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3D POLARISATION OF A STRUCTURED LASER BEAM AND PROSPECTS FOR ITS APPLICATION TO CHARGED PARTICLE ACCELERATION

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Abstract

A Structured Laser Beam (SLB) is a type of optical beam with spatially inhomogeneous 3D polarisation structures. Generating SLBs from vector beams allows the creation of Hollow Structured Laser Beams (HSLB) with a dark central core. In this way, atypical electric and magnetic field vectors, which are purely longitudinally polarized in the dark zones of the beam, are obtained. The SLB spatial distribution can also include regions with both the electric and magnetic fields longitudinally polarized and oriented in the same or opposite directions. The SLB has a transverse distribution similar to that of a Bessel beam but can theoretically propagate to infinity, therefore giving the potential to generate strong, longitudinally oriented electric fields over long distances, which could possibly allow the acceleration of charged particles. The results of the study of this phenomenon, including simulations of the spatial distribution of the electromagnetic field components, are presented in this paper.

INTRODUCTION

Although a Structured Laser Beam (SLB) generally differs from a Bessel beam (BB) through its field vector distribution or infinite range propagation, in the vicinity of the optical axis the distribution of the SLB field vectors is very similar to that of a BB[1].

The distribution of electromagnetic (EM) field in a BB is similar to the field distribution in RF cavities, see[2]. This has led to a consideration of using a BB to accelerate charged particles[3–5]. In principle, the Hollow SLB (HSLB), which contains longitudinally oriented vectors of EM fields in its core, could also be a suitable optical beam for such a purpose. Although this study is focussed on simulations, HSLBs have already been successfully created experimentally[6].

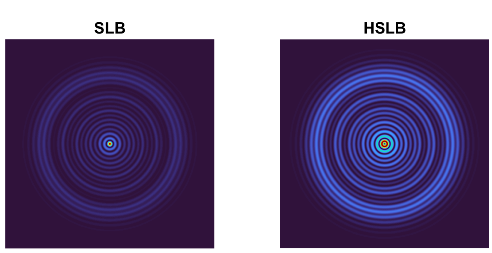

Figure 1: Transversal profiles of the SLB and HSLB.

This work investigates if it is possible to use an SLB to accelerate charged particles.

PRINCIPLE OF THE SLB GENERATION

The main idea is to create an optical beam with the desired wavefront. One of the methods is described here[7].

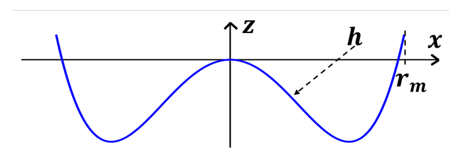

Figure 2: Wavefront profile, represented by the function h, in the x-z plane at $y = 0$. SLB propagates along the z-axis.

The wavefront immediately after the SLB generator can be described in polar coordinates by the relation

$$h = \lambda(K_S\rho^4 + K_D\rho^2), \tag{1}$$

where h is the z coordinates of the wavefront (see Fig. 2), λ is the laser wavelength, K_S and K_D are Seidel coefficients corresponding to spherical aberration and defocus, and $\rho = r/r_m$ is the normalized radial distance. The real radius is define as $r = \sqrt{x^2 + y^2}$ and r_m is the maximal possible radial distance (see Fig. 2) given by the output aperture of the SLB generator. K_S should be positive. K_D can generally be arbitrary, however one of the conditions for infinite range SLB generation is $K_D < 0$.

PRINCIPLE OF THE HSLB GENERATION

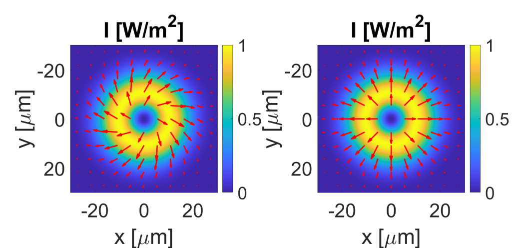

Figure 3: On the left, input beam with spiral polarization ($\gamma = 30°$). On the right, input beam with radial polarization ($\gamma = 0°$). The red arrows show the electric field vector directions at a given time.

HSLB generation can be achieved when the SLB generator is illuminated with a beam having a spiral polarisation. The plane of polarization of such a beam is at a constant angle γ with respect to the radial line. Such a beam also has an atypical optical intensity distribution and is known as doughnut beam (see Fig. 3).

