A SLAB-SYMMETRIC DIELECTRIC-LOADED STRUCTURE FOR HIGH-GRADIENT ACCELERATION AT THZ*

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Abstract

We present a design for a slab-symmetric accelerating structure to be resonantly excited at terahertz frequencies. The device, consisting of a vacuum gap between dielectric-lined walls, combines the advantages of a slab geometry (including strong suppression of transverse beam wakefields and low power density) with the existence of a resonant mode having phase synchronism with relativistic electrons. Accelerating fields of hundreds of MeV/m are predicted when the structure is powered by a high-power FIR radiation source in development at UCLA. Simulation of the structure fields is described and compared with theory, and an experimental program is discussed.

INTRODUCTION

In all laser-based acceleration concepts, the large transverse fields of a laser pulse must be converted to useful longitudinal fields, a problem solved in the microwave regime by coupling radiation into resonant structures. While this acceleration method is venerable, conceptually simple, and capable of generating very large axial fields, the well-known physical and technical limitations of scaling such structures to near-optical wavelengths have strengthened the cases for plasma-based and far-field optical accelerators, despite the considerable challenges of these latter approaches. However, many of the harmful effects produced by the presence of field-shaping boundaries near the accelerating particles are mitigated if the system is allowed to become very large in one transverse dimension, in effect producing a two-dimensional device. This paper extends and refines previous work on laser-based acceleration in a "slab-symmetric" device, and introduces a new design for a structure driven resonantly at 340 μm, which is to be experimentally investigated at UCLA using a novel high-power terahertz source.

The case for slab structures rests on the inherent translational symmetry of their geometry, which forces the fields of a speed-of-light wave to be invariant in the small transverse dimension; this leads in turn to the suppression of transverse (dipole-mode) wakefields, which otherwise would dominate the beam-structure interaction. A slab-beam can then contain very high charge, acting in effect as a large number of parallel beamlines. The use of dielectric materials (which can withstand surface fields of a few GV/m for pulses of a few picoseconds) [1], coupled with the relatively low Q (100–1000) of a planar structure, allow the production of large gradients (hundreds of MeV/m) before breakdown limitations are reached.

Structure Overview

Fundamentally, our device consists of a pair of parallel dielectric planes, separated by a narrow vacuum gap and bounded above and below by a thin conductive layer. Periodic slots in the conductor provide a means for coupling radiation into the gap and also enforce longitudinal periodicity in the structure fields. When the correct resonant geometry is achieved, the mode pattern is dominated by a longitudinal standing wave having a phase velocity exactly equal to the speed of light. The concept is illustrated in Fig. 1.

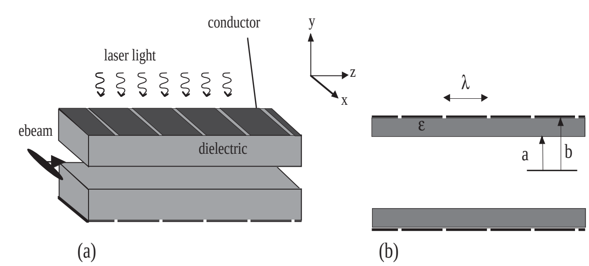

Figure 1: (a) Schematic drawing of the slab-symmetric structure; (b) a cross-section in x, showing the parameter definitions. The 'infinite' dimension (x) extends into the page; electron beam propagation is in $+z$, with radiation (also polarized in z) impinging on the structure from the $+y$ direction.

A number of versions of this concept have been proposed [2, 3, 4], each of which took a slightly different approach to generating the correct longitudinal periodicity in the structure properties. Periodic slots, as used here, represent the optimum choice for coupling power preferentially into the accelerating mode while satisfying the speed-of-light resonance condition. Numerical modeling of the structure, discussed below, is used to optimize the coupling slots for best performance.

Structure Modes

Mode analyses for this class of slab-symmetric structures have been outlined in several recent papers [3, 5]; the solutions hold for any periodically-modulated structure, regardless of the mechanism used for the modulation. We summarize the results briefly here for the fundamental

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speed-of-light mode, which is the one of interest for acceleration. Using the axes and structure parameters defined in Fig. 1, and assuming initially that the structure is truly infinite in the x direction, we obtain an axial electric field

$$E_z(y,z) = \left\{ \begin{array}{c} E_0 \\ AE_0 \cos[\sqrt{\epsilon - 1}\, k_z(b-y)] \end{array} \right\} \cos(k_z z) e^{i\omega t} \tag{1}$$

where the upper line holds within the vacuum gap ($|y| < a$) and the lower within the dielectric ($a < |y| < b$), and where $A = \csc[\sqrt{\epsilon-1}(b-a)k_z]/\sqrt{\epsilon-1}$. The transverse fields are proportional to y and zero on axis. Imposition of boundary conditions at metal and dielectric boundaries gives a resonance condition which specifies allowed values of a, b and ϵ for a given $k_z = 2\pi/\lambda_0$, where λ_0 is the free-space laser wavelength.

