Quasistatic magnetic fields generated by a nonrelativistic intense laser pulse in uniform underdense plasma*

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Quasistatic magnetic fields generated by nonrelativistic intense linearly polarized (LP) and circularly polarized (CP) laser pulses in an initially uniform underdense plasma in the collision-dominated limit are investigated analytically. Using a selfconsistent analytical model, we perform a detailed derivation of quasistatic magnetic fields in the laser pulse envelope in the collision-dominated limit to obtain exact analytical expressions for magnetic fields and discuss the dependence of magnetic fields on laser and plasma parameters. Equations for quasistatic magnetic fields including both axial componentB_z and the azimuthal one B_θ are derived simultaneously from such a selfconsistent model. The dependence of quasistatic magnetic field on incident laser intensity, transverse focused radius of laser pulse, electron density and electron temperature is discussed.

Keywords: quasistatic magnetic field, laser, plasma
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1. Introduction

The problem of the generation of quasistatic magnetic fields[1−18] in laser plasma interactions is an important issue related to many research areas, such as the formation of plasma channels in the context of fast ignition of fusion targets,[19,20] the plasma-based particle accelerators,[21] and the x-ray generation, or EM radiation of pulsars.[22]

The spontaneously generated magnetic fields actually can be produced by an electron current through a variety of mechanisms, including nonparallel electron density and temperature gradients ($\nabla n_e \times \nabla T_e$) in the ablated plasma,[2] the ponderomotive force of the laser,[3,4] the anisotropic electron pressure due to the collisional absorption of the laser[5] and the strong axial currents due to flows of relativistic electrons, axially comoving with the pulse.[6] Numerical simulations carried out by Wilks *et al.*[3] for the interaction of a relativistic ultraintense laser pulse with an overdense plasma target predicted that the extremely high self-generated magnetic fields could reach about 250 MG (1 MG=10^2 T). Sudan[4] suggested that the dc currents driven by the spatial gradients and temporal variations of the ponderomotive force exerted by the laser on the plasma electrons, played roles as an origin of the strong magnetic field discovered in numerical simulations.[3] Kim *et al.*[10] and Berezhiani *et al.*[11] also pointed out that in interactions of circularly polarized relativistic ultraintense laser pulses with underdense plasmas the sources of axial magnetic field generation are the inhomogeneities of electron density and laser intensity. They showed that because of the strong plasma inhomogeneity caused by the intense laser beam, a low-frequency drag current was induced, which, due to the inverse Faraday effect, produced a quasistatic magnetic field in the beam propagation area. Recently, Qiao *et al.* studied the quasistatic magnetic field and the quasistatic electric field generated in relativistic intense laser plasma interaction.[18] In their paper, a self-consistent kinetic model based on relativistic Vlasov–Maxwell equations was presented for the generation of both the quasistatic magnetic field and the quasistatic electric field, in relativistic intense laser plasma interaction.

The problem of quasistatic magnetic field gener-

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ated by a nonrelativistic intense laser in an underdense plasma is important for studying the inertial confinement fusion. In an underdense inhomogeneous plasma the nonrelativistic two-dimensional treatment of self-generated magnetic fields was presented by Tripathi and Liu.[12] They showed that an amplitude modulated laser beam propagating along a plasma density gradient produced a rotational current that gave rise to a quasistatic magnetic field. Self-generated magnetic field due to the anisotropic electron pressure in the interaction of a nonrelativistic laser and a uniform underdense plasma was investigated by Mora and Pellat.[5] They showed that the collisional absorption of the laser induced a nonlinear anisotropy in the electron pressure tensor, which is responsible for a large source of the quasistatic magnetic field. They proposed a selfconsistent analytical model to obtain the evolution equation for the magnetic field. However, the analytical explicit expression for the magnetic field including both the axial part B_z and the azimuthal part B_θ in the collision-dominated limit and the dependence of magnetic field on laser and plasma parameters such as incident laser intensity, transverse focused radius of laser pulse, electron density and electron temperature were not given in their paper. We continue their work by performing the detailed derivation of selfgenerated quasistatic magnetic fields in the laser pulse envelope in the collision-dominated limit to obtain the analytical explicit expression for magnetic fields and discuss the dependence of magnetic fields on laser and plasma parameters. In this paper, we investigate the generation of quasistatic magnetic fields in the interaction of nonrelativistic intense linearly polarized (LP) and circularly polarized (CP) laser pulse with an initially uniform underdense plasma. Equations for quasistatic magnetic fields including both axial component B_z and the azimuthal one B_θ are derived simultaneously.

