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Letter

Zemax ray tracing model for plasma waveguides

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Abstract

Plasma-based waveguides are currently employed for laser wakefield acceleration to extend the focal region of laser beams. A parabolic transverse plasma density profile, suitable for laser guiding, can be established in a dielectric capillary as a consequence of a discharge in gas. In this work, we report on a new ray tracing model, based on the Zemax software, able to simulate the envelope of a laser beam propagating through a plasma waveguide. The potentialities offered by Zemax in terms of geometries and materials and the possibility to create custom objects do allow the simulation of complex and various scenarios, as for example curved plasma waveguides.

Keywords: laser, plasma, laser-wakefield acceleration (LWFA), waveguide

(Some figures may appear in colour only in the online journal)

1. Introduction

Gas-filled dielectric capillaries are becoming a very important components for the next-generation plasma wakefield accelerators. Indeed, they are employed for plasma channels generation via electric discharges in gas. Applying a voltage of the order of tens kV to the electrodes at the extremities of a few cm-long capillary, it is possible to induce gas-ionization, e.g. in light gases as hydrogen or helium, achieving electron densities within a range which is useful for plasma acceleration over centimeter scales, i.e. in the order of 10^{17} – 10^{18} cm⁻³. Plasma wakefields in dielectric capillaries have been studied in the last two decades both for beam and laser driven plasma acceleration [1–3]. One application of plasma discharge capillaries is that to use one (or more) electron beams for driving a plasma wakefield which establish an accelerating field for a following witness beam. Plasma discharge capillary is also used to exploit the huge magnetic field generated by the

discharge current (up to tens of times larger than what provided by permanent quadrupoles) to tightly focus charged particle beam on very short distance [4–7]. Another important application of plasma channels in dielectric structures can be found in laser-wakefield acceleration (LWFA). Indeed, after a characteristic time of heat exchange between the plasma and the capillary walls, the transverse plasma density profile can acquire a parabolic trend, with a minimum at the center of the capillary, i.e. on its symmetry axis. A generic functional expression for the plasma refractive index would be given by $n(r) = (1 - \omega_p(r)/(\gamma \cdot \omega_0))^{1/2}$, where r is the radial coordinate, ω_p is the plasma frequency, ω_0 is the laser frequency and $\gamma = (1 + a^2/2)^{1/2}$ is the Lorentz factor, taking into account for the electron relativistic quivering through the normalized laser intensity a [8]. It has been already shown that plasmas with parabolic transverse profiles can act as waveguides [9–13]. In this case, the associated refractive index is such that

Figure 1. Ray propagation along the plasma waveguide axis. The ray envelope shows the typical oscillating behaviour of a guided beam.

it can overcome the natural divergence of a properly matched laser beam, keeping it focused over several Rayleigh lengths. In detail, a laser beam is considered matched into a plasma channel if $w_0 = r_m$, where w_0 is the beam waist at the entrance of the channel and r_m is the radius of the guiding channel itself. This feature represents a very powerful tool for laser driven plasma accelerators, where the limit in the acceleration length due to the laser diffraction is one of the most critical. Several experiments [11, 14] have been performed using plasma channels also as waveguides, extending the effective acceleration length and leading to the generation of GeV-scale electron beams [15–18]. Similarly to any conventional particle accelerator component, it is important to well-characterize plasma waveguides [19]. One of the most diffused techniques for plasma density measurements is that to use an optical interferometer [20–23]. This method is largely employed for plasmas generated from supersonic gas-jets. The implementation of a Abel-inversion makes then possible the retrieval of plasma density profiles. On the other hand, for the gas-filled capillaries one has to take into account also for the outer dielectric structure that can introduce optical distortions of different kind. In this sense, the possibility to optically simulate such a structure can represent a very useful tool. Zemax is a ray-tracing software able to simulate the propagation of light through different materials and geometries. Moreover, it allows to define custom objects being very attractive for scientific purposes like in [24, 25]. In this work, we propose a ray-tracing model, based on a custom Zemax [26] dynamic-link library (DLL) which defines a waveguide starting from a parabolic plasma transverse density profile. It can model the propagation of a low intensity laser beam, i.e. $a \ll 1$ and $\gamma \sim 1$, in such a plasma channel inside a capillary. In detail, for laser power $P < P_c \simeq 17(\omega/\omega_p)$ GW, where ω_p is the plasma frequency, self focusing does not affect the surrounding plasma and the beam propagation as well. Although this limitation, our model can be properly used to study laser propagation for linear regime LWFA, e.g. plasma wave excitation for external injection experiments [27, 28], and related diagnostics, usually employing low power probe beams. At this regard, we have realized an ideal Mach–Zehnder interferometer experiment in the Zemax environment, analyzing the interferograms *a posteriori* with a Abel-inversion software and retrieving the starting plasma profile to benchmark our model of plasma profile. Finally, we have pushed the potentiality of Zemax for

