Particle Accelerators

WarpX: Exascale Modeling of Advanced Particle Accelerators

Particle accelerators are used in many areas of fundamental research. A total of 30% of all Nobel prizes in physics since 1939, and four of the last 14 Nobel prizes in chemistry, have been enabled by this technology. Among the candidate new technologies for compact accelerators, the advent of plasma-based particle accelerators stands apart as a prime game-changing technology. The development of these devices depends critically on high-performance, high-fidelity modeling to capture the full complexity of acceleration processes that develop over a large range of space and timescales. WarpX is developing an exascale application for plasma accelerators that enables the exploration of outstanding questions in the physics of the transport and acceleration of particle beams in long chains of plasma channels. These new breeds of virtual experiments, which are not possible with present technologies, will bring huge savings in research costs, leading to the design of a plasma-based collider, and even bigger savings by enabling the characterization of the accelerator before it is built.

For most applications, the size and cost of particle accelerators are limiting factors that can significantly impact the funding of projects or adoption of solutions. Development of plasma-based particle accelerators depends critically on high-performance, high-fidelity modeling to capture the full complexity of acceleration processes that develop over a large range of space and timescales. However, these simulations are extremely computationally intensive, due to the need to resolve the evolution of a driver (laser or particle beam) and an accelerated beam into a structure that is orders of magnitude longer and wider than the accelerated beam. Studies of various effects, including injection, emittance transport, beam loading, tailoring of the plasma channel, and tolerance to nonideal effects (e.g., jitter, asymmetries), that are needed for the design of high-energy colliders, will necessitate a series of tens or hundreds of runs. This will require orders-of-magnitude speed-up over the present state of the art, which will be obtained by combining the power of exascale computing with the most advanced computational techniques.

This project is combining the AMR framework AMReX with novel computational techniques that were pioneered in the PIC code Warp to create a new code (WarpX) and porting the software to exascale platforms. WarpX's team is incorporating the most advanced algorithms in the code, including the optimal Lorentz boosted frame approach, scalable spectral electromagnetic solvers, and mitigation methods for the numerical Cherenkov Instability. To ensure speed and scalability, WarpX is taking advantage of the latest features in portable vectorization algorithms and hierarchical parallelism (on CPUs and GPUs), as well as AMReX's dynamic gridding capabilities, to load-balance the combined computational work associated with both the particles and the mesh. The new software will enable the exploration of outstanding questions in the physics of the transport and acceleration of particle beams in long chains of plasma channels, such as beam-quality preservation, hosing, and beam breakup instabilities.

The exascale challenge problem involves the modeling of a chain of tens of plasma acceleration stages. Realizing such an ambitious target is essential for the longer-range goal of designing a single- or multi-TeV electron–positron high-energy collider based on plasma acceleration technology. The WarpX application uses AMReX for AMR and employs PIC methodology to solve the dynamic Maxwell equations to model the accelerator system. The minimum completion criteria are designed to demonstrate that the project is on track toward the modeling of multi-TeV high-energy physics colliders based on tens to thousands of plasma-based accelerator stages. The main goals are to enable the modeling of an increasing number of consecutive stages to reach higher final energy and to increase the precision of the simulations by performing simulations at higher resolutions, in a reasonable clock time.

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Progress to date

- Implemented parallel finite-difference 3D electromagnetic PIC solver on GPUs.
- Implemented parallel pseudo-spectral analytical 3D electromagnetic PIC solver on CPUs.
- Implemented and verified AMR (initially with single refined level) using AMReX.

The validation of plasma-based accelerators using exascale modeling through WarpX may lead to the development of tens of thousands of particle accelerators for various applications impacting our lives, from sterilizing food or toxic waste to implanting ions in semiconductors, treating cancer, or developing new drugs.