A TAPERED DIELECTRIC STRUCTURE FOR LASER ACCELERATION AT LOW ENERGY*

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Abstract

This paper extends the physics of the Micro-Accelerator Platform (MAP), which is in development as an optical structure for laser acceleration of relativistic electrons. The MAP is a resonant, optical-scale, slab-symmetric device that is fabricated from dielectric materials using layer-deposition techniques. For stand-alone applications, low-energy electrons ($\beta \sim 0.3$) must be synchronously accelerated to relativistic speeds for injection into the MAP. Even lower energies are desired for other particle species (e.g. protons or muons). In this paper, we present design and simulation studies on a tapered geometry and associated coupling scheme that can produce synchronous acceleration at $\beta < 1$ within a MAP-like structure.

INTRODUCTION

The Micro-Accelerator Platform (MAP) is a resonant cavity designed to accelerate electrons from approximately 25 KeV to 10's of MeV [1]. It consists of two Distributed Bragg Reflector (DBR) stacks coated with a dielectric and separated by a vacuum gap in which the particles will be accelerated. Power is coupled into the structure via an incident finite-bandwidth laser centered around an optical wavelength (with Poynting vector along the *y*-axis) that strikes periodic coupling slots before propagating through the DBR and forming a resonance. Particles accelerate along this direction of periodicity (denoted by the *z*-axis). For sections of the MAP designed to accelerate highly relativistic particles, the structure is invariant in the *x* direction so as to minimize wakefield effects [2], though this invariance may be sacrificed in future designs in order to achieve focusing for subrelativistic particles (discussed below). The dimensions of the MAP scale with the optical wavelength (which is 800 nm in Figure 1). In the *y* direction, the structure is on the order of 1 µm thickness, whereas in the *x* and *z* directions, the size is roughly 1 mm for a 1 MeV device.

When resonance is achieved within the vacuum gap of the MAP, the electric field is given by:

$$E_z = E_0 \cosh\left(\frac{\omega y}{\beta c \gamma}\right) \cos(k_z z). \qquad (1)$$

Here, ω is the radial frequency of the incident laser, and β and γ have their usual relativistic definitions. The periodicity of the field depends on the velocity of the travelling particles.

$$k_z = \frac{\omega}{\beta c}. \qquad (2)$$

To achieve a standing wave inside the gap that has a period smaller than the central wavelength of the incident laser, the coupling slots are placed closer together (the slot spacing is $\beta\lambda$, where λ is the wavelength of the incident laser). As will be discussed below, this presents many challenges in terms of achieving resonance as well as particle focusing.

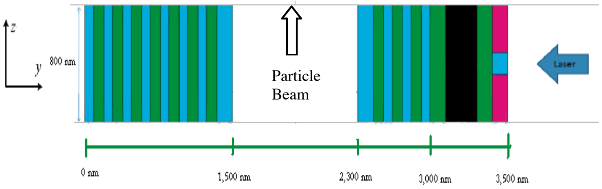

Figure 1: General structure of the MAP. Laser input is from the right to left.

RESONANCES

The high frequency electromagnetic simulation program HFSS has been used to investigate the resonances of the MAP structure. One period of the MAP is constructed within HFSS and periodic boundary conditions are enforced. To determine whether resonance has been found, a field overlay of the *z* component of the electric field over the vacuum gap of the structure is examined. Equation 1 shows that when beta is nearly 1, the variation of the *z* component of the electric field with y is minimal; hence a poor resonance is distinguished by a large variation in the z component of electric field with respect to y. Due to the isoclines of the field contours, we have termed this phenomenon the "Coke bottle effect." This is illustrated in Figure 2.

On the other hand, for sections of the MAP designed to accelerate highly relativistic particles, we have found many high quality resonances (characterized by rectangular isoclines of the field contours) for a large set of dielectric combinations, which draw from hafnia, fused silica, zirconia, rutile, sapphire and MgF_2. Ultimately, ease of fabrication will determine which recipe is implemented in the final design [3]. The quality factors of these resonances generally fall between 200 and 300.

