Simulation of electron trapping with quasistatic code

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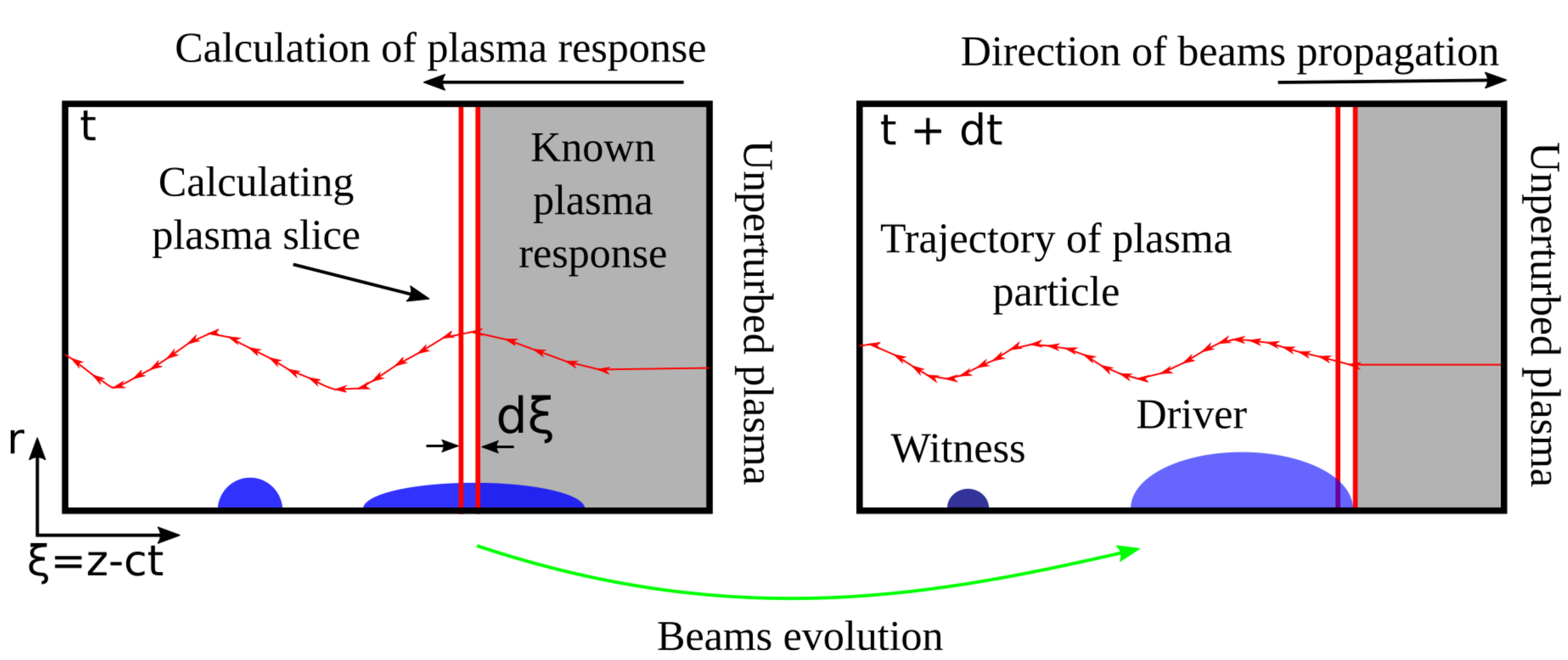
Abstract

Laser plasma wakefield acceleration is a hot topic of research in new acceleration methods. A lot of laboratories with suitable lasers investigate the laser-plasma interaction in many configurations. Nevertheless, numerical simulation is still a necessary tool to study processes occurring in the interaction region. Full PIC codes are the most powerful instruments, but they are computationally demanding. Quasistatic codes use non-trivial assumptions to speedup simulation by several orders of magnitude, but this model does not take electron trapping into account. Each time step only a small part of plasma electrons is trapped and does not impact plasma fields much for some time. We move all plasma particles as test beam particles with the general equation of motion. If they stay in the simulation window, we continue simulating evolution of these particles with the beam particles model. The scaling of the solution is compared with full-3D PIC code. The new numerical instrument allows to perform wide and detailed parametric scanning with a fast code and use heavy codes only for benchmarking.

Quasistatic simulations

Usually, the beam evolution becomes significant after the time larger than $1/\omega_p$, where $\omega_p = \sqrt{4\pi n_e e^2/m_e}$, m_e and e — electron mass and charge, n_e — nominal plasma density. The plasma response remains constant behind the beam while its shape doesn't change a lot. Then, one can separate the calculation of plasma response and beam evolution. Using co-moving coordinate $\xi = z - ct$ for calculation plasma response with small step $d\xi$ allows to describe plasma wake very well and the large step of beam changing dt results in faster simulation, where z is the coordinate along beam propagation, c — speed of light, t — time for observer.

