

A PROPOSAL TO EXPERIMENTALLY DEMONSTRATE A NOVEL REGIME OF ELECTRON VACUUM ACCELERATION BY USING A TIGHTLY FOCUSED LASER BEAM*

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Abstract

The trajectory of most vacuum laser acceleration schemes is a straight line and the electron beam can obtain a small net energy gain only within two times of laser-Rayleigh length. A novel regime of electron beam dynamics trajectories in intensive laser field has been studied recently [1-2]. The most prominent feature of those dynamics trajectories is that the incident electron beam can be captured into an intensive laser field region in a curved trajectory, rather than expelled from it as predicted by the ponderomotive potential mode. A proposal to demonstrate a proof-of-principle experiment at Brookhaven Accelerator Test Facility (ATF) is presented. The key parameters to meet the experiment requirements are discussed. The preliminary simulation results using existing ATF laser and electron beam are presented.

1 INTRODUCTION

Current laser driven particle acceleration schemes can be divided into two categories: one with a medium and the other without a medium in the electron acceleration path. The one with a medium includes the plasma-based laser acceleration [3] and the Inverse Cherenkov Acceleration (ICA) [4]. The one without a medium includes inverse free-electron laser (IFEL) acceleration [5] and the structure-loaded vacuum laser acceleration [6-7]. The acceleration schemes adopting media along the particle acceleration path often comprise with material properties, including scattering and stability. The IFEL acceleration suffers from excess radiation loss when scaled to high energies. In recent years there has been a renewed interest in the possibility of accelerating electrons by laser field in vacuum [8-12], where the laser acceleration of electrons in vacuum can be realized using the non-linear or ponderomotive forces associated with the laser-electron interaction. The use of ponderomotive forces can result in a very limited net energy gain by using the lower laser energy even in the limit of a finite interaction region truncated by using the optical components.

In the recent years, a new mechanics has been invented to accelerate the electrons in vacuum by using high-intensity tightly focused laser [1, 13]. Unlike the straight electron beam dynamics trajectory in most vacuum laser acceleration, the most prominent feature of this vacuum

laser acceleration is its curved electron dynamics trajectory. The electron beam has an incident angle to the laser when injecting into the laser region. The incident electron beam can then be captured into this intensive laser field region, rather than expelled from it as predicted by the conventional ponderomotive potential model. Immense acceleration to energies in excess of 1 GeV in few centi-meters has been observed in the simulation with high intensity focused laser beam. The demonstration for the first proof-of-principle experiment at Accelerator Test Facility (ATF) Brookhaven National Laboratory is proposed by using the novel vacuum laser acceleration mechanics. In the next sections, we will briefly review the theory, and then the possibility to obtain some critical parameters to realize the acceleration experiment is discussed. The schematic layout of the experiment at ATF is presented.

2 THEORETICAL BASIS

For most vacuum laser accelerations, the electron dynamics trajectory is a straight line. A major difficulty in using lasers in vacuum to accelerate electrons is that the phase velocity of the electric field in the direction of the accelerated electrons is greater than the speed of the light for straight electron beam trajectory, $v_p / c \sim 1 + 1/(kZ_l)$, k is the laser wave number, Z_l is the laser Rayleigh length, $Z_l = \pi w_0^2 / \lambda$. This results in no net energy gain over the infinite interaction length, but a small finite net energy gain can be obtained by placing optical components near the laser focus to limit the interaction length. Actually, this mechanics can be described with the Ponderomotive potential model (PPM), which is typically valid in cases in which an electron experiences many quiver oscillations in the laser field such that a time averaging over the fast quiver motion can be justified. The motion to describe the interaction between the electrons and laser beam in this model can be simplified. The longitudinal and transverse electric field component in a focused Gaussian laser beam in PPM can be given by:

$$E_r = E_0 \frac{rw_0}{w^2} \exp\left(-\frac{r^2}{w^2}\right) \sin \psi \quad (1)$$

$$E_z = E_0 \frac{2w_0}{kw^2} \exp\left(-\frac{r^2}{w^2}\right) \times \left[\left(1 - \frac{r^2}{w^2}\right) \cos \psi - \frac{zr^2}{z_l w^2} \sin \psi\right] \quad (2)$$

