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INVERSE-TRANSITION RADIATION LASER ACCELERATION EXPERIMENTS AT SLAC*

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Abstract

We present a series of laser-driven particle acceleration experiments that are aimed at studying laser-particle acceleration as an inverse-radiation process. To this end we employ a semi-open vacuum setup with a thin planar boundary that interacts with the laser and the electromagnetic field of the electron beam. Particle acceleration from different types of boundaries will be studied and compared to the theoretical expectations from the Inverse-radiation picture and the field path integral method. We plan to measure the particle acceleration effect from transparent, reflective, black, and rough surface boundaries. While the agreement between the two acceleration pictures is straightforward to prove analytically for the transparent and reflective boundaries the equivalence is not clear-cut for the absorbing and rough-surface boundaries. Experimental observation may provide the evidence to distinguish between the models.

INTRODUCTION

The relativistic electron energy gain from laser-driven particle acceleration is typically analyzed in terms of a path integral of the external electric field $\vec{E}_{laser}$ that is acting on the travelling particle over a path Γ.

$$\Delta U = \int_{\Gamma} \vec{E}_{laser} \cdot d\vec{r} \tag{1}$$

In the limit where the laser field is much larger than the particle's wakefield and when no energy from the laser or the particle field remains stored in the interaction region Poynting's theorem leads to an alternate very simple expression that equates the particle energy gain to the laser and particle radiated field overlap [1,2]

$$\Delta U = -\frac{1}{\pi Z_0} \int_{-\infty}^{\infty} \oint_S \left(\vec{E}_R(\omega) \cdot \vec{E}^*{}_{TR}(\omega) \right) ds\, d\omega \tag{2}$$

Z_0 is the vacuum impedance, and $\vec{E}_R(\omega)$ and $\vec{E}^*{}_{TR}(\omega)$ are the phasors from the laser component leaving the volume of interest and the wake-field respectively.

First consider the interaction with a flat reflecting boundary. Direct evaluation of equations 1 and 2 for the energy gain of a laser-driven electron in the presence of a reflective flat boundary at any orientation yield the same result [3]. In a situation where the electron and the laser interact in the upstream space of the boundary, and in the relativistic limit $\gamma >> 1$ equation (1) leads to

$$\Delta U = \int_{-\infty}^{0} q E_{z,laser}(z, t(z)) dz \tag{3}$$

In this situation, when $\gamma >> 1$, the reflected laser beam produces a negligible contribution to the electron energy change, and therefore only the incident laser field plays an important role in the path integral equation (3). For a laser plane wave of amplitude E_0, crossing angle α and polarization angle ρ it is found to be [3]

$$\Delta U = -\frac{qE_0\lambda}{\pi} \frac{\alpha}{\alpha^2 + 1/\gamma^2} \cos\rho \sin\phi_L \tag{4}$$

q is the electron charge, λ the laser wavelength, and is ϕ_L the optical phase. It can be appreciated that the electron energy gain ΔU is expected to be proportional to E_0 and λ, to depend on the laser polarization angle and on the optical phase of the laser. The dependence on the laser-crossing angle $F(\alpha) = \alpha / (\alpha^2 + 1/\gamma^2)$ follows the transition radiation cone amplitude and has a maximum at $\alpha_{\max} = \pm 1/\gamma$. Evaluation by the inverse radiation picture can be shown to lead to exactly the same energy change expression as in equation (4).

The equivalence between the two pictures can also be shown straightforwardly for laser acceleration in the presence of a transparent boundary. Both interaction pictures predict an energy gain of the form

$$\Delta U \sim \frac{qE_0\lambda\cos\rho}{\pi} \frac{\alpha}{\alpha^2 + 1/\gamma^2} \left\{ \sin\phi_L - \sin(\phi_{ret} + \phi_L) \right\} \tag{4}$$

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where ϕ_{ret} describes the optical delay introduced by the transparent boundary, and not surprisingly, a π–phase shift of the optical field at the boundary allows for net energy gain both upstream and downstream of the boundary and hence for twice the interaction strength than that found with the reflective boundary.

