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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

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.

67 3. Analytical or semi-analytical tools

68 The beam description in terms of phase space moments
69 is a new theoretical technique for rapid calculation of av-
70 erage phase space properties of electron beams in plasma-
71 based accelerators [7]. This technique has been general-
72 ized to realistic longitudinal profiles of the plasma [8] and
73 constitutes a computationally efficient and accurate alter-
74 native to time-consuming PIC simulations, enabling rapid
75 prediction of the evolution of beam phase space properties
76 such as emittance.

77 The concept of coupling impedance in the plasma wake-
78 field excitation was introduced in full analogy with conven-
79 tional accelerators [9]. This new tool allows for describing
80 the self-consistent interaction between the driving beam
81 and the surrounding plasma and, in particular, makes pos-
82 sible the Nyquist-type stability analysis.

83 4. Topical studies

84 Both Architect and Aladyn codes were used to simu-
85 late a possible working point for the Sparc_Lab LNF facil-
86 ity that preserve bunch quality: witness is positioned and
87 shaped so to preserve, over the entire acceleration length,
88 both emittance and energy spread. This configuration is
89 characterised by a 200pC driver and a 20pC follower wit-
90 ness. The one driver plus one witness is extended to a
91 COMB (train of bunches) configuration: 3 drivers plus
92 a witness. Bunch characteristics are taken from recent
93 Sparc_Lab experimental results [10].

94 A critical aspect of Laser Wakefield Accelerators
95 (LWFA) is the self-injection mechanism which can influ-
96 ence the shot-to-shot stability. It was reported on a re-
97 cent experimental study on self-injection aimed at the op-
98 timization of a LWFA used for radiobiology and secondary
99 sources. The experimental results obtained at ILIL labo-
100 ratory were also compared with the PIC simulation code
101 Jasmine [11].

102 Laser wakefield acceleration (LWFA) has achieved many
103 notable successes in recent years. However, the lasers
104 used today have low wall-plug efficiency and pulse repe-
105 tition rates typically limited to a few pulses per second.
106 With these limitations LWFA would not meet the require-
107 ments of many applications such as next generation light
108 sources with high average brightness and short pulses. In
109 multi-pulse laser wakefield acceleration (MP-LWFA) the
110 plasma wakefield is instead driven by a train of low-energy
111 laser pulses separated by the plasma period. This opens
112 plasma accelerators to laser technologies, such as fibre and
113 thin-disk lasers, which cannot provide high pulse energies,
114 but can produce low-energy pulses at kHz repetition rates
115 with high efficiency. For this approach the response of the
116 plasma to a train of laser pulses must be well understood.
117 Results were presented of a study of the effects of errors
118 in the pulse train and/or plasma density, including tun-
119 ing errors and random fluctuations around the ideal pulse

spacing. An analytic theory is found to be in good agree-
ment 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, demonstrat-
ing 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 be-
cause absence of plasma ions on the path of the accelerated
beam is favorable for emittance preservation and for min-
imizing the energy spread. Various regimes of wakefield
excitation known in the uniform plasma have their anal-
ogues 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 ana-
lytical [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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