Laser-driven electron cyclotron autoresonance accelerator with production of an optically chopped electron beam

J. L. Hirshfield[1,2] and Changbiao Wang[1]
[1]*Department of Physics, Yale University, New Haven, Connecticut 06520-8120*
[2]*Omega-P, Inc., Suite 100, 345 Whitney Avenue, New Haven, Connecticut 06511*
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Analysis is presented of the gyroresonant acceleration of electrons in a vacuum using a focused laser. Continuous and equal acceleration is shown for electrons injected at all optical phases over an interaction length of tens of centimeters. Beam stalling is avoided as beam energy increases. Acceleration from 50 to 178 MeV is predicted for a 4 TW, 10.6-μm laser focused to a waist radius of 1.0 mm; these parameters correspond to a planned experiment. A beam stop with an off-axis hole after acceleration is shown to create a train of optically chopped bunches with 3-fs bunch lengths and a 35-fs period.

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Electron acceleration using intense lasers has engendered widespread attention within the accelerator research community, stimulated mainly by the enormous optical electrical field strengths E that can be obtained with a focused laser in a vacuum, i.e., of the order of $E = 3\times 10^{-9}\sqrt{I}$ TV/m, where the intensity I is in W/cm^2 [1]. Since compact terawatt-focused lasers can have $I > 10^{18}$ W/cm^2, field strengths of the order of TV/m are possible. Of course, since this field is transversely polarized, it cannot give much net energy gain directly to a charged particle, so a number of indirect means have been devised to achieve cumulative acceleration. For example, in the laser wake field accelerator [2], an intense laser pulse is used to create a strong longitudinally polarized plasma wake field for acceleration. In the vacuum beat-wave accelerator [3], two laser pulses of different frequencies are combined to create a slow optical ponderomotive beat wave that can exert a strong force for acceleration. Electron acceleration to over 100 MeV has been observed in laser wake field accelerator experiments, corresponding to an acceleration gradient of the order of 30 GeV/m [4]. The energy spread of electrons that are accelerated in this manner is usually not small, since particles are acted upon throughout the nonuniform plasma wake. Moreover, the acceleration length is limited to a few Rayleigh lengths, usually less than a few millimeters for tightly focused optical radiation. These facts have led to experiments in which an optically prebunched beam is created, so that injected electrons in an inverse Čerenkov accelerator might all enjoy nearly the same acceleration [5,6]; or by exploitation of an injection mechanism (laser ionization and ponderomotive acceleration), wherein an energetic highly directed bunched beam is born within the optical focus [7]. Channeling has been suggested as a means to allow acceleration over many Rayleigh lengths [8]. Progress in the wide field of laser-based accelerators is summarized in a recent review [9].

This Brief Report describes a laser-driven acceleration mechanism in a vacuum that does not require a prebunched beam; nevertheless, all injected electrons can enjoy nearly the same acceleration history, regardless of their initial optical phase. A tight laser focus is not required, so the Rayleigh length can be tens of centimeters for a 10.6-μm laser wavelength, and continuous acceleration over meter-length paths is predicted. Furthermore, since the accelerated beam gyrates in a transverse plane at the laser frequency, an interposed beam stop with a judiciously placed off-axis hole can be employed to produce a transmitted beam comprising a train of optically chopped bunches with bunch lengths below 1 μm (3 fs). An example is presented of the acceleration of a beam from 50 to 178 MeV using a 4 TW, 10.6-μm wavelength laser in a nonuniform magnetic field peaking at 81 kG; a rf linear accelerator and a CO_2 laser with these parameters are to be available for a proposed experiment at Brookhaven National Laboratory [10].

The underlying mechanism, cyclotron autoresonance acceleration (CARA), has heretofore been studied mainly as a microwave interaction, where theory predicts and experiments show efficiencies exceeding 95% for transforming microwave energy into directed beam energy [11]. Phase bunching—but not spatial bunching—occurs in CARA, so that all injected electrons can be arranged to experience nearly the same magnitude of accelerating fields. However, a microwave CARA is in practice only a ''γ doubler,'' in that the relativistic energy factor $\gamma = W/mc^2$ cannot in practice be increased much beyond a factor of 2 in a single stage, due to stalling of the electron beam in the required up-tapered guide magnetic field. In this expression, W is the electron rest energy mc^2 plus kinetic energy. It will be shown below that the CARA stalling limit can be circumvented when a focused optical field is used in place of a guided microwave field since, in the optical case, the axial magnetic need not necessarily be continuously up-tapered. Another feature of the laser-driven CARA, hereafter dubbed LACARA, is the relatively low level of magnetic field required for the cyclotron resonance interaction: for high beam energies, the magnetic field scales roughly as $1/\gamma\lambda$, where λ is the optical wavelength. As a result, state-of-the-art superconducting solenoid magnets are suitable for a 100-MeV demonstration of LACARA operating at $\lambda = 10.6$ μm.

