Proposed Physics Experiments

for Structure-based Laser-driven Acceleration in a Vacuum

Submitted to

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For Access to the Accelerator Test Facility

Submitted by

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ABSTRACT

The goal of this proposal is to experimentally confirm electron acceleration from a laser-driven accelerator structure in a vacuum. The project takes advantage of the 75 MeV electron beam and the CO_2 pulse laser at ATF. Due to the high electron energy and the long laser wavelength, the accelerator structure can be as large as 10 cm, consisting of 5 accelerator cells. The predicted electron energy gain ranges from 190 keV to 1.35 MeV. The uncertainty arises from laser-induced material damage as a function of the laser pulse width. The experimental result of this project is to answer the question of the possibility of vacuum laser-driven particle acceleration in a solid structure. The first goal of this proposal is to measure the laser damage thresholds on various CO_2 optics materials as a function of the laser pulse width. Once the optimal material and the laser pulse width are determined, the accelerator structure will be designed, fabricated and optically tested at National Tsinghua University, Taiwan. The laser-driven acceleration experiment is to be carried out at the ATF facility, Brookhaven National Laboratory, USA. The experimenters include Y.C. Huang, the principal investigator, Y.H. Chen, the postdoctoral research associate of Huang's group, and two graduate students from Huang's group. The amount of beam time needed is approximately three weeks near the end of the proposal period. The funding is primarily from National Science Council, Taiwan, with the possibility of joint supports from other agents in the US.

STATEMENT OF WORK

National Tsinghua University, Taiwan

1) CO_2 laser optics preparation for laser damage test

2) Structure fabrication of a CO_2 laser-driven accelerator structure.

The structure consists of five accelerator cells with electron transmitting holes along the acceleration path. The whole accelerator structure is installed in a vacuum chamber that may fit into the ATF beam line.

2) Optical test of the accelerator structure

The test includes laser coupling to the accelerator structure, excitation of the acceleration laser mode, and the phase control of individual accelerator cells.

ATF, Brookhaven National Laboratory, USA.

1) CO_2 laser damage fluence test

2) Laser acceleration chamber installation.

3) Cold test of the accelerator structure by using the ATF CO_2 laser.

4) Electron beam energy gain/loss measurements

PROJECT DESCRIPTION

1. Introduction

Laser driven particle acceleration finds potential applications in two areas: 1) high-gradient acceleration, leading to table-top accelerators or 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 often comprise 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 one by one. 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 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 ATF. 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. The Proposed Experiment

A. 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.

3) The accelerator structure mimics a laser resonator or a lens array that can be assembled by commercial optical components.

4) The excitation of the TEM_{10} laser mode is a standard, well-known mode-matching technique.

5) The characterization and analysis of the TEM_{10} laser mode is well developed in laser technologies.

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

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

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.

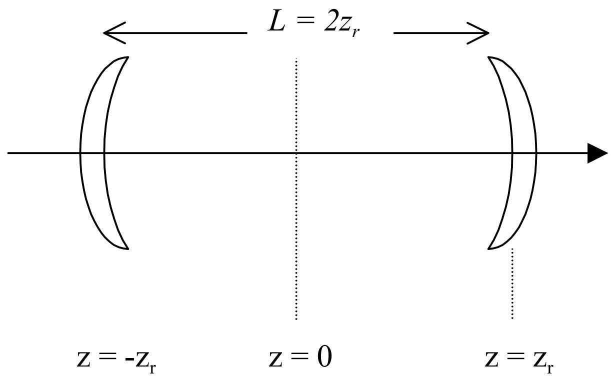

Figure 1. The confocal laser resonator as a single-accelerator cell.

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

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

where $k = \frac{2\pi}{\lambda}$ is the wave number, ω is the laser angular 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 length becomes

$L = 0.1\gamma_{\min}^2 \lambda$, 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.

B. Acceleration Gain Subjected to Material Damage

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. For laser pulse widths longer than a few hundred picoseconds, laser damage mechanism is due to thermal heating, yielding the relation between the laser damage fluence F and the laser pulse width τ, $F \propto \tau^{0.35}$. The scaling law is applicable to dielectric for the wavelengths between 1 µm and 10 µm[6]. It is tabulated in Ref [6] that the damage fluence of ZnSe coating is about 23.6 J/cm^2 for 10 nsec CO_2 laser pulses. With the scaling $\tau^{0.35}$, the laser damage fluence of ZnSe coating is about $F = 5.4$ J/cm^2 (or the damage intentisy 36 GW/cm^2) for the $\tau \approx 150$ psec ATF CO_2 laser pulse width. Typically a bulk material sustains a higher laser fluence than a coating of the same material[6]. However the ATF published laser damage flence[7] of 0.5 J/cm^2 on ZnSe for ~100 psec CO_2 laser pulses (or damage intensity ~5 GW/ cm^2), which is much lower than that predicted by the scaling law and can be considered a lower limit at this moment. We feel that the actual damage fluence of a bulk ZnSe at $\tau \approx 150$ psec deserves more careful measurements. Some heat-treated, doped hard materials for CO_2 laser, like NaCl, KCl, Ge and GaAs, were reported to sustain much higher laser fluence than undoped ones[8], which will be investigated as well in this proposal.

