Proposed Waveguide Structure for Laser Driven Electron Acceleration

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ABSTRACT

Solid state lasers have achieved high energy output with very short pulses (several Joules with pulses shorter than 1ps, peak power in the order of terawatts)[1]-[5]. Lithography and micro machining enables fabrication of features much less than 1μm[13]-[17]. Combined with the fact that material damage threshold increases with shorter pulses[20][21], it is now possible to achieve electric field gradient on the order of GV/m inside a waveguide structure. This paper proposes a capacitor-loaded periodic waveguide structure for the acceleration of $5x10^8$ electrons at 2.4kHz repetition rate with 0.56GeV/m acceleration gradient.

INTRODUCTION

One approach to accelerating an electron to TeV energy levels without building a linac of unrealistic length is to increase the acceleration gradient. As is well known, the acceleration gradient is not directly dependent upon the frequency of the drive source. However, the maximum acceleration gradient is limited by breakdown of the waveguide structure and field breakdown is dependent upon the pulse width through the empirical scaling law $F_{th} \propto (T_m - T_o)\sqrt{KC\tau_p}$ where T_m is the melting temperature, K is the thermal conductivity, C is the volume heat capacity and τ_p is the pulse width. Figure 1 shows the optical damage fluence dependence on pulse width. For solid state laser sources pulses of less than one picosecond are available at peak and average power levels that are consistent with the requirements for a laser driven accelerator. In this regard, the laser is a form of transformer in which a near DC field is applied to the pump source and energy is stored in atomic medium for extraction in picosecond times. The power gain of the laser is therefore more than 10^9 for a field gain of more than 10^4 times. Diode pumping of solid state lasers also brings high efficiency approaching 10% electrical with a potential for reaching 20% electrical along with average power levels in excess of 100W [9] with kilowatt power level lasers underdevelopment. The rapid improvement in diode pumped solid state lasers in power and efficiency, coupled with long lifetime and decreasing cost per watt, open the possibility that it may be time to accelerate electrons with picosecond optical pulses rather than microsecond microwave pulses.

In this paper, we propose a waveguide structure for laser acceleration of relativistic electrons. Our goal is to reach GeV/m of acceleration gradient, i.e., an electron can be accelerated to one TeV with only one or two kilometers of waveguide length. The goal is to accelerate $5x10^8$ electrons at 2.4kHz, same number of electrons as in SLAC, which accelerates 10^{10} electrons at 120Hz. The advantages of higher repetition rate are the transverse dimension of waveguide can be smaller, which will be shown later, and the ability to improve feedback for alignment control against ground motion.

WAVEGUIDE STRUCTURE

Our idea is to use lithography as the micro machining technique to build a waveguide structure similar to the SLAC structure but with dimensions on the order of the optical wavelength. However, the SLAC structure is circular to accommodate the manufacturing

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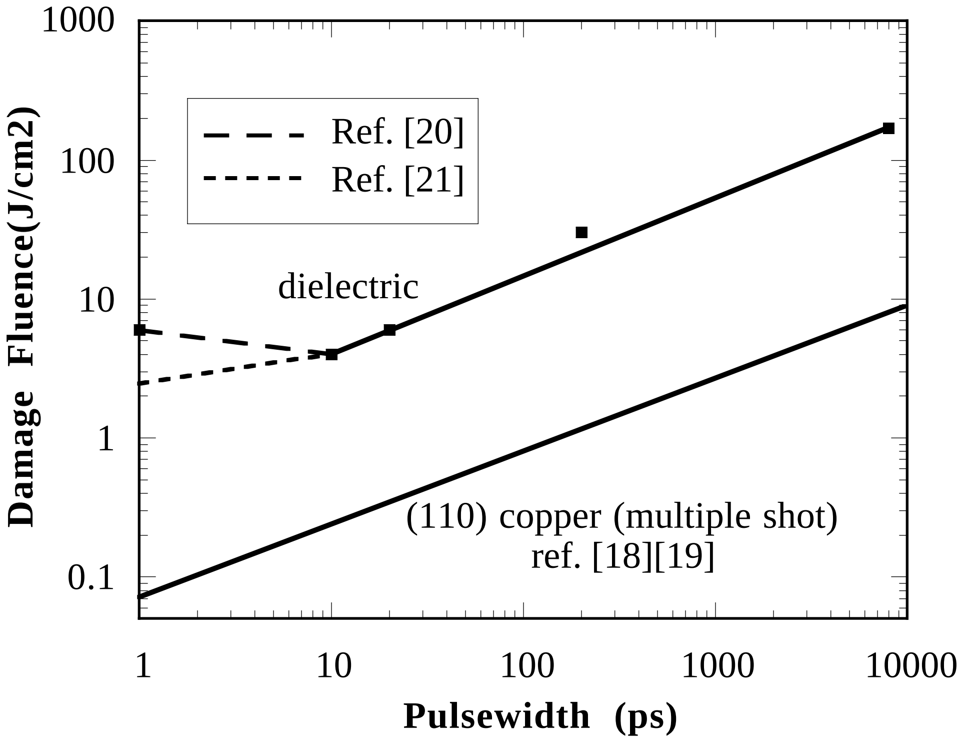