Laser acceleration based on cyclotron resonance was first analyzed by Sprangle, Vlahos, and Tang [12] using fields approximating a focused Gaussian. These authors identified the need for a nonuniform guide magnetic field to preserve gyroresonance, and gave an example with an acceleration

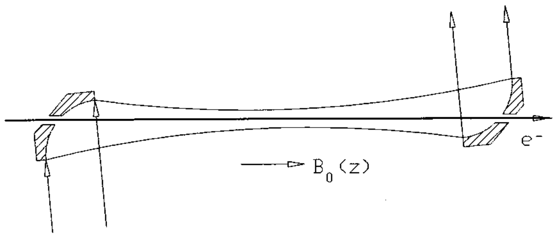

FIG. 1. Schematic diagram of LACARA. The incoming Gaussian CO_2 laser beam is focused by the left mirror, travels with the accelerating electron beam, and is deflected out of the beam path by the right mirror. Gyrations of the beam orbit are too small to be seen on the scale of this diagram.

gradient of 31 MeV/m for a $\lambda=10.6$-μm, $I=1\times10^{13}\,\mathrm{W/cm^2}$ laser. More recently, other authors have analyzed acceleration that is based on cyclotron resonance [13–15]. However, none of this prior analysis considered acceleration into and beyond a laser focus, and thus failed to show that the magnetic field will fall in magnitude after the focus, thereby avoiding stalling so that no upper limit to acceleration is imposed.

The analysis presented below is for a traveling Gaussian laser beam focused by a parabolic mirror, as shown in Fig. 1. The second mirror is solely to direct the spent laser beam away from the beam axis. The electron beam is taken to be injected and extracted through holes in each mirror. An axisymmetric nonuniform magnetic field is imposed on the system, as provided by a system of surrounding coils not shown in the figure. The form of this magnetic field is determined self-consistently by requiring that gyroresonance be maintained along the particle orbits. The electromagnetic fields in cylindrical coordinates (r, θ, z) for the lowest-order Gaussian mode in such a configuration excited with circular polarization are given by [3]

$$E_r=cB_\theta=E_0\frac{w_0}{w}\exp(-r^2/w^2)\cos(\psi-\theta), \tag{1}$$

$$E_\theta=-cB_r=E_0\frac{w_0}{w}\exp(-r^2/w^2)\sin(\psi-\theta), \tag{2}$$

$$E_z\approx-E_0\frac{2}{kw}\frac{w_0}{w}\frac{r}{w}\exp(-r^2/w^2)\times\left[\sin(\psi-\theta)+\frac{z}{z_R}\cos(\psi-\theta)\right], \tag{3}$$

$$B_z\approx-\frac{E_0}{c}\frac{2}{kw}\frac{w_0}{w}\frac{r}{w}\exp(-r^2/w^2)\times\left[\cos(\psi-\theta)-\frac{z}{z_R}\sin(\psi-\theta)\right], \tag{4}$$

where the waist radius w_0 in the focal plane $(z=0)$ and the Rayleigh length z_R are related by $w_0=(\lambda z_R/\pi)^{1/2}$, with $\lambda=2\pi/k$ the radiation wavelength. The radius of the radiation pattern for $z\neq0$ is $w(z)=w_0[1+(z/z_R)^2]^{1/2}$, the phase is $\psi(z,r,t)=\omega t-kz+\tan^{-1}(z/z_R)-kr^2/2R$, and the radius of the curvature of the rays' normal surfaces is given by $R(z)=z+z_R^2/z$. The coordinates (r,z) on surfaces of constant phase, i.e., where $d\psi/dt=0$, lead to $\omega=k_zv_{p,z}+k_rv_{p,r}$, with axial and radial phase velocities $v_{p,z}=dz/dt$ and $v_{p,r}=dr/dt$. The effective axial and radial wave numbers, found from $k_z=-\partial\psi/\partial z$ and $k_r=-\partial\psi/\partial r$, are

$$k_z=k-\frac{z_R}{z_R^2+z^2}+\frac{k}{2}\frac{(z_R^2-z^2)r^2}{(z_R^2+z^2)^2},\quad k_r=\frac{kzr}{z_R^2+z^2}. \tag{5}$$

Laser power P_L is related to the electric-field amplitude E_0 by $P_L=\pi\sqrt{\varepsilon_0/\mu_0}E_0^2w_0^2/2$. Some prior analyses [13,14] of gyroresonant acceleration consider uniform optical fields, thereby neglecting both diffraction and axial components.