where

$w = w_0[1 + (z^2 / z_l^2)]^{1/2}$ is the laser beam radius, w_0 is the beam radius at the focal waist, ω is the laser frequency, E_0 and ϕ_0 are constants. Thus, the energy gain is the integral of the E_z from z_1 to z_2 , z_1 and z_2 are interaction region, which is determined by phase velocity:

$$V_\phi \approx c[1 + \frac{1 - f_\phi}{kZ_R(1 + z^2 / Z_R^2)}] \quad (3)$$

where

$$f_\phi = \frac{r^2(1 - z^2 / Z_R^2)}{w_0^2(1 + z^2 / Z_R^2)}$$

In order to make $V_\phi < c$, both conditions must be met, i.e.:

$$-Z_R < z < Z_R, \text{ and } r > w_0$$

In this case, the electron trajectory is completely parallel to the Z-axis, i.e., a straight line, and the electrons can be accelerated within the laser Rayleigh length. In addition, this conclusion is only limited within the low laser energy. However, when the electrons move in a curved trajectory, the phase velocity can be smaller than the speed of the light in a significant length [13] and thus results in a significant net energy gain over a longer distance. When the electron beam has a small incident angle to the laser electric field, the phase velocity along the trajectory is:

$$V_\phi \approx c[1 + \frac{1 - f_\phi}{kZ_R(1 + z^2 / Z_R^2)} - \frac{rz\theta_i}{Z_R^2(1 + z^2 / Z_R^2)} + \frac{\theta_i^2}{2}] \quad (4)$$

where θ_i is the electron beam incident angle to the laser beam axis. Usually θ_i is smaller. It is obvious that when the electron is incident to the laser field and thus the phase velocity is not a constant at each point. However, the key point is the phase velocity is smaller than speed of the light. Thus, contribution from term $\mathbf{v} \times \mathbf{B}$ in Lorentz force becomes noteworthy. Since the phase velocity is smaller than the speed of the light in such curved trajectory, the electron can be accelerated over a significant distance and thus obtain a significant net energy gain.

3 BEAM PARAMETERS AT BROOKHAVEN ATF

Based on the simulations, the electron beam can be captured and significantly accelerated by focused laser beam with higher accelerating gradient when the a_0 specifying the laser energy is greater than 8 [1], which corresponds to $8 \times 10^{17} \text{ W/cm}^2$ of the laser intensity for 10.6 micron CO2 laser. The conversion of the laser intensity into laser peak power for different laser spot size is given in Table 1.

The sensitive role played by the injection energy is considered. On the one hand, an initially slow electron will not be able to penetrate the high intensity regions of the beam and may be reflected with little or no energy

gain. On the other hand, an initially fast electron may pass through undeviated and gain or lose a small amount of energy. Simulations show that the optimum electron injection energy is in range of 5-20 MeV. To achieve a significant net energy gain, basically three requirements need to be met:

- strong intensity laser at least in Terra Watt level
- incident injection angle, ~ 5 degrees.
- low injection momentum (5-20 MeV)

Table 1: Laser peak power vs laser spot size

Laser spot size (microns)	Peak power (TW)
10	0.8
30	7
50	20

The ATF electron accelerator system consists of a photocathode based RF gun, two SLAC type S-band linac sections and three dedicated beam lines. At the exit of the RF gun, the energy is around 4 MeV. For most experiments, the electron beam energy at the end of the linac is about 40 MeV, where two linac sections provide 35 MeV. As mentioned in the above, this novel vacuum laser acceleration experiment favors the low electron beam momentum to injection the laser channel, ~ 20 MeV. This lower energy is readily achieved after lowering the RF power for two linac sections. The electron beam performance at this energy, energy spread, emittance pulse length, may become a little worse, but not severely. The simulations show that the emittance and energy spread are $\sim 2 \text{ mm.mrad}$, 0.1%, respectively for 0.3 nC and 20 MeV beam. The small electron incident angle to the laser beam, ~ 5 degrees, is easily met.

Compared with existing beam parameters at the ATF, the most challenging parameter for this experiment is the laser peak power. At the ATF, we use the CO2 laser (wavelength is 10.6 microns) to synchronize and interact with the electron beam. Presently, with a high-pressure, big-aperture booster amplifier, the ATF CO2 laser system can operate up to 30 GW of the peak power in longer pulse, 180 ps with FWHM, as shown in Figure 1.

