

Proposed structure for a crossed-laser beam, GeV per meter gradient, vacuum electron linear accelerator

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We propose a dielectric-based, multistaged, laser-driven electron linear accelerator structure operating in a vacuum that is capable of accelerating electrons to 1 TeV in 1 km. Our study shows that a GeV/m gradient is achievable using two 100 fs focused crossed-laser beams, repeated every 300 μm , operated at a peak power of 0.2 GW and an energy density of less than 2 J/cm² on the accelerator structure. © 1996 American Institute of Physics. [S0003-6951(96)00406-4]

In a conventional S-band rf accelerator, field emission on the copper wall occurs when the peak acceleration gradient reaches ~ 100 MeV/m.¹ The average acceleration gradient for a rf accelerator is thus limited to about 50 MeV/m. To reach the TeV energy region desired for the next linear collider using presently existing rf schemes requires tens of kilometers of accelerator structure.

The laser accelerator gradient, like the rf accelerator gradient, is limited by damage. Dielectric materials, which are commonly used for optical components, have a damage fluence an order of magnitude higher than copper.² It can be shown that the surface damage threshold field on a dielectric is ~ 10 GV/m for 100 fs pulse lasers.³ A laser accelerator structure using dielectric boundaries is therefore an appealing scheme for achieving GeV/m gradients and for building future TeV electron accelerators at existing laboratory sites.

In this letter, we propose a crossed-laser-beam accelerator structure and evaluate its feasibility with current laser technology. Similar schemes were discussed in several papers,⁴⁻⁶ but no accelerator structure was presented. In calculating the GeV/m gradient, we take into account several practical considerations such as laser damage, the drift space occupied by optical components, and the geometrical limitation for coupling laser beams into the structure.

The Lawson-Woodward (LW) theorem^{7,8} rules out the possibility of a net energy gain for a relativistic electron interacting linearly with electromagnetic waves in an unbounded vacuum. In the following, the proposed accelerator structure consists of repetitive dielectric boundaries over a distance no greater than a π phase slip between the laser field and the electron in a vacuum.

Figure 1(a) shows the proposed crossed-laser-beam accelerator geometry, wherein an electron traverses the focal zone at an angle θ with respect to the two laser beams. The insert in Fig. 1(a) defines the coordinates used in this letter. The two laser beams are derived from a single laser source, carry equal power, and are phased such that on the z axis the transverse fields (in x and y) cancel, and the longitudinal fields (in z) add.

Figure 1(b) shows a single stage of the proposed dielectric accelerator optical configuration. Two laser beams are back-reflected from the $\pm x$ directions into the *microstage* using two prisms. The total internal reflection (TIR) inside the prisms permits the use of antireflection (AR) coatings for beam coupling. Two high-reflectivity coated flat mirrors pro-

vide a secondary reflection and direct the two laser beams into the center of the microstage. The back-reflection scheme allows the coupling points (labeled A and A') on the prisms to be away from the z axis so that the laser beam clipping at the prism edges can be minimized. Beam clipping at the prism determines the geometrical beam coupling condition given by

$$3l \times \theta > w, \quad (1)$$

where l is half of the interaction length measured from the focal point, and w is the Gaussian beam electric field beam radius at A and A'. For a small angle θ , a minimum prism width (in z) of $2w$ is required for coupling $>90\%$ of the laser power into the structure. Thus, the minimum drift space per microstage, where no laser fields exist, is approximately $2w$. The proposed structure can be constant in y which allows cylindrical focusing if necessary.

