LASER-POWERED DIELECTRIC STRUCTURE AS A MICRON-SCALE ELECTRON SOURCE*

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Abstract

We describe a resonant laser-powered structure, measuring 1 mm or less in every dimension, that is capable of generating and accelerating electron beams to low energies (∼ 1–2 MeV). Like several other recently investigated dielectric-based accelerators, the device is planar and resonantly excited with a side-coupled laser; however, extensive modifications are necessary for synchronous acceleration and focusing of nonrelativistic particles. Electrons are generated within the device via a novel ferroelectric-based cathode. The accelerator is constructed from dielectric material using conventional microfabrication techniques and powered by a 1-μm gigawatt laser. The electron beams produced are suitable for a number of existing industrial and medical applications.

INTRODUCTION

Laser acceleration of electrons in a resonant structure has been a topic of recent interest, with several schemes proposed [1],[2],[3] in the past few years. These designs have several characteristics in common: they are built from dielectric material and hence able to withstand high electric fields for short pulse lengths; they minimize beam wakefields by exploiting symmetry; and they operate in the relativistic limit, with electron velocity $v \to c$. These structures exhibit high gradients (∼ 100s of MeV/m) but require external beam injection into a narrow aperture, as the characteristic dimensions are on the order of the laser wavelength.

A laser-powered resonant structure *incorporating* a cathode or particle source would avoid this injection issue and essentially become a monolithic particle source. Given that these devices scale with laser wavelength, such a source could be extremely small. However, accelerating particles from rest introduces significant complication into the physics. We will show that a submillimeter electron beam source can be constructed using slab-symmetric dielectric layers and an integrated cathode; the energies produced will be weakly relativistic (1–2 MeV). The resulting device is unsuitable for high-energy physics applications, with low trapping fraction, poor efficiency, and diverging output beam, but could have a variety of applications in industry or medicine as a micro-sized radiation source. Furthermore, planar dielectric-based structures can be constructed to very demanding tolerances using layer-deposition techniques common in the integrated-circuit industry.

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STRUCTURE OVERVIEW

The structure described here is based on the relativistic slab-symmetric dielectric-based accelerator proposed in [1]. In these structures, a pair of parallel dielectric slabs is separated by a narrow vacuum gap and bounded above and below by a reflective layer. Periodic slots in the reflector provide a means for coupling radiation into the gap and also enforce longitudinal periodicity in the structure fields. In the relativistic device, the invariance of the structure in the wide transverse dimension (x) leads to a longitudinal accelerating field which is also constant in the short transverse dimension y. The physical consequence of this independence is a suppression of transverse wakefields. If the structure dimensions (vacuum gap and dielectric thickness) are correctly chosen, the structure will be resonant at the laser frequency; the field pattern will be dominated by a longitudinal standing wave with phase velocity c. The field enhancement factor depends on the details of the coupling into the structure, but the accelerating field is typically 4 to 10 times larger than the incident laser field.

Accelerating Mode

To construct a sub-relativistic accelerating structure, we require first that the phase velocity along the beam trajectory (the z direction) match the particle velocity, or $\omega/k_z = \beta c$. We begin by analyzing a structure which is uniform and very wide in the x dimension. Assuming transverse invariance of the fields, or $k_x = 0$, the dispersion relation is $k_x^2 + k_y^2 + k_z^2 = \omega^2/c^2$, which gives an imaginary value for k_y. The accelerating mode is then described by

$$E_z(y,z) = \cosh(\sqrt{1-\beta^2}k_z y)\cos(k_z z) = \cosh\left(\frac{\omega y}{\beta c\gamma}\right)\cos(k_z z) \quad (1)$$

and a resonance condition on the structure dimensions, which is found by applying boundary conditions and matching field components, is given by

$$\frac{\gamma\beta}{\epsilon_r}\sqrt{\epsilon_r - \frac{1}{\beta^2}} = \coth\left(\frac{\omega}{\gamma\beta c}a\right)\cot[k_\perp(b-a)], \quad (2)$$

where ϵ_r is the relative permittivity of the dielectric, $k_\perp = \sqrt{\epsilon_r - 1/\beta^2}(\omega/c)$, and a and b are as shown in Figure 1(a). We note immediately that the structure dimensions will vary with beam velocity β—and must hence be tapered as the beam energy increases—and that there is no eigensolution for $\beta < 1/\sqrt{\epsilon_r}$. As the structure must also be modulated in the z direction by coupling slots having periodicity

$2\pi/k_z$, the slot spacing must be tapered as well and equal to $\beta\lambda$, where λ is the free-space laser wavelength. A drawing of the structure is shown in Figure 1(a).

Eq. 1 shows an inherent inefficiency of the structure: the accelerating field increases off-axis, though the degree of nonuniformity lessens for larger $\beta\gamma$. However, Eq. 2 does not constrain the half-gap spacing a, and for sufficiently small a the nonuniformity can be minimized.

