VACUUM LASER ACCELERATION EXPERIMENT PERSPECTIVE AT BROOKHAVEN NATIONAL LAB-ACCELERATOR TEST FACILITY

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Abstract

This first stage experiment is a Proof-of-Principle to support our novel vacuum laser acceleration (VLA) theory, published previously. Simulations show that based on current experimental conditions at the Brookhaven National Laboratory Accelerator Test Facility (ATF), an electron beam with initial energy of 15 MeV can get net energy gain from an intense CO_2 laser beam. The difference of electron beam energy spread is observable by the ATF beam line diagnostics system. Further this energy spread expansion effect increases along with the laser intensity increasing. The proposal has been approved by the ATF committee, and this experiment will be the next project.

INTRODUCTION

Laser acceleration offers the potential for realizing much more compact and less expensive accelerators, which are capable of reaching energies much higher than possible using conventional microwaves. With modern high-power ultra-intense lasers, they can produce extremely high electric field (up to 10^7 MVm^{-1}) and can then either directly or indirectly accelerate electrons to very high energies. For instance, in a new vacuum laser acceleration scheme called a CAS (capture and acceleration scenario), the electrons can be captured and significantly accelerated in vacuum by using a high-intensity tightly focused laser [1-3].

As shown in Figure 1, for a focused laser beam propagating in vacuum, the diffraction changes not only the intensity distribution of the laser, but also its phase distribution, which results in V_φ <c in some areas. Based on this feature—a subluminous phase velocity region surrounding the laser beam axis in conjunction with a strong longitudinal electric field component—a natural acceleration channel has been demonstrated to exist for a laser beam in vacuum. Relativistic electrons injected into this channel can be trapped in an acceleration phase and remain in it synchronously for a sufficiently long time, thereby obtaining considerable energy from the field.

In Figure 2, Z_R is the Rayleigh length and the quantity Q is defined as $Q=Q_0(1-v_\varphi/c)\{x/w(z)\}\exp[-(x^2+y^2)/w(z)^2]$ for $v_\varphi \le c$ and Q=0 for $v_\varphi \ge c$. We can look at Figure 3 and find that for a laser with beam width w_0 = 30 μm and incoming electrons at 5 MeV, electrons can be violently accelerated to energies of more than 1 GeV with the laser field of $a_0 = eE0/me\omega c = 100$, where −e and me are the electron's charge and rest mass, respectively, ω is the laser circular frequency and the wave number $k = \omega/c$.

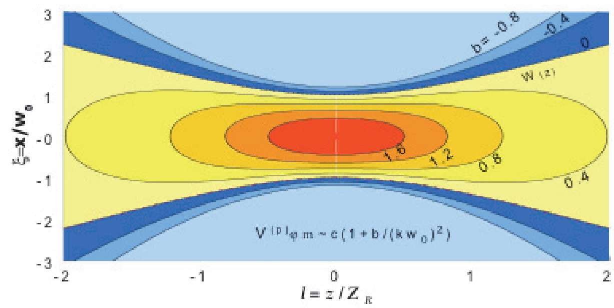

Figure 1: The distribution of the minimum phase velocity v_φ in the plane y=0.

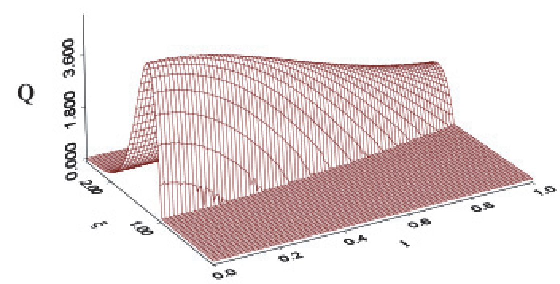

Figure 2: The distribution of the acceleration quality factor Q on the plane y=0. $\xi=x/w_0$, $\zeta=z/Z_R$.

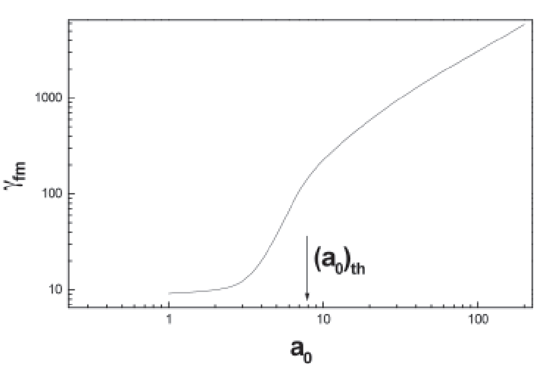

Figure 3: Final energy as a function of laser intensity a_0.