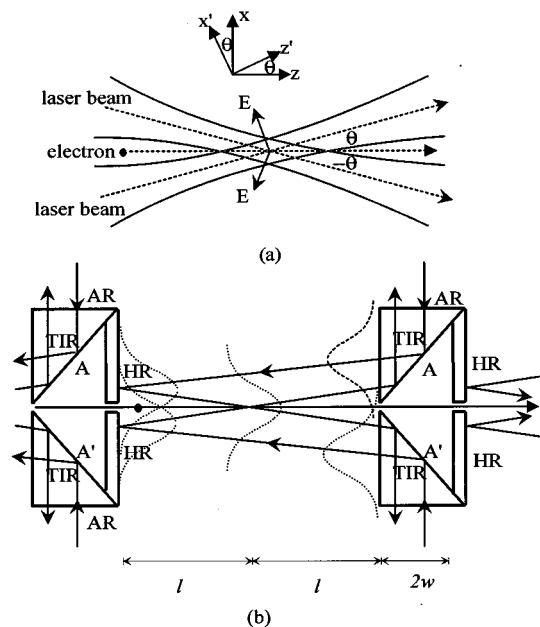


FIG. 1. (a) The schematic for a crossed-laser-beam accelerator. The electron traverses the focal zone at an angle θ with respect to each of the two beams. The two laser beams are phased so that the longitudinal fields add and the transverse fields cancel. (b) The back-reflection scheme for a single microstage. This scheme avoids clipping the laser beam at the coupling prisms when θ is small. The drift space occupied by optical components for each microstage is approximately two laser spot sizes $2w$.

A linearly polarized fundamental Gaussian beam can be described by a vector potential polarized in x' with Gaussian profiles in the x' and y' .⁹ The two electric field components which are important to the on-axis electrons are $E_{x'}$ and $E_{z'}$. With the appropriate coordinate transformation, the electrical field seen by an on-axis electron, summed from $E_{x'}$ and $E_{z'}$ of the two crossed laser beams, is

$$E_z = -4 \sqrt{\frac{\eta P}{\pi}} \frac{\sin \theta}{w_0(1+z^2/z_r^2 \times \cos^2 \theta)} \times \exp\left(-\frac{(z/w_0 \times \sin \theta)^2}{1+z^2/z_r^2 \times \cos^2 \theta}\right) \times \cos(\phi_p + \phi_g + \phi_r), \quad (2)$$

where η is the wave impedance in vacuum, P is the laser power, w_0 is the laser waist size, $z_r = \pi w_0^2/\lambda$ is the optical Rayleigh length, and ϕ_p, ϕ_g, ϕ_r are the plane wave phase, Guoy phase term, and radial phase, respectively. For a relativistic electron with an energy γ and a small crossing angle $\theta \ll 1$, the three phase terms are

$$\phi_p = \omega t - kz \cos \theta \approx \frac{kz}{2} \left(\theta^2 - \frac{1}{\gamma^2} \right), \quad (3)$$

$$\phi_g = 2 \times \tan^{-1}(z/z_r), \quad (4)$$

and

$$\phi_r = -\frac{(z/z_r) \times (z/w_0)^2}{1+z^2/z_r^2}. \quad (5)$$

The small angle assumption, $\theta \ll 1$, is necessary for achieving phase coherence over a distance much longer than an optical wavelength. However, for highly relativistic electrons with $1/\gamma^2 \ll \theta^2$, the plane wave phase shift can be simplified to $\phi_p \approx kz\theta^2/2$. A typical Gaussian field carries a Guoy phase,¹⁰ $\tan^{-1}(z/z_r)$, which gives a π shift from $z = -\infty$ to $z = \infty$. However, in Eq. (4) an additional Guoy phase is contributed from summing $E_{x'}$ and $E_{z'}$. The sum of the plane wave phase and radial phase terms is $\phi_p + \phi_r = [z \times z_r (\theta/w_0)^2/1 + (z/z_r)^2]$, which has the same sign as the Guoy phase term. Since the Guoy phase term, $2 \times \tan^{-1}(z/z_r)$, produces a π phase shift from $-z_r$ to $+z_r$, net acceleration is possible only if the laser field is terminated for $z < |z_r|$.

