PROPOSED FEW-CYCLE LASER-PARTICLE ACCELERATOR STRUCTURE*

T. Plettner#, R.L. Byer, P.P. Lu, Stanford University, Stanford, CA, 94305, USA

Abstract

We describe a transparent dielectric accelerator structure that is designed for ultra-short laser pulse operation. The structure is based on the principle of periodic field reversal to achieve phase synchronicity for relativistic particles. To preserve the possibility of ultra-short pulse operation it does not resonate the laser field in the vacuum channel, which enables the structure to support higher peak electric fields. Gradients on the order of a few GeV/m are expected to be possible with 10 fsec laser pulses. The proposed structure has a two-dimensional geometry which is ideally suited for micro-fabrication techniques and for integration with other optical MEMs components.

INTRODUCTION

Ultra-short pulse few-optical cycle tabletop lasers have become a reality in recent years. Application of such short pulses for laser-driven particle accelerators appears especially appealing from a gradient point of view. The shorter pulses enable the structure to sustain higher peak electric fields and also improve the temporal overlap of the laser pulse envelope and the electron bunch, which potentially leads to higher efficiencies.

However, few-cycle laser pulses have a very large bandwidth. This places a serious constraint on the possible structure geometries that could function with such pulses. Commonly described waveguide and resonator schemes present serious difficulties with ultra-short pulse operation. One might consider waveguides, however the dispersion present in typical waveguide geometries seriously affects the group velocity of the accelerating laser mode in the structure, while the quality factor of a resonator seriously limits its bandwidth. Here we explore a geometry that neither guides nor resonates the electromagnetic field [1]. It relies on the principle of quasi-phase matching of a semi-free electromagnetic wave for the maintenance of extended phase synchronicity with the particle.

THE ACCELERATOR STRUCTURE

A laser plane wave is launched at normal incidence into a vacuum channel with a periodic modulation whose period equals the laser wavelength. To match the timing of the laser pulse envelope to the electron bunch the laser plane wave is pulse-front-tilted at an angle near 45° [2]. The pulse front tilt angle, and hence the effective velocity of the group along the vacuum channel, can be controlled by external angular dispersion elements such as prisms or gratings [3]. In the author’s view this degree of freedom is an important advantage that allows for precise tuning of the effective group velocity. Figure 1 shows a perspective drawing of a section of the proposed accelerator structure.

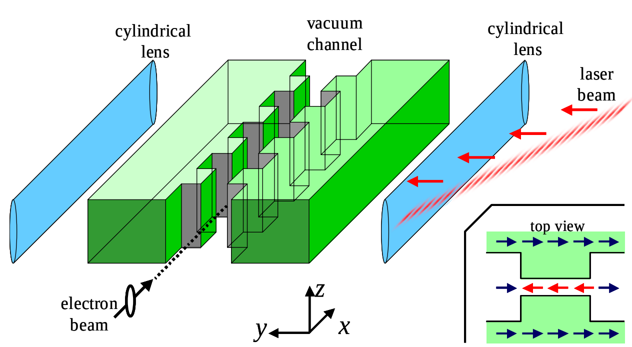

Figure 1: Perspective view of the accelerator structure.

Periodic structures that rely on this general phase-matching principle and that resonantly enhance the field in the vacuum channel have been proposed in the past [4]. However, if we specifically seek operation with few-cycle laser pulses the structure has to be a very poor resonator. The structure proposed here is an uncoated dielectric substrate, which allows for relatively low reflection coefficients at the interfaces such that most of the laser field exits vacuum channel in a single pass. In the proposed scheme the vacuum channel periodic modulation is generated by a binary step function grating surface. This binary shape is possible to manufacture by common micro-fabrication techniques and hence will be used as an example to study the proposed accelerator concept. Other periodic forms are possible and are presently being investigated for improved efficiency and for improved gradient.

Two of the key shape parameters that determine the performance of the binary structure in figure 1 are the vacuum channel width and the depth of the binary grating grooves. FDTD methods were employed to evaluate the electromagnetic field components in one vacuum channel period and the average accelerating field component sampled by a speed-of-light particle, and how it depends on the shape parameters.

* Work supported by DOE FG-06-97ER41276
# tplettne@stanford.edu

Figure 2 shows the dependence of the average acceleration gradient as a function of these two parameters for a quartz substrate of index n ~1.5. The average fields are normalized to an input laser plane wave of amplitude $E_{laser} = 1$. The maximum attainable gradient occurs at a grating pillar height of about 0.9 λ, with a value close to ½ the amplitude of the incident laser field. For channel gaps <λ/4 the gradient remains almost unchanged at a value of $\langle G \rangle \sim 0.5\, E_{laser}$. Since the periodic field modulation has a feature size λ/2 it does not propagate into the far field, and hence for wider channel gaps the gradient starts to drop. Further widening of the channel to a width of λ lowers the average gradient to approximately one half the original value. Extending the gap width further is not feasible if the high gradient is to be preserved.