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By modulating the angle γ it is possible to change the representation and orientation of the individual EM field vectors. For $\gamma = 0°$ radial polarization is achieved, while $\gamma = 90°$ leads to azimuthal polarization.

REAL COMPONENTS OF EM FIELD INSIDE HSLB

As can be seen from Figs. 1, the optical intensity of the HSLB is 0 on axis. Thus, there are no transverse electric or magnetic field components. However, longitudinally oriented vectors of the EM field do exist. This is evident from Fig. 4, 5 and 6, where the transverse and longitudinal real components of the complex amplitude of the HSLB EM fields are shown at a distance $z_0 = 3.5$ m from the generator, in the transverse (x-y) and in the longitudinal (z-x) cross sections of the HSLB.

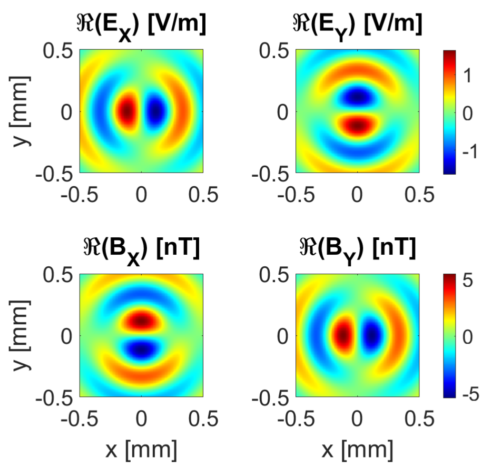

Figure 4: Transverse components of the HSLB EM field at distance $z_0 = 3.5$ m in the HSLB transverse cross section.

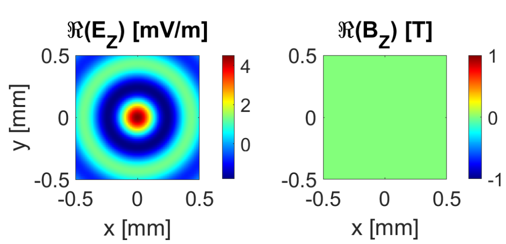

Figure 5: Longitudinal components of the HSLB EM field at distance $z_0 = 3.5$ m in the HSLB transverse cross section.

A careful study of the images in Fig. 6 shows that the longitudinal wavelength is slightly higher than the original optical wavelength. This phenomenon, described for example here[8], is related to the fact that the phase velocity of the wave v_f is higher than the speed of light in vacuum c by the relation

$$v_f = c/\cos(\theta), \tag{2}$$

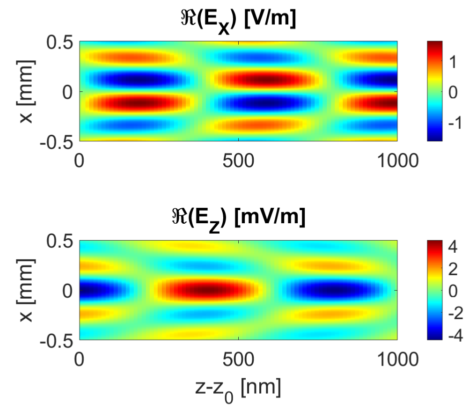

Figure 6: Transversal (top) and longitudinal (bottom) components of HSLB electric field in longitudinal cross section starting at $z_0 = 3.5$ m.

where $\cos(\theta)$ is given by the ratio of the longitudinal component of the wavevector k_T to the wave vector k. The angle θ decreases with distance for both the SLB and HSLB.

ACCELERATION

Simulations have been performed to look at the interaction of an electron with the EM field of an HSLB generated with a radially polarized beam. The interaction was mediated using the relativistic Lorentz equation. The simulation parameters were as follows: $\lambda = 800$ nm, $K_D = 0$, $K_S = 1000$ with the maximal radial distance $r_m = 6$ mm. Three different situations were considered, changing the power of the input beam and the angle θ. In all models, the particle was initially located on the optical axis, where only a longitudinally oriented electric field can occur, and thus the particle could not be deflected in the transverse direction. The initial velocity of the particle was always zero.