2. Derivation of quasistatic magnetic fields

Mora and Pellat[5] proposed a self-consistent analytical model, starting with the momentum equation for an electron in the Krook model

$$m_{\rm e}\left(\frac{\partial \boldsymbol{v}_{\rm e}}{\partial t}+\boldsymbol{v}_{\rm e}\cdot\nabla\boldsymbol{v}_{\rm e}\right) = -e(\boldsymbol{E}+\boldsymbol{v}_{\rm e}\times\boldsymbol{B}) -\frac{1}{n_{\rm e}}\nabla\cdot\boldsymbol{P}_{\rm e}-m_{\rm e}\nu\boldsymbol{v}_{\rm e}, \quad (1)$$

where e, $m_{\rm e}$, $n_{\rm e}$, $\boldsymbol{v}_{\rm e}$ and ν are the electron charge, mass, density, velocity, and electron–ion collision frequency, respectively. The electron pressure tensor is $\boldsymbol{P}_{\rm e} = n_{\rm e}(T_{\rm e}\boldsymbol{I}+m_{\rm e}\langle\boldsymbol{v}_{\rm h}\boldsymbol{v}_{\rm h}\rangle)$, where collision between electrons and ions induces anisotropy, i.e. term $n_{\rm e}m_{\rm e}\langle\boldsymbol{v}_{\rm h}\boldsymbol{v}_{\rm h}\rangle$. The physical quantities are divided into a slowly varying component and an oscillating component at the laser frequency ω, thus, $\boldsymbol{E}=\langle\boldsymbol{E}\rangle+\boldsymbol{E}_{\rm h}$. The evolution equation for the quasistatic magnetic field is obtained as[5]

$$\frac{\partial\langle\boldsymbol{B}\rangle}{\partial t}-\nabla\times\langle\boldsymbol{v}_{\rm e}\rangle\times\langle\boldsymbol{B}\rangle-\frac{c^2}{\omega_p^2}\nu\nabla^2\langle\boldsymbol{B}\rangle = \boldsymbol{S}_t(\boldsymbol{r},t)+\boldsymbol{S}_r(\boldsymbol{r},t). \quad (2)$$

In a uniform plasma $\boldsymbol{S}_t(\boldsymbol{r},t)=(m_{\rm e}/e)\nabla\times(1/\langle n_{\rm e}\rangle)\nabla\cdot\langle n_{\rm e}\rangle\langle\boldsymbol{v}_{\rm h}\boldsymbol{v}_{\rm h}\rangle$ and $\boldsymbol{S}_r(\boldsymbol{r},t)=\frac{m_{\rm e}}{e}\nabla\times\langle\boldsymbol{v}_{\rm h}\times(\nabla\times v\boldsymbol{r}_{\rm h})+(\nabla\cdot v\boldsymbol{r}_{\rm h})\boldsymbol{v}_{\rm h}\rangle$ are a thermoelectric source and radiative source, respectively. The electron current which induces the quasistatic magnetic field in the collision-dominated limit is obtained as[5]

$$\langle\boldsymbol{J}\rangle=(e/\nu)\nabla\cdot\langle n_{\rm e}\boldsymbol{v}_{\rm h}\boldsymbol{v}_{\rm h}\rangle+e\langle\boldsymbol{v}_{\rm h}(\nabla\cdot n_{\rm e}\boldsymbol{r}_{\rm h})+\boldsymbol{v}_{\rm h}\times\nabla\times n_{\rm e}\boldsymbol{r}_{\rm h}\rangle. \quad (3)$$

