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MODELING OF CAPILLARY DISCHARGE PLASMAS FOR WAKEFIELD ACCELERATORS AND BEAM TRANSPORT*

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Abstract

Next generation accelerators demand sophisticated beam sources to reach ultra-low emittances at large accelerating gradients, along with improved optics to transport these beams without degradation. Capillary discharge plasmas can address each of these challenges. As sources, capillaries have been shown to increase the energy and quality of wakefield accelerators, and as active plasma lenses they provide orders-of-magnitude increases in peak magnetic field. Capillaries are sensitive to energy deposition, heat transfer, ionization dynamics, and magnetic field penetration; therefore, capillary design requires careful modeling. We present simulations of capillary discharge plasmas using FLASH, a publicly-available multi-physics code developed at the University of Chicago. We report on the implementation of 2D and 3D models of capillary plasma density and temperature evolution with realistic boundary and discharge conditions. We then demonstrate laser energy deposition to model channel formation for guiding intense laser pulses. Lastly, we examine active capillary plasmas with varying fill species and compare our simulations against experimental studies.

INTRODUCTION

Improved electron sources and optics are required to achieve energy and brightness metrics for next generation collider designs. Capillary discharge plasmas can generate structured plasma profiles for a range of accelerator applications. These devices have been successfully used as waveguides to couple intense laser pulses, increasing the acceleration length and peak energy during laser wakefield acceleration [1]. Because they generate high azimuthal magnetic fields, capillaries have been employed as compact, efficient lenses for beam transport [2, 3] and for multi-stage coupling of plasma accelerators [4]. Recently, these devices have also been used as a tunable dechirper for electron beams [5].

The plasma dynamics within a capillary discharge are governed by Ohmic heating of the plasma balanced by conductive dissipation at the capillary wall. The discharge current drives a strong, time-dependent magnetic field, which necessitates self-consistent magnetohydrodynamics (MHD) modeling. Thermal conductivity and magnetic field transport require additional models, and a detailed equation of state must be implemented to compute ionization and augment the hydrodynamic equations. In this paper, we demonstrate two- and three-dimensional modeling of capillary discharge plasma simulation using the publicly available multiphysics code FLASH [6]. Our results build upon previous implementations to incorporate improved transport models and embedded boundaries [7]. We apply this model to perform 2D and 3D simulations of cylindrical capillary geometries.

TRANSPORT MODELS

Time-dependent capillary dynamics are sensitive to the competing heating and cooling effects within the plasma. Electrical discharge drives heating of the plasma through magnetic resistivity, while thermal conduction transports energy from the hot plasma to the cool walls. Previous efforts [7–9] to simulate these systems relied upon the Spitzer-Harm [10] or Braginskii [11] models for capturing the resistivity coefficient η and conductivity κ. The Braginskii

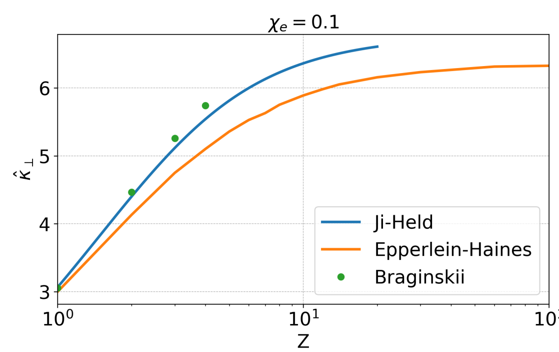

Figure 1: $\kappa_\perp$ for different models across common ionizations, for a given magnetization $\chi_e = 0.1$.

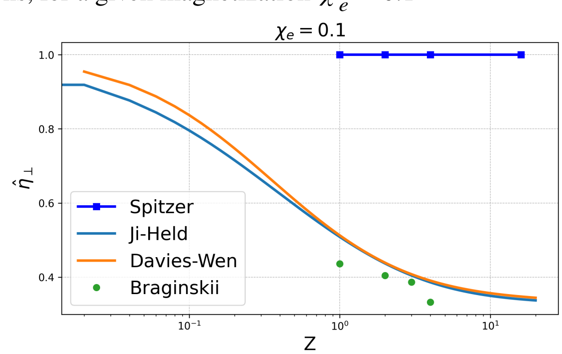

Figure 2: $\eta_\perp$ for different models across common ionizations, for a given magnetization $\chi_e = 0.1$.

