

A laser-driven particle accelerator with optical grating

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Abstract

We present a novel accelerating concept. A laser is used to excite a leaky mode within a vacuum waveguide. The high value of the transverse component of the electric field of the waveguide mode is used to accelerate charged particles. In order to achieve phase matching, a grating is fabricated on the surface of the prism. This is used to pattern the electric field within the vacuum core in such a way that a relativistic particle will always 'see' an accelerating electric field. A feature of the proposed accelerator is that the particle is accelerated in a direction orthogonal to the direction of mode propagation. Modelling suggests that in this scheme, accelerating fields of up to 7 GeV/m can be generated, using a rather modest laser intensity of 2×10^{13} W/m².

Introduction

The problem of accelerating electrons in vacuum using the electro-magnetic field of a laser has been addressed by a number of researchers, using several different optical structures. The advantage of using the electric field of a laser is that very high field strengths can be realised.

In 1962, Shimoda^[1] proposed the use of the transverse magnetic (TM) mode within a vacuum capillary. The charged particles were to accelerate in the same direction as mode propagation. The drawback with this scheme is that phase velocity of the mode is greater than c , and therefore there is a problem of phase slippage. To overcome this, it was proposed that the capillary be filled with gas in order to reduce the phase velocity to below c . However, breakdown of the gas sets an upper limit on the peak optical field that can be supported by the capillary waveguide. In addition, the longitudinal electric field (E_z) of the waveguide mode is generally much weaker than its transverse field (E_y). Therefore, only moderate acceleration gradients can be achieved in this scheme.

In one of the vacuum acceleration schemes was proposed by Lawson^[2], an expanded TM laser beam is incident on the dielectric-vacuum boundary. If the angle of incidence is above the critical angle, an evanescent wave is set up

extending into the vacuum region. The wave propagates along the boundary with a phase velocity that is lower than c . Thus the problem of phase slippage can be overcome. However, the value of the longitudinal electric field component in the evanescent field decreases as the phase velocity of the wave approaches c . Thus this scheme is rejected on the grounds that high energy particles cannot be generated.

The use of a grating was proposed in 1968 by Takeda and Matsui^[3]. In this scheme, one of the mirrors in a laser cavity had an embossed grating. The amplitude and period of the grating were chosen such that a relativistic charged particle travelling close to the surface of the mirror and in a direction orthogonal to the grooves of the grating, would 'see' a DC accelerating electric field. The drawback with this scheme was that the surface of the grating was destroyed by the flux of the high power laser beam.

The scheme proposed in the present paper also employs a grating to produce the required phase pattern. The grating is produced on the surface of a prism, and a planar superstrate is used to form a leaky waveguide, with the hollow (vacuum) core. The electric field of the transverse electric (TE) waveguide mode is used to accelerate the charged particle, which is consequently accelerated in a direction orthogonal to the direction of mode propagation. The basic setup is shown in Fig. 1 while Fig. 2 displays schematically the form of accelerating electric field inside the waveguide core.

Such a low-index waveguide based particle accelerator has several advantageous features. These are:

- The amplitude of the electromagnetic field in the centre of the waveguide can be much higher than that at the edges. Thus it is possible to generate fields, and therefore acceleration gradients, that are many times higher than the breakdown voltage of the substrate and superstrate materials.
- The pitch of the grating can be used to create an 'effective phase velocity' in the acceleration direction. A chirped grating may be used to allow for the increase in velocity of particles that are injected at sub-relativistic velocity. Phase matching can thus be maintained.
- Because the waveguide is leaky, prism coupling may be used as the method of mode excitation. This method allows for the excitation of a selected waveguide mode. The fundamental TE waveguide mode would be of interest in this application. However, other modes may be excited simply by altering the angle of incidence of the incident radiation.