studying the light propagation in a curved plasma-discharge capillary, interesting for a wide range of applications both in optics in general, and in laser plasma acceleration in particular [29–31].

2. Zemax model

Zemax editor provides two different scenarios, sequential (SC) and non-sequential (NSC) modes. In the first one, it is possible to design a setup by creating items, e.g. lenses, apertures, polarizers etc, as a succession of consecutive surfaces along the ray propagation axis. On the other hand, in the NSC scenario, one can place objects wherever in any point of the three-dimensional space. In this way, it is possible to design almost every kind of optical setup, as for example an interferometer. Once the layout has been completed and a light source has been activated, Zemax ray-tracing starts propagating each ray through the optical system. Placing a detector in the desired location, the user can visualize the ray position as propagated by Zemax. Therefore, only a geometrical optics analysis is possible, while the propagation in physical optics is reserved only to the SC mode. Nevertheless, both scenarios allow the user to customize his own setup, as for example defining a dispersion curve for a new material, designing a particular object geometry and programming special DLL for more advanced features. For our aim, working in the NSC mode, we wrote a custom DLL to define a parabolic refractive index profile, like for a gradient-index (GRIN) structure, starting from plasma parameters. The chosen electron density profile has been $n_e(r) = n_0 + (\Delta n/r_m^2) r^2$, with n_0 the on-axis density, Δn the density variation on the transverse plane of the capillary and r_m the capillary radius. Such a DLL can be used to define the refractive index of any kind of object. In this work, we have limited our study to cylindrical volumes, straight and curved.

3. Benchmarking

3.1. Interferometric measurement

To test the goodness of our model, firstly we have tested the longitudinal propagation of a matched laser beam through a plasma waveguide defined by $n_0 = 1 \times 10^{18} \text{ cm}^{-3}$,

Figure 2. Comparison between numerical solution of the envelope equation given by equation (1) (dashed lined) and Zemax simulation result (solid line), showing an excellent agreement.

Figure 3. Zemax shaded model of setup layout. A point source (S) is collimated by a lens (L1) to be used as optical probe into the interferometer. A first beam splitter (BS) makes two replica of the beam, one acting as reference and the other illuminating the capillary (C). A second BS merges the two beams and a lens (L2) images them on a rectangular detector (D), 4×4 mm with 2000×2000 pixels, resulting in $2 \mu\text{m}$ resolution.

$\Delta n = 5 \times 10^{18} \text{ cm}^{-3}$ and $r_m = 60 \mu\text{m}$. Figure 1 shows the propagation along the capillary axis of a ray fan, starting with a Gaussian transverse distribution matched with the plasma waveguide. Placing different detectors along the capillary to measure the beam radius, we have compared our results with the numerical solution of the envelope equation given by [32]

$$\frac{d^2 R}{dz^2} = \frac{1}{z_R^2 R^3} \left(1 - \frac{\Delta n}{\Delta n_c} R^4 \right) \quad (1)$$