Now, we come to consider the propagation of a laser pulse with wavelength λ_0 and wave number $k=2\pi/\lambda_0$ along the z direction in a uniform underdense plasma, where the electric field in the laser pulse envelope is usually expressed as

$$\boldsymbol{E}(\boldsymbol{x},t)=\frac{1}{2}E_0(r,t)(\boldsymbol{e}_r+{\rm i}\,\alpha\boldsymbol{e}_\theta){\rm e}^{{\rm i}\,\alpha\theta}{\rm e}^{{\rm i}\,kz-{\rm i}\,\omega t}+{\rm c.c.}, \quad (4)$$

where $\alpha=0,\pm1$ for the linearly polarized laser and the circularly polarized laser, respectively. The laser is assumed to have a transverse Gaussian distribution, i.e. $I=I_0\exp(-r^2/r_0^2)$ in intensity, and amplitude of electric field $E_0=\sqrt{I_0}\exp(-r^2/2r_0^2)=\hat{E}_0\exp(-r^2/2r_0^2)$. Equation (4) can be written in an equivalent expression as follows:

$$\boldsymbol{E}(\boldsymbol{x},t)=E_0(r,t)[\cos(\alpha\theta+kz-\omega t)\boldsymbol{e}_r-\alpha\sin(\alpha\theta+kz-\omega t)\boldsymbol{e}_\theta]. \quad (5)$$

The electric field exerts electrons an oscillation velocity

$$\begin{aligned}\boldsymbol{v}_{\rm h} &= -\frac{eE_0(r,t)}{m(\nu^2+\omega^2)}[\nu\cos(\alpha\theta+kz-\omega t)-\omega\sin(\alpha\theta+kz-\omega t)]\boldsymbol{e}_r\\ &\quad+\frac{\alpha eE_0(r,t)}{m(\nu^2+\omega^2)}[\omega\cos(\alpha\theta+kz-\omega t)+\nu\sin(\alpha\theta+kz-\omega t)]\boldsymbol{e}_\theta,\end{aligned}\tag{6}$$

thus the displacement of electron can be derived as

$$\begin{aligned}\boldsymbol{r}_{\rm h} &= \int \boldsymbol{v}_{\rm h}{\rm d}t = -\frac{eE_0(r,t)}{m(\nu^2+\omega^2)}\left[\frac{-\nu}{\omega}\sin(\alpha\theta+kz-\omega t)-\cos(\alpha\theta+kz-\omega t)\right]\boldsymbol{e}_r\\ &\quad+\frac{\alpha eE_0(r,t)}{m(\nu^2+\omega^2)}\left[-\sin(\alpha\theta+kz-\omega t)+\frac{\nu}{\omega}\cos(\alpha\theta+kz-\omega t)\right]\boldsymbol{e}_\theta.\end{aligned}\tag{7}$$

The three terms on the right-hand side of Eq. (3) are then written as

$$\begin{aligned}\nabla\cdot\langle\boldsymbol{v}_{\rm h}\boldsymbol{v}_{\rm h}\rangle &= \frac{e^2\hat{E}_0^2{\rm e}^{-r^2/r_0^2}}{2m^2(\nu^2+\omega^2)}[(-2r/r_0^2)+(1-\alpha^2)/r]\boldsymbol{e}_r,\\ \langle\boldsymbol{v}_{\rm h}(\nabla\cdot\boldsymbol{r}_{\rm h})\rangle &= \frac{\alpha e^2\hat{E}_0^2{\rm e}^{-r^2/r_0^2}}{2m^2(\nu^2+\omega^2)\omega}[(-r/r_0^2)+(1-\alpha^2)/r]\boldsymbol{e}_\theta,\\ \langle\boldsymbol{v}_{\rm h}\times\nabla\times\boldsymbol{r}_{\rm h}\rangle &= \frac{e^2\hat{E}_0^2{\rm e}^{-r^2/r_0^2}}{2m^2(\nu^2+\omega^2)\omega}[\alpha(-r/r_0^2)\boldsymbol{e}_\theta-k(1+\alpha^2)\boldsymbol{e}_z].\end{aligned}\tag{8}$$

