Simulations of Next-Generation Colliders

Axel Huebl, Remi Lehe, Ryan T Sandberg, Marco Garten, Arianna Formenti, Olga Shapoval, Chad E Mitchell, Carlo Benedetti, and Jean-Luc Vay*
Lawrence Berkeley National Laboratory
(Dated: March 27, 2024)

As part of the ALEGRO (Advanced LinEar collider study GROup) Workshop 2024, we presented an invited talk on simulations of staged plasma accelerators towards future colliders. The talk built on theoretical foundations for staging [1–4] and covered algorithmic options for modeling, the need for a compatible ecosystem of simulation codes and recent numerical modeling results.

a. Algorithmic Options were presented for modeling, from first principle simulations (with full, electromagnetic particle-in-cell) to effective approximations and data (ML) models. There are general algorithmic choices to make between speedy simulations, which are fast and as accurate as possible, and high fidelity simulations, which are accurate and as fast as possible. The former include reduced physics (e.g., quasi-static and electro-static approximations, cylindrical geometry, fluid backgrounds) and the latter high-resolution, 3D3V, electromagnetic modeling, with a near-continuum of hybrid models in between. Reduced physics models are required for rapid initial designs, optimizations and operations. Full fidelity physics models are needed for stability proofs, exploration and ML training data generation.

From particle source over staged acceleration to interaction point the modeling requirements vary: plasma source/beam generation often requires full electromagnetic PIC [5, 6], potentially with moderate boosted frame (e.g., $\gamma = 5$). Staged plasma acceleration benefits from full PIC with high relativistic gamma factor or quasi-static codes [7]. Transport is best performed with electrostatic PIC in the beam frame with s-based modeling [8, 9]. Interaction point physics at ultra-relativistic energies can use electrostatic PIC to model beam crossing coupled with Monte-Carlo QED modules [10]. A compatible ecosystem of codes, implementing and sharing models and data, needs to be striven for that uses standardized input/output and common principles/practices (e.g., open source development practices, continuous integration testing/benchmarking, open documentation) [11, 12].

b. Community Ecosystems. The Beam, Plasma & Accelerator Simulation Toolkit (BLAST) was presented as a compatible toolkit striving to address these modeling needs from laptop to Exascale supercomputer [6–9, 13–16]. BLAST codes are part of the Collaboration for Advanced Modeling of Particle Accelerators (CAMPA), which is highly synergistic with ALEGRO goals to design advanced plasma-based colliders. CAMPA also develops novel algorithms, supports standards such as the Particle-In-Cell Modeling Interface (PICMI) and open particle-mesh data standard (openPMD) [17–19], codes beyond BLAST [20, 21], laser manipulation and exchange (LASY) [22, 23], and ML-based optimization (optimas) [24, 25].

c. Modeling Staging: Levels of Realism. One of the pressing needs of the community towards trustworthy plasma-based collider designs is to systematically increase the realism via start-to-end modeling [26]. That requires stepwise maximizing energy gain while conserving transported charge, minimizing energy spread, controlling emittance growth, and ultimately ensuring compactness and energy efficiency as well as robustness under realistic profiles [22], fluctuations and uncertainties in operations. In modeling, this requires establishing workflows (e.g., optimization [24]) that are easy to reproduce, automate & repeat, memorize (with ML) [27, 28], and abstract away.

For acceleration stages, 3D WarpX simulations with low witness beam charge were presented, increasing the currently modeled number of stages from 3 to 50 [29, 30]. Individual stages were then optimized with electrostatic RZ modeling [13] using ML-guided optimization (Bayesian Optimization) [24, 31] to find LPA downramp profiles below the adiabatic limit for stages from 1 GeV to 10 TeV while preserving emittance growth up to 10 pC.

Addressing a need to model the plasma-conventional hybrid beamlines required for transport gaps in a collider, a novel surrogate approach for including plasma elements in beamline modeling was explored [28]. In the presented approach, high-fidelity, full PIC simulations (WarpX) were used to train a neutral network [27] that then enabled %-level accurate tracking of beam moments using ML inference of trained LPA stages via all-GPU accelerated ImpactX beamline simulations. The achieved performance for GPU inference was 63 ns / particles / stage with total simulation runtime of 15 stages and transport as low as 2-4 simulations per GPU and second. It is envisioned that this will enable rapid design studies of complex transport gaps, e.g., for HALHF [32, 33].

