Electron-beam focusing by the dipole force of an ultrashort laser pulse

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The possibility of using the dipole force of the spatially nonuniform field of the TEM_{01}^* mode (a hollow Gaussian beam) of an ultrashort-pulse laser to focus a low-energy electron beam into a region 10–100 Å in size is analyzed. This effect might be utilized to develop an electron scanning microscopy which would employ low-energy electrons and which would be sensitive to the atomic and molecular structure of surfaces. © *1995 American Institute of Physics.*

A particle in an electromagnetic field $E(\mathbf{r})\cos(\omega t)$ experiences a dipole (gradient) force

$$F_{\rm dip} \approx \alpha \nabla (E^2)_{\rm av}, \tag{1}$$

where a is the polarizability of the particle, and $(E^2)_{\rm av} = I/8\pi c$ is the square of the field amplitude averaged over the oscillation period, where I is the intensity of the electromagnetic radiation. The idea of utilizing this force to accelerate charged particles by radio waves was discussed[1] in the 1950s; the idea of utilizing it to change the concentration of neutral particles, leading to self-focusing of a light beam, was discussed[2] in the 1960s. More recently, the dipole resonant force acting on an atom in a laser beam of moderate intensity has been used successfully in atomic optics (for focusing, reflection, etc., of atoms).[3] In this letter we take a look at the possibility of using the dipole force acting on a free electron in an intense, spatially nonuniform laser field to focus, rather than accelerate, a beam of low-energy electrons (with energies in the eV or keV range). The size of the focal spot can reach several tens of angstroms. This idea might be utilized in a scanning electron microscopy controlled by laser light. Because of the low energy of the electrons, the microscope would be sensitive to the atomic or molecular structure of the surfaces under study.

The polarizability of a free electron in an optical field of frequency ω is described by

$$\alpha = -\frac{e^2}{m\omega^2}. \tag{2}$$

According to Eqs. (1) and (2), the electron is repelled from the strong-field region into the low-intensity region. This repulsion might be exploited to change the trajectory of the electron. Alternatively, with an appropriate (quadratic) field profile $E(\mathbf{r})$, where $\mathbf{r}$ is the radial displacement, it might be exploited to focus an electron beam. Quite sufficient for

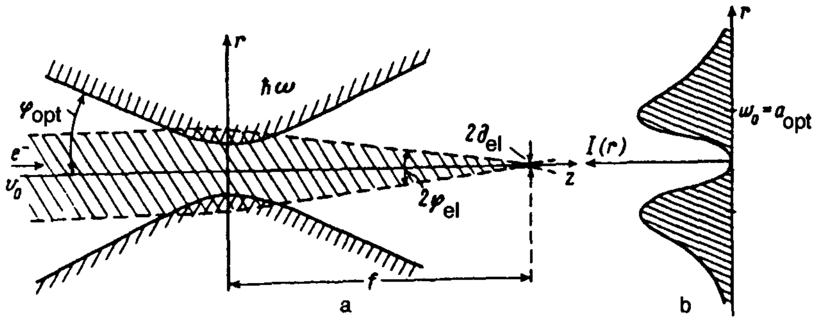

FIG. 1. Laser-field configuration for focusing an electron beam. a—Arrangement of laser and electron beams; b—transverse profile of the intensity of the laser field (the TEM_{01}^{*} mode).

this purpose would be, for example, the transverse laser mode TEM_{01}^{*}, which has a quadratic profile along the coordinate near the beam propagation axis and an intensity minimum at the axis[4] (Fig. 1):

$$I(\mathbf{r},\mathbf{z})=4I_0\frac{w_0^2}{w^2(z)}\frac{2r^2}{w^2(z)}\exp\left(-\frac{2r^2}{w^2(z)}\right), \tag{3}$$

where w_0 is the radius of the beam waist in the $z=0$ plane, $w(z)=w_0(1+z^2/z_R^2)^{1/2}$ is the radius of the waist in the z plane, $z_R=(\pi/\lambda)w_0^2$, w_0 is the Rayleigh length, $I_0=P_0/2\pi w_0^2$ is the intensity of the electromagnetic radiation, and P_0 is the power of this radiation. This field configuration was discussed in Ref. 5 for sharp focusing of an atomic beam.

The exact calculation will be reported in detail separately. Here we note that in the approximation of paraxial electron optics $(r/w\ll 1)$, i.e., near the beam axis, we can estimate the change in the electron velocity in the transverse direction as the electron crosses the half-intensity region of the laser field:

$$\Delta v_r\simeq\frac{e\lambda}{mc}\left(2\frac{I_0}{c}\right)^{1/2}\ll v_0, \tag{4}$$

where v_0 is the electron velocity in the longitudinal direction. We are assuming here that the optical field acts over the entire time take by the electron to pass through the focus, τ_{int}; i.e., the duration of the laser pulse satisfies $\tau_{pulse}\gg\tau_{int}=(2\lambda_{opt}/\sin\varphi_{opt})/v_0$.

