Free-Electron Laser and Laser Electron Acceleration Based on the Megagauss Magnetic Fields in Laser-Produced Plasmas

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(Received 27 November 1985)

It is suggested that the megagauss magnetic fields generated in laser-produced plasmas be applied for (a) the construction of a wiggler for an x-ray free-electron laser and (b) charged-particle acceleration to high energies using the inverse free-electron laser and the autoresonance laser acceleration schemes. Coherent amplification of 10-Å radiation with a 150-MeV electron beam seems feasible and gigaelectronvolt electron beams may induce a γ-ray laser. An acceleration gradient of about $[100\ \mathrm{MV/cm}][z/(10\ \mathrm{cm})]^{-1/3}$ can be achieved at a distance z along a 1-MG axial magnetic field in the autoresonance laser acceleration scheme, using a Nd:glass laser of $10^{18}\ \mathrm{W/cm^2}$.

PACS numbers: 42.55.Tb, 29.15.−n, 52.75.Di, 52.75.Ms

The spontaneous generation of strong magnetic fields in laser-produced plasmas is well known.[1–16] Many experimental observations confirming the existence of these megagauss magnetic fields were reported over more than a decade.[1–7] Different theoretical models concerning the origin and evolution of these fields were discussed.[8–16] Consideration of the fields within a fully self-consistent laser-plasma numerical code is complicated because of the two-dimensional geometry involved,[15] as shown in Fig. 1(a). However, their generation was investigated extensively by theoretical means as a possible cause for thermal-flux inhibition in fusion plasmas.[8,14]

In this paper we propose to use these large-scale dc magnetic fields for (a) construction of a wiggler for an x-ray free-electron laser (FEL), and (b) charged-particle acceleration to high energies using the inverse FEL[17] and the autoresonance[18–20] laser acceleration (ALA) schemes. For both purposes a series of close plasmas should be formed on a flat target. These plasmas can be achieved, for example, by means of the Aurora KrF laser system of Los Alamos National Laboratory.[21] This system produces 96 beams by use of angle and time multiplexing techniques. The automatic alignment system needed to direct the 96 individual beamlets through the amplifier system to a target is based upon beam-position sensing, which uses ordinary television technology linked to inexpensive small computers. These beams can be brought to the target simultaneously. A relativistic electron passes through each plasma at tenths of picoseconds, so that any hydrodynamic change in the plasma during this time is negligible. Furthermore, the formation of each plasma can be timed so that the magnetic field saturates as a known spatial structure as the electrons pass through it.

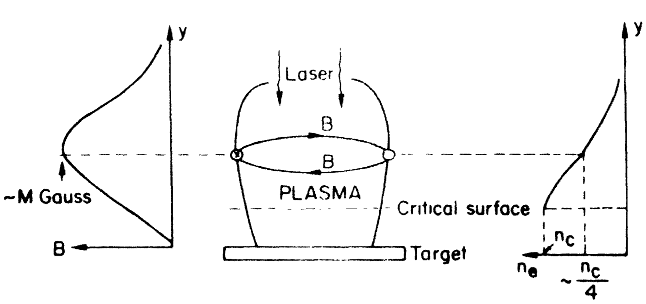

FIG. 1. Typical density (n) profile and magnetic field (B) geometry in laser-produced plasmas.

In a FEL[22–24] an electromagnetic wave is amplified at the expense of the kinetic energy of a relativistic electron beam, while in the inverse FEL (IFEL) this process is inversed.[17] The coupling between the electrons and the radiation's transverse electric field is due to a small transverse momentum given to the electrons by a periodic magnetic field, known as the wiggler. Net energy exchange between the laser field and the relativistic electron beam is possible in the FEL and IFEL schemes if the following synchronism condition is satisfied:

$$\gamma^2 = (\lambda_w/2\lambda_L)(1+a_w^2), \tag{1}$$

where γ is the relativistic factor of the electrons, λ_L and λ_w are the radiation and wiggler wavelengths, respectively, and for a linear wiggler $a_w = eB_0/\sqrt{2}mc^2k_w$, with B_0 the wiggler magnetic field amplitude, $K_w = 2\pi/\lambda_w$, c the light velocity, and e and m the electron charge and mass. When satisfying Eq. (1), a relativistic electron gains (IFEL) or loses (FEL) energy from the electromagnetic wave according to their relative phase. A possible construction of a linear-wiggler configuration of laser-produced plasmas is presented in Fig. 2(a). For this configuration, the magnetic field along the z axis ($x=0$) can be approximated by $B_w(z) \simeq B_0\cos(k_w z)$, where B_0 and k_w are both 3 orders of magnitude larger than in conventional FEL's. In addition, a plasma duct, with lower electron density at its center than at its edge, can be formed inside the wiggler by the creation of two parallel close rows of plasmas [see Fig. 2(a)]. Based on experimental evidence,[25] we assume that the magnetic field lines of two close laser-produced plasmas are connected.