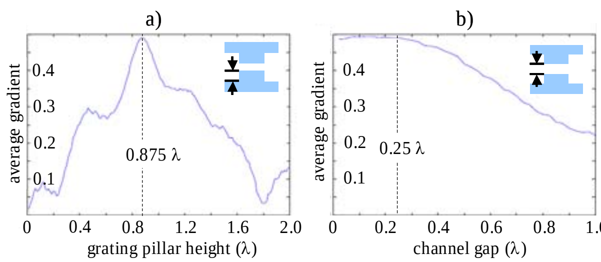

Figure 2: Average gradient as a function of the vacuum channel grating groove depth (a) and width (b).

The FDTD numerical simulations show that for this structure shape parameters the peak electric field is located at the center region of the pillar surface and has nearly twice the input laser amplitude; $|E_{\max}| \sim 2|E_{laser}|$. $E_{\max}$ determines the maximum laser fluence applicable to the structure, and for ultra-short near-IR laser beams it is not to exceed 1 J/cm^2 [5]. For a 10 fsec pulse this corresponds to $E_{\max} \sim 25\,\mathrm{GV/m}$. With $\langle G \rangle \sim 0.5 E_{laser}$ this leads to an average unloaded gradient of $\langle G \rangle \sim 5\,\mathrm{GV/m}$.

Other large bandgap substrates that have a higher index of refraction, such as Al_2O_3 or YAG (n~ 1.8), or SiC (n~ 2), require grating grooves that are less pronounced and allow for a moderate increase of the ratio between the gradient and the input laser field. For example, for diamond the optimum gradient is $\langle G \rangle \sim 0.75 E_{laser}$. Ultimately additional factors such as laser damage threshold, radiation hardness, chemical stability and ease of micro machining of the specific material determine the most convenient substrate.

Coupling of Power into the Structure

In an analogous fashion to crossed Gaussian laser beams is vacuum [6], the structure could be pumped from both sides. With the correct choice of optical phase between the two input laser beams the interference of the two beams leads to a cancellation of residual lateral deflection forces. However, for a moderate-energy relativistic electron beam transverse pumping from both sides may not be necessary. It can be shown that the deflection force from a single laser beam in this structure is not phase synchronous with a relativistic beam and averages to zero within one period [2]. For a 1 GeV electron beam the residual synchrotron radiation losses from a single laser beam in this structure would amount to ~15 keV/m. Hence for applications that require <10 GeV beams these losses are negligible compared to the expected acceleration gradient and illumination from both sides of the structure may not be not necessary.

Beam Loading and Structure Impedance

The non-resonant design of the structure naturally compromises its impedance. In this single-pass design the mode size of the field in the vacuum channel determines the coupling efficiency and hence focusing in the vertical plane by cylindrical lenses, as shown in figure 1, determines the effective structure impedance. With the standard structure impedance definition $Z_S = |G_0 \Delta z|^2 / \Delta P_{laser}$, and selecting a focus that produces a vertical laser spot size of ~5 μm yields a structure impedance of $Z_S \sim 20\,\Omega$. This value is comparable to the structure impedance evaluated for other proposed dielectric laser-driven accelerator structures [7]. However, since the field is propagating at right angles to the electron beam the coupling with the electron beam is even smaller, and with an electron bunch having N_b electrons the loaded gradient G_L can be shown to follow [1]

$$G_L = G_0 - \frac{N_b q c Z_S}{2\lambda^2} \tag{1}$$

where G_0 is the unloaded gradient. At the optimum coupling efficiency with the laser the loaded gradient is $G_L = \frac{1}{2} G_0$, which with the given parameters occurs at $N_b \sim 10^6$ electrons.

FABRICATION AND ASSEMBLY OF THE ACCELERATOR STRUCTURE

The accelerator structure will be fabricated from two separate quartz plates that have a binary grating with a period of 800 nm and a grating groove depth of ~700 nm etch on the surface. To produce such a pattern we have selected to utilize e-beam lithography and reactive ion etching. Binary gratings of fused silica substrate with similar grating parameters have been fabricated for other purposes. Figure 3 shows an electron microscope picture of a 1 μm period binary grating. The cut shown in the

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

picture was made to reveal the groove depth of the particular sample. A small gap between two opposing quartz grating plates will form the periodic vacuum channel. The gap forms the periodic vacuum channel and its width will be controlled by piezo-stacks that hold the two plates together. The alignment between the two grating surfaces during the assembly will be monitored by the far field diffraction pattern from an alignment laser illuminating the structure.

