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Beneficial effects of magnetic field generation by laser photon momentum deposition

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When a laser light beam of finite diameter interacts with a plasma, absorption, reflection and back-scatter can occur. These processes involve deposition of momentum from the photons of the laser beam onto the electrons. The forward push on the electrons can lead to an axial electric field being set up to maintain quasi-neutrality. Because of the transverse finite extent of the beam, the electric field is not entirely electrostatic in nature but can have a non-zero curl which leads to the generation of an azimuthal magnetic field. This magnetic field will be in the opposite direction to that generated by the more familiar $\nabla T \times \nabla n$ effect.

In the case of ultra high intensity $\left(\sim 10^{20} Wcm^{-2}\right)$ interaction with an overdense plasma magnetic field of hundreds of megagauss[1] can be generated in the first skin depth followed by a weaker magnetic field due to incomplete magnetic neutralisation of the electron beam. These fields play a beneficial role in channelling the energy in the fast ignitor scheme. In a second case of long pulse moderate intensity $\left(\sim 10^{15} Wcm^{-2}\right)$ laser beams propagating in a gas-filled hohlraum, the unwanted stimulated Brillouin back-scatter (SBS) in the ionised gas is known to last only for a time of ~ 1ns. One possible reason for the quenching of SBS is that there is a growing magnetic field which converts the ion-acoustic wave into a fast magnetosonic wave. However this wave has a spatially non-uniform group velocity, and causes a break-up of the planar wave-fronts and hence a quenching of the SBS[2]. A third cased considers the possible magnetisation of fast electrons produced in laser field hot spots by stimulated Raman back-scatter. The magnetic field can easily be strong enough to magnetise and confine the relatively collisionless hot electrons, and with a suitable addition of a small amount of a high Z noble gas might cause the electron energy to be absorbed by a resonant atomic process. Some evidence of quenching of fast electrons has been observed in recent experiments[3].

In each of these cases we need to identify the source of generation of magnetic field, the rate of rise of this field, and its saturation. In so doing an important parameter is the scale length $L_\perp$

perpendicular to both the laser direction and the azimuthal magnetic field. This is sometimes the radius of the focused laser spot, but it can be as small as the collisionless skin depth.

The next question is what determines the saturation level of the magnetic field? In an earlier paper[4] concerned with the more conventional $\nabla T \times \nabla n$ source close to the critical surface of a target, it was found that saturation was determined by outward convection of the plasma and field at the ion sound speed, c_s for $L_\perp > c/\omega_{pi}$; and for tighter laser spots the drift velocity of the current-carrying electrons exceeded c_s and lower-hybrid or ion-acoustic or two stream turbulence and associated anomalous resistivity and diffusion limited the magnetic field. The largest magnetic field theoretically was at $L_\perp = c/\omega_{pi}$ and this led to the magnetic pressure being approximately equal to the plasma pressure. For the situations considered here where there is no ablation in the domain, saturation can occur through the magnetic pressure exceeding the plasma pressure leading to pinching; and by outward convection by the heated plasma and associated radial heat flux[5] ; as well as by diffusion, particularly by anomalous resistivity, again triggerd by an electron drift velocity exceeding c_s. A further mechanism which permits the magnetic field energy to be rapidly converted to a high ion temperature through fine-scale MHD m=0 instabilities and ion viscous dissipation is presented elsewhere at this conference[6], though in the context of wire-array Z-pinches..

When photons are absorbed or reflected their momentum or momentum change is deposited in the electrons. The z-component of the electron momentum moment equation (or Ohm's law) can be written as

$$n_e m_e \frac{\partial v_{ez}}{\partial t} = -n_e e E_z - n_e e(\underline{v}_e \times \underline{B})_z + \frac{\alpha I_z}{c L_z} - n_e m_e \upsilon_{ei} v_{ez} - \nabla_\alpha P_{\alpha z} \qquad (1)$$

where I_z is the radiation intensity, $\alpha = \alpha_{abs} + 2\alpha_{refl}$ represents the fraction of laser light absorbed (α_{abs}) and reflected (α_{refl}) over a distance L_z in the z-direction. The new term $\alpha I_z / c L_z$ can be considered as the average radiation pressure. $P_{\alpha z}$ is the electron stress tensor and υ_{ei} is the electron-ion collision frequency. In all three cases that we are considering the initially dominant terms are those involving E_z and I_z, so that we can write approximately