PARTICLE ACCELERATION FROM ROUGH- SURFACE AND ABSORBING BOUNDARIES

The laser-electron interaction in the presence of these boundaries does not deliver an evaluation of the electron energy change that is as clear-cut. For example, the currents on a rough-surface boundary that are induced by the laser field or the particle's retarded field are not well defined. The exact form of the electromagnetic field radiated from these reaction currents and its corresponding action on the charged particle depends on the structure details of the surface. In light of this a precise analytical evaluation by either the path integral method or the inverse radiation picture is a very difficult approach.

However, in spite of this shortcoming a general statement on the approximate energy exchange between the free particle and the laser is possible to attain. If the boundary is an effective scatterer the electromagnetic field that is re-radiated from this type of surface can be expected to be distributed in an incoherent fashion over a large angular spectrum. For an incident wave with a k-vector $\vec{k}_0$ the angular spectrum $\vec{F}(\vec{k},\vec{k}_0)$ of the scattered wave from a boundary *S* is [5].

$$\vec{F}(\vec{k},\vec{k}_0) = \frac{\vec{k}}{4\pi i} \times \oint_S \left(e^{-i\vec{k}\cdot\vec{x}}\, \frac{\vec{k}\times(\hat{n}\times\vec{B}_s)}{k} - \hat{n}\times\vec{E}_s \right) d^3x \qquad (5)$$

$\vec{E}_s$ and $\vec{B}_s$ are the electric and magnetic fields at the surface *S*, and $\hat{n}$ is the local surface normal vector. As shown in equation 5, $\vec{F}(\vec{k},\vec{k}_0)$ depends on the detailed shape and local properties of the surface *S*.

In this scattering picture the total field is formed by the linear superposition of the incident plus the scattered electromagnetic waves. By conservation of energy, the power of the scattered electromagnetic waves is drawn from the incident wave. Therefore the total scattered radiation spectrum $\vec{F}(\vec{k},\vec{k}_0)$ from a very strong scatterer can be described by the superposition of a broad angular distribution function $\vec{G}(\vec{k},\vec{k}_0)$ and a delta function $\vec{\delta}(\vec{k},\vec{k}_0)$ that effectively cancels the incoming wave in the downstream space of the scatterer.

$$\vec{F}(\vec{k},\vec{k}_0) = \vec{G}(\vec{k},\vec{k}_0) - \vec{\delta}(\vec{k},\vec{k}_0) \qquad (6)$$

From a path integral perspective the energy change of the particle can be divided into an interaction in the upstream and another interaction in the downstream space. In light of equation 6 the interaction on the upstream space is given by the contribution from the laser field plus the total field of the backwards scattered spectrum, described by $k_z < 0$.

$$\Delta U_{upstream} = \int_{-\infty}^{0} q\left(E_{z,laser} + \int_{k_z<0} \vec{G}(\vec{k}) e^{i\vec{k}\cdot\vec{r}} d^3k \right) dz \qquad (7)$$

Since $k_{0z} > 0$ the delta function does not contribute in equation 7. Since the scattered waves travel opposite to the free particle their slippage distance and contribution to the energy change is negligibly small compared to the contribution from $E_{z,laser}$. Hence

$$\Delta U_{upstream} = \int_{-\infty}^{0} q E_{z,laser} dz \qquad (8)$$

In the downstream space the delta function cancels $E_{z,laser}$ and the energy gain is the remaining contribution from the scattered field

$$\Delta U_{downstream} = \int_{0}^{\infty} q \int_{k_z>0} \vec{G}(\vec{k}) e^{i\vec{k}\cdot\vec{r}} d^3k dz \qquad (9)$$

For a strong scatterer the phase between the plane wave components of different $\vec{k}$ is random, and hence the integral of this incoherent spectrum is negligibly small compared to the integral of the single plane wave in equation 8. Therefore the total energy change in the presence of a strong scatterer boundary can be expected to be approximately

$$\Delta U = \int_{-\infty}^{0} q E_{z,laser} dz \qquad (10)$$

A black absorber boundary, if viewed as a scatterer that in addition to radiating in a large angular spectrum also does so into a large frequency spectrum, is expected to yield a similar result when analyzed with the field path integral method.