The general scheme of quasistatic simulation in 2D geometry is shown below.



Quasistatic equations of the plasma particle motion:

$$\frac{d\vec{p}_p}{d\xi} = \frac{q_p}{v_{pz} - c}\left(\vec{E} + \frac{1}{c}[\vec{v}_p \times \vec{B}]\right), \frac{dr_p}{d\xi} = \frac{v_{pr}}{v_{pz} - c}, \vec{v}_p = \frac{\vec{p}_p}{\sqrt{M_p^2 c^2 + p_p^2}}.$$

General equations of the particle motion in co-moving frame:

$$\frac{dr_b}{dt} = v_{br}, \frac{d\xi_b}{dt} = v_{bz} - c, \frac{d\vec{p}_b}{dt} = q_b\left(\vec{E} + \frac{1}{c}[\vec{v}_b \times \vec{B}]\right), \vec{v}_b = \frac{\vec{p}_b}{\sqrt{M_b^2 c^2 + p_b^2}},$$

where $\vec{E}$ and $\vec{B}$ — electric and magnetic fields, q — charge, $\vec{p}$ and $\vec{v}$ — momentum and velocity, ξ and r — coordinates of the plasma or beam particles.

We use quasistatic 2D3V code LCODE [1–3] for developing the method of calculation plasma electrons trapping mechanism. Nevertheless, one can apply it to any code with quasistatic approximation.

Bibliography

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2. A.P. Sosedkin and K.V. Lotov, NIMA-829-350, 2016.
3. http://lcode.info
4. C.B. Schroeder et al., PoP13 - 033101, 2006.
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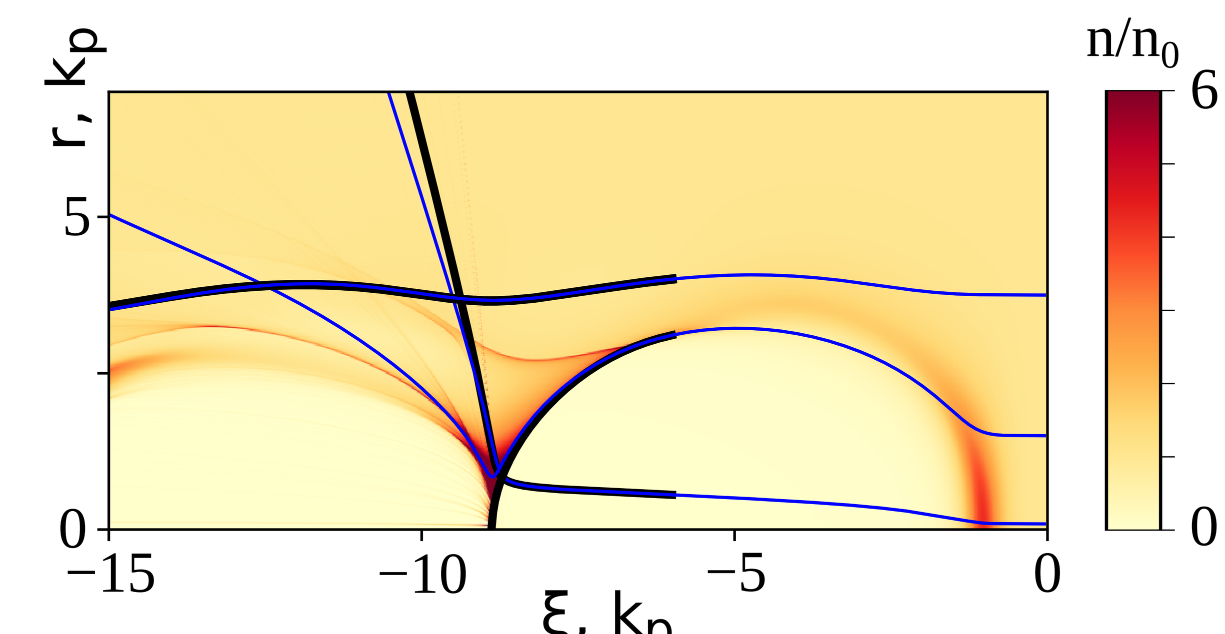
The scheme of modeling plasma electrons trapping with quasistatic code

Because the fraction of trapped electrons is small even with large fields [4], one can calculate plasma response with quasistatic approach. After that, test beam particles associated with plasma electrons at separate ξ are simulated with general equation of the motion. A part of them accelerates to relativistic speeds and stays in simulation window. Continuous generation of test particles along the propagation distance of the driver allows to simulate witness formation.