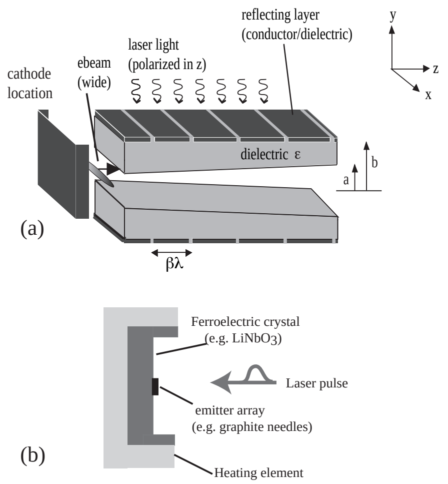

Figure 1: Conceptual drawings of (a) the accelerating structure; and (b) the cathode assembly. Typical dimensions: a = 0.05–0.1 μm; b = 0.27–0.3 μm; total length 1 mm or 1600 structure periods.

Cathode

The constraint on β mentioned above implies that to be trapped and accelerated, the beam may not start from rest. For example, if the dielectric is silicon or germanium ($\epsilon_r =$ 11.69 for Si), the minimum beam energy for acceleration is 23.4 keV. We propose a dual-function integrated cathode in which electrons are generated by field emission and then accelerated in a quasi-DC electric field to at least 25 keV.

The cathode design is shown conceptually in Fig. 1(b) and consists of a small field-emitting region, such as an array of graphite needles, deposited onto a ferroelectric crystal (FEC) such as lithium niobate ($LiNbO_3$). FECs generally have pyroelectric properties, that is, when heated or cooled they develop a temporary polarization charge σ_p on the crystal surfaces which is proportional to the temperature increase ($\sigma_p = \gamma\Delta T$, where γ is the pyroelectric coefficient of the material and ΔT is the temperature rise in kelvin) [4]. This polarization charge is eventually neutralized by bulk conduction in the material, but the process is slow (relaxation time on the order of seconds). For $LiNbO_3$, $\gamma = 10^{-8}$ C cm^{-2} K^{-1}, and a temperature increase of 10 K is sufficient to produce a surface charge of 10^{-7} C/cm^2, with a surface field on the order of 10 MV/m. The total energy gained by an electron accelerated in the surface field depends on the size of the FEC; for a circular FEC of radius R in the absence of boundaries, $\Delta U \leq e\sigma_p R/2\epsilon_0$, or 28.4 keV for $R = 0.5$ mm. Cathode operation is therefore a two-stage process: the cathode is heated to provide the quasi-static DC field, and then illuminated by the laser pulse to give field emission from the tips. A gap of less than a millimeter between cathode and acceleration structure will suffice to inject electrons at an energy high enough for trapping.

Focusing

One can determine, from the Maxwell equations, the field and force components on a charged particle within the vacuum gap for the x-invariant structure described above. While there can be no net force in x due to symmetry, we find that the force in the y-direction is given to first order by

$$F_y \approx \frac{qE_0}{\gamma}\sinh\left(\frac{k_z y}{\gamma}\right)\sin(k_z z), \quad (3)$$

that is, the transverse fields are defocusing in y for phases in the accelerating bucket, though they vanish in the relativistic limit. While this first-order effect is unavoidable unless the transverse symmetry in x is broken, it can be offset for relativistic velocities by a second-order (ponderomotive) focusing force due to the backward-going wave component in this standing-wave structure [5]. The backward wave does contribute to the dynamics for the sub-relativistic electrons, as described in the Simulation section below, but for low values of β ($\gamma \sim 1$) the defocusing still predominates. For low energies we must introduce field variation in x in order to address the focusing issue. By shaping the structure in the x-dimension, one in effect imposes a nonzero (real or imaginary) k_x. If k_x is large enough and imaginary, one obtains a structure which is focusing in the y direction and defocusing in x.

One possibility for stable acceleration over hundreds of periods is the use of a canted structure which maintains focusing in the small (y) direction while alternating transverse kicks in the x direction. (See Fig. 2.) In this scenario, the coupling slots are rotated by a small β-dependent angle, in effect using a nonzero transverse velocity to oppose the defocusing kick F_x. After several structure periods, when the particle has crossed the centerline, the slot angle is changed to the opposite sign, and the process can continue.

NUMERICAL RESULTS

The structure described is challenging to simulate in full, due to the variety of length scales, large aspect ratios for structure and coupling slots, and open boundary conditions in x. We present only preliminary results here, including semi-analytic and numerical approaches.