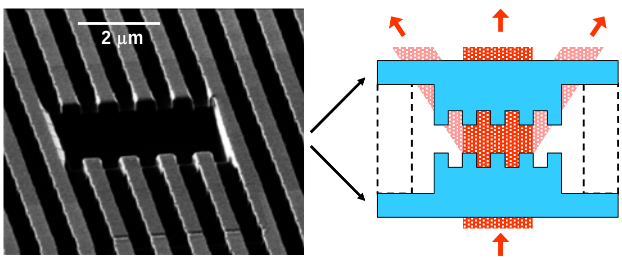

Figure 3: A quartz based grating and proposed assembly of two such grating plates to form an accelerator unit.

PROPOSED EXPERIMENTS

We plan to perform the first test of the proposed accelerator structure with electron beam at the E163 facility at SLAC, utilizing the available 60 MeV electron beam and a Ti:Sapphire based laser system producing a ~1 psec laser pulse. Shorter laser pulses could be delivered, but to accomplish good temporal overlap with the electron beam we will begin studies with the longer laser pulses. The laser beam will be pulse-front tilted at 45° by a grating and focused with a cylindrical lens to a 100 µm x 1 mm spot. With a ½ mJ/pulse available at the experiment such a spot produces a fluence of ~ ½ J/cm^2 and a peak electric field amplitude of ~0.8 GV/m, resulting in an average gradient of ~400 MeV/m. For a 1 mm long structure the corresponding energy modulation is ~0.4 MeV. These laser-focusing values are below the damage fluence. Tighter focusing of the laser spot and shorter pulse durations that lead to higher gradients approaching 1 GeV could be possible. The proposed setup is shown in Figure 4. The vacuum channel width will be controlled by the piezo-stacks and monitored by interferometry with an alignment laser illuminating a flat region of the two quartz plates.

The challenge for the experiment will be the loss of electron beam through the narrow, mm-long vacuum channel. The electron beam at E163 has an approximate emittance of 10π mm-mrad. The optimum focusing of that beam through a ~ ½ µm wide, 1mm long channel occurs for a beam focus of ~ 40 µm with a transmission of ~1%. A 10 pC input bunch charge will result in a 10fC charge at the spectrometer, which lies near the detection limit of the gated camera data acquisition system. The remaining electron beam traverses enough material such that at the spectrometer it can be discriminated from the small fraction traversing the vacuum channel. Somewhat comparable electron beam loss and transmitted beam detection method were encountered at the original LEAP experiment, where the electron beam was successfully transmitted through the ~5 micron wide aperture of a few-mm long dielectric cell [8] and detected at the spectrometer.

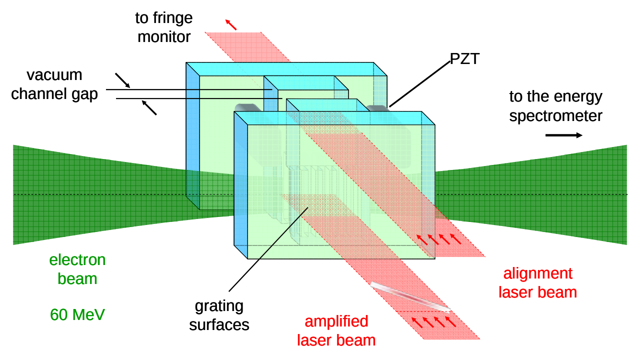

Figure 4: Proposed test setup of the structure with electron beam.

The detailed plans of further experiments with longer structures at E163 will depend on the amount of beam loss from the large emittance electron beam and the detection limit at the spectrometer. With a 3 mm long structure the transmission is expected to be 0.5%, and a 1 cm long structure would reduce it further to ~0.2%. Still, the eventual cascading of a few 1 mm accelerator units appears possible and would provide valuable experience towards developing an extended dielectric laser-driven accelerator structure.

REFERENCES

[1] T. Plettner, P.P. Lu, R.L. Byer, "Proposed few-optical cycle laser–driven particle accelerator structure", Phys. Rev. ST AB 9, 111301 (2006).

[2] T. Plettner, "Phase synchronicity conditions from pulse-front tilted laser beams in periodic structures", SLAC-PUB-12458 (2007).

[3] J. Hebling, "Derivation of the pulse front tilt caused be angular dispersion", Optical and Quantum Electronics 28 1759-1763 (1996).

[4] J. Rosenzweig, A. Murokh, C. Pellegrini, "A proposed dielectric-loaded resonant laser accelerator", Phys. Rev. Lett. 74, 002467 (1995).

[5] B. C. Stuart et al, "Laser-Induced Damage in Dielectrics with Nanosecond to Subpicosecond Pulses", Physical Review Letters 74, 2248 (1995).

[6] E. Esarey, P. Sprangle, and J. Krall, Phys. Rev. E 52, 5443 (1995).

[7] X. Eddie Lin, Phys. Rev. ST Accel. Beams 4, 051301 (2001).

[8] R.L. Byer et al, Proceedings of the 1999 Particle Accelerator Conference, New York, p 321-324 (1999).