For an on-axis electron, the energy gain from $-l$ to $+l$ is the integration of the longitudinal electric field over the distance:

$$\Delta W = \int_{-l}^l E_z dz. \quad (6)$$

By careful evaluation, it can be shown that the maximum energy gain for an on-axis electron is $\Delta W_{\max}(\text{MeV}) = 30\sqrt{P(\text{TW})}$, with a crossing angle $\theta = 1.37 \times w_0/z_r$ and an interaction length $2l = 0.92z_r$, corresponding to a π phase shift in the accelerator stage. However, the laser power is limited by the laser-induced damage on optical components and by the geometric coupling condition in Eq. (1).

The optical damage fluence and thus the acceleration gradient depends on the laser pulse length such that a short laser pulse is desirable for obtaining a high acceleration gradient.² For example, with a 100 fs pulse length, the dam-

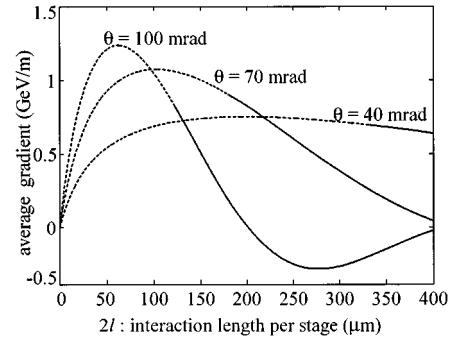


FIG. 2. Average acceleration gradient vs acceleration length for various crossing angles. Gradients approaching 1 GeV/m are predicted. The solid lines satisfy the geometric constraint of Eq. (1).

age threshold intensity is about $I_{\max} = 20 \text{ TW/cm}^2$, at a damage threshold fluence³ of $\sim 2 \text{ J/cm}^2$. The maximum laser power P_{\max} at the damage threshold intensity I_{\max} is given by $P_{\max} = I_{\max} w^2 \pi/2$.

In practice, the critical parameter is not the maximum energy gain per microstage but the average acceleration gradient. We define the average acceleration gradient as the energy gain per stage ΔW , divided by the repeat length of an accelerator stage, $L_{\mu} = 2l + 2w$. Substituting P_{\max} into (6) and dividing (6) by L_{μ} , one has the average acceleration gradient under the laser damage constraint given by

$$G = \frac{\Delta W}{L_{\mu}} \Big|_{P=I_{\max} w^2 \pi/2}. \quad (7)$$

In Eq. (7), the variables are the interaction length $2l$, the laser waist radius w_0 , the crossing angle θ , and the optical wavelength λ . We assume the wavelength $\lambda = 1 \mu\text{m}$ for the rest of our calculations.

Figure 2 shows the average acceleration gradient versus the interaction length per stage $2l$, for $w_0 = 20 \mu\text{m}$ and $\theta = 100, 70$, and 40 mrad . When the interaction length equals zero, the average gradient is reduced to zero instead of converging to the electric field strength at the focal point, because a finite drift distance of $2w$ per stage is taken into account in Eq. (7). The solid curves satisfy the geometrical constraint in Eq. (1). For $\theta = 100$ and 70 mrad , average gradients approaching 1 GeV/m are predicted. In the same plot a smaller angle, $\theta = 40 \text{ mrad}$, gives a maximum average gradient of $\sim 0.65 \text{ GeV/m}$. Note that for $\theta = 40 \text{ mrad}$ the acceleration gradient is less sensitive to the interaction length, which can be as long as $\sim 300 \mu\text{m}$. A larger structure size eases the fabrication process, reduces the radiation loss, allows a larger electron channel, and opens the fabrication tolerance. Thus, we evaluated the $G = 0.7 \text{ GeV/m}$ contours on the θ and w_0 space for different interaction lengths subject to the geometric constraint of Eq. (1) and the damage fluence of 2 J/cm^2 for a 100 fs laser drive. We find that the optimum parameters are $L_{\mu} = 334 \mu\text{m}$, $w_0 = 17 \mu\text{m}$, and $\theta = 42 \text{ mrad}$. On the 0.7 GeV/m contours, a larger or a smaller w_0 gives a larger θ or a shorter structure size. In our computer simulation, electron energy spread increases with the increase of θ due to the spatial variation of the laser fields.

