A DIAMOND CO_2 LASER-DRIVEN TEST ACCELERATOR

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ABSTRACT

This goal of this project is to demonstrate electron acceleration in a laser-driven accelerator structure in a vacuum. The proposed accelerator is driven by the pulsed CO_2 laser and the 75 MeV electron beam at the Accelerator Test Facility, Brookhaven National Laboratory. The accelerator, made of CVD-grown diamond, consists of 5 acceleration stages with a length of 10 cm. The predicted electron energy gain is 0.3 MeV.

1 INTRODUCTION

Laser driven particle acceleration finds potential applications in two areas: 1) high-gradient acceleration, leading to table-top accelerators or compact linear colliders; 2) ultra-short electron bunch generation, leading to coherent x-ray generation. Current laser driven particle acceleration schemes can be divided into two categories: one with a medium and one without a medium in the electron acceleration path. The one with a medium includes the plasma-based laser acceleration[1] and the inverse Cherenkov acceleration[2]; the one without a medium includes inverse free-electron (FEL) acceleration[3], and structure-loaded vacuum linear acceleration[4]. The acceleration schemes adopting media along the particle acceleration path are often complicated with material properties, including scattering and stability. The inverse FEL acceleration suffers from excess radiation loss when scaled to high energies. A structure-based laser accelerator, although having the material stability, has a lower acceleration gradient compared to other laser-driven accelerators due to structure damage. Nonetheless the laser acceleration technology has been making significant progresses, and problems are being solved gradually. Among all the laser acceleration schemes, the structure-loaded vacuum laser-driven acceleration still requires a proof-of-principle experiment to let the technology grow. The goal of this proposal is to overcome this barrier by verifying electron energy gain in a laser-driven accelerator structure in a vacuum.

Since the laser wavelength is on the order of a micron, the accelerator structure size scaled from the RF accelerators will be nearly impossible to fabricate or operate. Consequently novel designs for laser-driven accelerator structures are necessary. The possibility of having an accelerator structure size exceeding thousand times the laser wavelength does exist. However the overall size of the accelerator structure is still roughly scaled with the driving wavelength. Another factor that influences a laser accelerator structure size in a test experiment is electron slippage due to a small relativistic factor γ.

For ease of the experiment, the design criterion of the accelerator structure is to have a large structure size and a large electron energy gain. The acceleration gradient, on the other hand, is not taken into the consideration. Currently a dielectric-based vacuum laser acceleration experiment is being carried out at Stanford Hansen Experimental Physics Laboratory. Compared to the Stanford project, this proposal takes advantage of the 10 times longer wavelength and two times higher electron energy at the Accelerator Test Facility (ATF), Brookhaven National Laboratory. As a result, the overall size of the accelerator cell is on the order of centimeter and can be handled by human hands. The proposed project also adopts a multiple-cell design that predicts an overall electron energy gain approaching 1 MeV.

2 ACCELERATOR STRUCTURE DESIGN

Several structure-based vacuum laser-driven acceleration schemes have been proposed in the past. For this particular project, we employ the TEM_{10} laser-mode field for electron acceleration based upon the following considerations:

1) As a proof-of-principle experiment, the experimental results can be interpreted directly from the mode concepts in a conventional RF accelerator.
2) The accelerator structure mimics a laser resonator or a lens array that can be assembled by commercial optical components.
3) The excitation of the TEM_{10} laser mode is a standard, well-known mode-matching technique.
4) The characterization and analysis of the TEM_{10} laser mode is well known in laser technologies.

Laser-driven particle acceleration by using the TEM_{10} laser field has been analyzed by E.J. Bochove *et al*[5]. Without considering electron slippage due to finite electron energy γ, the maximum interaction length is two Rayleigh ranges $2z_r$, within which the electron acccumulates the largest possible energy from single-stage acceleration. The corresponding maximum, single-stage energy gain is given by

$$W = 2\left[\frac{\eta P(\mathrm{TW})}{\pi}\right]^{1/2} \quad (\mathrm{MeV}), \qquad (1)$$

where P is the pumping laser power and η is the wave impedance. The accelerator structure under consideration is therefore a confocal laser resonator, as illustrated in Fig. 1.