Figure 1. Damage fluence threshold vs. pulsewidth for dielectric and metal (ref. [18]-[21])

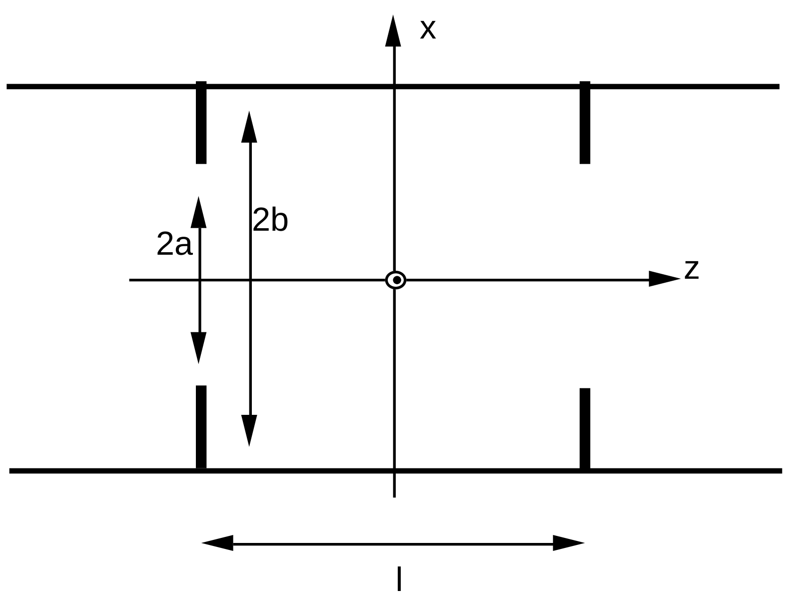

Figure 2. Capacitor loaded waveguide

tools of the time. Our proposed structure is planar-rectangular to accommodate the future lithographic machining method. For convenience, we assumed the driving wavelength to be 1μm, which is close to Nd:YAG laser wavelength (1.06μm). The periodic capacitor loaded structure is shown in figure 2. The accurate field solution can be obtained with numerical methods. In this paper, we make the approximation that the disturbance from the iris is localized to obtain analytical solutions. The susceptance B induced by the iris is

$$B = \frac{4b}{\pi}\beta_1 \cot^2(\frac{\pi}{2b}a) \tag{1}$$

$$\beta_1 = \sqrt{k^2 - (\frac{\pi}{2b})^2}$$

where $k=2\pi/\lambda$ is the wave propagation constant in free space and a and b are the waveguide iris width and wall width.

The propagation mode in the undisturbed (from the iris) region is a TM_1 mode. The field distribution is given by

$$E_z = E_0 \cos(\frac{\pi}{2b}x)e^{-j\beta_1 z}$$

$$E_x = \frac{j2b\beta_1}{\pi}E_0 \sin(\frac{\pi}{2b}x)e^{-j\beta_1 z} \tag{2}$$

$$H_y = \frac{j2b\omega\varepsilon}{\pi}E_0 \sin(\frac{\pi}{2b}x)e^{-j\beta_1 z} \quad .$$

The dispersion relation is

$$\cos(\beta_c l) = \cos(\beta_1 l) - \frac{B}{2}\sin(\beta_1 l) \tag{3}$$

where β_c is the wave propagation constant in this periodic structure.

For the waveguide to be useful for relativistic particle acceleration, it must meet the following requirements: the wave phase velocity inside the waveguide must match the speed of the electrons, which is nearly the speed of light in vacuum; the wave group velocity must be large enough so that a 1ps optical pulse can fill a 100μm long waveguide segment, which we refer to as a 'microchip'; $E_Z(x=a)/E_Z(x=0)$ should be small to avoid wall damage; $E_X<<E_Z$ so that the defocusing effect from transverse field is small, in our calculation, we set this criteria to be $E_X<10\%E_Z$; the mode is the propagation mode TM_1 and stable against higher order modes; and the structure has small dispersion relative to the pulse band-width. With these considerations, we selected a guide structure with the dimensions

