Beam Parameter Investigation for Vacuum Laser Acceleration at ATF*

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Abstract
Several schemes for the vacuum laser acceleration experiment will be conducted at the Brookhaven Accelerator Test Facility (ATF), using its high-power CO2 laser and small sized electron beam. The laser and electron beam parameters for one particular scheme, proposed by UCLA, are systematically simulated and optimized in order to have higher energy gain. Its energy gain, 0.5 MeV, is expected. The solution to measure energy gain is presented.

1 INTRODUCTION

Laser acceleration in vacuum has been studied theoretically for many years and recently some schemes have been proposed for experimental verification. The major difficulty in using a laser beam in vacuum to accelerate the electrons is that the phase velocity of the electric field of the accelerated electrons, $v_p \sim c(1+1/(kl_{ray}))$, is larger than speed of light c, where k is laser wave number and l_{ray} is the laser Rayleigh length. However, theoretical analysis shows that the electrons may be accelerated when the phase slip is within the range of the accelerating phase [1,2].

Various schemes for vacuum laser acceleration experiments have been proposed for a beam test at the Brookhaven Accelerator Test Facility (ATF). In this paper, the beam parameters for one particular scheme, proposed by UCLA [2] are optimized. The energy gain relation with the laser waist, interaction length and crossing angle of laser beams is investigated extensively in order to choose the best parameters for the experiment. The optimal solution for an energy gain measurement is presented.

2 ENERGY GAIN ANALYSIS

2.1 Laser Damage Fluence

The value of the laser damage Fluence, F, is determined by several parameters, including laser pulse width, laser wavelength, material absorption, material surface finish, etc. Based on a recent ATF CO2 laser damage test [3] with 100 ns and 200 ps laser pulse width and our experience in applying a donut-shaped Gaussian-distributed laser beam, 3 J/cm^2 of CO2 laser damage fluence on a copper mirror could be achieved for a 30 ps laser pulse width. The laser peak power, $P_{\max, laser.\tau} = \frac{F.\pi.w^2}{\tau}$, τ is the pulse length of the laser, assumed 30 ps, w is the laser spot size at the reflected mirror, which can be expressed: $w = w_0 . \{1+(l/l_{ray})^2\}^{1/2}$, w$_0$ is the laser spot size at the interaction point, l is the half interaction length, l$_{ray}$ is the laser Rayleigh length, $l_{ray} = \frac{\pi.w_0{}^2}{\lambda}$, λ is the laser wavelength. The laser peak power at Rayleigh length is given in Table 1.

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Table 1: Laser peak power vs laser spot sizes at IP

$w_0(\mu m)$	60	120	180	240	300	360
l_{ray} (mm)	1.06	4.27	9.6	17.1	26.7	38.4
Laser peak power at l_{ray} (MW)	31.6	86.4	194.4	345.6	540	780

2.2 Energy Gain

The crossed-laser beam acceleration scheme is shown schematically in Figure 1, where the electron is accelerated along the axis of the crossed laser fields. Radial polarized, axis-symmetric, donut gaussian-distributed laser beam is transported to vacuum chamber through ZnSe window. 1st copper mirror, a parabolic or a 45^0 copper mirror with a hole is positioned along the electron beam path in the chamber. The hole is located at the parabolic mirror optical center and allows the electron beam to meet with the laser beam in the focal region. And then the laser beam is scattered with the 2nd copper convex mirror after the interaction between laser beam and electron beam. The electron experiences the acceleration field from the radial polarized laser beam until the optical phase slips ahead of the electron by 180 degrees. The 180-degree slippage distance is the maximum acceleration distance in a single-cell interaction length. One of the advantages to use this scheme is that the interaction length can be changed readily with the adjustment of the 2nd copper mirror. For a highly relativistic electron propagating along the longitudinal axis, the energy gain of the electron can be obtained with [1,4]:

$$\Delta W = 88\sqrt{P}\,\frac{1}{\hat{\theta}}\cos\phi_0\,\exp\!\Big(-\frac{(\hat{l}\,\hat{\theta})^2}{1+\hat{l}^2}\Big).\sin\!\Big(\frac{l.\hat{\theta}^2}{1+\hat{l}^2}\Big), \tag{1}$$

where P is the laser peak power, $\hat{\theta} = \theta/\theta_d$ laser crossing angle normalized to the laser far-field diffraction angle θ_d , which is equal to w_0 / l_{ray}. It is obvious that the maximum energy gain is dependent on many beam parameters. In order to have maximum energy gain, the optimum laser-beam crossing angle vs laser waist at Interaction Point (IP) is simulated, as presented in Figure 2. It is shown that the crossing angle should be decreased for higher net energy gain when the laser beam with larger waist is used.