If the presented field path integral analysis for a strong scattering and strong absorbing boundary is accurate it implies that the surface currents from these boundaries have the same general structure impedance as an ideal reflective boundary, even if the scattered field spectrum is far from resembling a collimated reflected laser beam.

PROPOSED EXPERIMENTS

The prediction from the field path integral picture that the detailed surface properties of a strong scattering or absorbing boundary have no significant effect on the total particle energy change is interesting to investigate experimentally.

We plan to measure the dependence of the laser-driven particle acceleration strength as a function of the laser crossing angle and the laser polarization and compare to the dependence on these parameters as is shown in equation 4. In addition, we will record the scattered laser beam and look for a possible correlation between the angular spectrum of the scattered laser field and the observed laser-electron interaction.

Should a correlation between the scattered laser field angular spectrum and electron beam energy change be observed it will imply that the general field-path integral analysis presented earlier is not an accurate description of the interaction, and a more complete model that fully takes into account the surface currents of the scatterer will have to be implemented in future experiment which semi-open accelerator geometries. Figure 1 shows a diagram of the proposed setup.

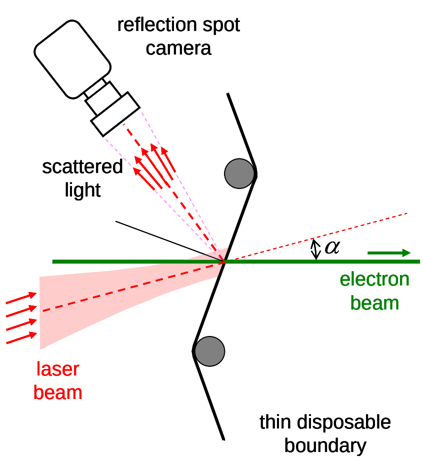

Figure 1

The laser beam will be oriented at crossing angles in the vicinity of $\alpha \sim 8$ mrad with respect to the electron beam. 8 mrad is the optimum crossing angle for an electron beam of 60 MeV. This corresponds to the peak of the transition radiation cone angular distribution. To be able to monitor a reflected or scattered beam without obstruction of the electron beam the boundary will be mounted at an oblique angle of about 20° to the electron beam. The boundaries available to us are

- Al-coated Kapton 8 μm thick
- Au-coated Kapton 8 μm thick
- uncoated clear Kapton, 8 μm thick
- uncoated clear Polyethylene, 6 μm thick
- black Kapton film, 30 μm thick
- audio tape, ~ 15 μm thick
- tape cleaner fiber, unknown thickness

Most of these tape varieties have already been tested with electron beam, and the energy spread degradation was observed to be negligible compared to the measured laser-driven energy modulation [6].

Experiments with the transparent boundary will require an optical phase delay monitor to measure ϕ_L in equation 4. This will be accomplished by monitoring the interference of the transmitted laser beam with a reference pickoff laser beam that does not traverse the transparent film. To minimize reflection losses the film will be mounted at near-Brewster angle with respect to the laser beam. Slight variation about Brewster's angle will provide tuning of the optical phase delay ϕ_{ret} and will enable us to verify the expected doubling or total cancellation of the laser-electron interaction as indicated in equation 4.

All these experiments will take place at the E163 facility at SLAC. In the past months we have commissioned the electron beam and have succeeded in testing the equipment and diagnostics of our beam line. We look forward to carrying out the proposed experiments in the very near future

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