$$l = \lambda / 4$$

$$a = 0.21\lambda \tag{4}$$

$$b = 0.35\lambda \; .$$

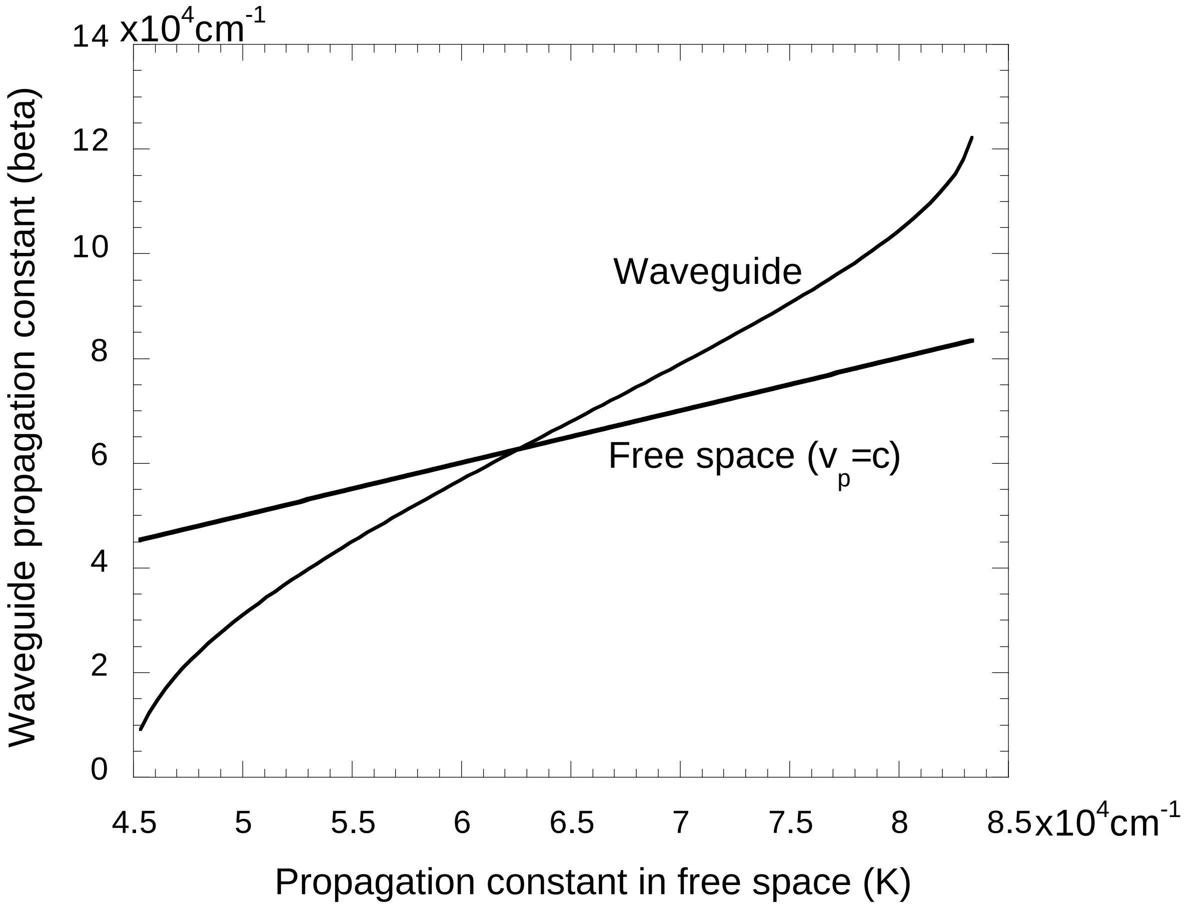

Figure 3. Dispersion relationship
(Waveguide parameters: l=λ/4, a=0.21λ, b=0.35λ)
(See text for definition of K and β)

The waveguide structure with these parameters has the dispersion relationship shown in figure 3. Working at wavelength of 1µm, the structure has a phase velocity of c, the speed of light in vacuum, at the least dispersive region. The group velocity is 0.4c, which means that a 1ps incident laser pulse can fill 100µm of the waveguide. The longitudinal field at the boundary $E_Z(x=a)$ is about 60% of the longitudinal field at the center $E_Z(x=0)$, and the electron beam size in x-direction should be smaller than 0.02µm so that the transverse field E_X is less than 10% of the longitudinal field E_Z. This requires a very tightly focussed electron beam. However it is not inconsistent with SLAC's recent developments[24].

COUPLING OF PUMP BEAM INTO THE WAVEGUIDE

It is desired that a large fraction of the total linac length is the acceleration section. Side filling is proposed to minimize the coupling section length. For b=0.35µm (1µm wavelength), a 53-degree incident nearly plane wave beam matches the phase and group velocity of the required TM_1 mode, and therefore can have a high coupling efficiency. The polarization is correct for Brewster angle optics. Figure 4 shows a schematic of our proposed planar waveguide structure for one 'microchip' of length L=100µm. The determination of the width of the microchip (3cm) is to be discussed in the next section.