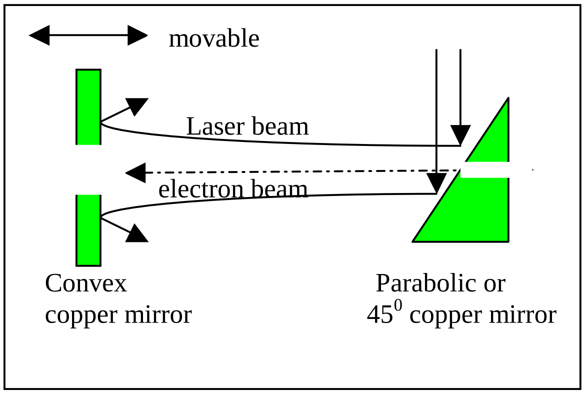

Figure 1: Schematic layout of VLA

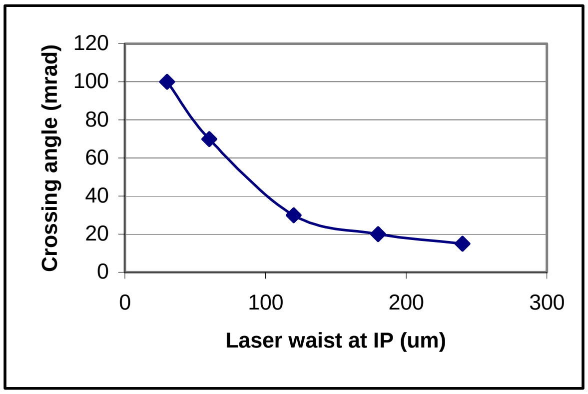

Figure 2: Optimum crossing angle

The net energy gain is strongly dependent on the interaction length. For different laser waist, the optimum interaction length for the maximum energy gain is simulated, as shown in Figure 3. It is shown at larger laser beam waist (>50 micrometer), the ratio of the optimum half interaction length to the laser

Rayleigh length is almost kept constant, about 0.85, for maximum energy gain. In such case, its corresponding maximum energy gain is calculated as shown in Figure 4 when the maximum laser peak power shown in Figure 5 is injected. It is shown that the optimized energy gain is almost proportional to the laser waist at IP.

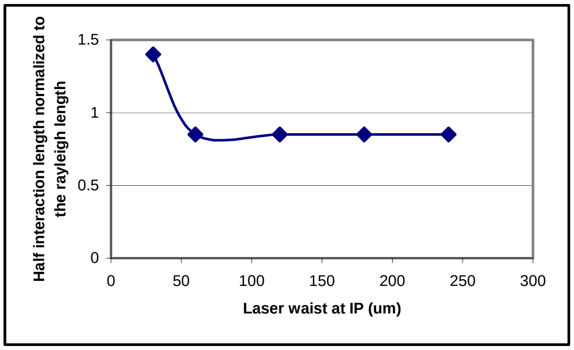

Figure 3: Optimum interaction length

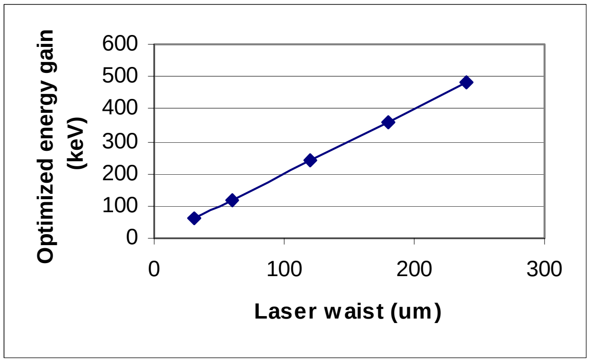

Figure 4: Optimum energy gain vs Laser waist

The advantages to use the larger laser waist have two points. One is the higher energy gain can be obtained. The other is one can adjust the interaction length with manual manipulation since it has longer interaction length. However, long interaction is implied to need the long vacuum chamber and the high peak laser power to acquire higher energy gain. To tradeoff these points, 240 μm of the laser beam waist is chosen for the first test. The energy gain as a function of interaction length for 240 μm of the laser waist is calculated, as shown in Figure 6. It is shown the energy gain about 0.5 MeV could be acquired with a wide range of the interaction length. Its injected laser peak power for corresponding interaction length is shown in Figure 7. About 300 MW laser peak power is needed to have 0.5 MeV energy gain.

