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ACCELERATION USING TOTAL INTERNAL REFLECTION

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This report considers the use of a dielectric slab undergoing total internal reflection as an accelerating structure for charged particle beams. We examine the functional dependence of the electromagnetic fields above the surface of the dielectric for polarized incident waves. We present an experimental arrangement for testing the performance of the method, using apparatus under construction for the Grating Acceleration experiment at Brookhaven National Laboratory.

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1 Introduction

Methods for using the very large electric fields in laser beams for accelerating charged particles have been under investigation for many years[1-4]. In one class of method the particles interact with slow, evanescent waves set up on the surface of an accelerating structure. This method is closely related to that employed in disk loaded linacs powered by RF sources[5]. The axially symmetric cavity fields can be considered as the infinite sum of surface fields. Examples of this technique explicitly using external laser beams include acceleration over a metallic grating or acceleration over a dielectric slab undergoing total internal reflection.

The phenomenon of total internal reflection is a well known subject in physical optics[6-9]. Consider a boundary surface with a dielectric of refractive index n on one side and vacuum on the other. Let a plane wave be incident on the boundary from the dielectric side. The wave will be totally reflected back into the dielectric provided the angle θ with the surface normal exceeds the *critical angle* θ_c given by

$$\sin\theta_c = \frac{1}{n} \quad (1)$$

However, the solution of the Maxwell equations requires that an evanescent wave exist on the vacuum side of the boundary surface.

The possibility of using the surface fields on a dielectric undergoing total internal reflection to accelerate particles was apparently first suggested by Lohmann[10] in 1962. He apparently realized that the accelerating field vanishes for relativistic particles in a geometry where the incident wave does not have a component perpendicular to the trajectory of the accelerated particle. We will call this the *classical geometry*, since it is the one that is customarily employed in discussions of total internal reflection.

The subject has been actively studied by a group at the Yerevan Physics Institute[11-12]. Kheifets[13] gave explicit expressions for the transmitted field components for the case of the classical geometry. He showed that the solutions could be broken into the two cases depending on the polarization of the incident wave. He also studied the conditions for stability for elliptically polarized waves. He found that a net force exists normal to the boundary surface and suggests cancelling it using an external magnetic field. Nagorsky et al[14] showed that the synchronism condition between the incident wave and a particle travelling along the

surface is equivalent to the condition for Cerenkov radiation. They showed that phase stability required a second magnetic field oriented normal to the particle trajectory and to the dielectric surface.

There have been a number of reviews of new acceleration techniques that also consider the possibility of using total internal reflection[5,11,12,15].

2 Wavevector relations

Consider the coordinate system shown in Fig. 1. The x - z plane represents the boundary between a region with dielectric constant n ($y < 0$) and free space ($y > 0$). The normal vector to the boundary surface lies along the y direction. A plane wave k^i is incident from the dielectric side. The angle θ is the polar angle between k^i and the $+y$ direction, while the angle ϕ is the azimuthal angle between the projection of k^i on the x - z plane and the $-x$ axis.

Fig. 1 Coordinate system

Our goal will be to produce suitable electromagnetic field configurations in order to accelerate a particle along the z direction.

The electric field of the incident wave can then be written as

$$\vec{E}^i = \vec{E}_0^i \exp[ik_1 (-x \sin \theta \cos \phi) + y \cos \theta + z \sin \theta \sin \phi] - i\omega t] \quad (2)$$

where

$$k_1 = \frac{2\pi}{\lambda_1} = \frac{2\pi n}{\lambda_0} \quad (3)$$

We will use the SI system of units in this report. The quantity λ_1 is the wavelength of the radiation inside the dielectric while λ_0 is the wavelength in free space.

There must be a reflected wave inside the dielectric that makes an equal angle with respect to the surface normal. Thus the electric field of the reflected wave can be written

$$\vec{E}^r = \vec{E}_0^r \exp[ik_1 (-x \sin \theta \cos \phi) - y \cos \theta + z \sin \theta \sin \phi] - i\omega t] \quad (4)$$

We write the expression for the electric field of the transmitted wave that exists on the free space side of the boundary in the general form

$$\vec{E}^t = \vec{E}_0^t \exp[ik_{2x}x + ik_{2y}y + ik_{2z}z - i\omega t] \quad (5)$$