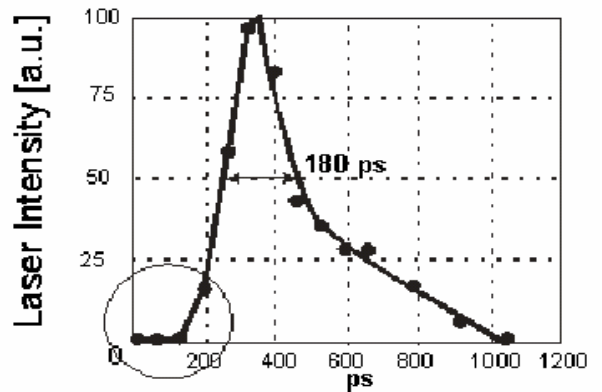


Figure 1: Measured time profile of the CO2 beam after the preamplifier

4 SUMMARY

The relatively long pulse duration is due to the narrow bandwidth of the preamplifier, 4 atm and 1 liter with $1/200 \text{ ps}^{-1}$ bandwidth. In this year, CO₂ laser upgrade for high peak power is being carried out at the ATF. Main steps of the on-going upgrade is [14]:

- To generate 1 ps second harmonic of YAG laser in KD*P crystal for slicing CO₂ laser
- Gate $\sim 1 \text{ ps}$ CO₂ pulse Kerr switch controlled by YAG second harmonic.
- Use 10-atm preamplifier 0.15 liter to match the present booster amplifier in bandwidth, 9 atm and 9 liter with 1 THz bandwidth.

In this summer, ATF can have the capability to provide intensive laser with $\sim 1 \text{ ps}$ pulse duration and the peak power in 1 TW level with these upgrades. The ultra small laser beam size can be achieved with strong focusing mirrors. To match the small laser beam size, electron beam size need to be focused down to several tens of microns, which has been obtained in the beam line with miniature permanent quads [15]. According to the simulations, the expected energy gain is in order of MeV with 1 TW laser peak power.

The proposed experimental elements can be accommodated in an existing vacuum chamber with many ports. The CO₂ laser has an incident angle to the electron beam. The schematic layout for the experiment is shown in Figure 2.

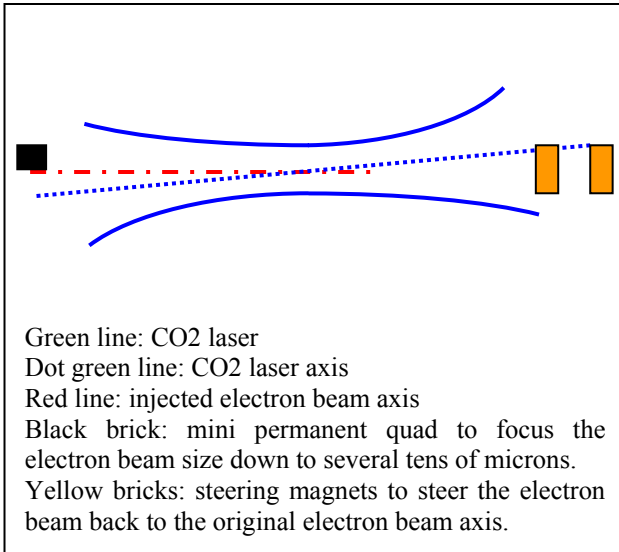


Figure 2: The schematic layout of the experiment

As mentioned in the above, electron beam trajectory is curved in the laser field region. The electron beam can be steered back to the original line (red straight line) with steering magnets after the electron beam obtains the energy and exit the laser field region.

A novel vacuum laser acceleration that is different from the most vacuum laser acceleration described with ponderomotive potential model is discussed. The prominent characteristic is that the electron beam dynamics trajectory is not a straight line, but a curved trajectory in the laser region relative to the Z-axis. In such mechanics, the phase velocity can be kept below the speed of the light for significant distance although it is not a constant. To meet this condition, the injected electron beam is incident to the laser, and its incident momentum is about 20 MeV and the laser peak power is at least in TW. An experiment to conduct the first proof-of-principle of this vacuum laser acceleration is proposed at Brookhaven Accelerator Test Facility. The possibility to realize these important beam parameters, incident angle, initial momentum and laser peak power in TW level, is discussed. It is shown that the requirement of the electron injection angle and momentum can be readily met. The CO₂ laser peak power in TW level can hopefully be achieved with the on-going CO₂ laser upgrades. Energy gain in order of MeV is observed in the simulations using 1 TW laser power.

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