The condition to be met for gyroresonance between electrons and the electromagnetic wave is given by the relation $\omega-k_{z0}v_z-\Omega_0/\gamma=0$, where v_z is the axial component of the electron velocity, $k_{z0}=k_z(z,r=0)$, and where the gyrofrequency on the axis is $\Omega_0(z)=eB_0/m$ with $B_0=B_z(z,r=0)$ the axially symmetric static magnetic field. The on-axis field can be used in the resonance condition in this case since radial excursions are much smaller than both the Rayleigh length and the scale length $|\partial\ln B_z/\partial r|^{-1}$. Clearly, resonance can be maintained along the orbit for an accelerated electron if the magnetic field is tailored in space to track the variations in γ and v_z. An equivalent way to write the resonance condition is $\Omega_0=\gamma\omega(1-n\beta_z)$, where $\beta_z=v_z/c$ and $n(z)=ck_{z0}/\omega=1-w_0^2/2zR(z)$ are the normalized axial velocity and effective index of refraction, respectively. When ensembles of particles with narrow variances are considered, the resonance condition can be approximated as $\Omega_0/\omega=\langle\gamma\rangle(1-n\langle\beta_z\rangle)$, where the angle brackets indicate ensemble average values.

The above field equations, Eqs. (1)–(4) together with the relativistic equation of motion for the electrons,

$$\frac{d}{dt}(\gamma\mathbf{v})=-\frac{e}{m}(\mathbf{E}+\mathbf{v}\times\mathbf{B}), \tag{6}$$

allow solutions to be found for single-particle orbits. In the results of computations, to be shown below, iterative solutions for the position, velocity, and energy of the particles are found at each computational stage by specifying the change in guide magnetic-field value necessary to maintain resonance. This insures that the solutions are internally consistent.

An example of predicted LACARA performance is shown in Fig. 2 for an incident 10.6-μm CO_2 laser power of 4 TW, an initial electron-beam energy of 50 MeV, a current of 1 A, and an initial normalized beam rms emittance of

$$\varepsilon_{nx}=\sqrt{(\gamma^2-1)(\langle x^2\rangle\langle x'^2\rangle-\langle xx'\rangle^2)}=\varepsilon_{ny}$$
$$=\sqrt{(\gamma^2-1)(\langle y^2\rangle\langle y'^2\rangle-\langle yy'\rangle^2)}=2.0\,\mathrm{mm\,mrad}$$

[10]. In the computation, a total of 904 computational particles were injected, uniformly distributed in the optical phase and transverse phase spaces within emittance ellipses having major and minor axes r_b and $\beta_{\perp\max}$, with the beam radius $r_b=0.1$ mm and $\beta_{\perp\max}=\max\sqrt{\beta_x^2+\beta_y^2}$. The waist radius w_0 was chosen to be 1.0 mm, or approximately 100 optical wavelengths. This leads to a Rayleigh length z_R

