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LASER-PLASMA ACCELERATION MODELING APPROACH IN THE CASE OF ESCULAP PROJECT

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Abstract

Objective of ESCULAP project is the experimental study of Laser-Plasma Acceleration (LPA) of relativistic electron bunch from photo-injector in 9 cm length plasma cell [1]. In parallel, numerical tools have been developed in order to optimize the setup configuration and the analysis of the expected results. The most important issue when dealing with numerical simulation over such large interaction distances is to obtain a good accuracy at a limited computing cost in order to be able to perform parametric studies. Reduction of the computational cost can be obtained either by using state-of-the-art numerical technics and/or by introducing adapted approximation in the physical model. Concerning LPA, the relevant Maxwell-Vlasov equations can be numerically solved by Particle-In-Cell (PIC) methods without any additional approximation, but can be very computationally expensive. On the other hand, the quasi-static approximation [2], which yields a drastic reduction of the computational cost, appears to be well adapted to the LPA regime. In this paper we present a detailed comparison of the performance, in terms of CPU, of LPA calculations and of the accuracies of their results obtained either with a highly optimized PIC code (FBPIC [3]) or with the well known quasi-static code WAKE [3]. We first show that, when considering a sufficiently low charge bunch for which the beam loading effect can be neglected, the quasi-static approximation is fully validated in the LPA regime. The case of a higher bunch charge, with significant beam loading effects, has also been investigated using an enhanced version of WAKE, named WAKE-EP. Additionally, a cost evaluation, in terms of used energy per calculation, has been done using the multi-CPU and multi-GPU versions of FBPIC.

INTRODUCTION

The laser parameters for ESCULAP project are : max power of 50 TW, waist of 50.5 μm, duration of 38.2 fs, a reduced potential $a_0 = 0.7$ and a wavelength $\lambda_0 = 0.8\mu m$. An electron bunch is injected at the entrance of the plasma with a charge Q, a transverse rms size $\sigma_r = 10.0\mu m$, a longitudinal rms size $\sigma_z = 5.0$ μm, a normalised emittance $1\mu m$, and an average energy of 10 MeV with a rms dispersion of 0.5 %. The plasma cell has a length of 9 cm with a uniform electron density of 2×10^{17} cm^{-3}. The laser focal plane is placed 4 cm after the entrance of the plasma, the focusing zone being used to compress the electron bunch before maximal acceleration in order to reduce the emittance and the dispersion in energy [1, 4]. Numerical studies of the injection and acceleration of low charge bunch was performed in [1, 4] with quasi-static code WAKE. In the present paper we characterise acceleration of Q = 1-30 pC e- bunch in order to determine the importance of beam loading effect, which is the influence of the field generated by the bunch charge and current. In-depth study of the beam loading effect for LPA of an injected bunch was performed in [5] at Q=30pC but at much higher electron energy and laser intensities.

The PIC simulations of LPWA were performed with the FBPIC code using cylindrical grids with azimuthal decomposition and dispersion-free field solver [3]. The calculations have been done on CPU / GPU and in cluster environment using a moving window with the boosted frame technique, which allows to greatly speed up the PIC simulation.

NUMERICAL MODELING

Computational Domain Parameters

In our PIC simulation, the moving window has a longitudinal size of 120 μm, the number of grid points being 4000, which leads to $\Delta z \approx \lambda_0/30$. Its radial size is 600 μm, which is 3 times the waist of the laser at the entrance of the target. The number of radial cells is 600 and the number of macro-particles per cell is 24. Numerical convergence of our simulation was checked on one calculation with a much larger grid of 6000x1500 cells. For the Wake calculations a similar moving window is used, however, thanks to the envelope approximation, the number of longitudinal cells is only 800.

Benchmarking

In Table 1 we present the average computing time for calculating 9 cm propagation in plasma using either WAKE-EP or FBPIC with a boosted-frame Lorentz factor of 5 . In case of FBPIC, we checked multi-CPU using only OpenMP with 48 cores or MPI-OpenMP with 7x20 cores. GPU calculations were also performed using two Nvidia Tesla V100 GPU. Without boosted frame the FBPIC simulation is 20 times longer. Simulation on GPU in boosted frame takes

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only 9 GPUxhour, which is similar to the hourxcpu needed for a Wake calculation and is a reasonable computation time for performing parametric studies.

Table 1: Total calculation time for 9 cm plasma cell. FBPIC modelling was performed in boosted frame with $\gamma_{\text{boost}} = 5$.

LPWA code	Hours x C(G)PU	Total, h
FBPIC CPU, OpenMP (48)	3456 HCPU	72
FBPIC CPU, OpenMP(20) MPI(7)	2730 HCPU	19.5
FBPIC GPU (2)	9 HGPU	4.5
WAKE-EP	9 HCPU	9

RESULTS AND DISCUSSION

In Fig. 1, we compare the Wake-EP and FBPIC distributions in energy of the electron at the plasma exit. We observe a very good agreement between the two calculations, showing that the envelope and quasi-static approximations used in Wake are well justified in our case.