In all simulations, the evolution of the longitudinal position z and velocity v_Z, the value of the field E_Z affecting the particle, and the electron energy gain from the electron rest energy $(\varepsilon - \varepsilon_0)$ were monitored. All models show a strong sensitivity to the initial conditions in terms of the wave phase φ_0 of the HSLB at the beginning of the simulation. In each model, simulations were performed for 4 different initial conditions, namely with initial phase of $\varphi_0 = 0, \pi/2, \pi$ and $3\pi/2$.

Case 1: Using Low Power

In this case the initial position of the electron was at a distance $z_0 = 11.47$ mm, where the angle $\theta = 27.32°$ and the power of the radially polarized input doughnut beam was $P = 324 MW$. The results of this simulation are shown in Fig. 7.

Case 2: Using High Power

This case is similar to case 1, but with the power increased to $P = 8.1$ PW. The results of this simulation are shown in Fig. 8.

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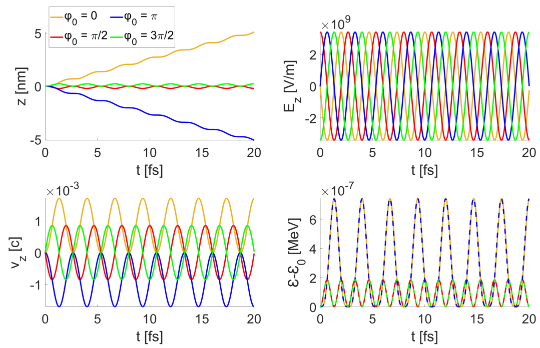

Figure 7: Simulation with laser power P = 324 MW, initial distance z_0 = 11.47 mm and angle θ = 27.32°.

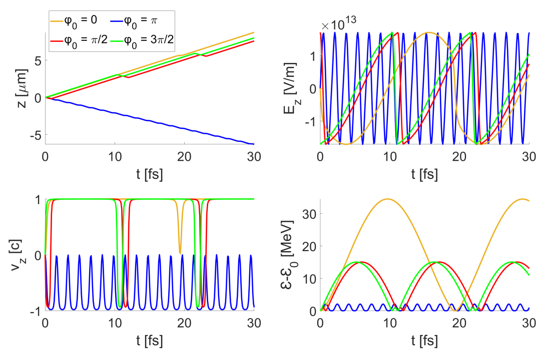

Figure 8: Simulation with laser power P = 8.1 PW, initial distance z_0 = 11.47 mm and angle θ = 27.32°.

Case 3: with High Power and Lower Angle θ

In this case the initial position was at a distance z_0 = 20 mm, where the angle θ = 12.13° and the power of the input radially polarized doughnut beam was again P = 8.1 PW. The results of this simulation are shown in Fig. 9.

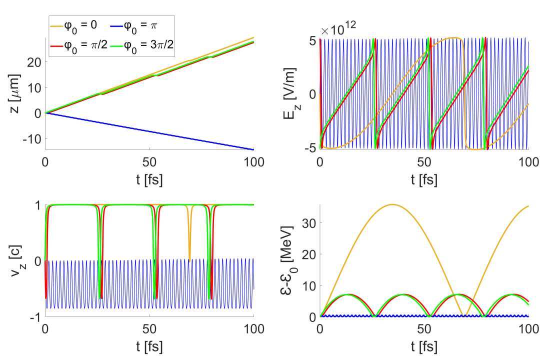

Figure 9: Simulation with laser power P = 8.1 PW, initial distance z_0 = 20 mm and angle θ = 12.13°.

DISCUSSION

It should be noted that these initial models are highly idealized and that continuous laser sources with such enormous power are currently unavailable. However, these simulations do show that an HSLB can, in principle be used to accelerate charged particles. Apart from the indefeasibly large power required to accelerate an electron to any meaningful energy, there is also extreme sensitivity to the initial phase, as well as the problem of extracting the particle at the point where it reaches its maximal energy. Additional work is underway to address these issues, with early results suggesting that they can be overcome through the use of pulsed lasers, which can reach peak powers of up to 10 PW[9].

The influence of the angle θ on the acceleration has turned out to be interesting to study. Even when the particle reaches a relativistic velocity it is overtaken by the wave due to the higher phase velocity, leading to deceleration by the inverse polarity of the subsequent half-wave (Fig. 8). However, when the electric field strength is slightly smaller but the θ angle also smaller, the resulting lower phase velocity of the wave means that the particle stays in the accelerating field for longer, so gaining more energy (Fig. 9). This hints at directions to follow for optimization of the acceleration process.

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