Modeling of structured plasmas for next generation accelerators

(Letter of Interest to Snowmass21, Computational Frontier)

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Abstract

Novel plasma devices, including capillary discharge plasmas and laser-ionized plasma columns, show promise for application across a range of essential beamline components, including acceleration stages, focusing, energy compensators, and non-destructive beam diagnostics. These systems could enable fundamental advances in high quality electron and positron beams and support TeV-class high luminosity lepton collider concepts. However, modeling these systems with high fidelity requires integrated multi-physics capabilities at computational scales which exceed those of traditional electromagnetic simulation tools. This letter outlines the prospective applications and corresponding modeling efforts currently being undertaken in the community, alongside promising approaches to capturing the essential dynamics of these systems, such as hydrodynamic, magnetohydrodynamic, and Vlasov models. These tools are complementary to existing simulation codes, and address the intermediary dynamics required for integrated, end-to-end accelerator modeling suites.

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1 Structured Plasma Applications

Laser-driven plasma (LPA) and beam-driven plasma wakefield (PWFA) accelerators rely on generating controllable plasma target structures for maximizing accelerating gradient, efficiency, and stability. Controlled plasma channels have been used for more than a decade to significantly increase the peak energy and quality of laser-accelerated electron beams [1, 2, 3]. For LPA schemes, generation of a plasma channel with specific radial density profiles enable matching of the drive laser to the plasma, reducing diffraction while maintaining peak on-axis intensities [4]. Longitudinal density control can be used to trigger injection via density downramp [5], and to modify dephasing through longitudinal tapering [6]. Similarly, PWFA schemes have benefited from the generation of meter-scale plasma channels with near-uniform density [7, 8, 9]. The use of pre-ionized channels reduces head erosion caused by defocusing of the drive beam, thereby permitting longer acceleration lengths [10, 11]. Finally, recent demonstrations of positron wakefield acceleration have relied on pre-ionized hollow-channel plasmas [12]. Hollow-channel plasmas improve accelerating gradients and phase-stability compared with uniform plasma channels [13], and may enable the independent control of focusing and accelerating fields for emittance preservation [14]. Finite radius plasma columns have also been proposed as plasma targets to accelerate positrons in an electron driven PWFA [15].

Beyond sources and stages, structured plasmas have found application as flexible focusing elements. Discharge capillaries are capable of producing orders-of-magnitude larger magnetic field gradients than traditional quadrupoles or solenoids [16], subsequently enabling the compact staging of plasma accelerators [17]. Alternative approaches include passive plasma lenses, consisting of a narrow plasma jet outflow generated by laser pre-ionization [18, 19], which can provide comparable focusing with sufficiently high density. Structured plasmas have been employed as tunable dechirpers, capable of removing correlated energy spreads from GeV-scale electron beams [20]. Finally, a promising class of non-destructive diagnostics with high spatiotemporal resolution will rely on controllable plasma densities under interaction with electron and laser beams [21].

2 Modeling Requirements and Current Approaches

Modeling requirements for structured plasma systems vary significantly with the device type, scale, and application. For capillaries, proper modeling requires the characterization of the discharge, corresponding magnetic field, and resulting plasma transport properties, including electrical resistivity and thermal conductivity. Magnetohydrodynamic (MHD) codes are well suited to capturing the basic physics of these systems, while maintaining larger timesteps and reduced resolution requirements from kinetic approaches. Significant progress has been made in demonstrating their agreement with 1D analytical models and experimental results for waveguides and active plasma lenses [22, 23, 24]. An efficient coupling of an MHD code with a ns-duration laser heater propagation simulation contributed to the record study of LPA of electrons up to 8 GeV in 20 cm capillary [24]. Similarly, active plasma lens studies have benefited from the application of MHD to reproduce species-dependent nonlinearities in current flow and magnetic field [25, 26].

Pre-ionized plasma sources, of the kind implemented for PWFA stages, passive plasma lenses, and hollow-channel plasmas, have traditionally leveraged high pressure gas jets or plasma ovens to produce the necessary neutral density profiles. Capturing the gas channel or sheet characteristics may necessitate hydrodynamic simulation on μs-timescales, while the subsequent laser ionization requires the computation of laser propagation and self-consistent field ionization profiles on fs-timescales. Furthermore, the pre-ionized plasma does not constitute a local thermal equilibrium (LTE), therefore the LTE dynamics implemented by most MHD codes is insufficient to capture the ionization and heating dynamics. Moreover, vacuum-plasma interfaces are of interest for matching incident drive beams [27], and multi-species plasmas have been employed for high-brightness injection scheme [28]. In these cases, kinetic codes, for example particle-in-cell techniques, may be coupled with hydrodynamic codes to obtain reasonable approximations, or alternatively, first principles models may be employed [29, 18, 30, 19, 31].