It is known that a CAS scheme requires several conditions to be met: (1) electron beam injection energy within 5-20 MeV; (2) laser intensity $a_0 \ge 2.5$; (3) small incident angle (~0.1) of the laser beam injection to electron beam. If the laser intensity is lower (a_0<2.0), the accelerating mechanism will not be CAS, but rather,

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"direct vacuum laser acceleration" (DVLA), where electrons may be accelerated directly by an intense laser pulse. In this scheme, some of the incident electrons may experience asymmetrical phase shift in the laser field: the strong field region gives acceleration, whereas the weak field region gives deceleration, resulting in net energy gain. One of the DVLA advantages is that the electrons can be injected along the laser beam axis (incident angle equals zero), whereas the CAS mechanism requires an incident angle of several degrees. Of course, energy and acceleration efficiency from DVLA are much lower.

In this paper, we will first show our simulation result based on current experimental conditions at ATF . Then, we will discuss the proposed experimental setup at the ATF for a proof-of-principle beam test of DVLA scheme. Finally, we report progress on the e-beam tuning for carrying out this experiment.

SIMULATION RESULTS WITH ATF PARAMETERS

The ATF at BNL includes a high-brightness photoinjector electron gun; a 70 MeV linac with two SLAC-type S-band linac sections; a high power CO_2 laser synchronized to the electron beam to a picosecond level; four beam lines (most with energy spectrometers); and a sophisticated computer control system. The current CO_2 laser at ATF can only deliver peak energy at 5 J with pulse length of 5 ps and focus spot around 40 μm at the Interaction Region. Such a laser is not sufficient for testing CAS, so we will test DVLA. Usually ATF runs at 40-70 MeV to avoid strong space charge effects. Both the CAS and the DVLA schemes for vacuum laser acceleration require the electron beam energy to be no more than 20 MeV. If we can adjust both linac sections phasing in acceleration but with a lower accelerating gradient, the PARMELA code shows that a small energy spread of 0.1% at 20 MeV is achievable at ATF [4].

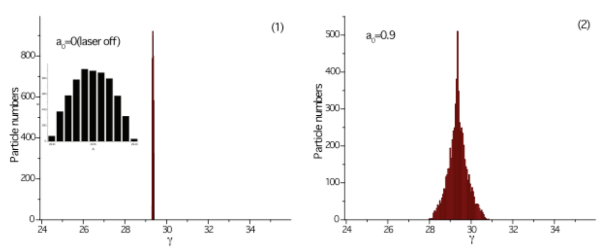

Figure 4: Electron beam energy spread distribution before (left) and after (right) interacting with laser beam.

Now we simulate the interaction between the electron beam and CO_2 laser. We assume that the electron beam enters along the same direction as the laser beam on the z axis and encounters the laser beam at the laser focus spot. The simulation assumed e-beam initial energy of 15 MeV, initial e-beam energy spread of 0.1%, e-beam size of 200 μm, and initial e-beam emittance of 1 mm·mrad, as well as these CO_2 laser parameters: peak energy of 5 J, spot size of 30 μm, and pulse length of 5 ps.

In Figure 4, we present our simulation results for electron beam energy spread distribution before and after interacting with the laser beam. We clearly see that energy spread is increased from 0.1% with laser off to around 1% with laser on [5].

EXPERIMENTAL SETUP FOR PROOF-OF-PRINCIPLE TEST OF DVLA SCHEME

Based on our simulation, we plan to carry out a proof-of-principle experiment for testing the DVLA scheme at ATF. This test is of significance. It can demonstrate that the Lawson-Woodward Theorem [6] is not generally applicable, and VLA is available.

Our proposed experimental setup is shown in Figure 5. The flat mirror, the target (pinhole and germanium plate) and the focused parabolic mirror will be installed in the Compton chamber on beam line 1 in the experiment hall of ATF. The pinhole is used for electron beam and laser beam alignment. The germanium plate is used for synchronization. The parabolic mirror with a focal length of 3" will focus the incoming CO_2 laser to form a waist of 40 μm at the IR and reflect the CO_2 laser again to propagate forward (in the same direction as the electron beam). In addition, a 5 mm hole is drilled in the center of parabolic mirror for the electron beam to go through. There is a dipole spectrometer downstream of the Compton chamber to bend the output electron beam 90^0 and measure its energy spread.