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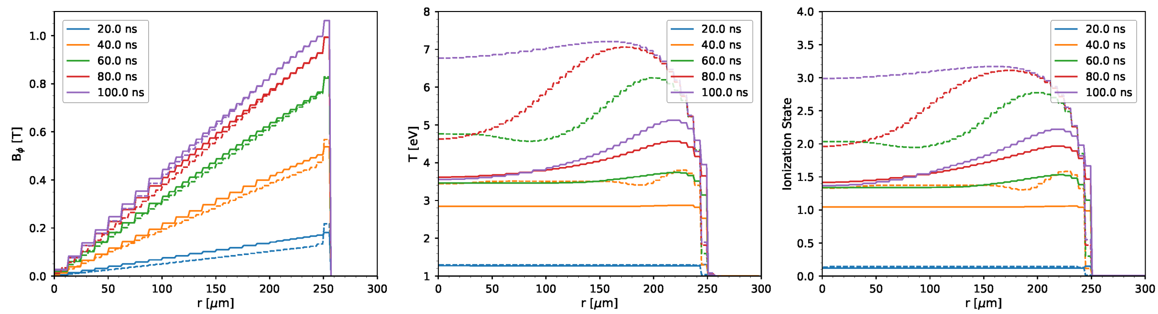

Figure 3: Magnetic field B_ϕ, electron temperature T_e, and ionization state for an Argon-filled capillary: (solid) Davies-Wen resistivity and Ji-Held conductivity in use vs. (dashed) Spitzer resistivity and Epperlein-Haines conductivity in use.

model does not extend well to high Z materials, minimizing its application for Argon-filled lenses, while Spitzer does not provide guidance on anisotropic transport.

Because the axial discharge current is perpendicular to the magnetic field and to the resulting temperature gradients in the plasma, these terms are important to correctly compute the Ohmic heating and thermal dissipation in the system. To address these concerns, we've updated our FLASH model to use modern anisotropic transport implementations. For conductivity, we use the model prescribed by Ji & Held [12], and for resistivity we use the model prescribed by Davies & Wen [13]. Figures 1 and 2 illustrate the differences between scaled conductivities $\kappa_\perp$ and resistivities $\eta_\perp$, respectively for common ionization states, given a fixed magnetization $\chi_e = 0.1$. Standard capillary configurations achieve peak magnetizations in the range of 0.05 – 0.2.

The application of different transport models can significantly alter the predicted capillary evolution, especially for higher fill-Z species such as Argon, wherein the discrepancies between models are more significant. Figure 3 compares the evolution of two capillaries with identical initial conditions and discharge currents, but for which the magnetic resistivity and thermal conductivity models have been exchanged. Solid lines reflect the use of the new Davies &Wen resistivity and Ji & Held conductivity models, while dashed lines indicate the use of older Spitzer resistivity and Epperlein-Haines [14] conductivity models. Previous models over-estimate the heating and ionization of the plasma, despite comparable magnetic field penetration. This is in part due to the higher resistivity predicted by Spitzer, although only changing the conductivity model will still increase the plasma temperature. An improved understanding of heating rates is critical to predicting the capillary evolution, as waveguide experiments rely on the capillary having formed a channel prior to firing the laser, and lens studies are extremely sensitive to the onset of magnetic nonlinearities resulting from thermalization and channel formation.

EMBEDDED BOUNDARIES

Previous simulation configurations [7] did not include the capillary wall material within the simulation domain. Instead, magnetic field conditions and transport properties were calculated and applied as domain boundary conditions.

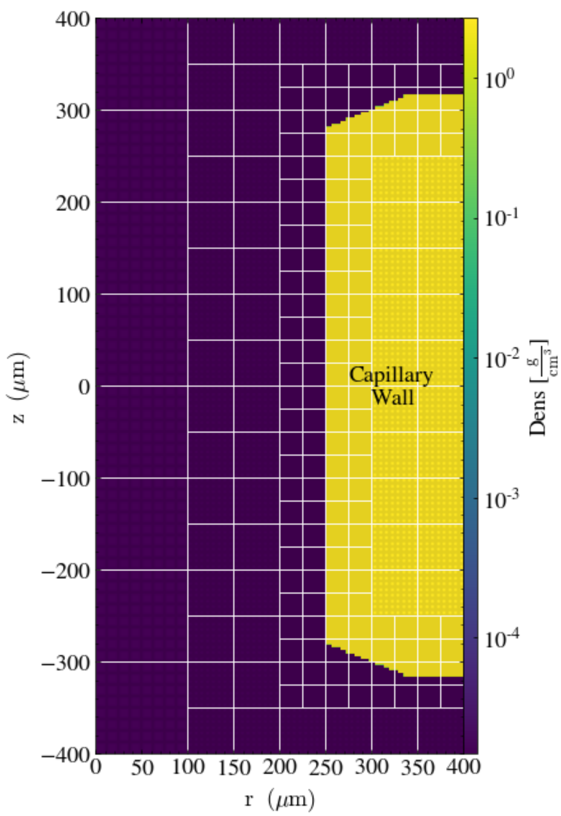

Figure 4: A longitudinal slice of the new embedded boundary configuration for an R-Z geometry.