Numerical Results

As shown in Fig. 3, the electric field amplitude at the centre of the waveguide increases with the thickness of the vacuum core. The intensity of the incident illumination is set to $2 \times 10^{13} \text{ W/m}^2$. At this intensity, the electric field amplitude at the prism-core boundary is approximately 10^8 V/m . This is typically the breakdown field of silica. In this example an accelerating field up to 7 GeV/m can

be generated. By further increasing the thickness of the vacuum core, theoretically it is possible to increase the maximum value of the accelerating field. However, as illustrated in Fig 5, the range of angles of incidence that will efficiently excite the waveguide mode decreases sharply as the core thickness is increased. Thus the maximum core thickness that can be used (and therefore the maximum attainable accelerating field) will be limited by the level of collimation of the incident beam and the accuracy to which the angle of incidence can be set.

Conclusions

We have demonstrated numerically that a miniaturised optical linac can be designed that exhibits a peak acceleration gradient of 7 GeV/m. The issue regarding phase slippage is overcome by designing a grating to produce the required phase pattern, and the particles are accelerated orthogonal to the direction of mode propagation. We believe, that given the promising numerical results, this design should now be investigated experimentally.

Acknowledgement

The work of Jiří Petráček has been supported by GAČR (contract 202/98/P274).

References

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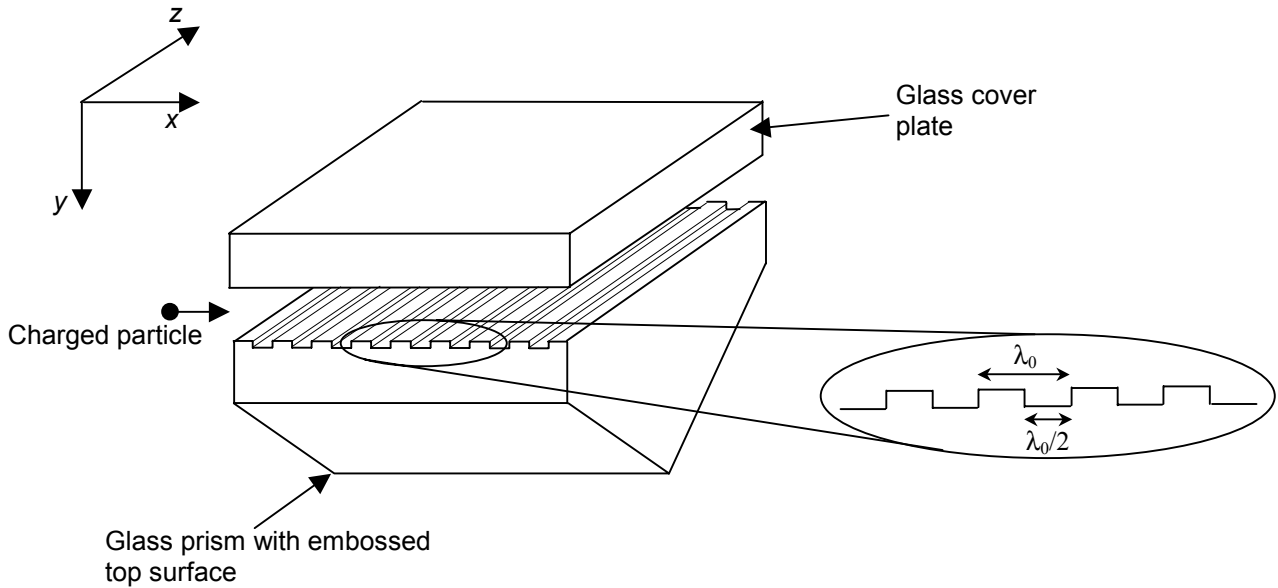


Figure 1. The basic setup is shown here. The substrate is shaped in the form of a prism to allow prism excitation of the waveguide mode propagating in z direction. The embossed surface serves to set up a phase modulation within the waveguide core. With a suitably chosen grating amplitude and period, a relativistic particle travelling parallel to the x -axis sees an accelerating field at all times.