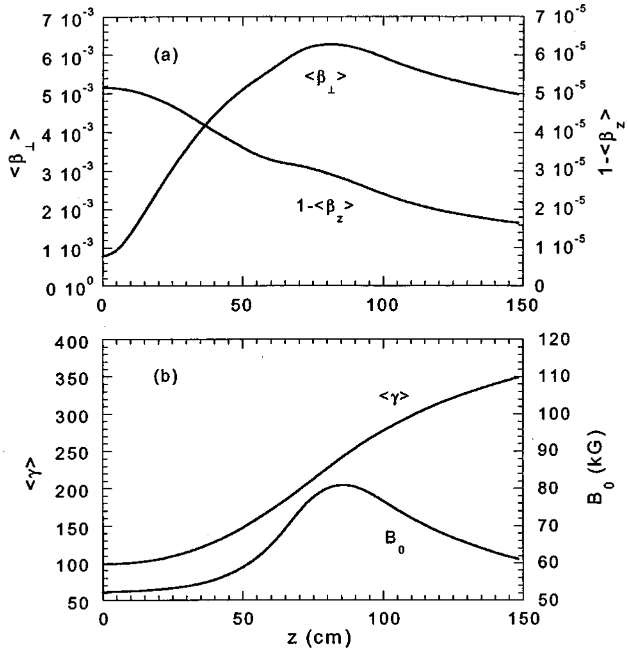

FIG. 2. (a) Average normalized transverse velocity $\langle\beta_\perp\rangle$ and normalized axial velocity, plotted as $1-\langle\beta_z\rangle$; (b) average relativistic energy factor $\langle\gamma\rangle$ and axial magnetic field B_0; (a) and (b) as functions of axial coordinate z in LACARA. For this example, the initial beam energy is 50 MeV, beam current is 1 A, Rayleigh length $z_R=29.64$ cm, laser-beam waist $w_0=1.0$ mm, interaction length $5z_R=148.2$ cm, and laser power $P_L=4.0$ TW. The acceleration gradient at $z=75$ cm is 147 MeV/m.

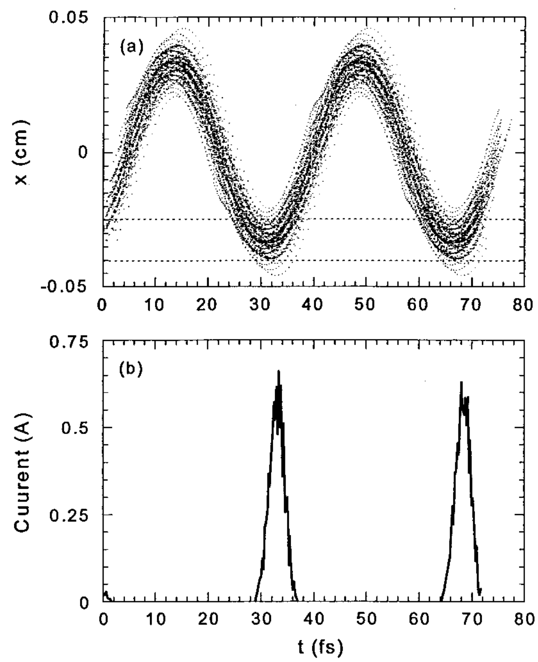

FIG. 3. (a) Phase plot for two optical cycles in the x-t plane at $z=2z_R=59.3$ cm for an ensemble of beam particles with initial normalized rms emittance $\varepsilon_{nx}=2.0$ mm mrad after acceleration from 50 to 110 MeV. Horizontal dashed lines show limits in x of the aperture in the beam stop. A similar plot, shifted one quarter-cycle in phase, depicts the y-t phase space. (b) Current transmitted through the 0.08-mm radius tunnel in a 2-cm beam stop. Incident current is 1.0 A. Microbunches in this example have FWHM widths of 3 fs, with an interbunch spacing of 35 fs. See text for details.

$=29.64$ cm. A mirror separation of $5z_R=148.2$ cm was chosen, with a mirror radius of 85.95 cm. Figure 2(a) shows the computed mean axial and transverse normalized velocities $1-\langle\beta_z\rangle$ and $\langle\beta_\perp\rangle$ as functions of distance along the axis, showing that the transverse momentum never exceeds 0.63% of the axial momentum; this insures that the motion remains well within the 2-mm-diam optical waist. Furthermore, $n>\beta_z$ throughout the interaction. The electrons execute about five gyrations in traversing the 148-cm intermirror distance, reflecting the strong Doppler down-shifted laser frequency experienced by the electrons, due to the small value of $1-n\langle\beta_z\rangle$. Figure 2(b) shows both the mean relativistic energy factor $\langle\gamma\rangle$ and the magnetic-field strength $B_0(z)$ versus axial distance. It is seen that the mean beam energy is predicted to rise monotonically from 50 to 178 MeV in a distance of 148 cm, corresponding to a maximum acceleration gradient at $z=75$ cm of 147 MeV/m and an average acceleration gradient of 86.6 MeV/m. The resonance magnetic field required rises from 52 to about 81 kG near the laser focus, and then falls back to about 60 kG. It is the fall in magnetic field beyond the focus that allows acceleration to continue without stalling; this fall in magnetic field can be traced to the fall in $(1-n)$ beyond the focus. This example demonstrates that LACARA is not limited to being a γ doubler. In fact, indefinite acceleration beyond the focus is possible—albeit with an ever-diminishing acceleration gradient.

