Modeling Laser Matter Interaction with Tightly Focused Laser Pulses in Electromagnetic Codes

Illia Thiele, Stefan Skupin, Rachel Nuter

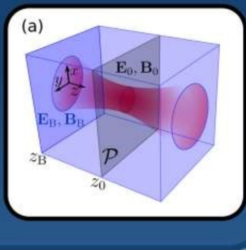
CELIA (Univ. Bordeaux - CNRS - CEA, Centre Lasers Intenses et Applications, UMR 5107, 33405 Talance, France)

Introduction

Investigation of laser matter interaction with electromagnetic codes requires to implement sources for the electromagnetic fields. A common practise to do so is to prescribe the fields at the numerical box boundaries in order to achieve the desired fields inside the numerical box. Very often, the paraxial approximation is used to calculate the required fields at the boundaries. However, the paraxial approximation is valid only if the angular spectrum of the laser pulse is sufficiently narrow. Thus, it is not possible to use this approximation for strongly focused pulses. We propose a simple and efficient algorithm for a Maxwell consistent calculation of the electromagnetic fields at the boundaries of the computational domain. We call them laser boundary conditions (LBCs).

Principle of Laser injection

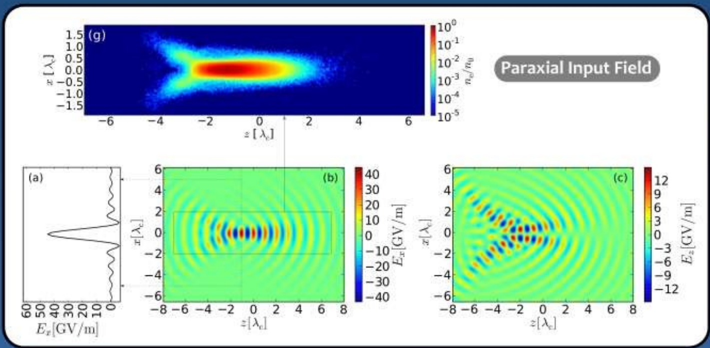
In numerical studies of laser matter interaction, it is common practise to define the laser by its propagation in vacuum, for example, by position and shape of the pulse at focus. Here, we choose to prescribe the pulse in a plane $\mathcal{P}$ parallel to a boundary of the rectangular numerical box, i.e., typically in the focal plane (see Fig. (a)). The laser (red) is passing through the plane $\mathcal{P}$, where the fields $\mathbf{E}_0$, $\mathbf{B}_0$ are prescribed for all times. The goal is to calculate the fields $\mathbf{E}_\mathrm{B}, \mathbf{B}_\mathrm{B}$ at the boundary from $\mathbf{E}_0$, $\mathbf{B}_0$. Choosing $\mathcal{P}$ parallel to a boundary allows us to resort to Fast Fourier Transforms (FFTs) in the numerical computation of the LBCs.

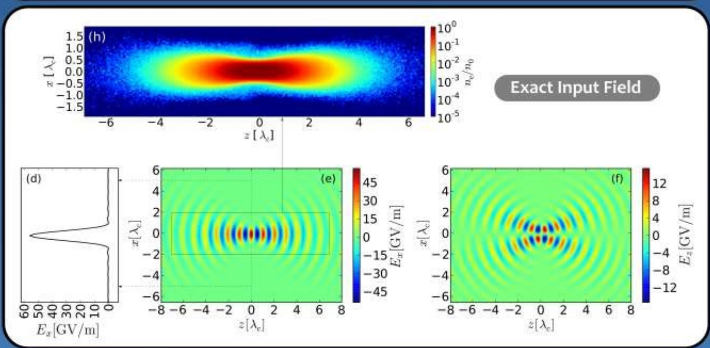


Tightly Focused Gaussian Beam

Tightly focused pulses are potentially interesting for various kinds of experiments giving the possibility to achieve high intensities at rather low pulse energy or to generate micro-plasmas. Here, we are going to simulate a tightly focused Gaussian pulse and its interaction with an initially neutral gas, that is going to be ionized during the interaction. A linear polarized Gaussian pulse is prescribed in the focal plane by the electric field

$$\mathbf{E}_{0,\perp}(x,t) = E_0 e^{-\left(\frac{x}{w_0}\right)^2 - \left(\frac{t}{t_0}\right)^2} \cos(\omega_c t)\mathbf{e}_x$$





