Modelling of Pulse Train Generation for Resonant Laser Wakefield Acceleration using a delay mask

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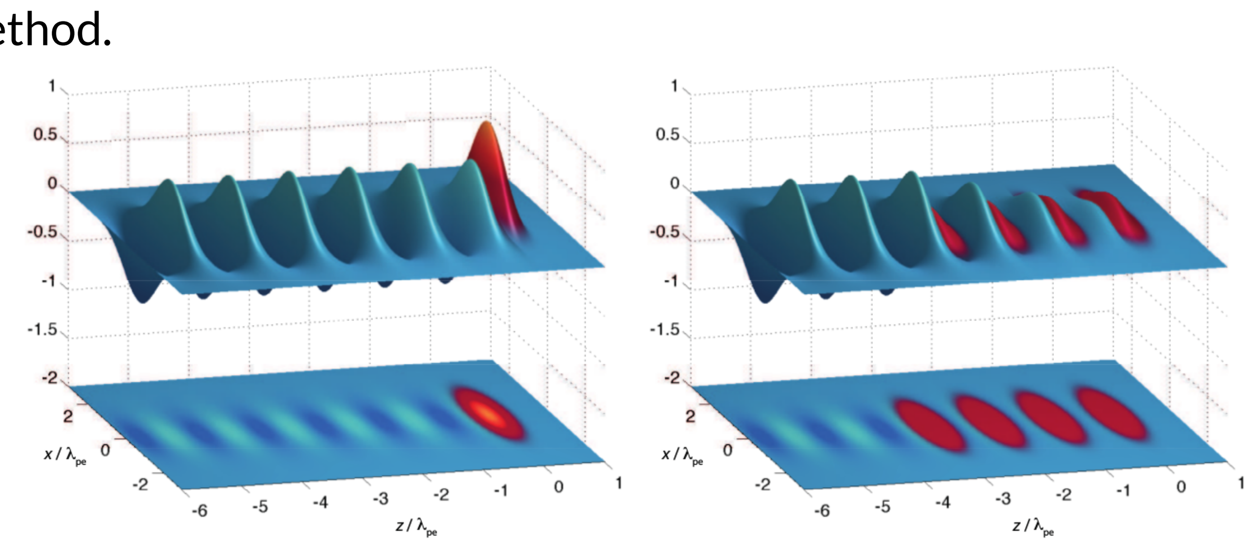
Abstract

The use of laser pulse trains is one of the promising methods to achieve laser wake- field acceleration because of the low-energy requirements and high repetition rate. A new design for the generation of a suitable train of pulses from a single high-energy fast pulse is presented, exploiting optical properties of the main pulse impacting, just before the last focusing mirror, on a "mask" sectioned in concentric zones with different thickness, in order to deliver multiple laser pulses. A hole in the middle of the mask lets part of the original pulse to pass through and provide electron injection. We will show how spatial and temporal profile of the laser emerging from each section are related to their radius and thickness. In particular we use (i) a self-developed code based on diffraction theory to calculate the e.m. field at the focus plane of an off-axis parabolic mirror, (ii) Mirò simulations to evaluate the effects on the pulse duration (iii) analytical solution for the time separation of the pulses. From this characterization it is possible to perform plasma wakefield simulations and use the results as feedback for the choice of different mask's parameters.

Multi-pulse LWFA

In Laser WakeField Accelerator (LWFA) a single high-energy fast laser pulse, focused with a peak intensity of order $10^{18}\,\mathrm{Wcm^{-2}}$, propagates through plasma, generating a density wave characterized by electric field of order $100\,\mathrm{GVm^{-1}}$. In the multi-pulse scheme a train of low-energy pulses, spaced by plasma period, generates the plasma wave by adding coherently the wakefields of each additional pulse. The weaker impact on optical components, the possibility of optimize every pulse in the train and a better efficiency in nonlinear regime [1] are the main advantages of this method.



Space characterization

Electric field at the focal plane $x'y'$ is calculated in the framework of the Stratton-Chu theory:

$$\mathbf{E}(\mathbf{x}_P) = \frac{1}{4\pi}\int_{\mathrm{OAP}} \mathrm{d}A\,[ik(\hat{\mathbf{n}}\times\mathbf{B})G + (\hat{\mathbf{n}}\times\mathbf{E})\times\nabla G + (\hat{\mathbf{n}}\cdot\mathbf{E})\nabla G]$$