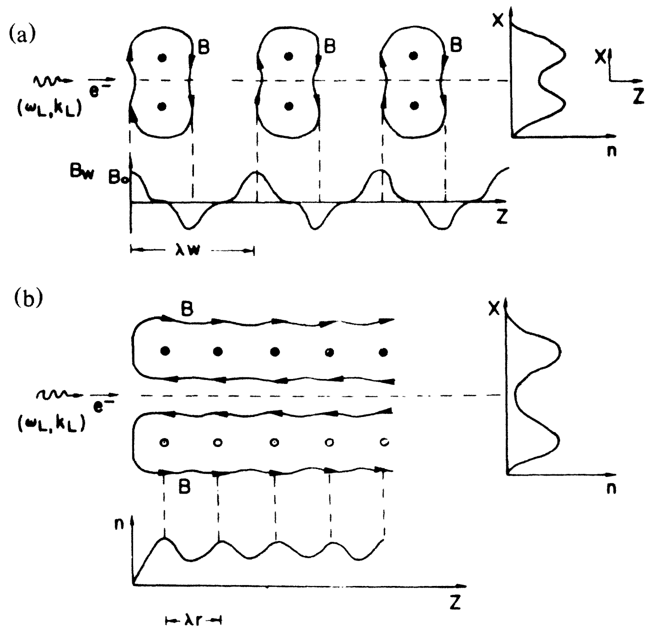

FIG. 2. (a) The configuration of laser-produced plasmas (the spot center is marked by filled circle) for FEL and IFEL applications. The radial density (n) profile decreases the divergence of the radiation which passes across it. The periodic magnetic field constructs a linear wiggler. The wiggler wavelength is approximately twice the laser spot diameter. (b) Two columns of oppositely produced plasmas form the needed magnetic field configuration for the autoresonance laser accelerator. The radial and axial density (n) profiles form a rippled plasma fiber with a wavelength λ_r.

The resulting plasma duct can decrease the divergence of the radiation field along the wiggler axis.[26]

The gain of a FEL decreases as the electron-beam energy increases.[27] By using the above mentioned wiggler under FEL operating conditions one is able to get amplification of coherent x rays with presently used (in FEL devices) electron-beam energy. Furthermore, for typical conditions of $\lambda_w = 100$ μm, $B_0 = 1$ MG, we get $a_w \simeq 1$, which gives optimal gain conditions in most conventional FEL devices.[23] The amplified radiation wavelength is obtained by setting $a_w \sim 1$ in Eq. (1); i.e., $\lambda_L/(25\text{ Å}) = [\lambda_w/(100\ \mu\text{m})][E_0/(100\ \text{MeV})]^{-2}$, where $E_0 = \gamma mc^2$ is the electron-beam energy. By use of gigaelectronvolt electron beams, a γ-ray laser may be obtained. For acceleration purposes in the IFEL scheme this wiggler should be used together with a high-irradiance, short-wavelength laser propagating across it. Thus, lower initial γ values and laser wavelengths, compared with conventional IFEL accelerators, can be used, according to Eq. (1). In principle, as the accelerating-laser wavelength decreases, higher electromagnetic fields can be used. As γ increases during the acceleration, the synchronism condition [Eq. (1)] can be maintained by a continuous increase of the laser spot diameter so that k_w and B_0 decrease[7] along the electrons' trajectory. The plasma duct inside the wiggler is a possible solution to the crucial problem of the laser-beam divergence in high-energy far-field accelerators.[27] Finally, we note that the gyration radius of the electrons in the wiggler is small; e.g., for $\lambda_w = 100$ μm it is $r = a_w/\gamma k_w = 16 a_w/\gamma$ μm.

In the autoresonance laser accelerator scheme the wiggler of the IFEL scheme is replaced by an axial magnetic field. The ALA is based on self-sustained cyclotron resonance.[18-20] This ALA concept allows acceleration of charged particles moving in phase with a circularly polarized electromagnetic wave along an axisymmetric magnetic field, i.e., they satisfy the resonance condition

$$k_L V_z - \omega_L - \omega_c/\gamma = 0, \tag{2}$$

where k_L and ω_L are the laser wave vector and frequency, γ and V_z are the relativistic factor and the axial velocity of the particles, and ω_c is the cyclotron frequency of the axial magnetic field. An exact solution for the nonlinear dynamics of electrons in the above-mentioned field configuration gives a possibility for time-unlimited phase locking between the electrons and the laser field for the luminous case, i.e., for $\omega_L/ck_L = 1$. High-current electron-beam acceleration with low radiation losses seems to be feasible for this case.[20] Furthermore, an electron beam with initially zero transverse momentum will be accelerated perpendicularly and "trapped" in phase with the laser field, if the mentioned resonance condition is satisfied initially. For this case the acceleration as a function of time is described by[20]

$$ct = \tfrac{4}{3}[(\gamma - \gamma_0)/A_1]^{1/2}(\gamma + 2\gamma_0), \tag{3}$$