In paraxial approximation the electromagnetic fields depending on the transversal propagation vector $\mathbf{k}_\perp$ and frequency ω propagating along z can be calculated from

$$\bar{\mathbf{E}}_\perp^\pm(\mathbf{k}_\perp, z, \omega) \approx \bar{\mathbf{E}}_{0,\perp}^\pm(\mathbf{k}_\perp, \omega) e^{\pm \mathrm{i}\left[\frac{|\omega|}{c} - \frac{c}{2|\omega|}(k_x^2 + k_y^2)\right](z - z_0)} \qquad \bar{E}_z^\pm(\mathbf{k}_\perp, z, \omega) \approx 0$$

$$\bar{B}_x^\pm(\mathbf{k}_\perp, z, \omega) \approx \mp\frac{1}{c}\bar{E}_y^\pm(\mathbf{k}_\perp, z, \omega) \qquad \bar{B}_y^\pm(\mathbf{k}_\perp, z, \omega) \approx \pm\frac{1}{c}\bar{E}_x^\pm(\mathbf{k}_\perp, z, \omega) \qquad \bar{B}_z^\pm(\mathbf{k}_\perp, z, \omega) \approx 0$$

However, the paraxial approximation is valid only if the angular spectrum of the laser is sufficiently narrow. Thus, it is not possible to use this approximation for strongly focused pulses. To describe strongly focused pulses the following exact solution of the Maxwell's equations has to be calculated [3]

$$\bar{\mathbf{E}}_\perp^\pm(\mathbf{k}_\perp, z, \omega) = \bar{\mathbf{E}}_{0,\perp}^\pm(\mathbf{k}_\perp, \omega) e^{\pm \mathrm{i} k_z(\mathbf{k}_\perp, \omega)(z - z_0)} \qquad \bar{E}_z^\pm(\mathbf{k}_\perp, z, \omega) = \mp\frac{\mathbf{k}_\perp \cdot \bar{\mathbf{E}}_\perp^\pm(\mathbf{k}_\perp, z, \omega)}{k_z(\mathbf{k}_\perp, \omega)}$$

$$\bar{\mathbf{B}}^\pm(\mathbf{k}_\perp, z, \omega) = \frac{1}{\omega k_z(\mathbf{k}_\perp, \omega)}\mathbb{R}^\pm(\mathbf{k}_\perp, \omega)\bar{\mathbf{E}}_\perp^\pm(\mathbf{k}_\perp, z, \omega) \qquad k_z(\mathbf{k}_\perp, \omega) = \sqrt{\omega^2/c^2 - k_x^2 - k_y^2}$$

$$\mathbb{R}^\pm(\mathbf{k}_\perp, \omega) = \begin{pmatrix} \mp k_x k_y & \mp\left[k_z^2(\mathbf{k}_\perp, \omega) + k_y^2\right] \\ \pm\left[k_z^2(\mathbf{k}_\perp, \omega) + k_x^2\right] & \pm k_x k_y \\ -k_y k_z(\mathbf{k}_\perp, \omega) & k_x k_z(\mathbf{k}_\perp, \omega) \end{pmatrix}$$