Inserting Eq. (8) into Eq. (3), the electron current is obtained to be

$$\begin{aligned}\langle\boldsymbol{J}\rangle &= (e/\nu)\nabla\cdot\langle n_{\rm e}\boldsymbol{v}_{\rm h}\boldsymbol{v}_{\rm h}\rangle+e\langle\boldsymbol{v}_{\rm h}(\nabla\cdot n_{\rm e}\boldsymbol{r}_{\rm h})+\boldsymbol{v}_{\rm h}\times\nabla\times n_{\rm e}\boldsymbol{r}_{\rm h}\rangle\\ &= C_1{\rm e}^{-r^2/r_0^2}[(-2r/r_0^2)+(1-\alpha^2)/r]\boldsymbol{e}_r\\ &\quad+C_2[(-2r/r_0^2)+(1-\alpha^2)/r]{\rm e}^{-r^2/r_0^2}\boldsymbol{e}_\theta+C_3{\rm e}^{-r^2/r_0^2}\boldsymbol{e}_z,\end{aligned}\tag{9}$$

where

$$C_1=\frac{en_{\rm e}e^2\hat{E}_0^2}{2m^2(\nu^2+\omega^2)\nu},\quad C_2=\frac{\alpha en_{\rm e}e^2\hat{E}_0^2}{2m^2(\nu^2+\omega^2)\omega},\quad\text{and}\quad C_3=-\frac{k(1+\alpha^2)en_{\rm e}e^2\hat{E}_0^2}{2m^2(\nu^2+\omega^2)\omega}.$$

With Ampere's law $\nabla\times\boldsymbol{B}=\mu_0\boldsymbol{J}$, we give the solutions of the quasistatic magnetic fields B_z and B_θ for the given focused laser beam in cylindrical coordinates (r,θ,z) as follows:

$$\frac{\partial B_z}{\partial r}=-\frac{\mu\alpha en_{\rm e}e^2\hat{E}_0^2}{2m^2(\nu^2+\omega^2)\omega}[(-2r/r_0^2)+(1-\alpha^2)/r]{\rm e}^{-r^2/r_0^2},\tag{10}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(rB_\theta)=-\frac{\mu k(1+\alpha^2)en_{\rm e}e^2\hat{E}_0^2}{2m^2(\nu^2+\omega^2)\omega}{\rm e}^{-r^2/r_0^2}.\tag{11}$$

We solve Eqs. (10) and (11) to derive the magnetic field for the linearly polarized laser and the circularly polarized laser, respectively. When the laser is linearly polarized ($\alpha=0$), the axial and the azimuthal magnetic fields have the forms

$$B_z=0,\tag{12}$$

$$B_\theta=\frac{\mu ken_{\rm e}e^2\hat{E}_0^2r_0^2}{4m^2(\nu^2+\omega^2)\omega}\frac{1}{r}[{\rm e}^{-r^2/r_0^2}-1].\tag{13}$$

For a circularly polarized laser ($\alpha=\pm1$), the axial and the azimuthal magnetic fields are expressed as

$$B_z=\mp\frac{\mu en_{\rm e}e^2\hat{E}_0^2}{2m^2(\nu^2+\omega^2)\omega}{\rm e}^{-r^2/r_0^2},\tag{14}$$

$$B_\theta=\frac{\mu ken_{\rm e}e^2\hat{E}_0^2r_0^2}{2m^2(\nu^2+\omega^2)\omega}\frac{1}{r}[{\rm e}^{-r^2/r_0^2}-1].\tag{15}$$

3. Discussion

We find that the axial magnetic field B_z is generated only by circularly polarized laser, while the azimuthal magnetic field B_θ can be produced by both

the linearly polarized laser and the circularly polarized laser. Figures 1–3 illustrate the curves for quasistatic magnetic field as a function of laser beam intensity I_0 and radial coordinate r in different transverse focused radii. The wavelength is $\lambda_0 = 0.531$ μm, the electron temperature and density are $T_e = 1$ keV and $n_0 = 0.1n_c$ respectively. We find from Fig. 1 that for both the linearly polarized laser and the circularly polarized laser B_θ is close to zero near the axis and increases with radial coordinate r increasing, after reaching the peak value near $r = r_0$ it decreases. Figure 2 shows that B_θ increases linearly with laser intensity I_0 increasing. Comparing the two different polarizations, we find that B_θ produced by a circularly polarized laser is twice that produced by the linearly polarized laser, subject to the same parameters. It can be seen from Fig. 3 that for a circularly polarized laser, B_z reaches a maximum value at $r = 0$ and decreases gradually with r increasing. B_z increases linearly with laser intensity I_0 increasing.