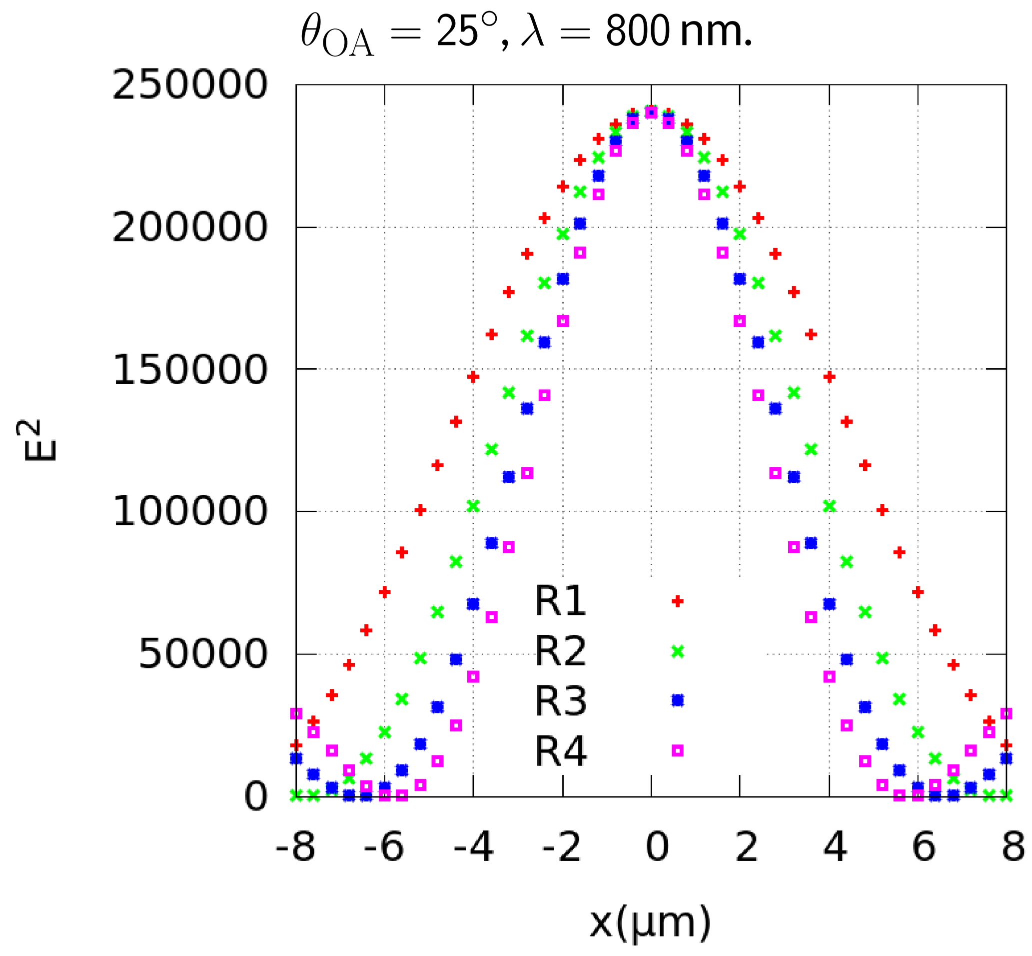
where G is the Green function for the Helmholtz equation and $\hat{\mathbf{n}}$ the normal to the paraboloid surface. Time dependence is intentionally omitted in this analysis and contour effects are negligible in the far-field calculation. Considering a flat-top profile and linear polarization for the original pulse $E(\mathbf{x}) = \exp\left[-\frac{1}{2}\left(\left(\frac{x-d_{\mathrm{OAP}}}{\sigma_x}\right)^2 + \left(\frac{y}{\sigma_y}\right)^2\right)^4\right]$, with $\sigma_x \equiv \sigma_y = \frac{\mathrm{FWHM}}{2(\ln 2)^{1/8}}$, and assuming perfect reflection, it is possible to perform a numerical integration using a C++ code we developed. In particular we integrate on the portion of the OAP surface selected by each section of the mask. For the case study we choose $r^{\mathrm{ext}}_{\mathrm{R4}} < \mathrm{FWHM}/2$, i.e. all sections' area are equal as the energy they carry.

Due to the cylindrical symmetry, we plot E^2 (intensity) on the x' axis of the focal plane. Peak intensities are the same for every section but the spot size become smaller for the external ones. Working in parallel with plasma simulation can underlines which one of these properties is most important, in order to adjust the mask.