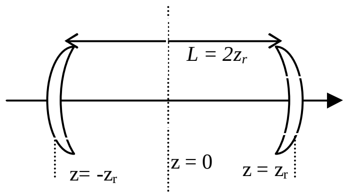

Figure 1. The confocal laser resonator as a single-accelerator cell.

The energy-related phase slippage is governed by the plane-wave phase term, given by

$$\Delta\phi = kL - \omega\frac{L}{v} \approx \frac{kL}{2\gamma^2}, \qquad (2)$$

where $k = 2\pi/\lambda$ is the wave number, ω is the laserangular frequency, v is the electron velocity, and L is the acceleration length. If one arbitrarily limits the phase slip to 10% of the 180° phase reversal $\Delta\phi < 0.1\pi$, the interaction lengthbecomes $L=0.1\gamma_{min}^2\lambda$, which clearly shows the advantage of having a high electron energe γ and a long laser wavelength. Thus for the 75 MeV electron beam and the 10 μm CO_2 laser wavelength at ATF, the single-stage accelerator cell length is approximately $L=2z_r=2.25$ cm. With this kind of accelerator size, the structure can be fabricated, adjusted by using conventional optical technologies.

In a practical accelerator cell, there exist two electron transmitting holes. In our computer simulation[6] we found no degradation in the laser mode and the single-stage energy gain, when we opened the transmitting holes with a diameter of 50 μm. We are currently investigating the effects of opening an even larger electron hole. The robust of the laser mode and the low optical loss are primarily due to the null field at the center of the TEM_{10} laser mode.

Cascading accelerator cells, as illustrated in Fig. 2, may increase the total electron energy gain in the test experiment. The focal length of each lens f is equal to the half the radius of curvature of the mirror in Fig. 1, or $f = z_r$. The high reflector in the downstream removes the laser energy and prevents it from taking away electron energies in the decelerating phase. The phase reset of individual cells can be accomplished by tuning temperatures or PZT positions associated with the lenses. To reduce the laser loss, all lenses are anti-reflection coated. In order to avoid the cumbersome process of converting the pump laser into the TEM_{01} mode, the first lens can be coated with an additional π-phase-shift layer in its upper half. This way the mode conversion from TEM_{00} to the acceleration mode is simplified and can be accomplished with good coupling efficiency.

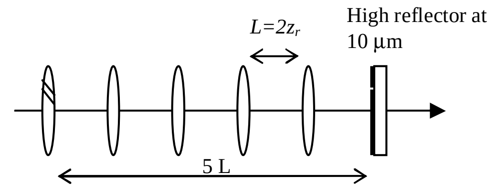

Figure 2. A lens array as a laser-driven linac.

The electrons intercepted by the 50 micron aperture is more than 50%, given normalized emittance = 2 pi-mm-mrad and a reasonable beta function ~ 0.5 m. With the nC per bunch electrons at ATF, half of it can be detected with ease.

3 CVD-GROWN DIAMOND AS THE CHOICE OF THE ACCELERATOR STRUCTURE

The single-stage energy gain is limited by laser-induced material damage. The value of damage fluence is influenced by several parameters, including laser pulse width, laser wavelength, material absorption, material surface finishing, and so on. To determine the suitable material for the accelerator structure at the 10 μm wavelength, we measured the laser damage fluence for three materials, CVD-grown diamond, ZnSe, and Ge. The laser fluence is the incident laser energy divided by the laser effective area, given by $F = \Delta U/(\pi w^2/2)$, where ΔU is the incident laser energy, and w is the laser radius of a Gaussian beam.