The true translational symmetry of the structure is of course broken in any physical device with finite extent. The effect of a non-infinite structure on the accelerating mode has been addressed in [5], where field variation in the x direction is imposed by the addition of conducting walls at $x = \pm L$, where $L \gg a$. It is shown that the axial field in the gap gains a $\cosh(k_\perp y)$ dependence, but with sufficiently large structure aspect ratio (and hence small wavenumber $k_\perp$), the deviation from flatness of the field can easily be kept below 1%.

Optimized Parameters

Starting from a wavelength of 340 μm, we choose $\epsilon = 3$ (close to values for e.g. silicon) and find that the lowest resonance occurs for $a = 115$ μm, $b = 145$ μm, or in other words a vacuum gap of full width 230 μm, bounded by a dielectric layer 30 μm thick. To optimize the coupling of external power into the structure, we can adjust the width of the coupling slots as well as the thickness, or depth, of the conducting layer itself. One must bear in mind that since the drive radiation is not cut off in the coupling slots (they are very long in the x direction), the slots are in effect waveguide sections which can perturb the resonance significantly. The high-Q results presented below are obtained for a slot of width 5 μm and 69 μm deep.

NUMERICAL RESULTS

Field Modeling

Extensive modeling of the ideal slab geometry has been carried out using a two-dimensional finite difference solver to verify the resonance condition and to optimize the coupling of external fields into the structure. In this code, a single structure period is illuminated by a plane wave, with symmetry enforced at the midplane; periodic boundary conditions are used in z. Typical output is shown in Fig. 2. Fig. 3 shows the field within the gap in more detail, where it is clear that the accelerating field is nearly invariant in y, as predicted by (1). The transverse field is zero at the location of the peak accelerating field; see Fig. 3. There is clearly a very strong field in the coupling slot itself; however, in this design the slot acts as a quarter-wavelength transmission line, causing the field to fall to zero at the inner aperture and hardly perturb the accelerating mode. The large slot field indicates that these slots can cause a substantial change to the structure resonant frequency; it also limits the amount of power that can be introduced. Eliminating the quarter-wave condition on the slot length, while mistuning the structure to compensate for the frequency shift, may overcome this problem.

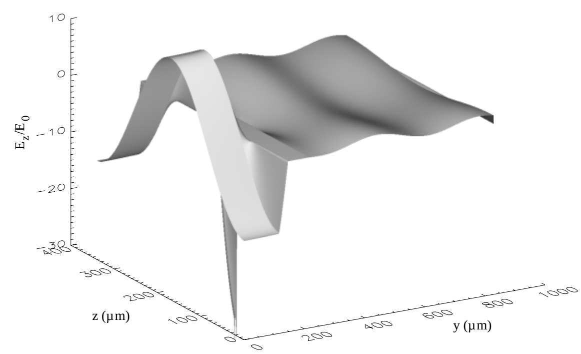

Figure 2: Surface plot showing time snapshot of axial fields, normalized to the amplitude of the incident wave. The field along the z axis shows the accelerating mode, with a field spike in the coupling slot and a plane wave in the space above the structure.

The growth of the accelerating fields in time is shown in Fig. 4, where we see that after a relatively long fill time (on the order of 500 ps) the accelerating field amplitude within the structure reaches a value near 15 times that of the incident wave. The same figure compares the amplitude of the accelerating mode with that of its most important competitor, the so-called ‘zero-mode’, with fields that are constant in z. As the figure shows, the zero-mode component of the fields remains less than 1% of the accelerating component. The fill time of 600 ps suggests a loaded $Q = \omega\tau$ for the structure on the order of 3000, a relatively high value. For experiments driven with pulsed lasers, it will be important to decrease this fill time while maintaining a reasonable shunt impedance. Nevertheless, the design exhibited here would produce an accelerating gradient of 400 MeV/m when illuminated at 100 MW/cm^2.