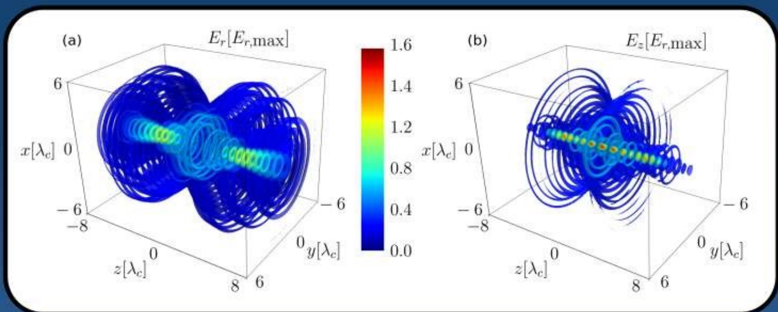
We consider a 2D 50 fs, 0.8 µm central wavelength pulse that is focused up to the diffraction limit. Applying the paraxial approximation in the calculation of the LBCs the transversal (b) and longitudinal (c) fields are assymetric with respect to the focus. The significantly strong longitudinal field reaches 30 % of the transversal that shows clearly the break down of the paraxial approximation. As the cut through the focal plane in Fig. (a) shows, the laser is focused non-tightly. In contrast, the exact solution gives as expected the perfect tightly focused laser as presented in Fig. (d) - (f).

We inspect the electron plasma generated by the tightly focused laser pulses in an initially neutral Argon gas for both cases. The distributions of the electron density after the laser pulse has passed through the interaction region are shown in Figs. (g), (h). The electron density profiles are even qualitatively different: The paraxial LBCs (g) give a fish-like shape, where before the focus (z < 0 µm) the peak electron density appears off-axis and only up to 60 % of the Argon atoms get ionized. In contrast, the Maxwell consistent LBCs (h) produce a cigar like shape with the peak electron density on the optical axis and a fully ionized plasma is produced. We would like to stress that these deviations in the plasma profile are far from negligible, and may have significant impact on features like back-reflected radiation or energy deposition in the medium. The observed sensitivity towards the LBC for tight focusing is not limited to ultrashort low energy pulses interacting with gaseous media, but should be equally important for solid targets and higher pulse energies.

Needle Beam

Laser beams can be much more complex than the often used Gaussian beam. We demonstrate the generality of the LBCs considering the so called needle beam. In [1], the authors describe the "creation of a needle of longitudinally polarized light" by tight focusing of a radially polarized Bessel-Gaussian beam.

Figure (a) shows the radial/transversal, Fig. (b) the longitudinal electric field of the needle beam introduced into the electromagnetic code OCEAN [2]. We find a longitudinal field amplitude that exceeds the radial one in the focal region along eight laser wavelengths. Globally, the maximal longitudinal field amplitude is about 1.6 times larger than the radial one. In the focus, the longitudinal field dominates the transversal even by a factor of 2.5. This exotic beam property offers unexploited opportunities for study and control of laser matter interaction.



References and Acknowledgements

[1] H. Wang et al., Nature Photonics 2 (2008) 501–505.
[2] R. Nuter and V. Tikhonchuk, Phys. Rev. E 87 (2013) 043109
[3] I. Thiele, S. Skupin, R. Nuter, arXiv:1511.08372.

Numerical simulations were performed using computing resources at Méso-centre de Calcul Intensif Aquitain (MCIA), Grand Equipement National pour le Calcul Intensif (GENCI, grant no. 2015-056129), and Partnership for Advanced Computing in Europe (PRACE, grant no. 2014112576).
The Implementation Phase of PRACE receives funding from the EU's Seventh Framework Programme (FP7/2007-2013) under grant agreement RI-312763 and from the EU'sHorizon 2020 Research and Innovation Programme (2014-2020) under grant agreement 653838"

Conclusion

Injecting laser pulses into Maxwell solvers requires to prescribe the electromagnetic fields at the boundaries of the numerical box. We have shown that for tightly focused beams the often used paraxial approximation does not give the expected results. We successfully employed our Maxwell consistent approach to simulate a tightly focused Gaussian pulse. An accurate handling of the laser injection turns out to be crucial for electron density profiles from ionization of neutral atoms due to field ionization. Consequently, the LBCs may have significant impact on features like back-reflected radiation or energy deposition in the medium. Furthermore, our algorithm offers a simple way to simulate more complex pulse configurations as has been presented exemplary creating a needle beam or even sampled experimental beam profiles.