VACUUM LASER ACCELERATION AT BNL-ATF *

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Abstract

The novel and revolutionary concept of real Vacuum Laser Acceleration proof of principle is described in this paper. The simulation with the current BNL-ATF parameter shows that electron beam can get net energy from intense laser beam. The initial 20MeV electron beam with energy spread of 10^{-3} can get hundreds of KeV energy gain with energy spread of 10^{-2} by interacting with a laser a_0=1.3. The proposal has been presented and approved by BNL-ATF. The planning of experiment is going to be performed.

INTRODUCTION

Laser-electron acceleration has been wildly aroused as the technology of intense laser is rapidly developing. With medium, laser wake field acceleration uses intense laser pulses to create a strong longitudinal wake field in plasma for acceleration [1], however the energy spread of electrons is not small. Without medium, we know inverse free-electron laser (IFEL) acceleration [2] and structure-based vacuum laser acceleration (VLA) [3]. Both of them have disadvantages: excess radiation loss and limited energy gain, respectively.

This letter goes over the new laser-driven electron acceleration mechanism [4] we proposed in recent years and describes the experiment plan in BNL-ATF. In this novel scheme of vacuum laser acceleration, there is no any optical element required to confine interaction length. If the laser intensity is very high, a_0 is around or greater than 5, we found out that the electron can be captured in and laser beam and violently accelerated. We call this mechanism: capture and acceleration scenario (CAS); otherwise, when a_0 is relatively smaller, like $a_0 \approx 1$, the net energy exchange, which still exists under certain conditions, is very limited. The key feature we pointed out of CAS is that in a tight focused laser there exists a special region in which the phase velocity of the laser field could be very low, lower than the light speed in vacuum c, so that parts of the fast electron beam can catch up with the acceleration phase of the laser and keep being violently accelerated in the channel by the longitudinal component of the field. The phase velocity of a laser wave field is calculated by the equation for a Hermite-Gaussian (0, 0) mode propagating along z-axis [5]:

$$\partial\varphi/\partial t + v_{\varphi} \cdot \nabla\varphi = 0$$

where φ is the phase field of the wave , $\nabla\varphi$ is the gradient of the phase.

$$\varphi = kz - \omega t - \tan^{-1}\alpha + \frac{kr^2}{2z(1+1/\alpha^2)}$$

where ω is the laser circular frequency, $k = \omega/c$, $\alpha = z/Z_R$, $Z_R = kw_0^2/2$ the Rayleigh length, w_0 is the laser beam radius at the focal point, $r^2 = x^2 + y^2$. Then the related phase velocity is:

$$v_{\varphi} = \frac{\omega}{|\nabla\varphi|} = c\left(1 + \frac{4}{q^4}\left(\rho^2 - q^2 + s^2 f_p^2\right)\right)^{-1/2}$$

where , $f_p = 1 - p^2(1-a^2)/(1+a^2)$, $q = (1+a^2)^{1/2}$, $\rho = r/w_0$ and $s = 1/kw_0$.

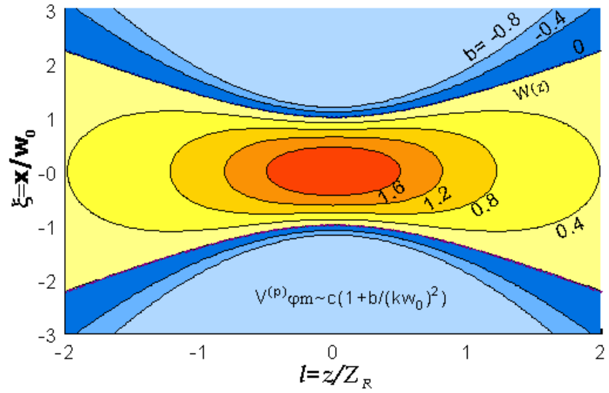

Figure 1: The distribution of the minimum phase velocity v_{φ} in the plane $y = 0$

Fig. 1 illustrates the two-dimensional contour of v_{φ} in the plane y=0. It can be seen that the region with the phase velocity less than *c* emerges just beyond the beam width and extends along the diffraction angle $\theta_m \sim 1/kw_0$. The magnitude of the minimum phase velocity scales as $v_{\varphi} \sim c\left(1 + b/(kw_0)^2\right)$. The physical basis of this subluminous phase velocity is that in a Gaussian beam field, not a plane wave, the radius of the curvature decreases from $z = \pm\infty$ to $z = Z_R$, and then increases from $z = Z_R$ to beam focus waist due to the diffraction effect of the optical beam.