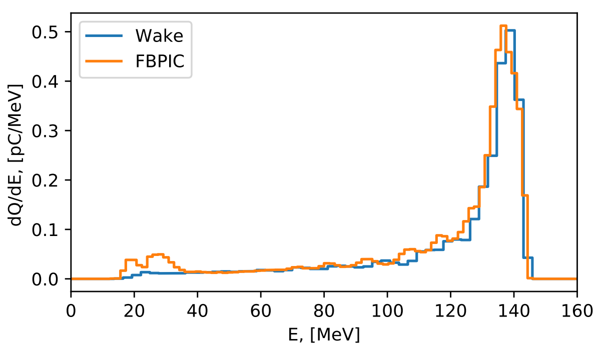

Figure 1: WAKE-EP vs FBPIC comparison for a 10 pC bunch.

Using the same configuration as in [4] we first confirm the obtained results for low charges at which beam loading effects are negligible. Next,we analyze charge effect at 3 bunch charges : 1 pC (low charge) , 10 pC (moderate charge) and 30 pC (high charge).

In Fig. 2 we present electron energy distributions at the plasma exit for the 3 charges and for different delay, expressed in μm , between the electron bunch and the laser. For all the cases, we observe a high energy peak, at energies close to 140 MeV, corresponding to the trapped electrons that are well accelerated by the plasma wave. The charge and shape of the peaks depend however on the injected charge and on the delay. The optimum value of the delay is $-10\ \mu m$, at 1 pC and 10 pC and $-20\ \mu m$ at 30pC. In Table 2 the percentage of captured electrons, emittance, and Lorentz factor of the high energy peak are shown. 99% of electrons are within the peak for 1 pC. At 10pC the fraction is about 88%, whereas at 30 pC, the space charge becomes important and only 30% of electrons are in the peak, with a charge similar to the 10 pC case. As seen from Fig. 3 the total charge remains almost constant during propagation for 1pC and 10 pC, whereas at 30 pC the loss of electrons starts after first cm, the trapped charge staying close to 10 pC after the focal plane.

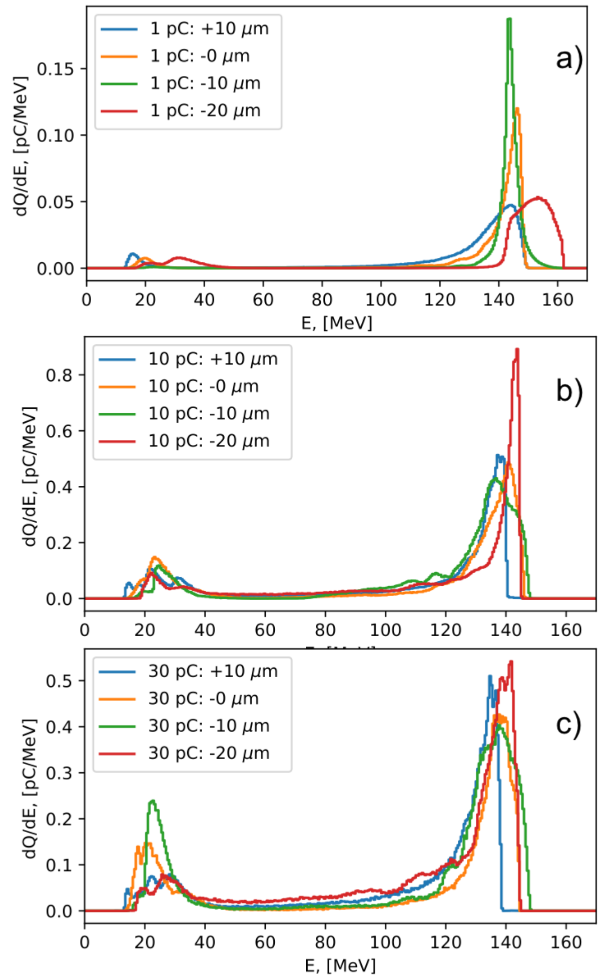

Figure 2: Distribution at plasma exit of the electron energy for 1, 10 and 30 pC (Figs. a-c) respectively).

Table 2: Physical Properties of the Accelerated Electron Bunch ($\gamma > 150$) from Fig. 2 at Optimal Delays.

