High-Efficiency Nonadiabatic Trapping of Electrons in the Ponderomotive Potential Wells of Laser Beats

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Abstract—We report experimental results on nonlinear interactions between a nonrelativistic electron beam and the ponderomotive field (beat wave) of two counterpropagating pulsed CO_2 laser beams, operating at different frequencies in a stimulated Compton scattering scheme. Very high electron trapping efficiencies were obtained by applying a new scheme of a nonadiabatic shift in the energy of the electrons in order to bring them into resonance with the ponderomotive wave. With an axial decelerating electric field applied along an interaction path of 12 cm, trapping efficiencies of above 60 percent with energy transfer of 6 eV between the electrons and the radiation field were obtained.

THE fundamental interaction scheme consisting of two high-power electromagnetic beams and a beam of freely propagating electrons has been of interest since the early developmental stages of quantum electrodynamics [1]. Presently, the interest in this interaction revolves around the development of new high-power radiation sources based on intense relativistic electron beams (free electron lasers). A basic distinction exists in the nonlinear regime between electrons that are trapped or untrapped by the ponderomotive potential wells generated by the electromagnetic fields [2]. This trapping process is the basic saturation mechanism in constant parameter FEL's. Efficiency enhancement schemes proposed for these lasers are based on the continuous energy extraction from deeply trapped electrons [2], [3]. For these schemes to operate well, it is necessary that a big fraction of the electrons will be trapped in the ponderomotive potential wells at the beginning of the interaction region and kept trapped along the entire interaction length. A different type of energy exchange between the electrons and the ponderomotive beat wave exists and is experienced by electrons which go through synchronism with the beat wave without getting trapped. This type of interaction, called phase area displacement (PAD), can only provide small energy transfer of the order of magnitude of the potential wall depths [3]. In previous articles [4], [5], we reported observations that clearly distinguished between electrons experiencing trapping or phase area displacement (PAD), depending upon their condition while approaching resonance. In the present letter we report the attainment of high trapping fractions by applying a new scheme that introduces abrupt (nonadiabatic) changes in the axial field within the inter-

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action region. This scheme permits the injection of the electrons right into the potential wells of the ponderomotive wave at a place along the interaction region where the ponderomotive field is in full strength. This is in contrast to the adiabatic injection scheme in which the electron beam must be kept in synchronism with the ponderomotive wave for many periods, while the wells deepen gradually and grow around the electrons. The abrupt injection scheme is not only a more efficient way to achieve high initial trapping fraction but may also be the only way to inject electrons efficiently into fully built up traps in interaction schemes such as electromagnetic pump FEL [6], two-stage FEL [7], and laser beat accelerators [8]. The significantly high trapping (more than 60 percent) measured in this first experiment suggests that this simple but highly effective trapping scheme deserves a detailed theoretical modeling and further experimental investigation.

The governing equation of motion of an electron in a ponderomotive field is the axial force equation [2], [9]:

$$\frac{d(\gamma m v_z)}{dt} = -eE_{ax}(z) - eE_p \cos\left\{(\omega_s - \omega_w)t - (k_s + k_w)z\right\}$$
(1)

where E_{ax} is the externally applied axial field and E_p is the ponderomotive field given by

$$E_{p} = \frac{e\sqrt{\mu/\epsilon}}{\gamma_{r}mc^{2}} \left(\lambda_{s} + \lambda_{w}\right) \left|\hat{e}_{s} \cdot \hat{e}_{w}\right| \frac{\sqrt{P_{s}P_{w}}}{\pi^{2}w_{s}w_{w}}.$$
 (2)

 \hat{e}_s , \hat{e}_w , P_s , P_w , w_s , w_w are the polarization unit vectors, powers and waists of the signal and wiggler waves, respectively. The resonance electron velocity v_r is given by

$$v_r = \frac{\omega_s - \omega_w}{k_s + k_w} \tag{3}$$

and the resonance phase ψ_r is given by

$$\psi_r = \sin^{-1} \left(\frac{E_{ax}}{E_p} \right). \tag{4}$$

Only electrons which are inserted into the ponderomotive field with an energy around γ_r and a phase around ψ_r are trapped inside the ponderomotive buckets and can exchange (gain or lose) energy with the radiation field. Electrons achieving the resonance energy γ_r within the interaction region do not get trapped since they follow open orbits in phase space. Instead of trapping, they experience