The boundary plane is uniform in the x and z directions. Thus in order that the combination of waves always satisfy the boundary conditions for all time and for any value of x or z the wavevector components of the transmitted wave along x and z must be identical to those for the incident and reflected waves. Thus we have

$$\begin{aligned} k_{2x} &= -k_1 \sin \theta \cos \phi \\ k_{2z} &= k_1 \sin \theta \sin \phi \end{aligned} \quad (6)$$

We can find an expression for k_{2y} by substituting Eq. 5 for E^t into the wave equation

$$\nabla^2 \vec{E}^t - \epsilon_0 \mu_0 \frac{\partial^2}{\partial t^2} \vec{E}^t = 0 \quad (7)$$

The result is

$$k_{2y} = \pm i k_1 A \quad (8)$$

where the parameter A is defined as

$$A = \sqrt{\sin^2 \theta - \frac{1}{n^2}} \quad (9)$$

Recall that this derivation is only valid for the conditions of

total internal reflection, where $\sin\theta > 1/n$, so A is a real, positive quantity. We have to choose the positive sign in Eq. 8 so that the electric field strength does not grow without bound as we move away from the boundary surface. Thus the transmitted electric field can be written as

$$\vec{E}^t = \vec{E}_0^t \exp[-k_1 A y] \exp[ik_1 (-x \sin\theta \cos\phi) + z \sin\theta \sin\phi] - i\omega t \quad (10)$$

The phase velocity of the transmitted electric field along the particle trajectory is

$$v_p = \frac{\omega}{k_{2z}} = \frac{c}{n \sin\theta \sin\phi} \quad (11)$$

We see that it is possible to make the particle move in a field of constant phase provided that we choose the index of refraction and the incident angles in such a way that the condition

$$n \sin\theta \sin\phi = \frac{1}{\beta} \quad (12)$$

is satisfied, where β is the particle velocity in units of c . Examining the angles drawn in Fig. 1, we see that the space angle α between k^i and the z axis satisfies the relation

$$\cos\alpha = \sin\theta \sin\phi \quad (13)$$

Thus the electromagnetic wave and the particle satisfy the same condition required for the production of Cerenkov radiation[14]

$$\cos\alpha = \frac{1}{n\beta} \quad (14)$$

3 Polarization of the incident wave

Consider a unit vector V that is constrained to be perpendicular to the incident wavevector k^i . We represent the orientation of V by using an azimuthal angle ψ as shown in Fig. 1. Then we can use the Euler angle transformation[16] to write the components of V as

$$\begin{aligned} V_x &= \sin\phi \cos\psi + \cos\theta \cos\phi \sin\psi \\ V_y &= \sin\theta \sin\psi \\ V_z &= \cos\phi \cos\psi - \cos\theta \sin\phi \sin\psi \end{aligned} \quad (15)$$

V can represent either the E or the H vector of the incident wave. Note that for a given value of the incident angle θ , it is always possible to choose an orientation angle ψ such that V_y is 0. This allows us to look at two simpler classes of problems: one with $E_y^i = 0$ and one with $H_y^i = 0$.

4 Solution for incident wave with $H_y^i = 0$

In this case we let V in Eq. 15 represent H^i . Choosing $\psi = 0$ gives the condition $H_y^i = 0$. The electric field can then be represented by $V(\psi = -\pi/2)$. The incident wave is therefore given by

$$\begin{aligned} H_x^i &= H_o^i \sin\phi \\ H_y^i &= 0 \\ H_z^i &= H_o^i \cos\phi \\ E_x^i &= -E_o^i \cos\theta \cos\phi \\ E_y^i &= -E_o^i \sin\theta \\ E_z^i &= E_o^i \cos\theta \sin\phi \end{aligned} \quad (16)$$

At the boundary surface the fields must satisfy the tangential boundary conditions

$$\begin{aligned} H_o^i \sin\phi + H_{ox}^r &= H_{ox}^t \\ H_o^i \cos\phi + H_{oz}^r &= H_{oz}^t \\ -E_o^i \cos\theta \cos\phi + E_{ox}^r &= E_{ox}^t \\ E_o^i \cos\theta \sin\phi + E_{oz}^r &= E_{oz}^t \end{aligned} \quad (17)$$

The boundary conditions for the normal components are

$$\begin{aligned} e_1 (-E_o^i \sin\theta + E_{oy}^r) &= e_o E_{oy}^t \\ H_{oy}^r &= H_{oy}^t \end{aligned} \quad (18)$$

where we have assumed that the permeability of region 1 is also μ_o . These 6 equations have a total of 12 unknowns so that 6 of the Maxwells equations are required in addition to solve for the unknowns.