where $A_1 = 8k_L\alpha_L^2|\Omega_0|$, $\Omega_0 = eB_0/mc^2$, $\alpha_L = eE_L/mc\omega_L$, B_0 and E_L are the amplitudes of the axial magnetic field and the laser electric field, respectively, and $\gamma_0 mc^2$ is the initial energy of the electron beam. The autoresonance solution is not sensitive to the initial electron-beam parameters for $\gamma >> \gamma_0$ where Eq. (3) yields that at an axial position z,

$$\gamma \simeq [3\alpha_L(\Omega_0 k_L/2)^{1/2} z]^{2/3}. \tag{4}$$

A possible configuration of laser-produced plasmas suitable for the ALA scheme is described in Fig. 2(b). Two columns of plasmas are formed on opposite sides of parallel flat targets so that their strong magnetic field contours are on a common plane. The accelerating electromagnetic wave is conducted between the columns as through a plasma fiber.[26] The wave's phase velocity can be kept equal to the light velocity as a result of the rippled structure of the fiber walls. For a similar purpose Tajima showed that the ripple wave number k_r should obey

$$\omega_L/c(k_L + k_r) = 1. \tag{5}$$

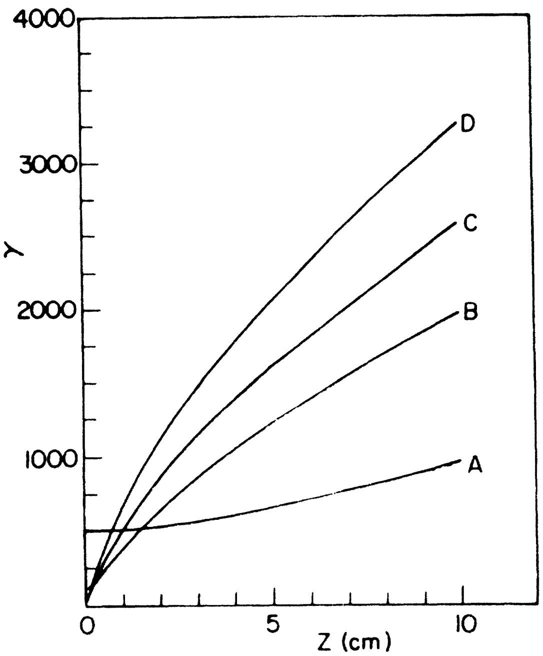

FIG. 3. The dependence of the acceleration γ vs z on the strength of the axial magnetic field for the luminous case ($\omega_L/ck_L=1$) in the ALA scheme with a 1.2×10^{18} W/cm^2 Nd:glass laser ($\alpha_L=1$, $\lambda_L=1$ μm) and $V_{\perp 0}=0$. In all the branches it is assumed that the electrons initially satisfy the resonance condition $\Omega_0=\gamma_0 k_L(V_z/c-1)$: curve a, $\gamma_0=500$, $B=100$ kG; curve b, $\gamma_0=100$, $B=500$ kG; curve c, $\gamma_0=50$, $B=1$ MG; curve d, $\gamma_0=25$, $B=2$ MG.

Therefore, the distance between each two plasma neighbors in a column [see Fig. 2(b)] should be $\lambda_r=2\pi/k_r=\lambda_L/(\omega_L/ck_L-1)>>\lambda_L$. Figure 3 demonstrates the advantage of using a megagauss axial magnetic field in the ALA scheme. An average acceleration gradient as high as 130 MeV/cm can be achieved in the first 10 cm of acceleration with an $\alpha_L=1$ accelerating Nd:glass laser pulse along a 1-MG axial magnetic field. This gradient is 3 orders of magnitude larger than the acceleration gradient of conventional linear accelerators.

Experimental observations[4,15] indicate that the spatial peak of the strong magnetic field in laser-produced plasmas is obtained at an electron density which is approximately a quarter of the critical density for the frequency ω_0 of the laser which produces the plasma (see Fig. 1). Thus for the above-mentioned applications, one should keep $\omega_0<<\omega_L$, so that the plasma density in the region of the strong magnetic field will not significantly affect the propagation of the accelerating or amplified radiation. In principle, the FEL and IFEL schemes are not very sensitive to small departures of ω_L/ck_L from 1. The use of CO_2-laser–produced plasmas together with a KrF or Nd:glass laser for acceleration in the IFEL and ALA schemes is possible. According to recent theoretical studies,[28] collisions between the plasma particles and the relativistic beam electrons have a minor effect on the beam emittance.

In summary, we suggest that future study should concern possibilities of combining more complicated magnetic field configurations (e.g., a helical wiggler configuration) by using nonparallel targets and different (e.g., cylindrical) lenses.

The authors are grateful to Dr. L. Friedland and members of the Plasma Physics Department at Soreq Nuclear Research Center for their helpful comments and assistance.

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