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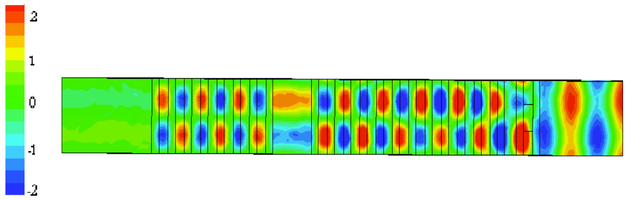

Figure 2: Color field map of E_z in the MAP exhibiting "coke-bottleing", normalized to the drive laser amplitude (color available online).

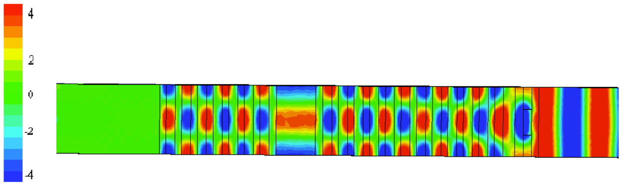

Figure 3: Color field map of E_z in the MAP exhibiting strong resonance, normalized to the drive laser amplitude. Materials used are zirconia, silica, and MgF_2. There are 7 pairs of zirconia and silica layers with quarter wavelength thicknesses in the reflective side DBR and 11 in the incident side DBR. The thicknesses of layers in the coupler are on the order of 100 nm.

Generally, combinations of materials that have large contrasts in the index of refraction are the most successful. For example, the model shown in Figure 3 consists of zirconia, silica, and MgF_2 (with indices of refraction of 2.13, 1.45, and 1.38 respectively). Additionally, we have been able to find resonance with sapphire and fused silica substrates included in the simulations. However, in all of these simulations a potential challenge is observed. Often, within 10 to 15 THz of the resonant frequency of the accelerating mode, one finds strong Fabry-Perot resonances. When a finite bandwidth laser strikes the MAP, avoiding these destructive modes will be crucial to achieving acceleration.

Low Beta Resonance

For particles travelling sub-relativistically, the length between slots is $\beta\lambda$. For such structures, it is much more difficult to find resonance than it is for relativistic structures. We were able to find such a resonance only for a simplified version of the MAP consisting of a perfect conductor with a coupling slot, a germanium layer, and a matching layer.

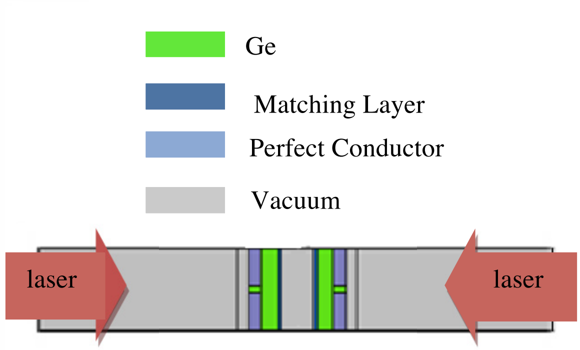

Figure 4: Simplified MAP Structure with a Ge layer with 59 nm thickness, a vacuum gap of thickness 100 nm, and a period of 240nm (for 25 KeV electrons).

For small beta, one needs to be concerned about the possible excitation of a mode that has the same z dependence as the accelerating mode but is odd with respect to y. We were able to filter out this odd mode by striking the structure with two lasers, one on each side, thus enforcing the even symmetry.

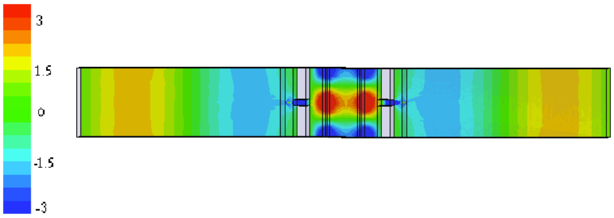

Figure 5: Resonance in low beta simplified MAP due to two incident oppositely propagating lasers, normalized to the drive laser amplitude.

Unfortunately, we have not yet been able to transfer this success to the dielectric structure. Currently, many ideas to achieve resonance are being explored, including two color illumination, using multiple slot layers of differing periodicity, two laser schemes, and the incorporation of a variety of diffractive optical elements.