ACCELERATOR POWER LOADING

The multiple shot damage threshold for 110-oriented copper is 0.07J/cm^2 at 1ps, assuming that the square root relation still holds in picosecond pulse region. For a 53-degree incident laser beam, the maximum electric field is $E_{\max} = \sqrt{2\eta P_{th} / \cos 53°} = 0.94 GeV$, therefore its E_Z component can reach 0.56GeV at the copper multiple shot damage threshold. At this acceleration gradient, each electron can gain 56KeV in a 100µm microchip length.

The energy gained by all the electrons must be held to a small fraction of the laser pulse energy so that the electrons do not significantly disturb the laser field. This condition sets the limitation of the coupling efficiency from the field to electrons. Here we assume this coupling efficiency to be 10%. In a 0.7µmx1µm cross-section area, a laser pulse of 8x10^{-10}J can be injected and the electrons can gain 8x10^{-11}J energy, which means 10^4 electrons can be accelerated. To accelerate 10^{10} electrons at SLAC's 120Hz, the waveguide needs to be 1 meter wide, which is unreasonable for micromachining. However, if we increase the repetition rate from 120Hz to 2.4kHz, which is convenient for laser drivers, the width of the waveguide is reduced to 5cm. Therefore, we define each 'microchip' to have a 5cmx100µm area, it consumes 0.04mJ energy for each pulse. A 5cmx1cm area waveguide comprises a chip, which consumes 4mJ per pulse, or 10W at 2.4kHz. The cooling system needs to dissipate 2W/cm^2, which is not a problem. So ideally, 1.8MW of coupled laser power accelerates electrons to 1TeV in a 1.8km long structure. If we assume only 50% of the incident laser light is coupled into the waveguide, the pico-second-pulse laser required for one 5cmx1cm chip should generate 20W at 2.4kHz. Further increase in laser repetition rate can reduce the chip width proportionally, however, the average laser power is determined by the electrons energy gain and should remain the same. The drive lasers can be phase locked[28]-[31], and interferometry can be used to monitor laser phase and wavefront relation to assure the electrons gain maximum acceleration at a desired planar wavefront.

SUMMARY

In this paper, we proposed a planar-rectangular waveguide structure for laser acceleration of relativistic electrons to TeV energies. The acceleration gradient in a waveguide structure is limited by the damage threshold of the waveguide material, which suggests shorter driving pulses (which can only be achieved with shorter wavelength) for a higher damage threshold fluence. For a 1ps laser pulse, the maximum acceleration gradient of 0.56GeV/m is expected inside a copper waveguide. It should be noted that dielectrics have a higher damage fluence threshold than copper, especially for pulses shorter than 10ps. We are evaluating dielectric structures with the possibility of achieving even higher acceleration gradients for a laser driven linac.

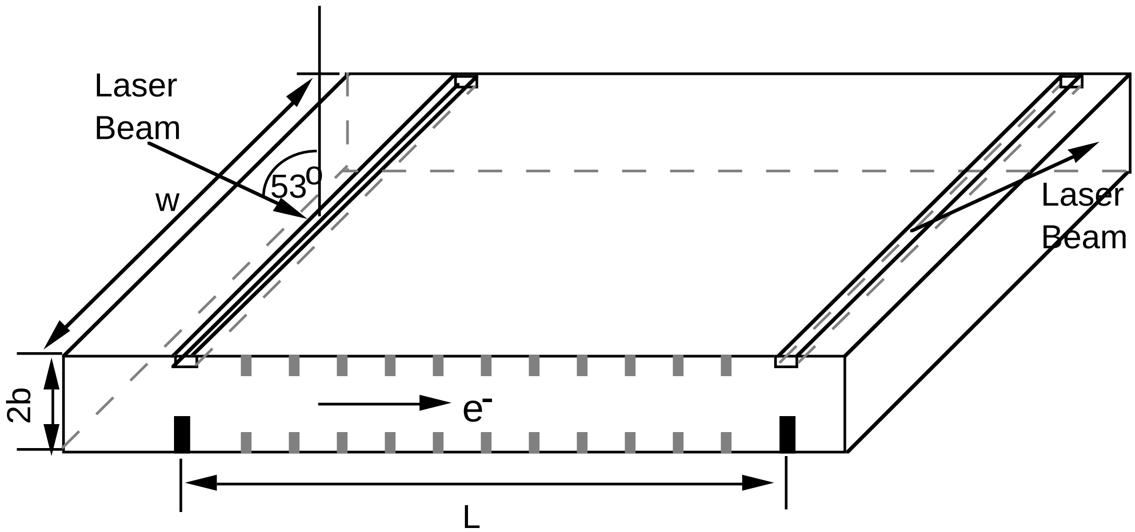

Figure 4. Scheme of one acceleration 'microchip'

(w is waveguide width, which is selected
to be 5cm, b = 0.35um, L = 100um)

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