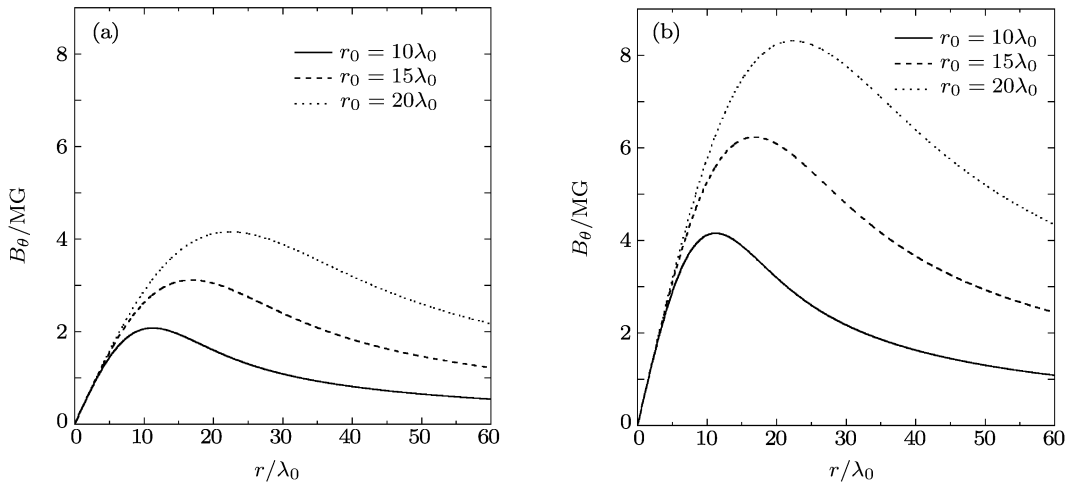


Fig. 1. Transverse profiles of azimuthal magnetic field B_θ for (a) linearly and (b) circularly polarized Gaussian lasers at intensity $I_0 = 0.05 \times 10^{18}$ W/cm^2, wavelength $\lambda_0 = 0.531$ μm, transverse radius $r_0 = 10\lambda_0$, $r_0 = 15\lambda_0$ and $r_0 = 20\lambda_0$, electron temperature $T_e = 1$ keV and electron density $n_0 = 0.1n_c$ (1 G=10^{-4} T).

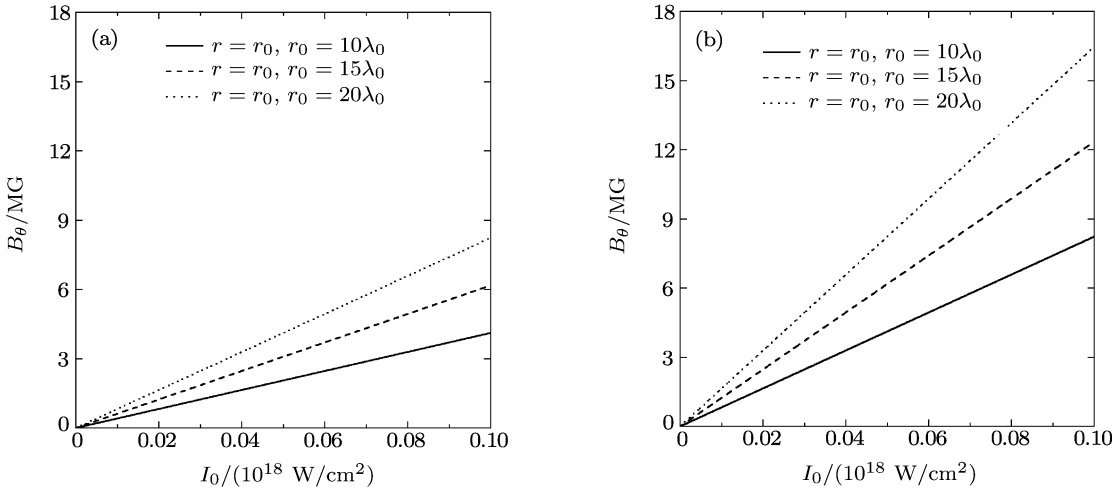


Fig. 2. Values of azimuthal magnetic field B_θ as a function of the laser intensity I_0 at $r = r_0$, for (a) linearly and (b) circularly polarized Gaussian lasers at wavelength $\lambda_0 = 0.531$ μm, electron temperature $T_e = 1$ keV and electron density $n_0 = 0.1n_c$.