3 Modeling Challenges

Below we summarize some of the principal challenges to addressing typical modeling demands. To begin, the diverse physics requirements and operating conditions of these systems presents a challenge for accurately modeling the potential range of devices using a single tool. For instance, capillary discharge plasmas may undergo a number of plasma processes which are not well described by traditional MHD in an LTE or perturbative environment.

The discharge process itself may exhibit numerous kinetic and plasma sheath effects, coupled with complex plasma-wall interactions. The entrance and exit of the capillary may similarly be ill-characterized by single fluid MHD. Enhancements such as extended MHD characterizations may improve the determination of energy exchange and transport coefficients at early timescales, while alternative algorithms, such as continuum kinetics using the discontinuous Galerkin method, could capture plasma-material or plasma-vacuum interactions [32]. Additionally, the need to capture laser pre-ionization coupled with gas and plasma flows, necessitates additional electromagnetic propagation capabilities. For laser-irradiated relativistic or collisional plasmas, Vlasov-Fokker-Planck methods provide a promising approach [33]. Lastly, subgrid-scale techniques have shown promise for modeling transport processes in fluid flows, and could be applied to the problems of electrical breakdown and plasma sheath at material interfaces [34].

Computational complexity remains an additional challenge to high fidelity modeling, even for systems which are well described by available simulation tools. Meter-scale plasma sections introduce spatiotemporal scale-length disparities which place extreme demands on simulation resolution and duration. Calculation of the plasma steady-state requires 100s of ns to μs simulation durations, while resolving nm-scale variations in plasma density and temperature. High repetition-rate operation in a plasma-based collider requires understanding the plasma evolution on the μs periods between subsequent beam interactions, but 3D particle-in-cell simulations are impractical for the expected domain sizes and timescales [35, 36, 37].

High fidelity three-dimensional capillary discharge simulation may require tens of millions of cells, regardless of block structure and boundary representation. Two-dimensional simulations have leveraged the axisymmetric nature of plasma devices to provide more inexpensive solutions with high fidelity. However, asymmetric features, including supply lines, curved or tapered channels, and rectangular cross-sections, may improve plasma control, focusing properties, and beam aperture, thereby necessitating fully 3D simulations [38, 39]. The introduction of laser heating or ionization further increases simulation complexity, requiring explicit algorithms for field propagation and/or ray-tracing, which can increase time-steps or introduce communication overhead. One promising strategy being employed by many codes is the adoption of mature, community-developed libraries to support different solvers and meshing capabilities. This strategy should enhance compatibility and performance on future exascale systems and novel architectures.

Finally, design and benchmark studies of structured plasmas would benefit from improved integration with existing accelerator and plasma codes. The development of a shared description, via a common, inherited API, would substantially alleviate difficulties in comparing simulations performed with different algorithms and interactions, while also streamlining end-to-end modeling of accelerator beamlines. This is especially valuable for fluid-based approaches, for which the relevant parameters may not exhibit a one-to-one correspondence with more commonly used particle-in-cell or accelerator codes. Furthermore, the intrinsic coupling between all beamlines elements necessitates rapid feedback and interoperability to successfully complete design studies. Future accelerators will benefit from a closer linking of the self-consistent multi-physical interactions influencing baseline performance. These suggestions are commensurate with a number of proposed efforts by other SnowMass community initiatives.

4 Summary

Structured plasma devices will comprise a critical path technology for future high energy accelerators, enabling orders of magnitude improvements in accelerating gradients and focusing fields, while facilitating supporting technologies for energy compensation and beam matching. These tools pose unique modeling challenges owing to the sophisticated physical and computational requirements to achieve high fidelity on relevant timescales. These challenges may be met with integrated fluid and hybrid modeling approaches with multi-physics support, alongside integration with community accelerator and plasma codes. This research is of primary importance to supporting community R&D towards a plasma-based collider.

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