The aperture angle of the electron beam being focused, $2\varphi_{el}$, is related to the aperture angle of the laser pulse causing the focusing, $2\varphi_{opt}$, by the simple approximation

$$\sin\varphi_{opt}\sin\varphi_{el}\simeq\left(l_{cl}\frac{2\lambda^2 I_0}{\pi E_{kin}c}\right) \tag{5}$$

or

$$\sin\varphi_{el}\simeq\left(\frac{4l_{cl}P_0}{\pi^2 E_{kin}c}\right)\sin\varphi_{opt}=K\sin\varphi_{opt}, \tag{6}$$

where $E_{kin}=mv_0^2/2$ is the kinetic energy of an electron, and $l_{cl}=e^2/mc^2=2.8\times 10^{-13}$ cm is the classical radius of the electron. Correspondingly, the diameter of the spot in which the electron beam is focused, $2a_{el}$, is related to the focusing diameter of the laser beam, $2a_{opt}=2w_0$, by an equally simple equation

$$a_{el}=a_{opt}\left(\frac{\lambda_{dBr}}{\lambda}\right)\frac{1}{K}, \tag{7}$$

where $\lambda_{dBr}=2\pi\hbar/mv_0$ is the de Broglie wavelength of an electron.

Let us consider the focusing of electrons with an energy $E_{kin}=100$ eV ($v_0=5.9\times 10^8$ cm/s, $\lambda_{dBr}=1.2$ Å) by electromagnetic radiation at $\lambda=10$ μm with an intensity $I_0=0.5\times 10^{12}$ W/cm^2 at the focus. In this case the coefficient K in (6) is $K=0.12$; with $\sin\varphi_{opt}=0.3$–0.5, for example, the electron beam can be focused to a spot with a radius $a_{el}\simeq 10$–15 Å . The transit time of the electron through the focusing region is $\tau_{int}\simeq 5$ ps, so focusing could be achieved with picosecond pulses with a length of 100 ps and an energy of only $E_{las}\simeq\lambda^2 I_0\tau_{pulse}\simeq 10^{-4}$ J.

A laser lens for electrons has spherical aberration, which has a negligible effect on estimate (7), and also chromatic aberration, which is a more serious matter. The chromatic aberration would make it necessary to use monochromatized electrons. If the chromatic aberration is not to increase the spot diameter beyond the size in (7), the electrons would have to be monochromatic at a level better than

$$\frac{\Delta K_{kin}}{E_{kin}}\lesssim(\lambda_{dBr}/\lambda)/K. \tag{8}$$

For the particular numerical example we are discussing here, the electrons would have to be monochromatic within something on the order of 0.01%. The same stringent requirement would be imposed on the stability of the pulse intensity. We would thus need a square pulse with minimal rise and decay times ($\tau_{fr}\simeq\tau_{int}\ll\tau_{pulse}$), since the position of the focal point will be a variable at the rising and trailing edges. On the other hand, a rapid scan of the electron focal point along the z axis induced by varying the intensity might be utilized to produce ultrashort electron pulses.

In the case of a continuous electron beam there would be a background due to unfocused electrons over the time intervals T between the laser pulses. The ratio of the intensity at the focus of the electron beam to the background, i.e., the contrast, can be estimated from $S=(a_{opt}/a_{el})^2(\tau_{pulse}/T)$. With $T=10^{-4}$ s and $\tau_{pulse}\simeq 10^{-10}$ s we would have $S\simeq 100$, i.e., a contrast quite sufficient for observing an electron spot. The effect of the scattering force would be negligible in comparison with the dipole force by virtue of the ratio $F_{dip}/F_{sc}\simeq\lambda/4\pi^2\cdot l_{cl}\gg 1$.

Space-charge effects are negligible since we are assuming that the number density of electrons does not exceed one electron in the region of the laser-pulse focus, i.e., 10^{10} cm^{-3}, and that the current through this region does not exceed $1\ e\ /\tau_{int}\simeq 10^{11}$ s^{-1}.

In quantum-mechanical terms, the electrons are focused as the result of stimulated Compton scattering in the laser beam. A photon with wave vector $\mathbf{k}_1$ undergoes stimulated scattering by an electron, with the result that a photon with a wave vector $\mathbf{k}_2$ forms within the angular spectrum of the focused laser beam. The process is analogous to stimulated Compton scattering by a standing optical wave. In this case a photon from one traveling wave undergoes a stimulated scattering into a counterpropagating light wave ($\Delta k=2k$) (the Kapitsa–Dirac effect[6]).

Finally, it is not difficult to imagine the use of this effect to develop a scanning electron microscopy using low-energy electrons with laser focusing and offering a picosecond time resolution. This modification of electron microscopy would be of interest because low-energy electrons are vastly more sensitive to the atomic or molecular structure of the surface of the specimen. The possibility is also of interest for ultrafast electron diffraction of molecules.

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