Lastly, 3D WarpX simulations and new collaborations were presented to study beam crossing for machines such as ILC, HALHF and others [33–35].

* {axelhuebl,jlvay}@lbl.gov

ACKNOWLEDGMENTS

This research was supported by the Exascale Computing Project (17-SC-20-SC), a collaborative effort of two U.S. Department of Energy organizations (Office of Science and the National Nuclear Security Administration) responsible for the planning and preparation of a capable exascale ecosystem, including software, applications, hardware, advanced system engineering and early testbed platforms, in support of the nation's exascale computing imperative. This work was also performed in part by the Laboratory Directed Research and Development Program of Lawrence Berkeley National Laboratory under U.S. Department of Energy Contract No. DE-AC02-05CH11231, Lawrence Livermore National Laboratory under Contract No. DE-AC52–07NA27344 and SLAC National Accelerator Laboratory under Contract No. AC02–76SF00515. Supported by the CAMPA collaboration, a project of the U.S. Department of Energy, Office of Science, Office of Advanced Scientific Computing Research and Office of High Energy Physics, Scientific Discovery through Advanced Computing (SciDAC) program. This research used resources of the Oak Ridge Leadership Computing Facility, which is a DOE Office of Science User Facility supported under Contract DE-AC05-00OR22725, the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility located at Lawrence Berkeley National Laboratory, operated under Contract No. DE-AC02-05CH11231, and the supercomputer Fugaku provided by RIKEN.

---

[1] A. G. R. Thomas and D. Seipt, Modeling chromatic emittance growth in staged plasma wakefield acceleration to 1 TeV using nonlinear transfer matrices, Phys. Rev. Accel. Beams **24**, 104602 (2021).

[2] C. B. Schroeder *et al.*, Physics considerations for laser-plasma linear colliders, Phys. Rev. ST Accel. Beams **13**, 101301 (2010).

[3] C. B. Schroeder *et al.*, Laser-plasma-based linear collider using hollow plasma channels, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **829**, 113 (2016), 2nd European Advanced Accelerator Concepts Workshop - EAAC 2015.

[4] C. B. Schroeder *et al.*, Linear colliders based on laser-plasma accelerators, Journal of Instrumentation **18** (06), T06001.

[5] J. Wang *et al.*, Injection induced by coaxial laser interference in laser wakefield accelerators, Matter and Radiation at Extremes **7**, 054001 (2022).

[6] L. Fedeli, A. Huebl, *et al.*, Pushing the frontier in the design of laser-based electron accelerators with groundbreaking mesh-refined particle-in-cell simulations on exascale-class supercomputers, in *SC22: International Conference for High Performance Computing, Networking, Storage and Analysis* (2022) pp. 1–12.

[7] S. Diederichs *et al.*, HiPACE++: A portable, 3D quasi-static particle-in-cell code, Computer Physics Communications **278**, 108421 (2022).

[8] A. Huebl *et al.*, Next Generation Computational Tools for the Modeling and Design of Particle Accelerators at Exascale, in *Proc. 5th Int. Particle Accel. Conf. (NAPAC'22)*, International Particle Accelerator Conference No. 5 (JACoW Publishing, Geneva, Switzerland, 2022) pp. 302–306.

[9] A. Huebl *et al.*, From Compact Plasma Particle Sources to Advanced Accelerators with Modeling at Exascale, in *Proc. 20th Advanced Accelerator Concepts Workshop (AAC'22)*, International Particle Accelerator Conference No. 20 (2022) in print, arXiv:2303.12873 [physics.acc-ph].

[10] L. Fedeli *et al.*, PICSAR-QED: a Monte Carlo module to simulate strong-field quantum electrodynamics in particle-in-cell codes for exascale architectures, New Journal of Physics **24**, 025009 (2022).