In general, computations for a range of laser power levels, waist radii, and acceleration lengths show that energy gain increases as laser power increases, but more slowly than linearly; that energy gain falls with increasing initial beam energy; that energy gain is approximately independent of waist radius when the overall interaction length is held constant; and that the average acceleration gradient increases as waist radius decreases, provided the overall acceleration length contains a constant number of Rayleigh lengths. For example, with $P_L=4.0$ TW, $w_0=0.60$ mm, $L=5z_R=53.4$ cm, and an initial beam energy of 50 MeV, one finds an energy gain of 65.6 MeV and an average acceleration gradient of 123 MeV/m. For $P_L=1.0$ TW, with the other parameters unchanged, the average acceleration gradient falls to 46.9 MeV/m. For $P_L=4.0$ TW, with the initial beam energy increased to 80 MeV and other parameters unchanged, the average acceleration gradient falls to 42.5 MeV/m. In yet another example, acceleration from 0.50 to 1.50 GeV is predicted for a 4.0-PW, 10.6-μm laser with a waist of 0.30 cm over a distance of $6z_R=16$ m, for an average acceleration gradient of 64.4 MeV/m. The magnetic field for this example varies from 6 kG up to about 24 kG, then down to 13 kG.

An accelerated beam emerges from LACARA with electrons on helical orbits. The number of gyrations executed by a single electron during the interaction is few, but the gyration phases for orbits of successive electrons advance rapidly, i.e., at the laser frequency. Thus if a beam stop with an off-axis hole is interposed after acceleration, the transmitted beam will be chopped at a frequency equal to the laser frequency. A phase plot that illustrates this possibility is shown in Fig. 3(a), where two cycles of the $x-\omega t$ coordinates are plotted for an ensemble of 18 080 electrons after acceleration through an interaction length of $2z_R=59.28$ cm, with other parameters the same as in the example shown in Fig. 2. The correlation between coordinate and time is evident, so that if an aperture limits beam transmission in x, then a temporally chopped beam will emerge. Similar considerations apply in y. A computed example of such an optically chopped beam is shown in Fig. 3(b), which shows the two cycles of beam current after transmission through a 0.08-mm radius hole in a 2-cm-thick tungsten beam stop. In this example, the beam is accelerated from 50 to 110 MeV (corresponding to an average acceleration gradient of 100 MeV/m) while the resonance magnetic field varies between 54 and 67 kG. The entrance aperture in the beam stop is centered at $x = -0.32\,\mathrm{mm}$, $y=0$; the exit is centered at $x=-0.305\,\mathrm{mm}$, $y=-0.11\,\mathrm{mm}$; so the beam channel is inclined at an angle of 0.32° with respect to the z axis. These limits of x are shown in Fig. 3. As is seen in Fig. 3(b), the peak transmitted current is 0.6 A (out of an incident 1.0 A) in a train of 3-fs [full width at half maximum (FWHM)] bunches with a period of 35 fs, or equivalently 0.9-μm bunches spaced by 10.6 μm. Such an optically chopped beam could find an application as an injector for other laser-based accelerators in a harmonic generator of optical radiation, in the generation of femtosecond x-ray pulses, or in studies of excitation and lifetimes in electron-induced nuclear reactions.

This Brief Report has presented computed predictions for the acceleration of electrons in a circularly polarized, focused CO_2 Gaussian laser beam, under conditions where gyroresonance is maintained along the electron trajectory. For currently achievable CO_2 laser power levels in the multi-TW range, acceleration gradients of over 100 MeV/m and overall acceleration in 150 cm of a 50-MeV beam to 178 MeV have been shown to be achievable for a mild laser focus with a beam waist of 1.0 mm. The parameters selected for the examples presented correspond to those soon to be available for a proposed experiment [10]. This laser-based accelerator treats all electrons in a bunch nearly identically, providing the laser pulse width exceeds the bunch width. The acceleration occurs in a vacuum, without any proximate material medium—except for a mirror to focus the laser. Experience with the microwave CARA where high efficiency (>95%) for the transfer of rf power to beam power has been observed [11], suggests that the laser-driven version of LACARA could be similarly efficient. It has also been shown that if a beam stop with a small slightly inclined beam tunnel is interspersed after acceleration with LACARA, then an optically chopped beam can be produced that consists of a train of femtosecond bunches spaced by the laser period. This simple idea is, to the author's knowledge, the only mechanism yet proposed for production of a beam fully chopped on an optical time scale.

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