However, this configuration is not scaleable to 3D geometries, for which the capillary may not conform to the domain, nor does it permit the inclusion of gas supply channels, outlets, and tapering. To permit these functionalities, we have implemented an embedded boundary representation of the capillary structure. The wall region is represented as an immovable fluid comprised of the wall material, Al_2O_3, which transports field and thermal quantities self-consistently without changing density. The discharge current is represented through the application of a magnetic field condition at the capillary-wall interface, as specified by Ampere's Law, and the entire wall material is initialized at a fixed temperature, although non-uniform specifications are permitted for 3D configurations. Figure 4 depicts this configuration for a 2D cylindrical geometry.

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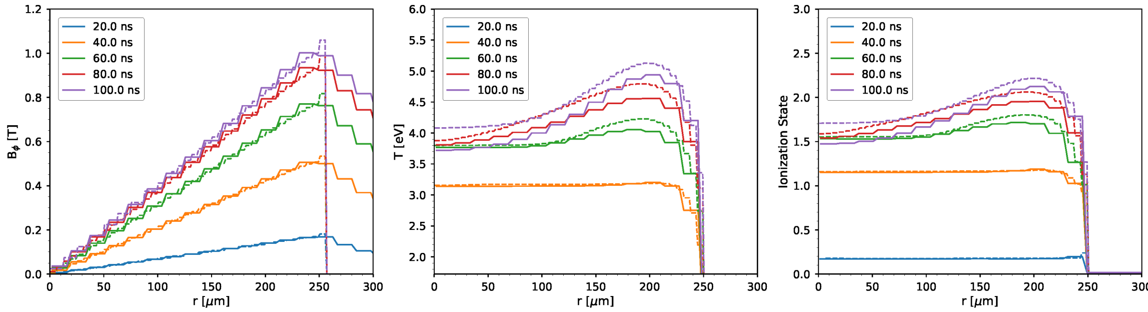

Figure 5: Comparison of the magnetic field B_ϕ, electron temperature T_e, and ionization state for an Argon-filled capillary discharge, between 3D Cartesian geometry (solid lines) and 2D cylindrical (dashed lines) geometry.

THREE DIMENSIONAL GEOMETRIES

We have extended our 2D cylindrical simulations to 3D Cartesian geometries. This extension requires characterization of the magnetic field in terms of its Cartesian components along the $\hat{x}$ and $\hat{y}$ axes. In 3D, these quantities are represented on the faces of the cells, and small adjustments must be made at the wall interface. Subsequent changes also follow from the non-conformal nature of the cylindrical capillary when represented on a block-structured mesh. Figure 6 illustrates a transverse cross-section of the capillary representation and plots the electron temperature at 100 ns.

Prototype 3D simulations were performed at NERSC Cori, using a 256 core decomposition and a reduced maximum refinement in comparison to 2D simulations, resulting in half the maximum resolution. Figure 5 depicts a comparative evolution for capillaries with identical initial conditions but different dimensionality. Magnetic field penetration is nearly identical within the body of the capillary, but deviates within the wall. Electron temperatures within the wall region remain nearly identical, suggesting this increased field does not substantially alter the physics. Additional deviations are seen in temperature and ionization state at the ~5% level, suggesting overall excellent agreement between the two configurations.

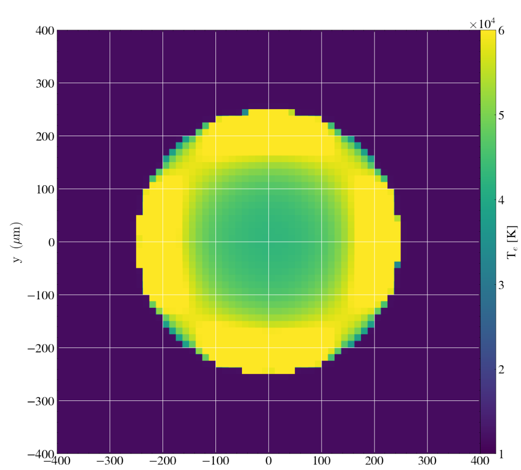

Figure 6: Electron temperature cross-section for an Argon-filled capillary simulated in 3D Cartesian geometry.

CONCLUSION

We report on 2D and 3D simulations of cylindrical capillary discharge plasmas with embedded boundaries using the FLASH code. We implement improved transport models to more accurately capture non-parallel flows native to capillary geometries, as well as embedded boundary descriptions. We then demonstrated a 3D Cartesian simulation geometry that shows good agreement with 2D R-Z simulations. These tools have been applied to simulations of Hydrogen and Argon filled capillaries with realistic operating conditions.

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