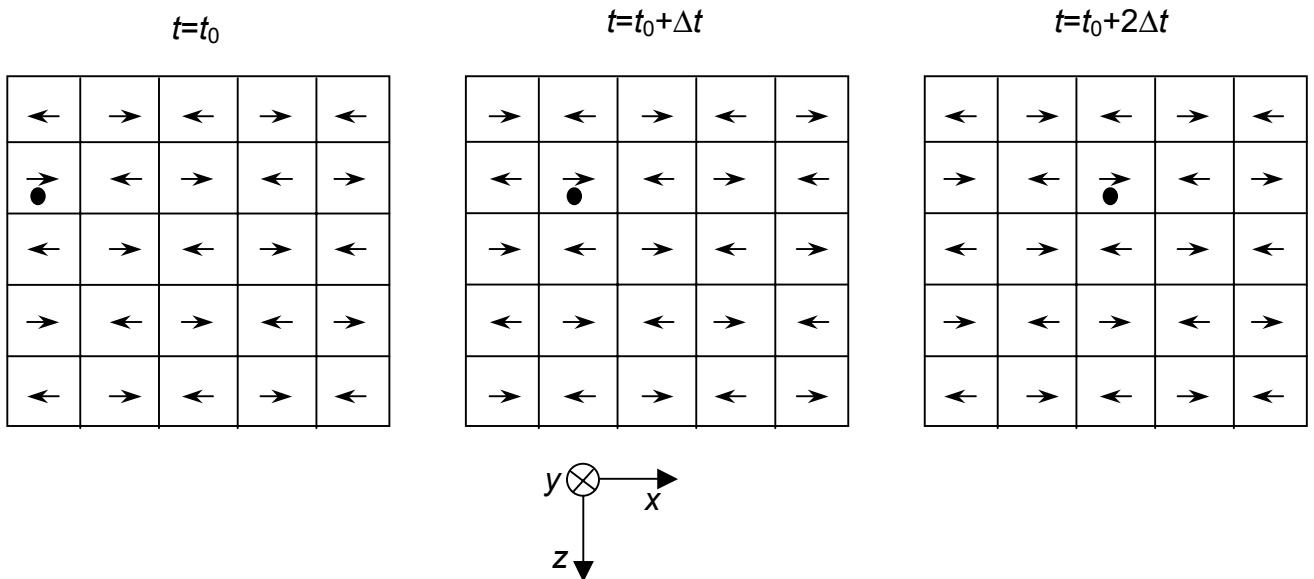


Figure 2. The arrows represent the electric field E_x inside the waveguide core. The direction of E_x changes every Δt seconds where $\Delta t = \lambda_0/2c$. If the grating period is set to λ_0 , then a relativistic charged particle (represented by the black dot) will 'see' a DC electric field.

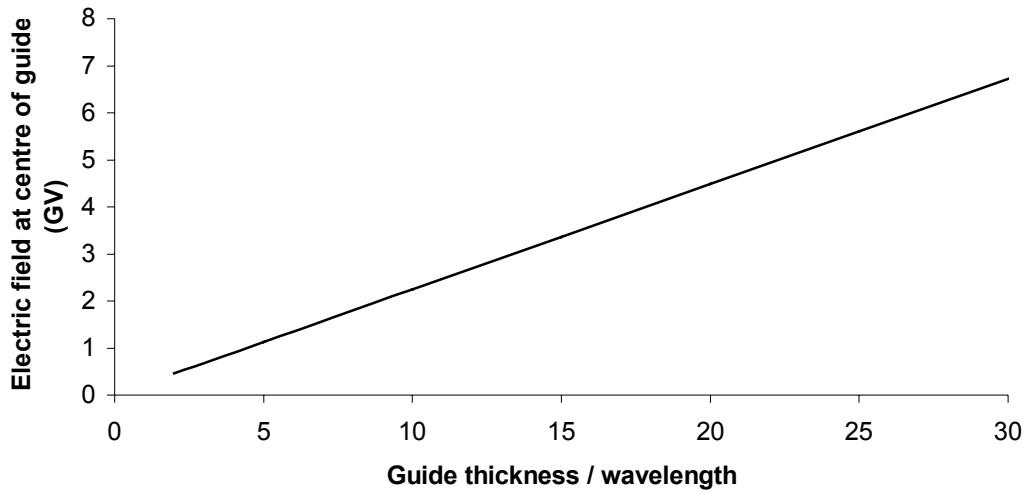


Figure 3. The relationship between the electric field strength at the centre of the vacuum waveguide is a linear function of the thickness of the guide. To achieve this strength, the z-extent of the illuminating beam must be greater than the propagation length of the waveguide mode. The propagation length increases with the guide thickness. This relationship is shown in Fig. 4.