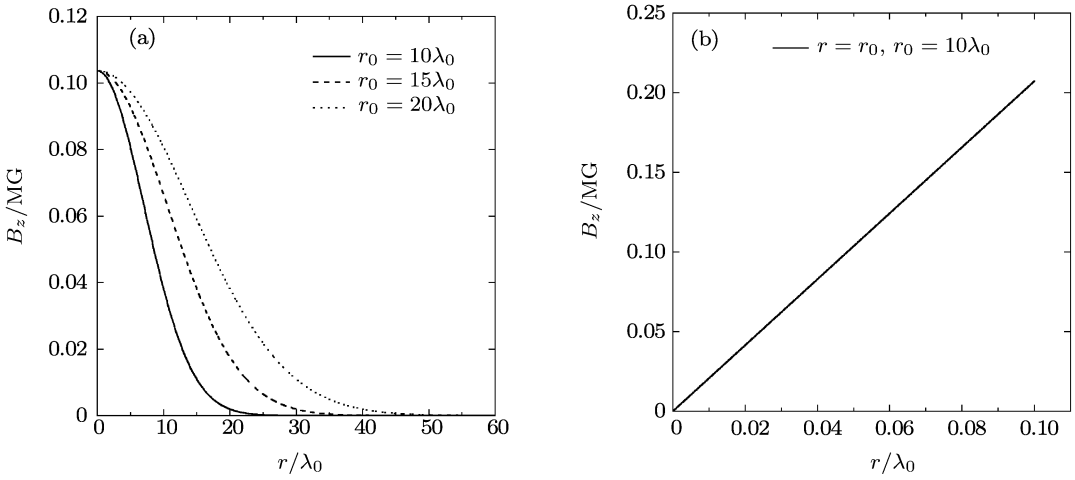


Fig. 3. Transverse profiles of axial magnetic field B_z for a circularly polarized Gaussian laser at $I_0 = 0.05 \times 10^{18}$ W/cm^2, $\lambda_0 = 0.531$ μm, $T_e = 1$ keV and $n_0 = 0.1n_c$ (a), and axial magnetic field B_z as a function of laser intensity I_0 at $r = 0$, $\lambda_0 = 0.531$ μm, $T_e = 1$ keV and $n_0 = 0.1n_c$.

The collisional absorption of the laser pulse in plasma induces a nonlinear anisotropy in the electron pressure tensor, which acts as a large source of the quasistatic magnetic field. The magnetic field depends greatly on electron–ion collision frequency ($\nu = 3 \times 10^{-5} n_e Z/T_e^{3/2}$), which is determined by electron density and temperature. Figures 4–6 illustrate quasistatic magnetic field components ($B_z B_\theta$) as functions of electron density n_e and electron temperature T_e. It is shown from Fig. 4(a) that for low electron temperatures ($T_e = 0.01$, 0.02 keV), the azimuthal magnetic field B_θ at $r = r_0$ increases with the increase of electron density n_e/n_c, after reaching a peak value it decreases. When electron temperature is relatively high ($T_e = 0.05$, 0.1, 1 keV), the azimuthal magnetic field B_θ nearly increases linearly with n_e/n_c increasing. Higher temperature induces larger magnetic field. We find that the curves for $T_e = 0.1$ keV and $T_e = 1$ keV almost overlap. This is because at relatively high temperatures, electron–ion collision frequency ν decreases with T_e, leading the variation of ν with ω to be neglected and B_θ to increase with n_e linearly and not to depend on T_e. Figure 4(b) shows that the azimuthal magnetic field B_θ at $r = r_0$ increases with electron temperature T_e and nearly remains unchanged at higher temperatures. Higher electron density induces larger magnetic field. It can be seen from Fig. 5 that the azimuthal magnetic field B_θ shows similar characteristics dependent on electron density and temperature but B_θ produced by a circularly polarized laser is twice that produced by a linearly polarized laser, subject to the same parameters. Figure 6 shows the curves for axial magnetic field B_z as a function of electron density and temperature at $r = 0$, with using a circularly polarized Gaussian laser.