Q_0, pC	captured%	ε_X ε_Y, μm	$<\gamma>$, σ_γ
1	98.7	2.79 2.14	279.3 4.9
10	88.3	3.08 2.52	250.1 14.0
30	29.9	2.44 2.29	256.6 5.9

During focusing, the laser strength a increases from 0.18 at entrance up to 0.72 at the focal plane. It indicates that the non-linear effects are rather weak in our quasi-linear regime. The longitudinal electric field on axis is reported in Fig. 4 for the three charges. At 1pC, the field generated

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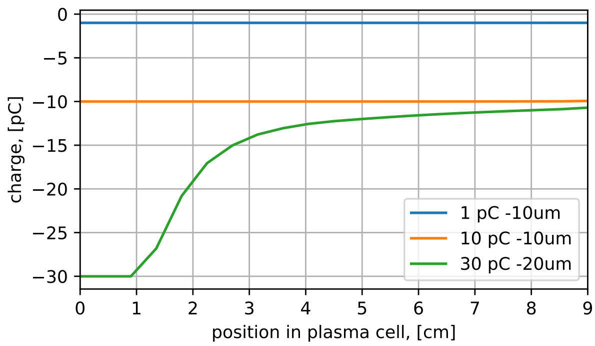

Figure 3: Charge of the electron bunch as a function of position in plasma cell.

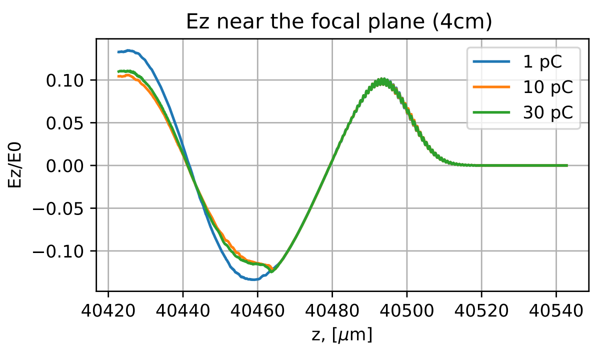

Figure 4: Longitudinal electric field in the focal plane.

by the bunch is small, so that we retrieve the plasma field without bunch. A significant modification of the field is observed for 10 pC at the bunch position due to the beam loading (region 40450-40465 μm), which slightly reduces the overall acceleration in comparison with 1 pC case. The electric field is quite similar for 10 pC and 30 pC, which is due to similar captured charges in the focal plane (see (Fig. 3).

In Fig.5 we show the evolution of the longitudinal beam size during propagation taking into account only the electrons with a final energy $\gamma > 150$. We observe a strong influence of the charge on the bunch compression, which occurs in the focusing zone, before the main acceleration process. For 1 and 10 pC, electron bunches get a significant longitudinal compression, and the initial radial position has no influence on the trapping. An opposite behavior is observed at 30 pC: only electrons initially close to the laser axis are trapped and they are not longitudinally compressed. We observe also a transverse focusing of the bunch by the plasma field during the last cms of interaction.

CONCLUSION

The laser plasma acceleration of an electron bunch in a plasma cell was simulated with FBPIC code using the ESCULAP parameters. In less than 5 hours one configuration can be computed by two NVIDIA TESLA V100

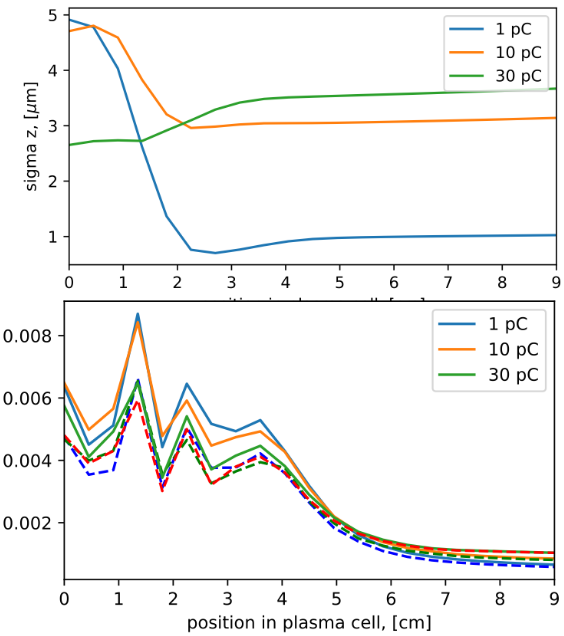

Figure 5: Evolution during propagation of the rms values for the longitudinal size and transverse angles for the bunch electrons with $\gamma_{final} > 150$.

GPU cards, which allowed us to perform several parametric studies. Quasi-static code WAKE-EP was also validated for charge up to 10pC.

We demonstrate that the acceleration scheme proposed in ESCULAP, which consist in trapping electrons before laser focal plane with consequent acceleration in the focal plane, is valid in case of low (1 pC) and moderate bunch charge (10 pC). At higher charges, the field generated by the bunch charge during focusing becomes dominant, preventing a good compression of the bunch and reducing the charges that can be accelerated.When injecting 30 pC, the plasma field induced by the laser should be increased by using higher intensities and/or the bunch energy has to be increased in order to mitigate the beam loading effects. This will be the subject of further studies.

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