Typical trajectories of plasma particles (blue lines) and beam particles associated with them (black lines) are shown below.

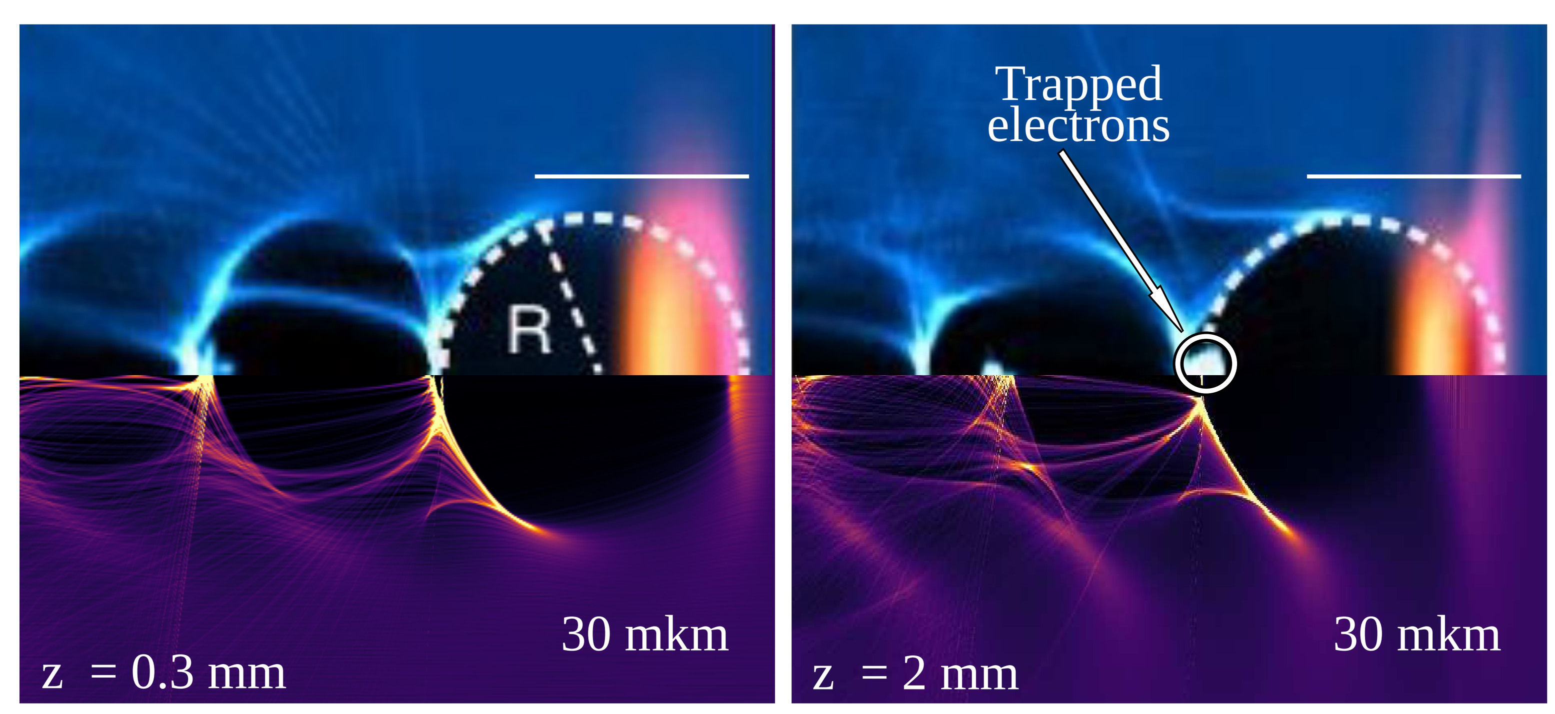


Driver parameters: $a_0 = 3.5$, $\tau_0 = \omega_p^{-1}$, $r_0 = 2.6 k_p^{-1}$, $k_0 = 30 k_p$.