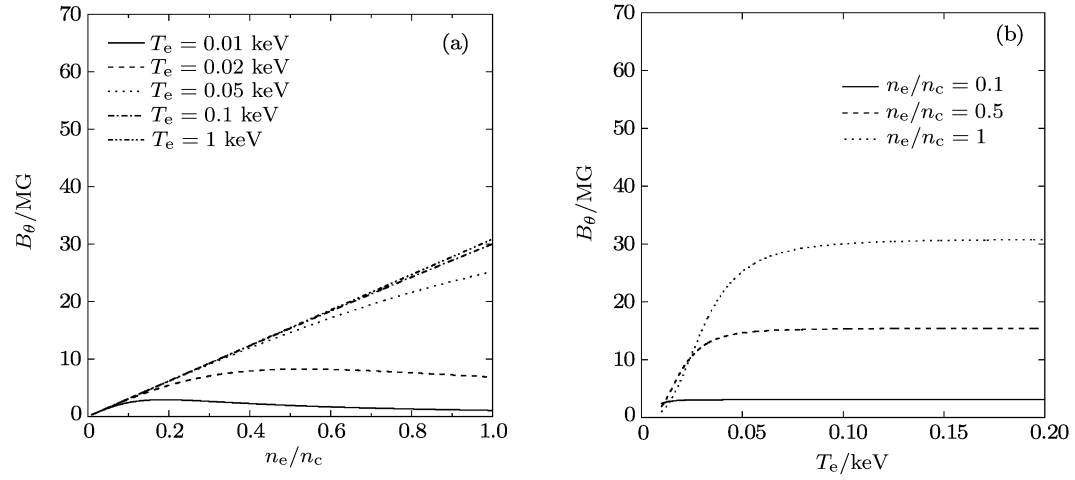


Fig. 4. Curves for (a) azimuthal magnetic field B_θ as a function of electron density n_e at $r = r_0$ for different electron temperatures with using a linearly polarized Gaussian laser at intensity $I_0 = 0.05 \times 10^{18}$ W/cm^2, wavelength $\lambda_0 = 0.531$ μm, and transverse radius $r_0 = 15\lambda_0$ (a) and for (b) azimuthal magnetic field B_θ as a function of electron temperature T_e for different electron densities at $I_0 = 0.05 \times 10^{18}$ W/cm^2, $\lambda_0 = 0.531$ μm, and $r_0 = 15\lambda_0$(b).