In the thermal heating limit, the damage fluence decreases when the laser pulse width becomes shorter, scaled as $F \propto \tau^{0.35}$, and therefore the laser damage intensity increases when the laser pulse decreases, scaled as $\propto \tau^{-0.65}$. When the laser pulse length is shorter than ~ 100 psec, the laser damage fluence stays flat over a certain pulse length variation[9]. It turns out that the laser damage field and thus the maximum acceleration gradient can be increased significantly with a picosecond laser pulse width. For example, the CO_2 laser damage intensity of NaCl is 250 GW/cm^2 for a 2 psec pulse width[10].

The laser radius at the mirror is $\sqrt{2}w_0$, where $w_0 = \sqrt{\frac{\lambda z_r}{\pi}}$ is the laser waist. The maximum power that the mirror may sustain is therefore $P = \frac{F}{\tau}\left(\frac{1}{2}\pi w_0^2\right)$ $= \frac{F}{\tau}\frac{\lambda z_r}{2}$ = 3 MW for 100 psec laser pulses on a ZnSe structure or 300 MW for 2 psec laser pulses on a NaCl structure. Subsitituting P into Eq. (1), one obtains the maximum single-stage energy gain in the range 38 keV ~270 keV, depending on the laser pulse width and the structure material. Note that, for this proposal, 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 is chosen.

C. Laser-driven LINAC Design

In a practical accelerator cell, there exist two electron transmitting holes. In our computer simulation[11] we found no degradation in the laser mode and the single-stage energy gain, when we opened the transmitting holes with their diameter = 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 $f = z_r$. With 5 accelerator stages at a total length of 11.25 cm, the maximum energy gain is 0.19 ~ 1.35 MeV, again depending on the parameters chosen in the last section. 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.

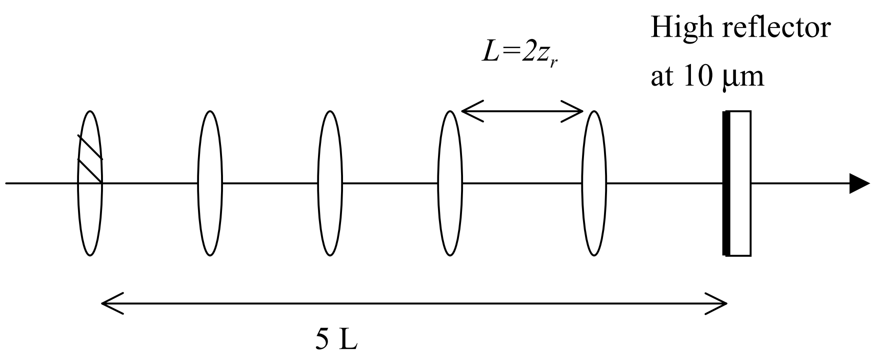

Figure 2. A lens array as a laser-acceleration linac.

Once the structure is fabricated and optically tested on Taiwan, the structure, along with the vacuum chamber, will be installed to the ATF beam line. The size of the vacuum chamber is around one foot at most. The vacuum chamber is self-contained, with all the control and tuning electronics built on Taiwan.

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, half of it can be detected with ease. The important apparatus in the downstream beam line that ought to be provided by ATF is an energy spectrometer capable of discerning the ± 1% energy spread resulting from the 5 acceleration stages. With this amount of energy spread, a typical energy spectrometer should be good enough for the experiment.

C. Comparison Between This Proposal with the Stanford LEAP Project

Since May 1997, Stanford has been engaged in a dielectric-loaded laser electron acceleration project (LEAP)[12]. LEAP is aimed to demonstrate vacuum laser-driven electron acceleration in a dielectric accelerator structure. Table 1 shows the comparison between this proposal and LEAP.

When LEAP was initially proposed, the system parameters are limited to those available at the Stanford Hansen Experimental Physics Laboratory. Also, the mission of LEAP is to demonstrate a novel dielectric accelerator structure driven by a state-of-the-art solid-state laser. As a result, the Stanford LEAP is highly challenging and significant.

Table 1. The comparison between Stanford LEAP and this proposal.