According to our study, CAS requires some critical conditions to get achieved. 1) a very intense and tight focused laser; 2) relatively low initial electron energy. In the laser intensity about $a_0 \approx 100$ the electron beam with initial energy of a few MeV can be accelerated to GeV in tens centimeters. This is a very remarkable acceleration gradient. With such a high intensity laser, the requirement of laser beam waist focused size is not much sensitive, usually we use beam size from 20 μm to 60 μm for simulation.

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Figure 2 shows the scan of different initial laser phase when encountering the electron of a whole wave length. Apparently half wave length for acceleration and half for deceleration. Figure 3 is a typical acceleration case of the spot A in Figure 2, other parameters are the same as Figure 2. In Figure 3 (c) we can obviously see that in the acceleration case the phase slippage between electron and laser becomes very slow after a certain period. This is because of the subluminous low phase velocity feature of tight focused laser beam. In this region, the electron gets chance to catch up with the acceleration phase and be continually accelerated.

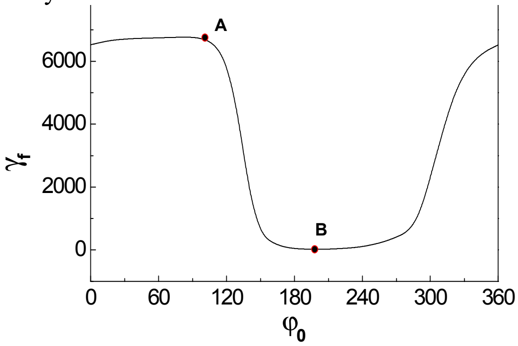

Figure 2: laser $a_0 = 100, w_0 = 30\mu m, \lambda = 1\mu m$; electron with the initial energy $E_0 = 15MeV$. The final energy of electron versus different initial laser phase.

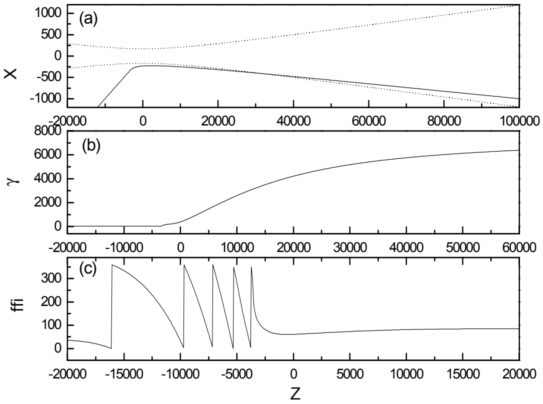

Figure 3: laser and electron have the same parameters as Fig. 2. (a) is the single electron trajectory along the laser propagation in $y = 0$ plane; (b) is the energy change; (c) is the phase slippage that electron experiences during interaction.

As we mentioned above that the approximate threshold value of laser intensity is around $a_0 \approx 5$ in order to accomplish CAS, however with this relative low intensity, the laser is required to focus very tight, such as 20 μm, 30 μm; and the initial electron energy is required as low as around 5MeV to get optimal result.

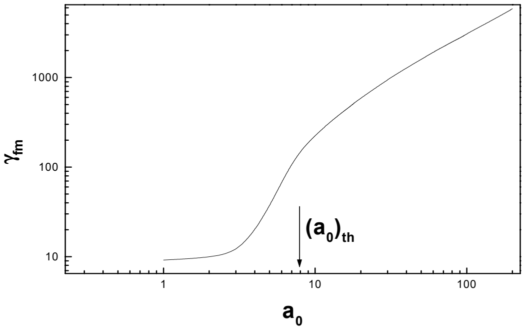

Figure 4: laser focus spot $w_0 = 20\mu m, \lambda = 1\mu m$, initial electron energy $E_0 = 5MeV$. Finial energy vs. a_0 .

From the Fig. 4, we can see that the final energy basically changes linearly to one order of a_0 . If the laser intensity is lower than a_0 =5, unlike CAS the electron beam can get net energy gain less than in CAS case. In this scheme the electron beam experiences asymmetric field during the interaction. In the focused laser, those electrons catching the acceleration phase close to the center of the laser waist gain more net energy than energy loss while electrons slip to deceleration phase in the far field, because the field close to focus center is stronger than the field far away along the propagating axis. This asymmetric feature is the physical explanation of this kind of acceleration scheme.

STUDY AT BNL-ATF CONDITIONS

The current situation is that laser intensity is at a_0=1.3 and the gun runs at electron beam energy around 40MeV to 70MeV. In order to perform novel VLA we need to tune the electron beam energy down and upgrade the laser intensity.

The electron beam tuning down to 20MeV in BNL-ATF has been attempted.