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Fig. 1. Electron trapping mechanism by a fast (nonadiabatic) change in the ponderomotive field amplitude.

the phase area displacement mechanism [2], [3] and exchange energy in an opposite direction relative to the trapping process. Fig. 1 shows the conservation of energy diagram of an electron in the combined ponderomotive and decelerating dc fields. The diagram is shown as viewed in the rest frame of the ponderomotive potential. In this moving frame all of the fields are static and the system is conservative. Electrons with a constant energy injected in a constant ponderomotive field are reflected and cannot get trapped in the ponderomotive buckets, as shown in curve (a). In order to trap the electrons inside the buckets either the amplitude of the laser fields has to rise gradually or alternatively the energy of the electrons has to go down steeply during the approach of the electron as shown in curve (b). Such a change in potential energy of the electron can only be attained by a force which looks time dependent in the moving frame. If the time variation of the field in this frame is faster relative to one synchrotron oscillation period transit time, a nonconservative abrupt reduction of the electron energy takes place and consequently the electron is inserted into the trap.

In our experiment the two different schemes for inserting electrons into traps are realized in two ways.

• 1) At the entry the electron beam is bent into the propagation axis of the field of the lasers using a gradually bent axial magnetic field. In this case, during the entry the electrons experience a gradual rise of the laser fields determined by the Gaussian profile of the beams and the curvature of the electron path at the entry.

• 2) The dc electrostatic potential is lowered steeply (nonadiabatically) to bring the electrons to the resonance energy, as shown in Fig. 1. This fast temporal variation field as witnessed in the moving frame is realized in the lab frame by means of fast spatial variation of the electrostatic potential along a short section (1 cm) of the interaction region. In the ponderomotive wave rest frame the spatial field variation looks like a temporal field impulse of 0.5 ns. In Fig. 2 we display the computer simulation results for the trapping efficiency achieved by the spatial field variation shown in Fig. 3(b). The ponderomotive field was 230 V/m superimposed on a dc axial field of 65



Fig. 2. Electron trapping efficiency against the relative electron energy using an abrupt axial field of 1000 V/m.



Fig. 3. Experimental tube (a), potential along the tube (b).

V/m, with a maximum axial abrupt field of 1000 V/m, and the electrons were assumed to be injected without energy spread. The periodicity of the efficiency variation as a function of electron energy is associated with the energy drop along one period of the ponderomotive potential (see Fig. 1).

In the experiment we used two intense TEA CO₂ laser beams with wavelengths of 10.6 and 9.3 μ m for the wiggler and the signal fields, respectively. Special techniques were used in order to make the lasers generate pure monochromatic signals [5]. Both beams are pulsed (about 150 ns) and are synchronized with each other. They interact inside the test tube with an electron beam that is guided along the tube using a strong static axial magnetic field generated by passing a 400 A current pulse through a copper coil surrounding the electron beam, as shown in Fig. 4. The electrostatic potential was varied along the tube as shown in Fig. 3(b) by using a combination of two effects: the uniform moderate axial decelerating field of 55 V/m is generated by the ohmic potential drop associated with the 400 A current pulse through the copper coil; the abrupt potential drop at location e in Fig. 3(a) is generated by two closely-spaced hollow electrodes which are biased by an external dc power supply. After the interaction the



Fig. 4. Schematic diagram of the experimental setup.

electrons are decelerated, bent and guided along a drift tube biased at low potential (about 10 eV). The drift tube serves as an energy analyzer dispersing the trapped electron current signal in time. Electrons that acquire energy from the radiation field during the laser pulse period move faster in the drift tube and appear in the collector as a negative excess current signal followed by a positive current deficiency signal, and vice versa for electrons that lose energy to the radiation field. The collected electron signal and the laser pulses are acquired by a real time computer using three high-speed digital recorders. See Table I for details on the experiment parameters.

Several experiments were performed using this setup in order to measure the various laser-electron interaction parameters.