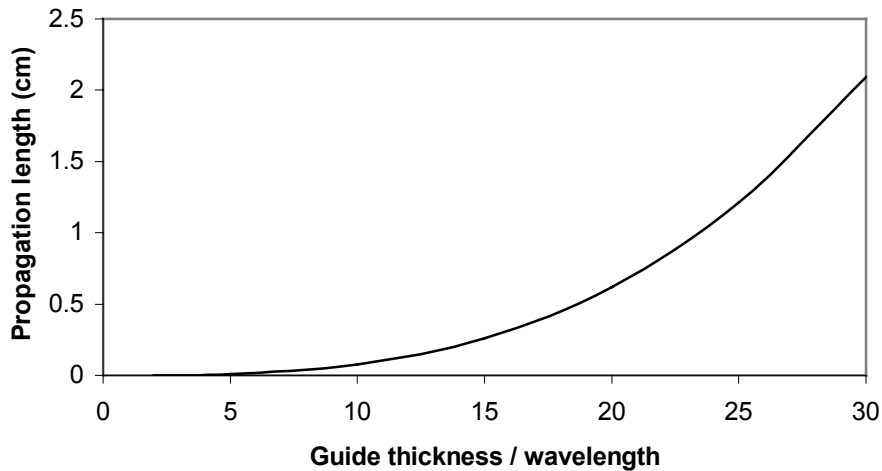


Figure 4. The propagation length of the fundamental TE mode in a vacuum core waveguide rises rapidly as the thickness of the guide is increased. To achieve the high electric fields within the core, the z-extent of the illuminating wavefront must be at least of the order of the propagation length.

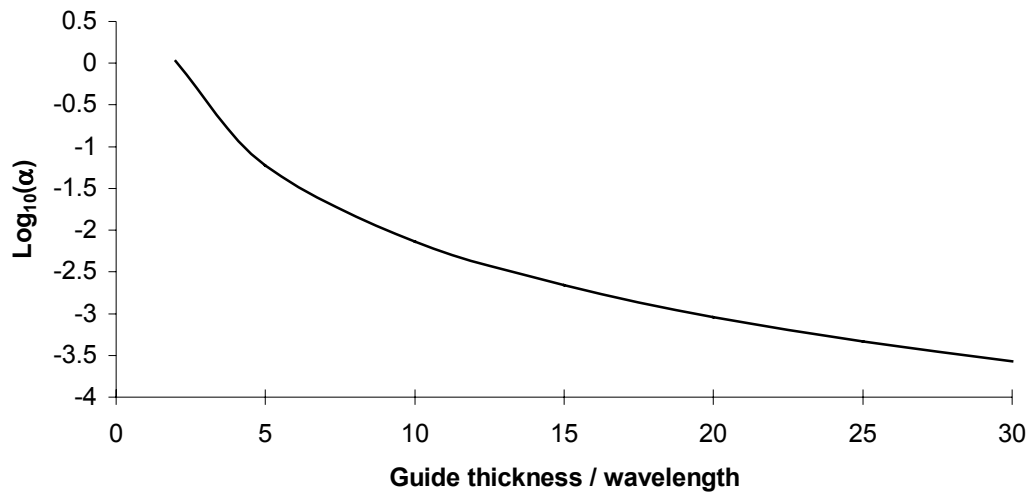


Figure 5. To achieve high electric field values within the waveguide core, the thickness of the core also needs to be high. However, the range of angles of incidence, α (in degrees), that will efficiently excite the mode decreases rapidly as a function of the guide thickness. The value of $\log_{10}(\alpha)$ is plotted as a function of guide thickness.