Reflected wave

The wavevectors are shown schematically in the classical plane in Fig. 2. The solution of the set of equations gives 6 complex expressions for the components of the reflected wave. The magnitudes of the magnetic field components are

$$\begin{aligned} H_{ox}^r &= H_o^i \sin\phi \\ H_{oy}^r &= 0 \\ H_{oz}^r &= H_o^i \cos\phi \end{aligned} \quad (19)$$

Fig. 2 Field orientation near the boundary for $H_T^i = 0$ polarization.

As we expect the magnitude of H^r is just H_0^i . Each component has a phase

$$\tan \Sigma = \frac{-2n^2 A \cos \theta}{\cos^2 \theta - n^4 A^2} \quad (20)$$

with respect to the incident wave. The magnitudes of the electric field components are

$$\begin{aligned} E_{ox}^r &= E_0^i \cos \theta \cos \phi \\ E_{oy}^r &= -E_0^i \sin \theta \\ E_{oz}^r &= -E_0^i \cos \theta \sin \phi \end{aligned} \quad (21)$$

The total electric field has the magnitude E_0^i as expected and each of the components also has the phase Σ with respect to the incident wave.

Transmitted wave

The magnitudes of the surface electric field components are

$$\begin{aligned}
 E_{ox}^t &= \frac{-2 E_o^i n^2 A \cos\theta \cos\phi}{\sqrt{\cos^2\theta + n^4 A^2}} \\
 E_{oy}^t &= \frac{-2 E_o^i n^2 \sin\theta \cos\theta}{\sqrt{\cos^2\theta + n^4 A^2}} \\
 E_{oz}^t &= \frac{2 E_o^i n^2 A \cos\theta \sin\phi}{\sqrt{\cos^2\theta + n^4 A^2}}
 \end{aligned} \tag{22}$$

The x and z components have the phase relation

$$\tan\Omega = \frac{\cos\theta}{n^2 A} \tag{23}$$

with respect to the incident wave. The y component is 90° out of phase and thus has the phase ($\Omega + \pi/2$). The magnitudes of the surface magnetic field components are

$$\begin{aligned}
 H_{ox}^t &= \frac{2 H_o^i \cos\theta \sin\phi}{\sqrt{\cos^2\theta + n^4 A^2}} \\
 H_{oy}^t &= 0 \\
 H_{oz}^t &= \frac{2 H_o^i \cos\theta \cos\phi}{\sqrt{\cos^2\theta + n^4 A^2}}
 \end{aligned} \tag{24}$$

All of the magnetic field components have the phase ($\Omega + \pi/2$).

5 Solution for incident wave with $E_y^i = 0$

In this case we let V in Eq. 15 represent E^i . Choosing $\phi = 0$ gives the condition $E_y^i = 0$. The magnetic field can then be represented by $V(\phi = +\pi/2)$. The incident wave is therefore given by

$$\begin{aligned}
 H_x^i &= H_o^i \cos\theta \cos\phi \\
 H_y^i &= H_o^i \sin\theta \\
 H_z^i &= -H_o^i \cos\theta \sin\phi \\
 E_x^i &= E_o^i \sin\phi \\
 E_y^i &= 0 \\
 E_z^i &= E_o^i \cos\phi
 \end{aligned} \tag{25}$$

At the boundary surface the fields must satisfy the tangential boundary conditions

$$\begin{aligned}
 H_o^i \cos\theta \cos\phi + H_{ox}^r &= H_{ox}^t \\
 -H_o^i \cos\theta \sin\phi + H_{oz}^r &= H_{oz}^t \\
 E_o^i \sin\phi + E_{ox}^r &= E_{ox}^t \\
 E_o^i \cos\phi + E_{oz}^r &= E_{oz}^t
 \end{aligned} \tag{26}$$

The boundary conditions for the normal components are

$$\begin{aligned}
 \epsilon_1 E_{oy}^r &= \epsilon_o E_{oy}^t \\
 H_o^i \sin\theta + H_{oy}^r &= H_{oy}^t
 \end{aligned} \tag{27}$$

where we have assumed that the permeability of region 1 is also μ_o . These 6 equations have a total of 12 unknowns so that 6 of the Maxwells equations are required in addition to solve for the unknowns.