The energy distribution of the electrons after interaction was measured by the time of flight technique, in order to study the effect of establishing synchronism between the electrons and the ponderomotive wave at different places along the tube. The kinetic energy of the electrons at the entrance to the interaction region was varied by changing the electron gun anode potential between 1100 to 1125 V. The drift tube potential was kept positive (10 eV) to allow transport of both electrons that lost or gained energy from the radiation field. The collector current signals were recorded for eight values of the e-gun voltage which correspond to establishing synchronism between the electron beam and the ponderomotive wave at eight different locations along the interaction length. These locations are marked in Fig. 3(a) by the letters a to h. Examination of the electron current signals reveals five distinct types of interactions.

• 1) No energy transfer betwen the electrons and the laser beams was detected when the electrons were made to synchronize with the wave before the interaction region. The ac-coupled amplifier hooked to the electrons collector displayed no signal as shown in Fig. 5(a).

• 2) A weak electron trapping effect was detected when the electrons were made to synchronize at point b on the tube shown in Fig. 3. The electron current pulse given in Fig. 5(b) shows a negative current pulse followed by a positive one. The first part indicates the arrival of electrons with excess energy, and the second part represents the electron deficiency created by the accelerated

TABLE I Experiment Parameters

Signal power	350	kW
Wiggler power	200	kW
Signal wavelength	9.2938	μm
Wiggler wavelength	10.591	μm
Laser beam waist	1.4	mm
Coil current	400	Α
Axial electric field	55	V/m
Electron current	7	μÀ
Resonance energy	1088	eV



Fig. 5. Collector current for synchronisms at various locations along the interaction region (letters *a* through *h* correspond to locations *a* through *h* shown in Fig. 3). Horizontal scale: 200 ns/div, vertical scale: 1 μ A/div.

electrons. This signal waveform indicates that electrons obtained energy from the radiation wave during the laser pulses. This can be explained by adiabatic trapping of the electrons in the region of location e. The trapped electrons maintained their velocity despite the decelerating field along the interaction region.

• 3) A strong electron trapping signal as shown in Fig. 5(e) was obtained when the electrons were made to synchronize at the electrodes gap (point e in Fig. 3). In this case the trapping effect is stronger because more efficient injection of the electrons into the traps was obtained by the nonadiabatic process at the electrodes.

• 4) When the synchronism between the electrons and the wave was established at the uniform fields region (location g) a current signal in which the negative pulse follows the positive pulse [Fig. 5(g)] indicated that the electrons lost energy to the radiation wave. This is fully consistent with the PAD energy exchange mechanism which is expected to take place without trapping effect under these conditions.

• 5) Signals demonstrating combined trapping and PAD effects were recorded when the electrons were made to synchronize at intermediate locations (points c, d, and f of Fig. 3). In these cases the collector current pulses of Fig. 5(c), (d), and (f) show various proportions of decelerated and accelerated electrons.

To measure the maximum achievable trapping efficiency we adjusted the initial kinetic energy of the electrons to synchronize at point e of Fig. 3. The drift tube potential lowered to a value that just cuts off the electron current at the collector when no laser pulses are present. This way we assured that the current measured at the collector originates only from electrons which acquired energy by the radiative interaction, namely by the trapping interaction process. The measured current in this case was in favorable conditions about 60 percent of the beam current. The trapping fraction may be even higher than this because the temporal dispersion of the accelerated electrons pulse during their transport in the drift tube reduces somewhat the pulse peak current.

We measured the amount of energy transfer from the radiation field to the electrons by the method of retarded potential. While trapping the electrons by the abrupt field at location e, we varied the potential of the drift tube changing it to negative values until no current was noticed, indicating that all of the electrons were reflected back. The highest negative value obtained was about 6 eV. This is quite close to the amount of energy expected to be acquired by the trapped electrons which keep constant velocity in a decelerating field of 0.55 V/m along the interaction length of 12 cm between points e and h.

In conclusion, we proposed and demonstrated in this letter a new scheme for enhanced trapping of electrons in the ponderomotive potential wells of laser beats by means of an abrupt change in the energy of the electrons. We also measured effects of adiabatic trapping and PAD. All these measurements agreed well with our theoretical model computations. Our experimental scheme is useful for the study of the physics of full-scale elaborate FEL's operating in the nonlinear and efficiency enhancement regime. The newly-proposed nonadiabatic trapping scheme may be useful in FEL configurations based on electromagnetic wigglers and in particular, two-stage FEL's.

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