The laser system used in our experiment was a hybrid TEA single-longitudinal mode CO_2 oscillator and amplifier[7] at the Accelerator Test Facility (ATF), Brookhaven National Laboratory. The oscillator generated 100-nsec CO_2 laser pulses. A 200-psec portion of the 100-nsec pulse was reflected from an optically gated germanium switch. A 1.2-m long, UV-preionized, 3-atm, multipass TE CO_2 amplifier increased the 200-psec pulse energy to a level high enough for the LIDT test. The laser pulsewidth in this pulse is defined to be the full width at the half maximum (FWHM) of the pulse. In addition to the 200-psec LIDT test, we took advantage of the 100-nsec pulses from the oscillator and conducted similar damage tests for our samples.

The CVD diamond sample was 14.5 mm x 4.5 mm x 1 mm, both sides polished to an optical finish with an absorption coefficient of 0.06 cm^{-1}. The sample is uncoated. Because the LIDT highly depends on the experimental conditions and the laser damage definitions, we also prepared optically polished ZnSe (Laser Research Optics Inc.) and Ge (Lambda Research Optics

Inc.) window flats for comparison under the same condition.

Table 1 shows the measured laser damage fluence, intensity, and electrical field for our samples. It is seen that at the 200 psec pulse width CVD diamond has the highest damage fluence of 1.2 J/cm^2, corresponding to an electric field of 200 MV/m. The particle acceleration gradient is thus limited at 200 MV/m, if CVD diamond is used for the accelerator structure. The actual acceleration depends on the accelerator design.

Material	200-psec pulse length			100-nsec pulse length		
	Fluence (J/cm^2)	Intensity (GW/cm^2)	Electric Field (MV/cm)	Fluence (J/cm^2)	Intensity (GW/cm^2)	Electric Field (MV/cm)
Ge	0.19	0.95	0.85	1.7	17	0.11
ZnSe	0.45	2.3	1.32	2.8	28	0.15
CVD Diamond	1.20	6.0	2.13	8.0	80	0.25

Table 1. The surface damage fluence, intensity, and electric field for CVD diamond, ZnSe, and Ge for 200-psec and 100-nsec CO_2 laser pulses.

The electron energy gain of the proposed diamond accelerator can be estiamted according to the derivation in the last session. The laser radius at the mirror is $w = \sqrt{2} w_0$, where $w_0 = \sqrt{\lambda z_r / \pi}$ is the laser waist.The maximum power that the mirror may sustain is therefore $P = (F / \tau)(\pi w^2 / 2) = (F / \tau)\lambda z_r = 7.2 MW$ for 200 psec CO_2 laser pulses on a CVD diamond structure. Subsitituting *P* into Eq. (1), one obtains the maximum single-stage energy gain of 60 keV. For this experiment, it is not intented to demonstrate high gradient acceleration.The proposed work is to achieve measurable acceleration gain at the sacrifice of the acceleration gradient. In other words, a maximum slippage distance permits a large accelerator size and the ease of a proof-of-principle experiment. With the success of this project, the acceleration gradient may approach the structure damage field ~ GV/m if a smaller accelerator cell and a shorter wavelength are chosen. For this experiment, with 5 accelerator stages at a total length of 11.25 cm, the maximum energy gain is 0.3 MeV.

4 DISCUSSION

Since May 1997, Stanford has been engaged in a dielectric-loaded laser electron acceleration project (LEAP)[8]. When LEAP was initially proposed, the system parameters are limited to those available at the Stanford Hansen Experimental Physics Laboratory. The mission of LEAP is to demonstrate a novel dielectric accelerator structure driven by a state-of-the-art solid-state laser near 1 μm wavelength. As a result, the Stanford LEAP is highly challenging and significant.

The laser-driven accelerator at 10 μm wavelength in this proposal is more conservative while being historically important. With the success of this project, the accelerator physics community may answer the question of the possibility of vacuum laser acceleration raised in the past several decades. Moreover this project is proposed under the following practical considerations:
a) The laser accelerator structure is large and can be handled by hands.b) The acceleration field is from a laser mode, permitting a direct comparison with the conventional RF accelerator theory.

The data collected in this project at the 10 μm wavelength will be complimentary to those collected in the more advanced and yet difficult Stanford LEAP at the 800 nm laser wavelength.

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