where $R = w(z)/r_m$, $z_R = \pi r_m^2 / \lambda$ and $\Delta n_c = (\pi r_m^2 r_e)^{-1}$. The quantity $w(z)$ represents the beam width at the $1/e^2$ fall of the light intensity profile, $\lambda = 800 \text{ nm}$ is the laser wavelength and r_e the classical electron radius. Figure 2 shows the comparison between the envelope equation solution and the Zemax simulation. As it is possible to see, they are in excellent agreement, confirming a proper definition of the plasma waveguide in the Zemax custom library. Figure 3 shows the Zemax shaded model of a setup layout. Here, a Mach-Zehnder interferometer has been designed, using a collimated ray source at 800 nm wavelength as optical probe. Along one arm, a dielectric capillary, defined as a hollow channel inside a parallelepipedic

Figure 4. Interferogram simulated by Zemax using 1×10^6 rays.

silica structure, has been placed with its axis orthogonal to the rays. These, in turn, are collected by a $f = 10 \text{ cm}$ lens, making a 1:1 image of the capillary longitudinal plane onto a rectangular detector, 4×4 mm with 2000×2000 pixels. The second arm, where rays propagate in vacuum, is used as reference beam. The plasma parameters used in this case are

Figure 5. Electron density map retrieved from the interferogram shown in figure 4.

Figure 6. Line profile of figure 5 showing the transverse electron plasma density, consistent with the input parameters defining the Zemax simulation. The parameters $n_0 = 1 \times 10^{18} \text{ cm}^{-3}$, $\Delta n = 5 \times 10^{18} \text{ cm}^{-3}$ and $r_m = 500 \text{ }\mu\text{m}$ have been retrieved.

$n_0 = 1 \times 10^{18} \text{ cm}^{-3}$, $\Delta n = 5 \times 10^{18} \text{ cm}^{-3}$ and $r_m = 500 \text{ }\mu\text{m}$. Figure 4 shows a simulated interferogram. This has been obtained using a source made by 1×10^6 rays illuminating the sample. Since only a portion of capillary is placed along the beam, the interferogram presents also straight lines on both sides and on the bottom, defining the background signal and acting as reference for the analysis. These fringes are due to a 0.1° horizontal misalignment of mirror M1. Data provided by Zemax have been processed by means of an external analysis tool.

The interferometry code we have used is made up by two main parts: the raw data manipulation and the 2D analysis. In the data manipulation section, the routine extrapolate, from the raw interferogram trace, the induced phase shift calculating the bending of the fringes, ΔK , respect to the reference ones. The phase shift ϕ results finally in

$$\Delta K = \frac{\phi}{2\pi}. \quad (2)$$

Successively, in the 2D analysis section the routine numerically calculates the gradient of the induced phase $\nabla\phi$ map. Considering the following general well-known relationships:

$$N(\mathbf{x}, \mathbf{y}) - N_0 \propto \alpha(\mathbf{y}) \int \nabla\phi F(\mathbf{x}) d\mathbf{x} \quad (3)$$

$$T(\mathbf{x}, \mathbf{y}) = \frac{N_0 - 1}{N(\mathbf{x}, \mathbf{y}) - 1} T_0 \quad (4)$$

where $\alpha(\mathbf{y})$ and $F(\mathbf{x})$ are respectively a constant taking into account the boundary condition and a form factor taking into account the geometry, T_0 and N_0 are, respectively, the room temperature and the index of refraction relative to it, the routine numerically extrapolates the 2D density/temperature map. However, for the purposes of the present work we have been only interested in the density profile.

Figure 5 shows the result of the analysis of figure 4, reporting the corresponding 2D electron plasma density map, where the density distribution of the plasma waveguide is recovered. Figure 6 shows the data extrapolated from a central row of figure 5. This plot represents the retrieved density profile due to plasma-induced fringe shift. The resulting curve well-reproduce the parabolic profile defined as input in the Zemax object modeling the plasma waveguide, i.e. $n_e(r)[\text{cm}^{-3}] = 1 \times 10^{18} + 5 \times 10^{18} \cdot r[\mu\text{m}]^2/500^2$.

