modeling

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Abstract

We propose a hybrid pipeline, involving integration of a differential equation (DE) based solver with data-driven deep learning (DL) model, tailored for plasma simulations to improve computational efficiency of plasma fluid modeling. As a proof of concept, we applied this hybrid method to simulate High-Power Microwave (HPM) breakdown, capturing the spatio-temporal evolution of plasma and the formation of plasma streamers [1]. The traditional fluid approach applied for this problem is inherently multiscale and multiphysics, involving coupling of an electromagnetic (EM) solver and a plasma solver. The EM solver, based on Maxwell's equations, models the interaction between microwaves and plasma, while the plasma solver addresses the plasma continuity equation. Notably, the EM solver consumes approximately 99.9% of the overall simulation time, whereas the plasma solver accounts for only 0.1%, underscoring the potential for optimizing the EM solver via DL to significantly accelerate simulations while preserving accuracy [2]. To achieve this, we employ a U-Net-based DL model, augmented with Vision Transformer (ViT) blocks, to replace the traditional EM solver in the traditional fluid approach, thereby speeding up the simulation process. The hybrid approach integrates the DL components, developed in Python, with the DE-based plasma solver implemented in C, allowing efficient communication between the two. Training data was generated via traditional fluid simulations and the DL model was trained using TensorFlow on GPUs for accelerated learning. Post-training, simulation using the hybrid approach was conducted on a CPU. Performance comparison of this hybrid approach against conventional 2D fluid simulations of microwave streamers demonstrated a 100x speedup, while achieving desirable accuracy. We believe, proposed hybrid approach is versatile and can be adapted for various plasma simulations, especially those involving fusion plasma investigations, which are highly computationally demanding.

References

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