We expect the energy spread of the output beam after its interaction with the laser to be increased from initial 0.1% to 1%. This difference of electron beam energy spread is observable by the 90^0 dipole spectrometer and its diagnostics system, which has a high resolution, distinguishing the energy spread of the electron beam with 0.1% accuracy.

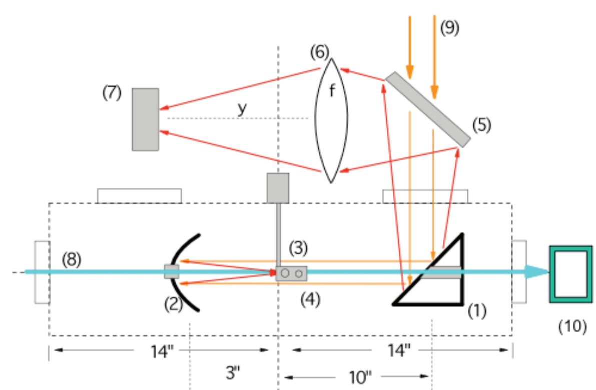

Figure 5: Schematic drawing of experimental setup. The list numberings are as following: (1) flat mirror; (2) focused parabolic mirror; (3) pinhole; (4) Germanium plate; (5) 45^0 beam splitter for alignment and diagnostic; (6) and (7) detector; (8) electron beam; (9) CO_2 laser beam; (10) 90^0 high resolution dipole spectrometer.

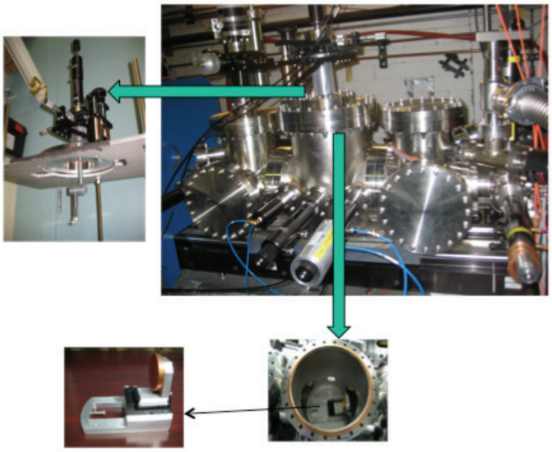

Figure 6: Compton chamber (*upper right*), pneumatic system with pinhole (*upper left*), and parabolic mirror mounted on an adjustable stage facing downstream (*bottom*).

ELECTRON BEAM TUNING AND DIAGNOSTIC

At the ATF, the electron beam is produced in a 1.6 cell, S-band rf photoinjector and is followed by a 70 MeV S-band linac with two sections. For the present experiment, the beam is directed to ATF beam line 1. We have preliminary tuned the e-beam in the linac with a solution that the beam is accelerated in one section and decelerated in another section. We get the following e-beam parameters: e-beam energy of 20 MeV, beam focused size of 200 μm (1σ), charge at spectrometer of 20 pC, and energy spread of 350-400 keV at 20 MeV (1.8%-2%).

The pinhole transmission is 15%-20% and the spectrometer resolution is 40 keV.

The e-beam images at the focal point of the parabolic mirror with and without the pinhole, and at the spectrometer, are shown in Figure 7. We will simulate the interaction of laser and e-beam with an energy spread at 2 % to compare the difference with our previous simulation using initial energy spread of 0.1%. We also hope we can try another solution described in Ref. [5] in order to get a much smaller energy spread.

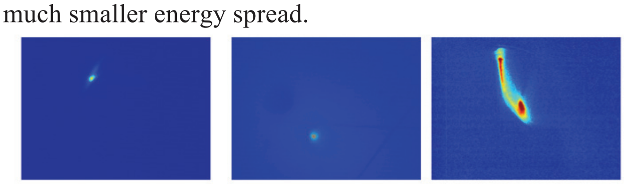

Figure 7: The images of electron beam at the focusing point without pinhole (left) and with pinhole (middle) and at the spectrometer (right).

CONCLUSION

We have simulated the interaction between the electron beam and laser beam under current parameters that ATF can deliver. We find the energy spread of the output beam after interaction with laser can be increased from initial 0.1% to 1%. This difference of electron beam energy spread is observable by a 90^0 high resolution dipole spectrometer and its diagnostics system. The e-beam tuning and experiment setup is underway. We hope to carry out the experiment at ATF to test the DVLA scheme and demonstrate that VLA is available.

ACKNOWLEDGMENT

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