# SLAB SYMMETRIC DIELECTRIC MICRON SCALE STRUCTURES FOR HIGH GRADIENT ELECTRON ACCELERATION[*]

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## *Abstract*

A class of planar microstructures is proposed which provide high accelerating gradients when excited by an infrared laser pulse. These structures consist of parallel dielectric slabs separated by a vacuum gap; the dielectric or the outer surface coating are spatially modulated at the laser wavelength along the beam direction so as to support a standing wave accelerating field. We have developed numerical and analytic models of the accelerating mode fields in the structure. We show an optimized coupling scheme such that this mode is excited resonantly with a large quality factor. The status of planned experiments on fabricating and measuring these planar structures will be described.

## 1 INTRODUCTION

Advances in the technology of lasers have led to increased interest in their potential applications for accelerating particles. Plasma beat wave[1] and laser wakefield[2] acceleration methods use laser radiation to drive a plasma wave with luminal phase velocity. The longitudinal electric fields in this plasma wave are in turn used to accelerate an electron beam. Inverse Cherenkov[3] and inverse free electron laser [4] acceleration techniques use light optics or magnetic fields respectively to achieve an electric field component parallel to the beam direction from the transverse electric field in the laser pulse. We have proposed a class of resonant dielectric loaded planar structures[5] capable of producing GeV/m accelerating gradients which are driven by laser radiation much as a conventional rf cavity is driven by microwave power from a klystron.

The basic idea is the use of a dielectric microstructure, analogous to a Fabry-Perot resonator, consisting of a two parallel dielectric planes separated by a vacuum gap and with a partially transmissive coating on the exterior (see Figure 1). Some parameters of the structure are assumed to vary periodically in the beam direction at the wavelength of the illuminating laser. A standing wave with an appropriate phase velocity forward component is induced in this periodic structure by the laser pulse, which in turn accelerates the beam. The laser pulse is swept along the surface of the structure such that the cavity is filled only in the neighborhood of the beam. The relatively low $Q$ of these devices (100-1000) and correspondingly short fill times (~0.5 ps) allows gradients of 1 GeV/m to be obtained before breakdown becomes problematic[9]. The beam aspect ratio is highly asymmetric; the ribbon beam-planar structure configuration is advantageous in that dipole deflecting modes are suppressed[6], analogous to the vanishing of the transverse deflection for TM0n modes in conventional structures.

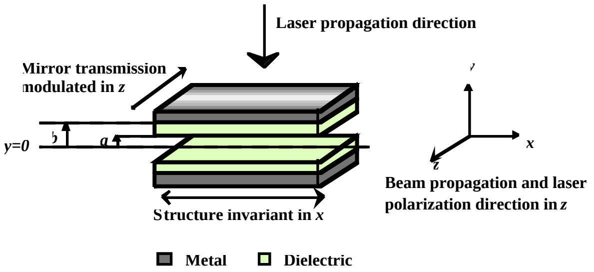

Figure 1. Geometry of slab-symmetric, laser-excited, dielectric-loaded resonant accelerator structure.

A number of different methods have been investigated to introduce the necessary periodic variation in the structure geometry. The original paper in this area[5] suggested the use of a longitudinally modulated permittivity in the dielectric. While this was attractive from the point of view of construction and analysis (one could concievably generate the modulation by “writing” an interference pattern in a photorefractive dielectric with a second laser) it proved to be difficult to obtain good coupling of the laser energy to the accelerating field. More recent analyses have concentrated on using a spatially unvarying dielectric medium and modulating the transmittivity of the coating [7]. This approach was found to improve the laser coupling to the structure significantly but was found to yield uncomfortably large surface fields on the structure.

We discuss here some recent progress in the understanding of slab structure design. We have investigated the use of finite thickness conductive cladding on the structure, with a single coupling slot per period. With this geometry good coupling of laser energy to the accelerating fields can be obtained, while at the same time reducing the surface field/accelerating field ratio significantly over our previous results. The shape of the coupling slot is also seen to be important, in that the

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introduction of a taper at the slot opening provides improved coupling over the case of a rectangular slot profile.

## 2 NUMERICAL RESULTS

In the study of these structures we have found it useful to rely on numerical solution of the Maxwell equations in slab geometry. We use a custom finite difference time domain code to inject and propagate the laser fields into the structure geomerty under study. The program implements periodic boundary conditions in $z$ (the beam propagation direction) and absorbing boundary conditions in $y$ (the laser propagation direction) to handle any reflected laser energy from the structure. The structure is assumed to be of infinite extent in the $x$-view. For a given structure geometry, the integration is continued until a steady state condition is reached. The structure is “tuned” numerically by adjusting one of its parameters (typically the dielectric constant) until the asymptotic stored energy is maximized. (In the laboratory one would tune the structure by changing a geometrical parameter like the vacuum gap size.)