$$E_z \approx \frac{\alpha I_z}{n_e ec L_z} \tag{2}$$

This follows similar arguments to an earlier paper on the absorption of photon spin[7]. Faraday's law gives

$$\frac{\partial E_z}{\partial r} = \frac{\partial B_\theta}{\partial t} \tag{3}$$

which leads to an estimate of the magnitude of the magnetic field at time τ of

$$B_\theta = -\frac{\tau}{L_\perp} \cdot \frac{\alpha I_z}{n_e ec L_z} \tag{4}$$

where $L_\perp$ is the appropriate radial distance over which E_z falls. To illustrate this, for $I = 10^{23} Wm^{-2}, L_\perp = 10^{-5} m, \tau = 10^{-12} s, n_e = 1.7 \times 10^{29} m^{-3}, \alpha = 1$ and $L_z = \gamma^{1/2} c / \omega_{pe}$ gives $B_\theta = 7 \times 10^4$ tesla (or 700 MG), similar to recent magnetic field measurements[8]. The saturation level will be determined by the relativistic limitation that the current density associated with this magnetic field cannot exceed $n_e ec$ in magnitude, and the magnetic pressure, which will both expel the plasma from the region and cause pinching cannot exceed the plasma pressure, which relativistically is equal to $n_e m_e \gamma v^2$. As $v \to c$ these conditions together give $L_\perp = \gamma^{1/2} c / \omega_{pe}$ consistent with the skin depth for an overdense plasma. It can be argued that the magnetic field will be concentrated near the edge of the laser beam, again by skin depth considerations, and then writing $L_\perp = L_z = \gamma^{1/2} c / \omega_{pe}$ we obtain in saturation that B_θ will scale weakly as $I^{1/4}$.

Most of the photon momentum is deposited in fast electrons that have a large axial component of velocity. They will proceed into the overdense plasma, and a return cold current of electrons will be induced. Due to the finite diameter of the laser beam and fast electron beam, the electric field necessary to drive the return cold current will fall off with radius, and the resulting $\nabla \times \underline{E}$ will generate a magnetic field. In addition a Weibel instability can occur causing filamentation[9], and the electrothermal instability[10] can dominate to cause a single hot filament on axis. The fast electron flow however will only penetrate if the net current density J_z on axis is sufficiently small so that the generalised singular current of fast electrons, I_{fast} is that required for a fast ignitor to work and satisfies the equation

$$I_{fast} = \frac{4\pi}{\mu_0} \frac{P_{\perp fast}}{J_z}\Big|_{r=0} \tag{5}$$

where $P_{\perp fast}$ is the perpendicular pressure of the fast electrons[11]. The beneficial effect of this magnetic field is that it collimates the flow of fast electrons, but a self-consistent model is required to take care of the diffusion of the magnetic field (and net current density) to the axis which could limit the flow of fast electrons.

Turning to SBS in long pulse laser-plasma experiments we employ Eq.(4) for speckle of radius $L_\perp$ of 1.8 μm, and axial length $L_z = 50\mu m$, $I = 6\times10^{19} Wm^{-2}, \alpha = 0.5, n_e = 10^{27} m^{-3}$ for 100ps. This gives a magnetic field of 1.4 $\times 10^3$ tesla. For hydrogen at a temperature of 2 keV this converts the sound speed from 4.4 x 10^5 ms^{-1} to a fast magnetosonic speed some 2.4 times this. This phase velocity is very non-uniform spatially as B_θ rises from zero on the axis of the speckle. Thus the original planar sound wave fronts of the SBS leading to high reflectivity, are broken up, and the SBS will die away together with the large value of α. The ion flow is far less significant, especially as the mean-free-path of ions to some 20 times $L_\perp$. Stimulated Raman backscatter can now develop when density variations associated with finite amplitude ion waves have decayed. Here fast electrons in the >10keV energy can arise. A preliminary experimental result[3] shows that a 1% addition of Kr can suppress their electrons. Atomic cross-sections alone are too small to absorb these electrons unless a magnetic field is present to confine them with a Larmor radius smaller than the relevant transverse dimension. This is easily possible from the photon momentum typically absorbed in such experiments.

Thus in all three cases the magnetic field is beneficial.

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