Section radii are:

$r^{\mathrm{int}}_{\mathrm{R1}} = 5\,\mathrm{mm} \equiv r$ $\quad r^{\mathrm{int}}_{\mathrm{R2}} = \sqrt{2}r$
$r^{\mathrm{int}}_{\mathrm{R3}} = \sqrt{3}r$ $\quad r^{\mathrm{int}}_{\mathrm{R4}} = 2r$
$r^{\mathrm{ext}}_{\mathrm{R4}} = \sqrt{5}r$

Simulation parameters: $\mathrm{FWHM} = 40\,\mathrm{mm}$, F/5, $\theta_{\mathrm{OA}} = 25°$, $\lambda = 800\,\mathrm{nm}$.



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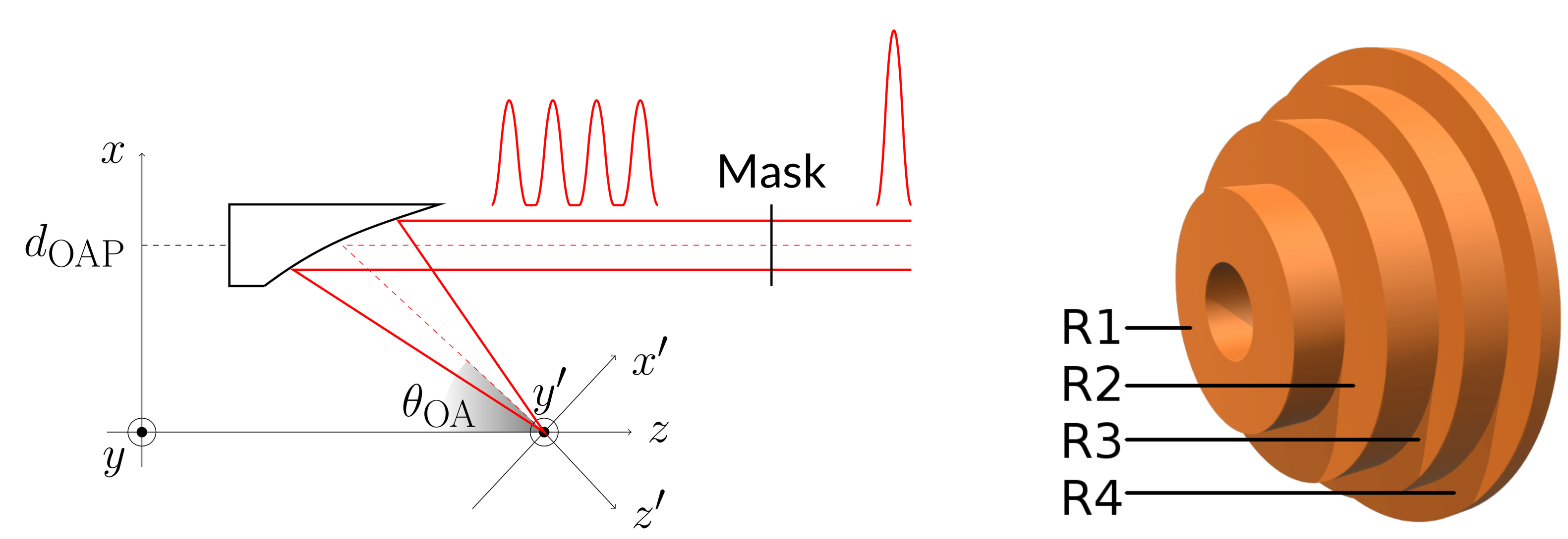
Model and mask

Among the different methods of producing pulse trains we propose a simple one: a single high-energy pulse that impacts, before the last focusing mirror, on a "mask" sectioned (as in figure) in concentric zone (in order to preserve the cylindrical symmetry) with different thickness, introducing a delay for each section. This technique, after experimental testing, could enable pulse train generation for already existing laser systems. For a first model study we consider a mask with 4 sections and a hole in the middle which accounts for the ionizing pulse in the Resonant Multi-Pulse Ionization injection (ReMPI) scheme [2]. Geometrical model is the same presented in a previous work on a laser beam focused by an Off-Axis Parabola mirror (OAP) [3].