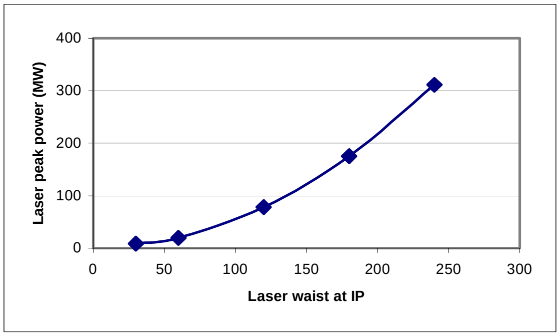

Figure 5: Employed the laser peak power

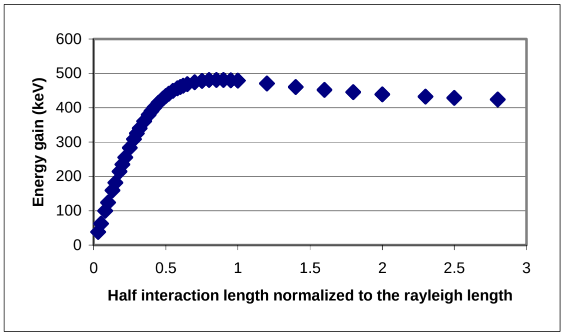

Figure 6: Energy gain vs interaction length
(240 μm of laser waist)

3 SOLUTION OF ENERGY GAIN MEASUREMENT

The beam size can be expressed as: $\sigma_x = D_x \cdot \frac{\Delta p}{p_0} + \sqrt{\beta_x \varepsilon_x}$, where the first term is from dispersion contribution, and the second term is from emittance contribution. Only when the emittance term is negligible compared with the dispersion term, the beam size is then dominated by the dispersion term, i.e., the beam size is proportional to the energy spread. Energy P_0 is constant for fixed bending angle at ATF beam line, and thus the energy gain is measured in term of the energy spread Δp, i.e., beam size. With the proper adjustment of the beam optics, the twiss parameters at vacuum laser accelerator center with β_x =0.2 m, β_y =0.055 m, α_x =0, α_y =0 have been achieved. At this point, we employ the energy spread from –0.06 to 0.06 and simulate its optics from the center to the end of the spectrometer. The ratio of the dispersion term to the emittance term at the end of spectrometer as a function of the energy spread is presented in Figure 8. It is shown that the ratio is proportional to the energy spread. Therefore, energy gain may be derived from the measured beam size.

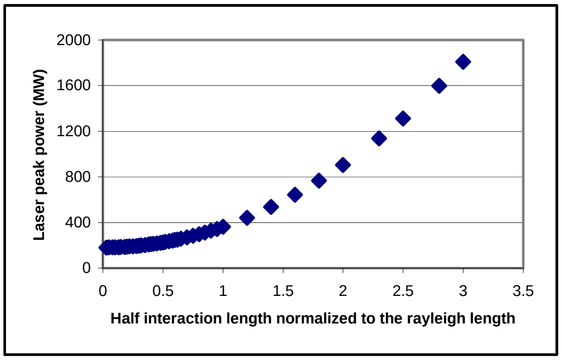

Figure 7: Peak laser power vs interaction length (240 μm of laser waist)

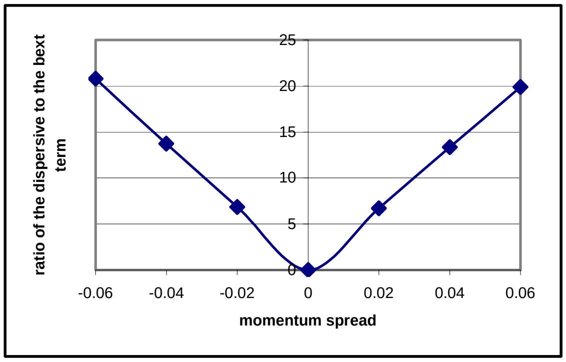

Figure 8: Ratio of the dispersion to emittance term

4 SUMMARY AND FUTURE PLAN

The laser beam parameters are optimized for vacuum laser acceleration. With 240 μm of laser waist, about 0.5 MeV of net energy gain is expected with the interaction length of about twice laser Rayleigh length when 300 MW laser peak power is injected. The beam optics for the experiment at ATF beam line is presented. The energy gain can be measured in term of the measurement for the horizontal beam size. Its real beam experiment is to be tested at ATF very soon.

References:

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