Reflected wave

The wavevectors are shown schematically in the classical plane in Fig. 3. The solution of the set of equations gives 6 complex

expressions for the components of the reflected wave.

Fig. 3 Field orientation near the boundary for $E_y^i = 0$ polarization.

The magnitudes of the magnetic field components are

$$\begin{aligned} H_{ox}^r &= -H_o^i \cos\theta \cos\phi \\ H_{oy}^r &= H_o^i \sin\theta \\ H_{oz}^r &= H_o^i \cos\theta \sin\phi \end{aligned} \quad (28)$$

As we expect the magnitude of H^r is just H_o^i . Each component has a phase

$$\tan\Pi = \frac{-2A\cos\theta}{\cos^2\theta - A^2} \quad (29)$$

with respect to the incident wave. The magnitudes of the electric field components are

$$\begin{aligned} E_{ox}^r &= E_o^i \sin\phi \\ E_{oy}^r &= 0 \\ E_{oz}^r &= E_o^i \cos\phi \end{aligned} \quad (30)$$

The total electric field has the magnitude E_o^i as expected and each of the components also has the phase Π with respect to the incident

wave.

Transmitted wave

The magnitudes of the surface electric field components are

$$\begin{aligned} E_{ox}^t &= \frac{2E_o^i n \cos\theta \sin\phi}{\sqrt{n^2 - 1}} \\ E_{oy}^t &= 0 \\ E_{oz}^t &= \frac{2E_o^i n \cos\theta \cos\phi}{\sqrt{n^2 - 1}} \end{aligned} \quad (31)$$

The electric field components have the phase relation

$$\tan \Psi = -\frac{A}{\cos\theta} \quad (32)$$

with respect to the incident wave. The magnitudes of the surface magnetic field components are

$$\begin{aligned} H_{ox}^t &= \frac{2H_o^i n A \cos\theta \cos\phi}{\sqrt{n^2 - 1}} \\ H_{oy}^t &= -\frac{H_o^i n \sin\theta \cos\theta}{\sqrt{n^2 - 1}} \\ H_{oz}^t &= \frac{-2H_o^i n A \cos\theta \sin\phi}{\sqrt{n^2 - 1}} \end{aligned} \quad (33)$$

The x and z components of the magnetic field components have the phase $(\Psi + \pi/2)$. The y component of the magnetic field has the phase Ψ .

6 Forces

We consider the forces on a relativistic particle with charge e travelling along the z axis.

$$\begin{aligned} F_x &= e(E_x - cB_y) \\ F_y &= e(E_y + cB_x) \\ F_z &= \frac{dW}{dz} = eE_z \end{aligned} \quad (34)$$

The force component F_z gives the rate of change of the particle's energy with distance.

$E_y^i = 0$ polarization

$$\begin{aligned} F_x &= \frac{2eE_o^i n \cos\theta}{\sqrt{n^2 - 1}} (\sin\phi - \sin\theta) e^{i\tau} G \\ F_y &= \frac{2ieE_o^i n A \cos\theta \cos\phi}{\sqrt{n^2 - 1}} e^{i\tau} G \\ F_z &= \frac{2eE_o^i n \cos\theta \cos\phi}{\sqrt{n^2 - 1}} e^{i\tau} G \end{aligned} \quad (35)$$

where

$$G = \exp[-k_1 Ay] \exp[ik_1 (-x \sin\theta \cos\phi + z \sin\theta \sin\phi) - i\omega t] \quad (36)$$

We see that the surface accelerating field can never exceed a limiting value of 2. All field components decrease exponentially with distance above the surface according to Eq. 10. Higher values of n more closely approach the limiting value. Because of the symmetry of θ and ϕ in F_z , the maximum acceleration rate will be obtained with $\theta = \phi$. Note that the condition $\theta = \phi$ also causes the force in the x direction to vanish. There is a nonvanishing vertical force perpendicular to the surface, but it is 90° out of phase with the acceleration. Since the vertical force is proportional to A , it vanishes at the critical angle.

