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Summary of working group 6: Theory and simulations

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Abstract

The article briefly summarizes the contributions presented during the working group 6 sessions on theory and simulations.

Keywords: Theory and numerical simulations, Plasma based accelerators, Laser wakefield accelerator

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1. Introduction

Most of the talks in "Theory and Simulations" sessions were related to perspective techniques (both numerical and analytic ones) and subject areas which are not closely linked to a particular experimental project. The theoretical studies which are linked were reported in other working groups. The diversity of presentations indicates that currently there is no mainstream direction of theoretical researches that attracts a major deal of effort.

2. Development of codes

Plasma Wakefield Acceleration (PWFA) needs efficient simulation tools to assess possible scenarios of experimental interest. The need for fast running simulation tools to perform online analysis of PWFA experiments leads to studies on the validity of reduced models. To address these necessities, a 2D hybrid fluid-kinetic code for PWFA is presented: Architect [1]. The beam particles are treated in a kinetic PIC-like mode, while the plasma wake is treated as a fluid. The reduced number of particles involved in the hybrid model significantly reduces the number of operations required in a simulation with respect to full PIC codes with the same number of dimensions. The accuracy and validity of the hybrid scheme developed in Architect was assessed against 3D full PIC code ALaDyn [2] simulations [3].

SMILEI (Simulating Matter Irradiated by Light at Extreme Intensities) is a new open source Particle-In-Cell (PIC) code [4], developed jointly by physicists and High Performance Computing (HPC) experts with emphasis on performance on the newest supercomputers architectures. Recent simulation campaigns of laser wakefield electron acceleration, showed that, performance-wise, the most urgent concern is to find a way to face the strong load imbalance that arises on very large full 3D simulations. The hybrid MPI-openMP typical implementation performs quite well on systems with a couple hundreds of cores. But the accessible number of openMP threads is limited and, as the number of MPI processes increases, this relatively small number of threads is not able to balance the load adequately. A better and more efficient dynamic load balancing algorithm was implemented. The algorithm is based on the division of each MPI domain into many smaller patches organized along a space-filling curve. These patches are used as sorting structures and can be exchanged between MPI processes in order to balance the computational load. Preliminary results on 24 nodes showed a significant speedup using the newest load balancing algorithm [5].

Numerical simulations have been critical in the recent rapid developments of plasma-based acceleration concepts. Among the various available numerical techniques, the PIC approach is the method of choice for self-consistent simulations from first principles. Several recent advances in PIC related algorithms that are of interest for application to plasma-based accelerators were reported [6], including: (a) detailed analysis of the numerical Cherenkov instability and remediation for the modeling in laboratory and Lorentz boosted frames, (b) analytic pseudo-spectral electromagnetic solvers in Cartesian and cylindrical (with azimuthal modes decomposition) geometries, (c) arbitrary-order finite-difference and generalized pseudo-spectral Maxwell solvers, (d) novel analysis of Maxwell's solvers' stencil variation and truncation, in application to domain decomposition strategies and implementation of Perfectly Matched Layers in high-order and pseudo-spectral solvers.

3. Analytical or semi-analytical tools

The beam description in terms of phase space moments is a new theoretical technique for rapid calculation of average phase space properties of electron beams in plasma-based accelerators [7]. This technique has been generalized to realistic longitudinal profiles of the plasma [8] and constitutes a computationally efficient and accurate alternative to time-consuming PIC simulations, enabling rapid prediction of the evolution of beam phase space properties such as emittance.

The concept of coupling impedance in the plasma wakefield excitation was introduced in full analogy with conventional accelerators [9]. This new tool allows for describing the self-consistent interaction between the driving beam and the surrounding plasma and, in particular, makes possible the Nyquist-type stability analysis.

4. Topical studies

Both Architect and Aladyn codes were used to simulate a possible working point for the Sparc_Lab LNF facility that preserve bunch quality: witness is positioned and shaped so to preserve, over the entire acceleration length, both emittance and energy spread. This configuration is characterised by a 200pC driver and a 20pC follower witness. The one driver plus one witness is extended to a COMB (train of bunches) configuration: 3 drivers plus a witness. Bunch characteristics are taken from recent Sparc_Lab experimental results [10].

A critical aspect of Laser Wakefield Accelerators (LWFA) is the self-injection mechanism which can influence the shot-to-shot stability. It was reported on a recent experimental study on self-injection aimed at the optimization of a LWFA used for radiobiology and secondary sources. The experimental results obtained at ILIL laboratory were also compared with the PIC simulation code Jasmine [11].

Laser wakefield acceleration (LWFA) has achieved many notable successes in recent years. However, the lasers used today have low wall-plug efficiency and pulse repetition rates typically limited to a few pulses per second. With these limitations LWFA would not meet the requirements of many applications such as next generation light sources with high average brightness and short pulses. In multi-pulse laser wakefield acceleration (MP-LWFA) the plasma wakefield is instead driven by a train of low-energy laser pulses separated by the plasma period. This opens plasma accelerators to laser technologies, such as fibre and thin-disk lasers, which cannot provide high pulse energies, but can produce low-energy pulses at kHz repetition rates with high efficiency. For this approach the response of the plasma to a train of laser pulses must be well understood. Results were presented of a study of the effects of errors in the pulse train and/or plasma density, including tuning errors and random fluctuations around the ideal pulse spacing. An analytic theory is found to be in good agreement with simulations using the PIC code EPOCH [12].

The generation and propagation of strong currents of laser-accelerated hot electrons in solid density foils is of importance in many applications such as resistive heating, generation of resistive magnetic fields and ion acceleration. Results were presented from particle-in-cell simulations for the scaling of hot electron currents in solids, demonstrating the importance of a full description of the currents with respect to its spectral distribution and spatio-temporal structure. Taking them into account, analytic scalings were derived from first principle conservation laws that proved to be consistent with the simulations [13].

Deep plasma channels now attract much attention because absence of plasma ions on the path of the accelerated beam is favorable for emittance preservation and for minimizing the energy spread. Various regimes of wakefield excitation known in the uniform plasma have their analogues for channels. In particular, the bubble regime can be realized. It turned possible to generalize the analytical bubble theory developed for uniform plasmas to the deep channels [14]. The theory predicts the bubble shape (for the rear part of the bubble), the fields inside the bubble, and the witness shape that provides 100% efficiency and a low energy spread. The theoretical predictions agrees with PIC simulations.

Self-modulation of long particle beams in a plasma is of interest thanks to AWAKE experiment that is under preparation at CERN [15]. Both numerical [16] and analytical [17] attacks to this phenomenon were reported, and mechanisms of the self-modulation instability are now well understood.

New exact solutions of the relativistic wave equations of a charged particle propagating in a plasmon wave of arbitrary high amplitude were analyzed [18].

A curious effect was found in PIC simulations of laser wakefield acceleration driven by a short pulse (full width at half-maximum equals two wavelength) [19]. Three witness electron bunches are initially trapped and accelerated by the bubble-like structure, but eventually the first two turn to drivers and help to accelerate the last one.

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