Wakefield Stability

The advantageous transverse wakefield properties of the slab-symmetric geometry are one of the reasons for interest in these structures, and our assertion that damaging transverse wakefields vanish for very wide beams has been verified by analysis and simulation. Ref. [5] contains an analytical calculation of the wake potentials in a slab-symmetric structure, and OOPIC simulations of particle wakes in this 340 μm structure were presented in an earlier paper [7]. In both cases, the transverse electric and magnetic forces in

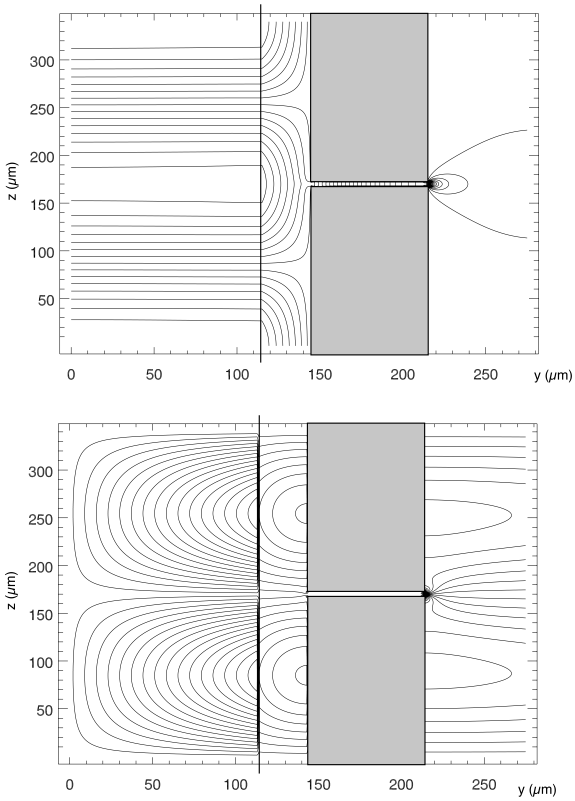

Figure 3: Contour plots showing E_z (above) and E_y (below) over one structure period. The shaded area represents the conductor (with coupling slot), and the dark line shows the dielectric/vacuum boundary.

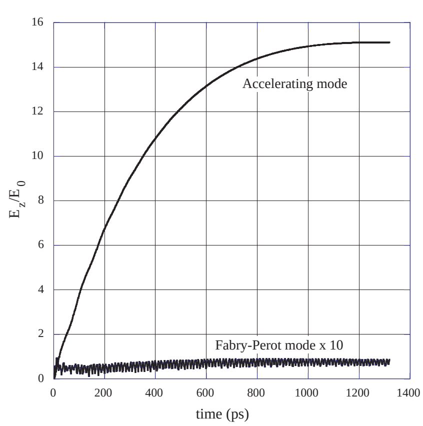

Figure 4: Amplitude of axial electric fields within the vacuum gap vs. time, normalized to amplitude of the incoming wave. The accelerating mode has longitudinal periodicity; the non-accelerating Fabry-Perot mode (multiplied by 10 here) does not.

the vacuum gap canceled within machine precision.

EXPERIMENT

The geometry of the experiment which is planned for the UCLA Neptune facility is dictated by available radiation wavelengths. As mentioned earlier, the accelerator is to be driven with a new terahertz source under development at UCLA. The large resonant vacuum gap in this wavelength range—more than 0.2 mm—makes it feasible to inject the 11–14 MeV beam from the Neptune photoinjector, with normalized transverse emittance in the range of 6–10 π mm mrad, into the structure successfully.

We expect to obtain multimegawatt laser radiation at 340 μm using a difference frequency generation scheme: two frequencies from the Neptune terawatt CO_2 laser will be mixed at high power in a gallium arsenide crystal, with conversion efficiency into the difference frequency near 1%.[6] The two input frequencies, as well as the output radiation, are non-collinear in order to maintain synchronism over a relatively large (several centimeter) interaction length. Output power levels in excess of 100 MW are projected; experimental work is currently in progress.

Diagnosis of the structure can be carried out through cold testing as well as by acceleration experiments and the possible detection of wake radiation. Transmitted light from the lower coupling slots, as shown in Fig. 1, can be used to measure the filling of the structure. Since the design is easily scaleable to other wavelength regimes, it may also be useful to evaluate prototype structures using conventional laser radiation, e.g. at 10.6 μm.

CONCLUSION

We have described a slab-symmetric dielectric-loaded structure which serves as a resonant laser-driven accelerator with advantageous transverse stability for high-charge beams. When such an accelerator is powered by a submillimeter-wave source at 340 μm, the structure dimensions become ample for acceleration of a slab electron beam with achievable transverse size, and with realistic input power levels we calculate acceleration gradients of 400 MeV/m. Experimental investigation of these structures, including cold testing in several wavelength regimes, is planned at the UCLA Neptune facility.

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