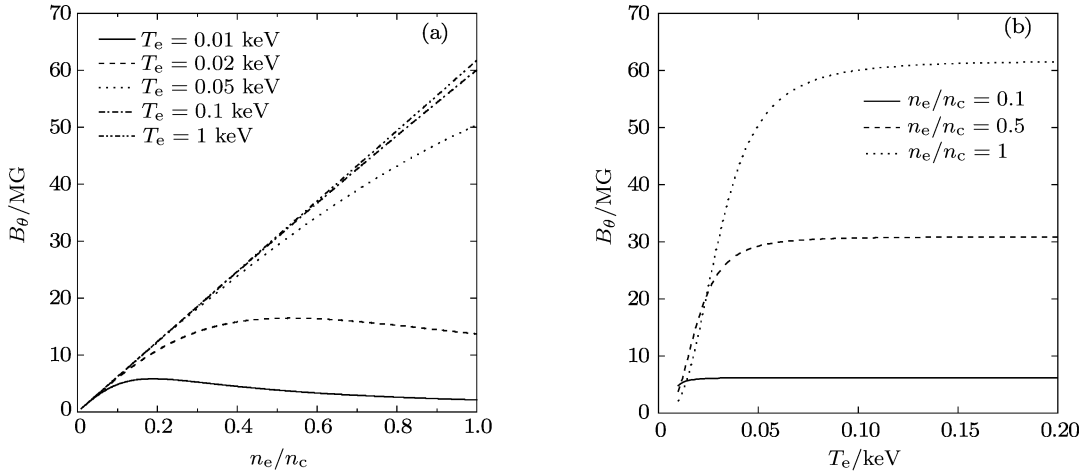


Fig. 5. Curves for (a) azimuthal magnetic field B_θ as a function of electron density n_e at $r = r_0$ for different electron temperature, with using a circularly polarized Gaussian laser at intensity $I_0 = 0.05 \times 10^{18}$ W/cm^2, wavelength $\lambda_0 = 0.531$ μm, and transverse radius $r_0 = 15\lambda_0$ and for (b) azimuthal magnetic field B_θ as a function of electron temperature T_e for different electron densities at $I_0 = 0.05 \times 10^{18}$ W/cm^2, $\lambda_0 = 0.531$ μm, and $r_0 = 15\lambda_0$.

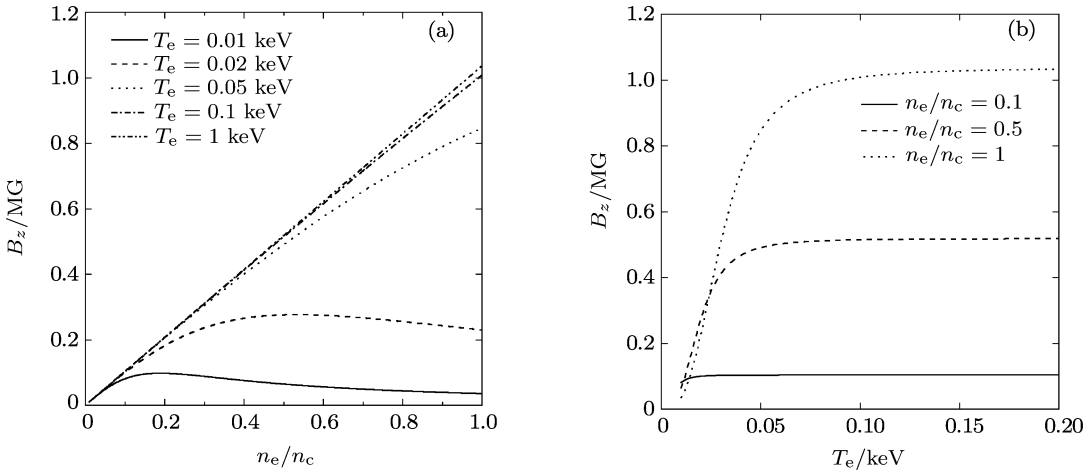


Fig. 6. Curves for (a) axial magnetic field B_z as a function of electron density n_e at $r = 0$ for different electron temperatures, with using a circularly polarized Gaussian laser at intensity $I_0 = 0.05 \times 10^{18}$ W/cm^2, wavelength $\lambda_0 = 0.531$ μm, and transverse radius $r_0 = 15\lambda_0$ and for (b) axial magnetic field B_z as a function of electron temperature T_e for different electron densities at $I_0 = 0.05 \times 10^{18}$ W/cm^2, $\lambda_0 = 0.531$ μm, and $r_0 = 15\lambda_0$.

4. Conclusion

The quasistatic magnetic fields generated by a nonrelativistic intense linearly polarized (LP) and circularly polarized (CP) laser pulses in an initially uniform underdense plasma in the collision-dominated limit are investigated analytically. A self-consistent analytical model is presented for the generation of quasistatic magnetic fields in laser–plasma interaction. The exact analytical expressions for magnetic fields including both axial component B_z and the azimuthal one B_θ are derived simultaneously from the analytical model.

We find that the axial magnetic field B_z is generated only by circularly polarized laser. Both the linearly polarized and the circularly polarized lasers can generate the azimuthal magnetic field B_θ. The dependence of the quasistatic magnetic field on laser intensity I and radial coordinate r at different transverse focused radii are discussed. It is shown that the collisional absorption of the laser pulse induces a nonlinear anisotropy in the electron pressure tensor, which acts as a large source of the quasistatic magnetic field. The magnetic field components including both B_z and B_θ depend greatly on the electron–ion collision frequency ν, which is determined by the electron density n_e and temperature T_e.

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