Comparison with FullPIC code

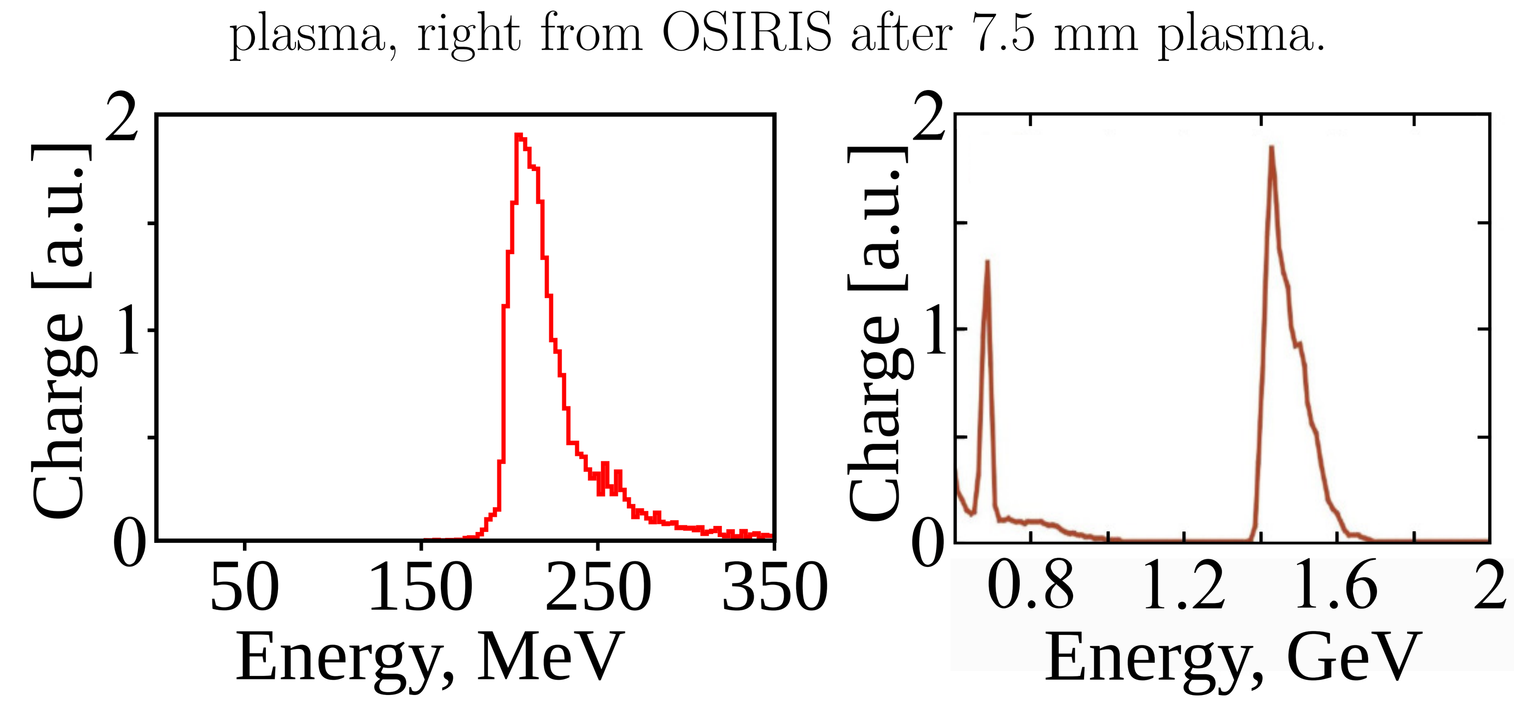
We compare our results to simulation with OSIRIS code described in the paper [5]. Simulation parameters: $\lambda = 810$ nm, $a_0 = 4$, $\tau = 17$ fs, $r_0 = 28$ mkm, $n_e = 1.5 \cdot 10^{18}$ 1/cm^{-3}.

The structure of the plasma wake after 0.3 mm and 2 mm. Top halves are simulated with OSIRIS, bottom ones — with LCODE.



The structure of the first bubble is similar even though the influence of the trapped charge is significant. We consider trapping only in this wake period. Moreover, the length of interaction is reduced to 1 mm, in comparison with 7.5 mm in the work [5] to prevent the influence of witness space charge. Note that association of the real charge with the trapped test particles allows to extend the method's applicability.

Energy spectrum of the trapped beams, left from LCODE after 1 mm plasma, right from OSIRIS after 7.5 mm plasma.



The main energy peak is 224 MeV. Scaling that to full length would result in 1.65 GeV. The main beam in OSIRIS simulation is 1.5 GeV. The small difference can be naturally explained by the reduction of acceleration field associated with laser pulse exhaustion. Also the normalised transverse emittance from LCODE simulation is $\epsilon_n = 7.5$ mm mrad, which is smaller than $\epsilon_n = 45.5$ mm mrad. This fact doesn't have any contradiction with reality, because this value can not diminish along propagation distance in wakefield acceleration.