[11] A. Huebl *et al.*, Aspiration for Open Science in Accelerator & Beam Physics Modeling, Snowmass 2021 - Computational & Accelerator Frontiers (2020).

[12] R. Lehe *et al.*, Embracing modern software tools and user-friendly practices, when distributing scientific codes, Snowmass 2021 - Computational Frontier (2020).

[13] A. Ferran Pousa *et al.*, Wake-T: a fast particle tracking code for plasma-based accelerators, Journal of Physics: Conference Series **1350**, 012056 (2019).

[14] WarpX & ImpactX GitHub repositories (2017).

[15] HiPACE++ GitHub repository (2020).

[16] AMReX & pyAMReX GitHub repositories (2017).

[17] PICMI Standard repository (2016).

[18] A. Huebl *et al.*, openPMD: A meta data standard for particle and mesh based data, https://github.com/openPMD (2015).

[19] openPMD GitHub repositories (2014).

[20] Synergia GitHub repository (2005).

[21] QuickPIC GitHub repository (2015).

[22] M. Thévenet *et al.*, LASY: LAser manipulations made eaSY, in *Proc. 6th European Advanced Accelerator Concepts workshop (EAAC'23)*, European Advanced Accelerator Concepts workshop (2024) under review, arXiv:2403.12191 [physics.optics].

[23] LASY GitHub repository (2023).

[24] A. Ferran Pousa, S. Jalas, M. Kirchen, A. Martinez de la Ossa, M. Thévenet, S. Hudson, J. Larson, A. Huebl, J.-L. Vay, and R. Lehe, Bayesian optimization of laser-plasma accelerators assisted by reduced physical models, Physical Review Accelerators and Beams **26**, 10.1103/physrevaccelbeams.26.084601 (2023).

[25] optimas GitHub repository (2023).

[26] Particle Physics Project Prioritization Panel (P5), Exploring the Quantum Universe - Pathways to Innovation and Discovery in Particle Physics, Report of 2023 (2023).

[27] R. T. Sandberg *et al.*, Hybrid beamline element ML-training for surrogates in the ImpactX beam-dynamics code, in *Proc. 14th International Particle Accelerator Conference*, IPAC'23 - 14th International Particle Accelerator Conference No. 14 (JACoW Publishing, Geneva, Switzerland, 2023) pp. 2885–2888.

[28] R. T. Sandberg *et al.*, Synthesizing Particle-in-Cell Simulations Through Learning and GPU Computing for Hybrid Particle Accelerator Beamlines, in *Proceedings of the Platform for Advanced Scientific Computing Conference*, Platform for Advanced Scientific Computing Conference (PASC24) (Association for Computing Machinery, New York, NY, USA, 2024) under review, arXiv:2402.17248 [physics.acc-ph].

[29] J.-L. Vay, A. Huebl, *et al.*, Modeling of a chain of three plasma accelerator stages with the WarpX electromagnetic PIC code on GPUs, Physics of Plasmas **28**, 023105 (2021).

[30] J.-L. Vay *et al.*, WarpX ECP Milestone Reports FY23.1 and FY23.2 (2023).

[31] A. Ferran Pousa *et al.*, Efficient simulation of multistage plasma accelerators, in *Proc. 14th International Particle Accelerator Conference*, IPAC'23 - 14th International Particle Accelerator Conference No. 14 (JACoW Publishing, Geneva, Switzerland, 2023) pp. 1533–1536.

[32] C. A. Lindstrøm and E. Adli, Design of general apochromatic drift-quadrupole beam lines, Phys. Rev. Accel. Beams **19**, 071002 (2016).

[33] B. Foster *et al.*, A hybrid, asymmetric, linear Higgs factory based on plasma-wakefield and radio-frequency acceleration, New Journal of Physics **25**, 093037 (2023).

[34] M. Tigner, Imperatives for future high energy accelerators, AIP Conference Proceedings **279**, 1 (1992).

[35] T. Barklow *et al.*, Beam delivery and beamstrahlung considerations for ultra-high energy linear colliders, Journal of Instrumentation **18** (09), P09022.