Simulation tools for plasma-based accelerators and physics colliders

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Accelerator physics has been at the forefront of scientific and technological developments, supporting some of the most important breakthroughs in our fundamental knowledge of the fabric of the universe. Future developments in this field will require exploring novel accelerator techniques, which may rely on plasma-based acceleration schemes, such as the ones being exploited in the ESFRI roadmap EuPRAXIA project, the new Higgs factory concept (Hybrid Asymmetric Linear Higgs Factory-HALHF), or the AWAKE experiment at CERN, where our team has made significant contributions. Exploring these concepts and technologies will require the most advanced numerical tools to model the accelerator stages at full scale and to accurately simulate the extreme physics environment of beam-beam collisions at extreme energies.

The OSIRIS simulation framework, developed by our group, has been one of the key simulation tools supporting plasma-based acceleration development. However, the problems to be addressed push the boundaries of what is achievable even with state-of-the-art HPC systems. We continue to evolve our code and adapt it to novel architectures and computing paradigms, to enable us to deploy our simulation toolkit in the most advanced Exascale computing resources available worldwide, and perform these simulations at full scale. Concurrently, we continue expanding our reduced geometry/physics models to address these problems with lower computational overhead. The quasi-3D algorithm implemented in OSIRIS retains 3D features while requiring computational resources comparable to 2D simulations, and quasi-static codes such as QuickPIC and QPAD enable precise and cost-effective simulations of plasma-based accelerators.

Our simulation tools also play a critical role in the theoretical understanding of beam disruption, helping to design beam dynamics and predict the outcomes of collisions in linear colliders. Practically, managing disruption involves a combination of advanced particle beam physics, strong field QED, and plasma physics to optimize the beam quality and the interaction point environment. Whereas beam dynamics was originally simulated with reduced model codes such as Guinea-Pig, the extreme regime of beam interaction requires a self-consistent simulation that considers the first-principle electromagnetism and QED physics that the OSIRIS framework is uniquely poised to deliver.