	This proposal	Stanford LEAP
Electron beam energy	75 MeV	40 MeV
Laser wavelength	10 μm (CO_2)	800 nm (Ti:sapphire laer)
Electron transmitting hole	$\phi = 50\ \mu m$	$\phi = 3\ \mu m$
accelerator cell length	2.3 cm	0.25 cm
Accelerator structure	A 5-cell linac	A single accelerator cell
Total energy gain	190 keV ~ 1.35 MeV	300 keV
Acceleration field	TEM_{10} mode	Crossed laser beam

The physics experiment proposed in this project 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 total energy gain may approach 1 MeV, allowing definitive energy measurements.

c. The acceleration field is from a laser mode, permitting a direct comparison with the conventional RF accelerator theory.

The data collected in this proposal 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.

3. The Ability of Huang's Group for Carrying out this Project

A. Huang's Group

The principle investigator, Y.C. Huang, has an extensive experience in laser, electron beam, and radiation. The following is a brief sketch of Y.C Huang.

a. Under R.H. Pantell of Stanford, Huang designed, built, and characterized a compact far-infrared free-electron laser[13].

b. Under R.L. Byer, Huang initiated the Stanford LEAP project for laser-driven electron acceleration.

c. Under M. Cornacchia, Huang worked part time at Stanford Synchrotron Radiation Laboratory as an infrared-laser-detection consultant Scientist.

Currently Huang's group consists of 12 graduate students and one postdoctoral research associate, being supported by the National Science Council (NSC) and industrial affiliates on Taiwan. Huang is currently the principal investigator of the proposed NTHU Relativistic Photon-electron Dynamics Laboratory.

B. Funding

The expense of this project is fairly moderate, primarily for the accelerator fabrication on Taiwan and travel to ATF. The fabrication and optical test of the accelerator structure, and the manpower cost will be supported by an existing NSC-funded proposal. In addition, Huang will submit a proposal to NSC-Taiwan as well as to DoE-USA for the travel budget. Huang's group in the last two years was well funded at a level of US$300k per year. We do not expect undue difficulties in carrying the proposed work in this project.

4. Estimated ATF Support and Gantt Chart

The work to be conducted at ATF includes

1. laser damage fluence measurements on ZnSe, Ge, NaCl, GaAs with various ATF CO_2 laser pulse widths.
2. High-power laser test on accelerator structure: laser coupling, mode conversion, phase control, and structure damage will be investigated.
3. CO_2 laser-driven particle acceleration: electron acceleration gain will be measured.

To test laser material damage, Huang's group has to work closely with the ATF laser group. We suggest that the ATF laser group and Huang's group conducts the laser damage measurement with polished ZnSe, Ge, and GaSe supplied by Huang's group. These materials can be antireflectively coated at the 10.6 μm CO_2 laser wavelength.

The ATF's additional support on laser-driven acceleration can be divided into two parts: manpower and equipment. For manpower, the Huang's group would appreciate some operator's time during the electron acceleration experiment. If necessary, Huang's group may have a graduate student trained at ATF prior to conducting the major experiment. Therefore the graduate student from Taiwan may be the assistant to the machine operator. Huang's group will be responsible for all the other manpower necessary for the vacuum chamber installation and laser acceleration experiments, while welcoming any help and collaboration from local groups.

The experiment is designed to fit into one of three high-energy beam lines at ATF. The chosen beam line should have an energy spectrometer in the down stream and easy access to the pulse CO_2 laser. The required laser energy is much lower than that ATF can actually provide. For example, if the laser pulse width is 100 psec, the pulse energy needed is only in the range of 0.5 mJ ~ 3 mJ.

The major laser acceleration experiment will be carried out in the last two months of this proposal period. During the acceleration test, we would like to have three experiment sessions with one-week beam time in each session. Based upon the Stanford LEAP experience, we propose one-week intermittence between adjacent experiment sessions for any major modifications. To complete this project in a one-and-half-year period is not an easy task. If necessary, we will propose the continuation of the acceleration test beyond the 18th month based upon a reasonable progress. Table 2 shows the Gantt charge of our tentative plan.

Table 2 Gantt Chart of the proposed work

work items \ month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
sample (ZnSe, Ge, GaAs) preparation for damage test: purchasing and polishing (NHTU)	x	x	x															
sample preparation for damage test: antireflective coating (NTHU)			x	x														
Laser damage test (ATF)				x	x	x												
Structure design (NTHU)	x	x	x															
Structure fabrication (NTHU)			x	x	x	x	x	x										
Low-power Optical Test (NTHU): laser coupling, mode conversion, phase control							x	x	x	x								
Vacuum chamber fabrication (NTHU)									x	x	x	x						
Beam line installation and test (ATF)												x	x	x	x	x		
Laser acceleration test (ATF)																x	x	x
If necessary, the acceleration test can be extended beyond the 18th month.																		

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