Figure 3 shows the schematic of a multistage accelerator that can be integrated on a silicon wafer by using the low-

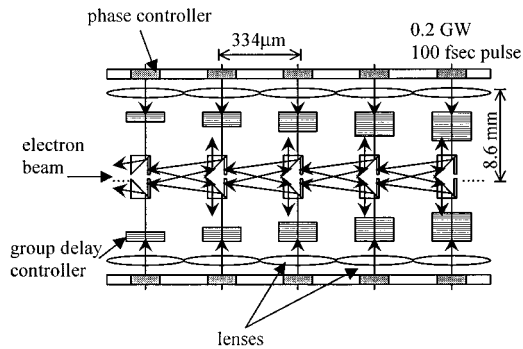


FIG. 3. A multistage accelerator that can be integrated on a silicon wafer using lithographic technology. The phase of laser fields is controlled by electro-optic phase controllers and the group velocity delay is controlled with slabs of dielectric.

cost, high-precision lithographic technology. The phase of the laser fields is controlled by electro-optic phase controllers and the group velocity delay is controlled with slabs of dielectric. If necessary, microactuators or micromotors can be integrated into the same wafer in a batch process. The dimensions are consistent with the optimum parameters found on the 0.7 GeV/m average gradient contours. Optical components occupy $\sim 10\%$ of the length in the electron acceleration direction. In Fig. 3, we assume that a plane wave is incident on each focusing lens and thus a nominal $7 \text{ mm} \times 34 \mu\text{m}$ elliptical beam profile from a single laser source may drive 20 microstages simultaneously. A dielectric

channel for a few microns can be opened for transmitting the electrons. For GeV electron beams, it has been demonstrated that the transverse beam size can be as small as 75 nm .¹¹

Precise phase locking of individual lasers is necessary for multimicrostage acceleration. Locking the phase between two cw solid-state lasers has been demonstrated in the past.¹² The principle of a mode-locked laser is essentially the same as that of a cw laser except that there is a fixed phase relationship among the longitudinal modes in a mode-locked laser. We believe locking the phase between two mode-locked lasers is achievable without undue difficulty.

Future work includes the study of beam loading, radiation loss, wake field issues, and multistage particle simulations.

¹E. Tanabe, *Appl. Surf. Sci.* **76**, 16 (1994).

²D. Zheng and R. L. Byer in *Proceedings of the 6th Workshop on Advanced Accelerator Concepts*, Fontana, WI, June 12–18, 1994.

³B. C. Stuart, M. D. Feit, A. M. Rubenchik, B. W. Shore, and M. D. Perry, *Phys. Rev. Lett.* **74**, 2248 (1995).

⁴T. Hauser, W. Scheid, and H. Hora, *Phys. Lett. A* **186**, 189 (1994).

⁵C. M. Haaland, *Opt. Commun.* **114**, 280 (1995).

⁶P. Sprangle, E. Esarey, J. Krall, and A. Ting, *Opt. Commun.* (to be published).

⁷J. D. Lawson, *IEEE Trans. Nucl. Sci.* **NS-26**, 4217 (1979).

⁸P. M. Woodward, *J. IEE* **93**, 1554 (1947).

⁹L. W. Davis, *Phys. Rev. A* **19**, 1177 (1979).

¹⁰A. E. Siegman, *Lasers* (Mill Valley, CA, 1986), p. 683.

¹¹D. F. Cioffi, *Phys. Today* **22**, (1994).

¹²T. Day, E. K. Gustafson, and R. L. Byer, *IEEE J. Quantum Electron.* **QE-18**, 1106 (1992).