Figure 7. Rays propagation inside a curved capillary. A parabolic plasma profile has been defined using the following parameters: $n_0 = 1 \times 10^{18} \text{ cm}^{-3}$, $\Delta n = 5 \times 10^{18} \text{ cm}^{-3}$ and $r_m = 60 \text{ } \mu\text{m}$.

3.2. Laser propagation in a curved capillary

After having performed these benchmarks, we have exploited one of the main features offered by Zemax, consisting in the possibility to define different object geometries. Thus, we have studied a curved plasma waveguide. For this aim, we have used a torus volume object in Zemax adapting our DLL to this case. Figure 7 shows the propagation of a matched ray fan inside such a structure, as done for figure 1. The capillary has a curvature radius $R_c = 20 \text{ mm}$ and a length equals to 25 mm . As for the straight capillary simulation, the parabolic plasma profile employed has been defined by $n_0 = 1 \times 10^{18} \text{ cm}^{-3}$, $\Delta n = 5 \times 10^{18} \text{ cm}^{-3}$ and $r_m = 60 \text{ } \mu\text{m}$. Also in this situation, the model has well-reproduced the guiding effect due to the plasma channel, taking into account also for the bent structure of the dielectric capillary. The hard challenge of studying toroidal shapes of plasma waveguides has been anticipated in [33], here solved via the exploitation of our powerful and custom DDL for Zemax.

Furthermore, the use of detectors along the curved capillary allows for reconstructing the field profile $E(r)$ of the guided beam at any chosen cross-section of the plasma waveguide. Indeed, by an expansion over electromagnetic hybrid modes EH_{1n} [3, 34], say $E(r) = \sum_n c_n EH_{1n}$, it becomes possible studying the excited modes together with the corresponding amplitudes c_n :

$$c_n = \frac{\int_0^1 E(x) J_0(u_n x) dx}{\int_0^1 J_0(u_n x) dx} \quad (5)$$

where the normalized integration variable is $x = r/r_m$ and $|c_n|^2$ indicates the energy stored in each mode n .

4. Conclusion

In conclusion, we have reported on a new ray tracing model based on the Zemax software that is able to reproduce the

behaviour of a plasma waveguide, commonly used to guide a laser in LWFA experiments, realized by means of a gas discharge inside a dielectric capillary, for a low intensity laser beam ($a_0 \ll 1$). Starting from the plasma parameters defining the transverse electron plasma density profile, we have exploited a custom DLL for calculating the correspondent refractive index profile, responsible for light guiding. To test the goodness of our model, firstly we have injected a ray fan through a straight plasma channel and we have observed its behaviour. In particular, placing several detectors along the capillary, we have been able to compare the simulated beam size with respect to that evaluated with the envelope equation (1), demonstrating an excellent agreement. Then, we have performed an ideal experiment, by setting-up a Mach-Zender interferometer in Zemax, placing a plasma waveguide along the path of one arm. After running a Zemax simulation, so obtaining an interferogram (figure 4), we have analyzed the interferometric data to retrieve the electron plasma density from the plasma-induced phase shift. As shown in figure 6, the result for the density profile retrieval is in perfect agreement with the values given as input to Zemax. Exploiting further its potentialities, Zemax can be used to test the feasibility of new geometries and material to be employed in the realization of plasma waveguides as well as to study their behaviour in specific experimental setups. In this sense, we have presented also the possibility to study the ray propagation in a curved capillary (figure 7), showing and modeling the laser beam guiding in a bent plasma channel. Furthermore, our model is not limited to parabolic plasma density profiles only, but it is possible to implement any sort of profile with an analytical description by realizing a proper DLL. Future studies will be devoted to the possibility of including other effects related to high intensity laser beams ($I > 10^{18} \text{ W cm}^{-2}$), e.g. relativistic self-focusing and pump depletion due to the formation of high-amplitude plasma wakefields.

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