FOCUSING

As a particle is travelling through the resonating MAP, it experiences the following forces due to the electromagnetic fields (assuming that $\beta_z \approx \beta$):

$$\begin{aligned} F_z &= qE_0 \cosh\left(\frac{\omega y}{\beta c\gamma}\right)\cos\left(\frac{\omega z}{\beta c}\right); \\ F_y &= \frac{qE_0}{\gamma}\sinh\left(\frac{\omega y}{\beta c\gamma}\right)\sin\left(\frac{\omega z}{\beta c}\right). \end{aligned} \qquad (3)$$

Here, q is the charge of the particle. It is apparent that when the particle is at a phase that focuses in the z direction, the transverse force is positive, i.e. defocusing. For highly relativistic particles ($\gamma \gg 1$), the transverse force vanishes. Hence, we only need to concern ourselves with defocusing for particles with lower energies.

There have been a few schemes proposed to simultaneously focus transversely and longitudinally. One scheme consists of periodically modulating the spacing between the coupling slots. In the original design, the distance between the slots is $\beta\lambda$. However, if we periodically dither the slot positions away from their original design positions, we can effectively oscillate the phase at which the electron travels along the accelerating mode, alternating between phases that longitudinally focus and transversely defocus and phases that longitudinally defocus and transversely focus. In our preliminary analysis, the synchronous phase of acceleration is assumed to take on the form

$$\begin{aligned} &\phi_s = \phi_c + \phi_a \sin\left(\frac{2\pi z}{\lambda_p}\right); \\ &\phi_s = \text{synchronous phase}; \\ &\phi_c = \text{center of dithering}; \\ &\phi_a = \text{amplitude of dithering; and,} \\ &\lambda_p = \text{period of dithering.} \end{aligned} \tag{4}$$

This synchronous phase oscillation has been shown to provide simultaneous transverse focusing and longitudinal stability. The longitudinal acceptances and bucket depths for various dithering parameters are given below (note that $k_p = 2\pi/\lambda_p$).

Table 1: Bucket Depths and Acceptances for various dithering parameters (with ϕ_c=0)

$\frac{k_p}{k_z}$	ϕ_a (radians)	Acceptance (radians)	Bucket Depth (eV)
0.035	0.785	0.667	06.15
0.035	0.900	0.800	13.00
0.025	0.785	0.940	22.10
0.020	0.785	1.100	44.10

Clearly, the small bucket depths present a potential difficulty. This is a problem that is currently being addressed. Additionally, studies concerned with simulating the particle dynamics of this alternating phase focusing are currently underway.

A second scheme that has been proposed to achieve simultaneous focusing in the y and z directions involves introducing variation to the fields in the x direction. If the structure of the MAP is altered so that the electric field takes on the form:

$$\begin{aligned} E_z &= E_0 \cosh(k_y y)\cos\left(\frac{\omega z}{\beta c}\right)\cos(k_x x); \\ E_y &= \frac{\omega E_0}{\beta c k_y}(1-\Lambda)\sinh(k_y y)\sin\left(\frac{\omega z}{\beta c}\right)\cos(k_x x); \\ E_x &= \frac{\omega E_0}{\beta c k_x}\Lambda\cosh(k_y y)\cos\left(\frac{\omega z}{\beta c}\right)\sin(k_x x). \end{aligned} \tag{5}$$

Here, Λ is any real number (included to guarantee that the divergence of E is 0). Then the particle would experience the following forces:

$$\begin{aligned} F_z &= qE_0 \cosh(k_y y)\cos\left(\frac{\omega z}{\beta c}\right)\cos(k_x x); \\ F_y &= \frac{k_y \beta c q E_0}{\omega}\sinh(k_y y)\sin\left(\frac{\omega z}{\beta c}\right)\cos(k_x x); \\ F_x &= -\frac{k_x \beta c q E_0}{\omega}\sinh(k_y y)\sin\left(\frac{\omega z}{\beta c}\right)\sin(k_x x). \end{aligned} \tag{6}$$

Thus, the particles can be simultaneously focused in the y and z direction while being defocused in the x direction, though in achieving this we have sacrificed the advantages of x invariance mentioned above.

CONCLUSION

A successful design for the relativistic MAP has been verified using real materials, showing that our structure can feasibly be fabricated. Fabrication has recently begun [3]. However, the challenging design for the part of the MAP meant to accelerate sub-relativistic is still underway, with the goal of finding both resonance and maintaining particle stability.

REFERENCES

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