The results of single-particle tracking through analytic fields are shown in Figure 3(a) and (b). Energy gain for a particle on the axis appears smooth, with output energy of 1 MeV reached in just over 1 mm of travel, but for low

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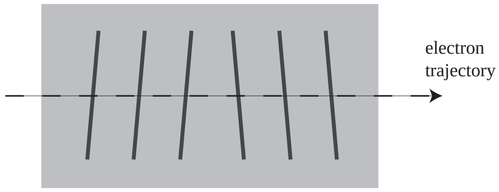

Figure 2: An alternating-angle canted structure which would be focusing in both x and y, shown viewed from above ($+y$). The coupling slots are rotated by a small angle from the perpendicular and alternate in sign every few structure periods.

energies ($\beta = 0.3$–0.4) the particle phase in fact slips, due mostly to the large percentage change in velocity (roughly 1%) per structure period. Acceleration remains steady in this regime because of contributions from the backward-going wave component. For these results, we have optimized the structure taper and injection phase for the field strength on axis (3.5 GV/m). In Fig. 3(b), which incorporates the canted-slot focusing scheme, stable trajectories are shown in both transverse dimensions. The initial slot rotation angle θ determines the acceptance of the structure; these results take $\theta = 10^{-6}\delta x/\gamma$, where δx is the deviation from the axis and γ is the z-dependent electron velocity factor.

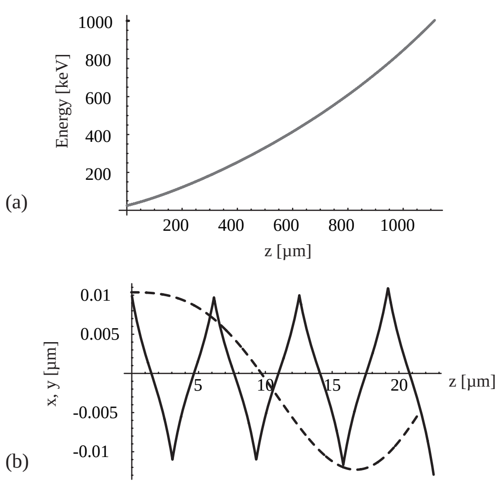

Figure 3: Numerical results from single-particle pushing through analytic fields. (a) Particle energy along the structure, assuming a GW-class laser (3.5 GV/m field strength within the gap). (b) Focusing using the canted-slot approach, showing values of x and y in the first 20 periods of the structure. The structure is focusing in y (dashed line) and alternates defocusing kicks in x (solid line).

Simulation of the electron energies produced by the cathode was estimated using the particle-in-cell code OOPIC. A stationary polarization charge layer was used to produce an electric field, with "emitted" electrons created on its surface. Fig. 4(a) shows the field produced, which approaches uniformity in y, and Fig. 4(b) shows the electron energy spectrum after an electron bunch of 0.01 pC has propagated 16 μm from the FEC.

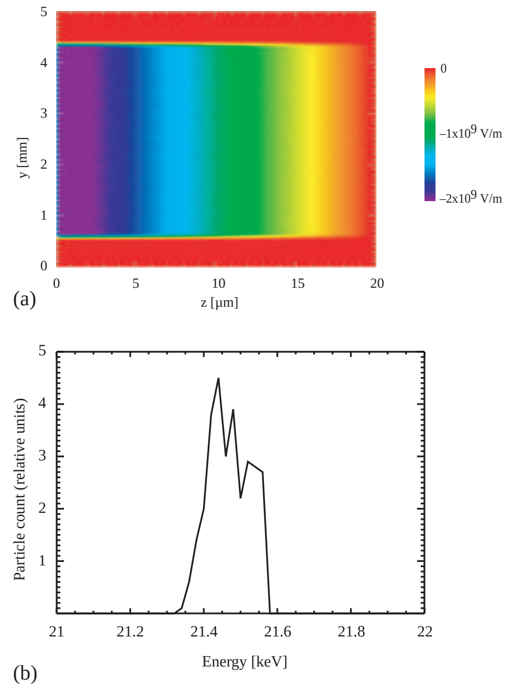

Figure 4: (a) PIC simulation of quasi-DC accelerating field produced at a 5-mm-wide cathode using a heated FEC, with $\sigma_p = 4 \times 10^{-7}$ C/cm^2. (b) Electron energy spectrum for 0.01 pC beam after propagation over 16 μm in the field in (a).

CONCLUSIONS

A laser-powered micro-accelerator appears to be possible, according to preliminary investigations. Many questions remain to be answered, including the particle dynamics in full simulated fields, the optimal slot design for coupling the laser to the structure, breakdown and heating limits on the dielectric material, and detailed construction method. The tolerances required for the micro-accelerator are well within those achieved by modern microfabrication techniques, and the dielectric materials proposed for the micro-accelerator (such as silicon and germanium) are well suited to these construction methods.

REFERENCES

[1] R. B. Yoder and J. B. Rosenzweig, *Phys. Rev. STAB* **8**, 111301 (2005), and references therein.

[2] Z. Zhang, S. G. Tantawi, R. D. Ruth, *Phys. Rev. STAB* **8**, 071302 (2005).

[3] A. Mizrahi and L. Schächter, *Phys. Rev. E* **70**, 016505 (2004).

[4] G. Rosenman *et al.*, *J. Appl. Phys.* **88**, 6109 (2000).

[5] J. Rosenzweig, A. Murokh, C. Pellegrini, *Phys. Rev. Lett.* **74**, 2467 (1995).

1-4244-0917-9/07/$25.00