The ATF has two SLAC-type S-band linac sections. Basically there are two solutions to obtain a lower-energy beam: one is to adjust the first linac section phasing in acceleration with a larger accelerating gradient but phasing the second linac section in deceleration to obtain a lower energy; and the other is to adjust both linac sections phasing in acceleration but with a lower accelerating gradient. PARMELA code was firstly used to simulate beam energy spectrums for both solutions at 20 MeV, as shown in Figure 5. It shows the second solution can offer a very small energy spread, 0.1%, while the first one offers a large energy spread, 5%. Therefore, the second solution was used to tune the real beam, and it was successfully tuned to the end of the beam line at 20 MeV beam energy. The achieved beam test results at 200 pC are summarized: normalized transverse emittance is below 3.5 µm, energy spread smaller than 0.15%.

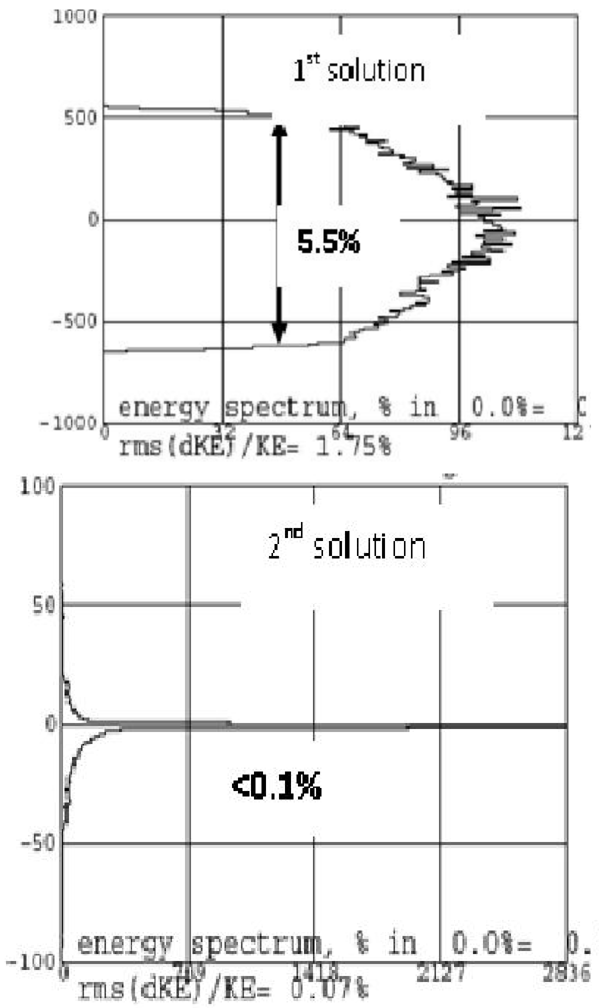

Figure 5: PARMELA simulations for beam energy spectrum for the two solutions at 20 MeV; ordinate axis is particle number; abscissa axis is the energy offset from the central energy in units of keV.

Even though under the laser intensity a_0=1.3 the violent acceleration with gradient ~GeV/m cannot be performed, we still can observe obvious net energy gain.

CONCLUSION

Based on the theoretic research and computer simulations, vacuum laser acceleration can be achieved under certain conditions. This is going to be a proof-of-principle experiment. And this new concept of acceleration is going to be a revolution and will have a lot significant applications.

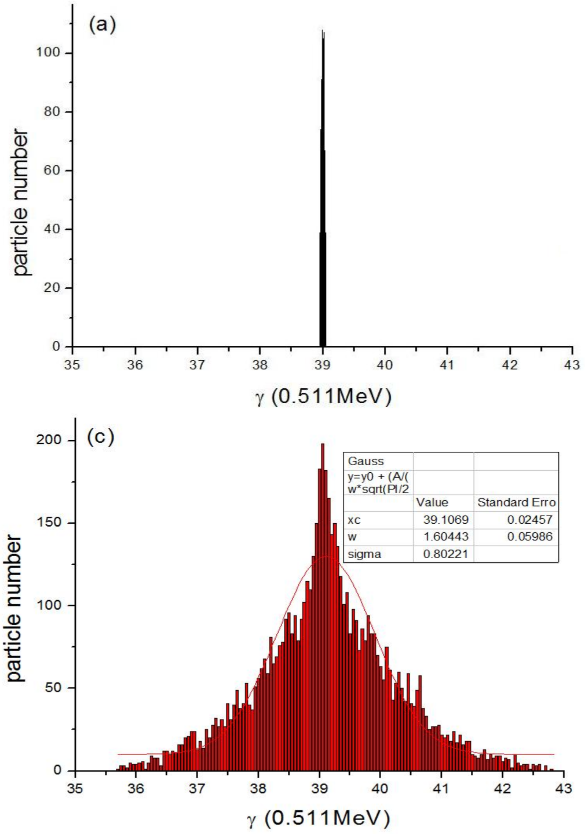

Figure 6: a_0=1.3, initial e-beam energy 20MeV, energy spread distribution.

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