Time characterization

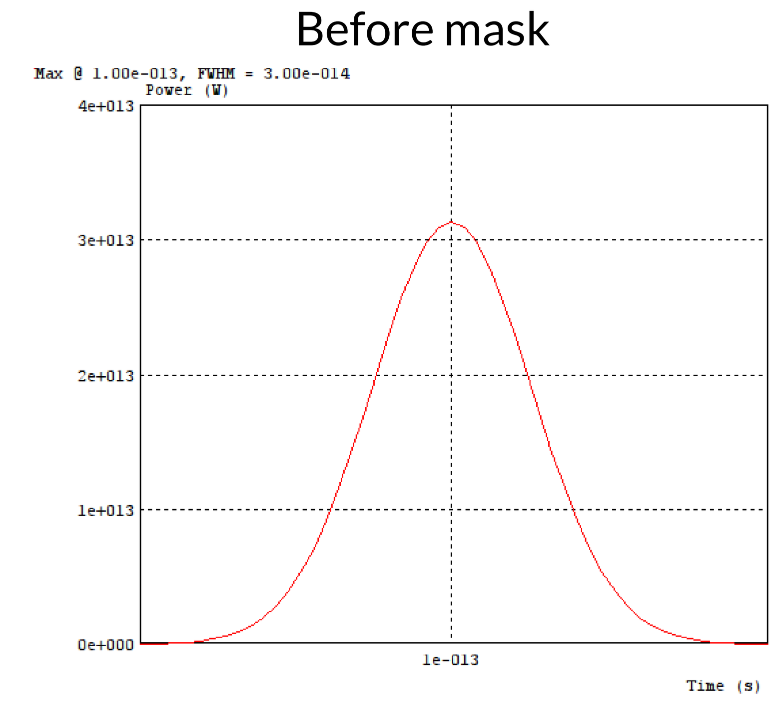
The separation between pulses depends on the group velocity delay of the original pulse passing through the different sections. For a given thickness d we have:

$$t_d = \frac{d}{c}\left(n - \lambda\frac{\mathrm{d}n}{\mathrm{d}\lambda}\right)$$

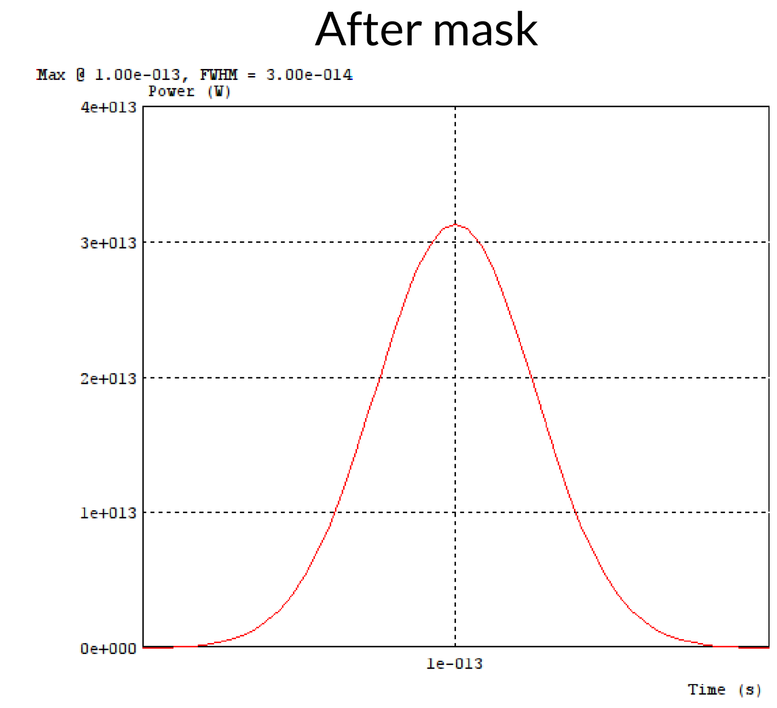
where c is the light velocity, n and $\mathrm{d}n/\mathrm{d}\lambda$ are characteristic of the material and λ is the central wavelength. Equalling t_d and the plasma period $T_p = 2\pi/\omega_{pe}$ it is possible to calculate the thickness. For a slab of fused silica at $800\,\mathrm{nm}$, with an initial electron density of $10^{18}\,\mathrm{cm^{-3}}$, we get $d = 22.77\,\mathrm{\mu m}$, which is reasonable enough for modern technology.

The second order effect on a pulse travelling through matter is the group velocity dispersion, which cause a broadening in the duration. To account for that we perform a mono-dimensional simulation on Mirò, using the same previous parameters and a pulse with $1\,\mathrm{J}$ energy and $30\,\mathrm{fs}$ duration. In these condition there is no appreciable broadening, the difference is, at most, 0.0001%.

Before mask



After mask



References

[1] S. M. Hooker et al., *Multi-pulse laser wakefield acceleration: a new route to efficient, high-repetition-rate plasma accelerators and high flux radiation sources*, J. Phys. B 47, 234003 (2014).
[2] P. Tomassini et al., *The Resonant Multi-Pulse Ionization Injection*, accepted on Phys. Plasmas.
[3] L. Labate et al., *Effects of small misalignments on the intensity and Strehl ratio for a laser beam focused by an Off-Axis Parabola*, Appl. Opt. (2016).