We have analyzed a structure with dielectric thickness ($b$-$a$) equal to the vacuum gap ($a$ =1.6 µm), period of 10.6 µm (corresponding to a commone CO$_2$ laser line), and dielectric constant $\varepsilon \cong 3.7$. The conductive cladding thickness in the simulation is 0.3 µm. The laser coupling and field strengths in the structure were studied as a function of the shape of the coupling slot. While not exhaustive, these calculations indicate a promising approach to the problem of coupling optimization. The following results are normalized to a peak laser electric field of 0.25 Statvolt/cm = 75 kV/m.

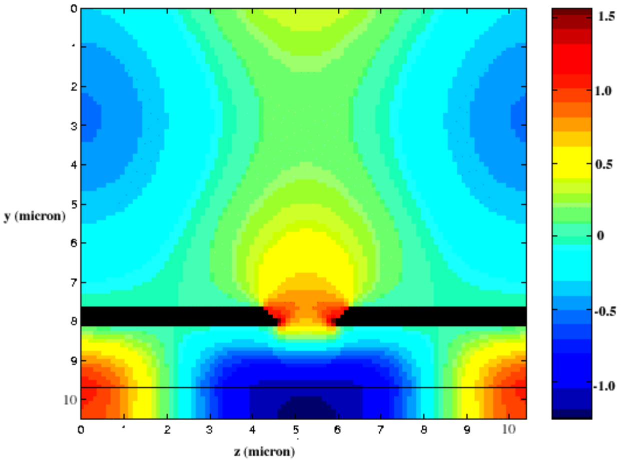

Figure 2. Pseudocolor contour map of $E_z$ in the computational area for the tapered aperture structure. Laser radiation is incident from the top of the figure ($y$=0). The area depicted in solid black is the conductive cladding, and the thin black line indicates the dielectric-vacuum boundary.

In reference[7], the fields of a similar structure having an infinitesimally thick, sinusoidally modulated transmittivity outer cladding were computed. While reasonable coupling was achieved, it was also pointed out that the surface electric field on the mirror-dielectric interface was undesirably large, roughly twice the maximum field in the vacuum gap. The case of a *finite* thickness mirror with a rectangular aperture was studied for this paper. For a 2 µm slot width the corresponding peak surface field is 2.0 Statvolt/cm for a gap field amplitude of 1.06 Statvolt/cm. The largest surface fields in this device occurred at the exterior corners of the slot; this might be further improved by rounding the corners. (The present version of the simulation code cannot handle curved boundaries except via a stairstep approximation.) An increase in the coupling slot width to 3 µm produced slightly worse results with a surface field/gap field ratio of 1.9/0.87.

The effect of tapering the aperture of the coupling slot is shown in Figure 2. The surface field/gap field ratio is relatively small, 1.56/1.23, while the gap field strength is also a maximum for all similar device geometries. Stored energy and gap field strengths vs time are shown in Figure 3. From the energy history we can read off a fill time of 0.57 ps, corresponding to $Q$=102. As we have discussed previously[7], the fields in the vacuum gap are a superposition of Fabry-Perot-like (zero phase shift per period, providing no net acceleration) and accelerating (forward wave componet resonant with an ultrarelativistic particle) modes. The Fabry-Perot mode amplitude has been diminished to 20% of the accelerating mode amplitude in the present case, solely through through the periodicity of the coupling. This proportion seems to be about the most favorable we have been able to obtain.

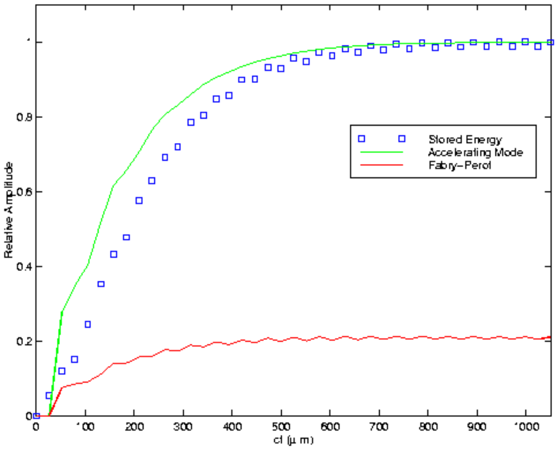

Figure 3. Fill curves for the tapered aperture structure. The fill time is 0.56 ps, corresponding to $Q$=102. The stored energy is normalized to its maximum value, while the accelerating and Fabry-Perot modes are shown relative to the accelerating field amplitude.

## 3 CONCLUSIONS

We have studied a class of dielectric loaded structures for laser acceleration which can potentially produce GeV/m gradients. We have given some consideration to questions of structure breakdown and preservation of beam quality. Resonant planar structures showing good coupling of laser radiation to the desired accelerating mode have been demonstrated numerically, with reasonable surface field/vacuum field strengths and quality factors commensurate with the requirements of a practical accelerator. These properties imply that the structure is a good candidate for further development as an accelerator, as it can be coupled well (it can be fully impedance matched upon filling, just as a standing wave linac cavity). This development will probably proceed at 10.6 micron design wavelength. Choice of this wavelengthe is based both on availability (e.g. at the UCLA Neptune laboratory[9]), and on mitigation of the experimental challenges one faces on moving orders of magnitude down in accelerator wavelength.

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