$H_y^i = 0$ polarization

$$\begin{aligned} F_x &= \frac{-2eE_o^i n^2 A \cos\theta \cos\phi}{\sqrt{\cos^2\theta + n^4 A^2}} e^{i\Omega} G \\ F_y &= \frac{2ieE_o^i \cos\theta}{\sqrt{\cos^2\theta + n^4 A^2}} (\sin\phi - n^2 \sin\theta) e^{i\Omega} G \\ F_z &= \frac{2eE_o^i n^2 A \cos\theta \sin\phi}{\sqrt{\cos^2\theta + n^4 A^2}} e^{i\Omega} G \end{aligned} \quad (37)$$

The accelerating field in this case is considerably more complicated than before. The optimal angles for peak acceleration are calculated numerically in the table below. Note that the force in the y direction vanishes if $\sin(\phi) = n \sin(\theta)$. However, this is not the same condition required for optimum acceleration.

Table 1 gives examples of the optimal angles and peak surface forces in units of eE_0 for three materials. Note that for a given material it is possible to optimize the values of the incident angles such that the peak acceleration rate is the same for both polarizations. It thus appears that the peak surface accelerating field enhancement will always be less than 2. We have imposed the constraint

$$n \sin \theta \sin \phi = 1 \quad (38)$$

required for synchronism with a relativistic particle.

Table 1 Optimal Accelerating Forces			
material	quartz	ZnSe	Ge
n	1.54	2.40	4.00
θ_c	40.49	24.62	14.48
$E_y^i = 0$ polarization			
θ	53.69	40.20	30.00
ϕ	53.69	40.20	30.00
F_x	0	0	0
F_y	0.440	0.633	0.671
F_z	0.922	1.284	1.549
$H_y^i = 0$ polarization			
θ	48.00	29.00	16.00
ϕ	60.90	59.25	65.09
F_x	-0.513	-0.763	-0.719
F_y	-1.094	-2.020	-3.220
F_z	0.922	1.282	1.549

7 Practical considerations

Previous authors[13,14] have considered how an actual total internal reflection accelerator could in principle be assembled from a series of crystals, together with external magnetic fields for stability. We want to examine here whether it would be possible to easily (and cheaply) measure the important parameters of the method experimentally using the apparatus from the Grating Acceleration experiment[17] currently under construction at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory[18]. Measured quantities should include the strength of the acceleration gradient, transverse forces, sensitivity to the direction and polarization of the incident wave, and the breakdown strength of the dielectric medium.

Some aspects of a possible experimental arrangement are shown in Fig. 4. We use incident light from the ATF CO_2 laser. A total energy of up to 100 mJ should be available in a 6 ps long pulse. A parallel beam is focussed with a cylindrical lens through an observation window in the interaction chamber. The dielectric medium must have at least one flat side and must be transparent to CO_2 radiation. Thus we choose to use a ZnSe prism. The CO_2 beam enters the prism face along a normal and strikes the flat bottom surface. The ZnSe prism is held off the mounting plate using four precision spacers. The electron beam axis is within 10 μm of and parallel to the bottom surface. The image of the cylindrical lens should be along the electron beam direction.

Unfortunately for this application, the geometrical configuration of the chamber does not allow the use of the optimal incident angles for ZnSe given in Table 1. The most practical location for an observation port for this purpose has $\theta = 65.4^\circ$ and $\phi = 27.3^\circ$. The predicted forces (in units of $e E_0^1$) are given in Table 2. The transverse forces dominate the acceleration for $H_y^1 = 0$ polarization. The other polarization state has a larger acceleration. However, since we had to give up the $\theta = \phi$ condition, it also has a substantial x component of transverse force.

The analysis spectrometer following the interaction chamber will use point to point focusing in the bend (x-z) plane. Thus to lowest order in the beam optics the F_y forces simply represent an additional divergence at the source and they will not be measured by the spectrometer. The F_z force changes the particle's momentum so the dipole in the spectrometer will spread the trajectories accordingly in the x direction. The spectrometer will use point to parallel focusing in the non-bend (y-z) plane. This causes the distribution of trajectories to be spread out along y at the detector in proportion to the force F_y .

Fig.4 Experimental arrangement for testing acceleration of electrons passing near a ZnSe prism.

Table 2 Proof of principle performance			
material	ZnSe		
n	2.40		
θ	65.38°		
ϕ	27.28°		
	F_x	F_y	F_z
$H_y^i = 0$	-0.738	-0.852	0.380
$E_y^i = 0$	-0.413	0.658	0.815

The performance of the device should be determined chiefly by (1) the strength of electric field that can be tolerated by the ZnSe prism before breakdown and (2) the alignment accuracy for positioning the electron beam parallel to the surface of the prism.

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