Magnetic field production by charged-particle fluxes losing energy in plasmas

L. I. Rudakov
I. V. Kurchatov Institute of Atomic Energy, Moscow

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The excitation of conduction currents in a medium entered by a particle flux is analyzed with reference to laser plasmas and plasmas in space. Manifestations of the effect are the production of a magnetic field and an increase in the energy loss of the particles.

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As an introduction to the problem we will consider the well-studied case of the injection of an intense relativistic electron beam into a conducting medium.[1,2] The beam excites a return current of conduction electrons in the medium which cancels the beam current. The magnetic field of the beam arises as the return current undergoes ohmic dissipation:

$$\mathrm{rot}\, H = \frac{4\pi}{c}\,(j(E) + j') = \frac{4\pi}{c}\, j\,. \tag{1}$$

Here j, $j(E)$, and j' are the "pure" difference current, the current of plasma electrons, and the external current (i.e., the beam current), respectively. As long as there is a magnetic cancellation of the currents, $|j| \ll |j(E) + j'|$, a description of the appearance of the magnetic field can be found from the condition $j' + j(E) = 0$. Assuming a cylindrical beam, and using Ohm's law, $j_z = \sigma E_z$, we find the following from this condition:

$$H_\varphi = c\int_0^t dt\, \frac{\partial}{\partial r}\, \frac{j'}{\sigma}\,. \tag{2}$$

A complete "freezing" of the field of the external current occurs over the skin time ($4\pi\sigma r^2 c^{-2}$), but intense beams have another scale time: the field freezing time, which strongly affects the motion of the beam particles when the radius of the beta-

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tron oscillations of the beam particles in the frozen field becomes comparable to the channel radius, i.e., when the pure current reaches the value $I_A\theta^2$, where $I_A = m'vc^2/e$ is the Alfvén current, and $\theta^2 = v_\perp^2/v^2$. For beam particles, this magnetic field is frozen in over the scale time of the problem,

$$\frac{4\pi\sigma r^2}{c^2} \cdot \frac{I_A\theta^2}{I'}, \qquad I' \text{ – beam current,} \tag{3}$$

where I' is the beam current. The beam radius has dropped out of this estimate, so it is natural to expect that a magnetic field will be produced even in a homogeneous flux of particles. In other words, a homogeneous flux will be unstable with respect to breakup into current streams. Radial fluctuations of the particle density in the beam, $\delta n'$, lead to an inhomogeneity of the current and to the appearance of a magnetic field in accordance with (2). The relationship between $\delta n'$ and H_φ can be found from the equation for the radial balance of forces in the flux:

$$\frac{\partial}{\partial r} m' v^2 \theta^2 \delta n' = -\frac{1}{c} j' H_\varphi . \tag{4}$$

Substituting $\delta n'$ from (4) in (2), we find the growth rate for the filamentation instability of a charged-particle flux in a conducting medium (ν_{ei} is the rate of electron–ion collisions in the medium):

$$\gamma = \frac{m}{m'} \frac{n'}{n} N_{ei} \theta^{-2}. \tag{5}$$

A competing process is the diffusive spreading of the magnetic field, so that the unstable perturbations are those which have a scale dimension smaller than the skin thickness:

$$k^2 < 4\pi\sigma\gamma c^{-2} \cong \frac{\omega_p^2}{c^2} \frac{n'}{n} \frac{m}{m'} \theta^{-2} . \tag{6}$$

This instability has been studied in detail[3,4] in connection with the transport of intense beams of ions and relativistic electrons through dense plasmas to fusion targets. In contrast with the familiar high-frequency ($\gamma = ku\, n'/n^{1/2} \gg \nu_{ei}$) anisotropic instability,[5] which can be suppressed by a small angular spread, $\theta^2 > n'/n$, the instability in (5) occurs simply if the longitudinal energy of the particles in the flux is greater than their transverse energy.

We wish to call attention to the fact that the production of a magnetic field by a charged-particle flux and the breakup of this flux into streams can occur in both laser plasmas and plasmas in space.

Experiments have shown that the fast epithermal electrons which result from collective effects in the subcritical part of the plasma corona play an important role in the plasmas produced by high-power lasers at power densities of 10^{13} W/cm^2 and above. These electrons carry a substantial fraction of the absorbed power to the dense part of the medium, where they lose energy and accumulate. The integrated flux density of these particles, normalized to the Alfvén current, would have the following value for a typical experiment on the bombardment of a spherical target with a radius of (1-3) × 10^{-2} cm:

$$en'v\,4\pi R^2/I_A = \frac{4\pi e^2}{m'c^2} R^2 \cong 10^{-15} n' .$$

Since the density of the fast particles has been found experimentally to be well above 10^{15} cm^{-3}, the situation corresponds to that discussed above. For a typical laser plasma (T_e = 1 keV, $z_{\text{eff}} \cong 5$), the instability growth rate in (5) is

$$\gamma \cong \frac{n'}{n} \nu_{ei}\, \theta^{-2} \cong 10^{-8} n' ,$$

Over the typical time of an experiment (10^{-9} s), an instability can thus occur if $n' > 10^{17}$ cm^{-3}. The radius of the streams is determined by inequality (6); taking into account the requirement on n', we find $r > c/\omega_p (n/n')^{1/2} > 2 \cdot 10^{-3}$ cm. This instability is dangerous because, by breaking up into streams the heat flux carried by the fast particles, it can cause an inhomogeneous heating and disrupt the symmetric compression of the target jacket.

Turning to plasmas in space, we note that the typical densities are 10-10^{-3} cm^{-3} and the typical temperatures are 0.1-100 eV. In, say, the flux represented by the solar wind at the position of the earth we would have $n \cong 1$ cm^{-3}, T_e = 10 eV, and a proton velocity up to 3×10^7 cm/s.

We wish to emphasize that although all the arguments of this paper have dealt with electron beams, and all the equations have been derived for electron beams, the effects described above also occur when a quasineutral swarm enters a plasma, over a distance shorter than the mean free path of the ions of the swarm but greater than the mean free path of the electrons. For this case, m' in the equations above would have to be understood as the ion mass.

Despite the low density, the integrated fluxes in a plasma in space are large. The flux in the solar wind is comparable to the ion Alfvén current, Mvc^2/e, for a transverse dimension of 10^8 cm; in other words, the particle flux at the intersection with the earth's magnetosphere exceeds the Alfvén flux by a factor of hundreds. The scale time for the field production in the solar wind as it interacts with a plasma of comparable density is

$$\frac{M}{m} \frac{n}{n'} \nu_{ei}^{-1} \cong 10^9 \text{ s} \cong 30 \text{ yr}.$$

Let us examine the physical picture of the magnetic-field production as a fast plasmoid of length l enters a denser cosmic cloud. Over the time spent by the plasmoid in the cloud, $t = l/v$, a magnetic field is produced in accordance with (2). This field, frozen in the plasma of the cloud, will remain as a "wake" of the plasmoid, gradually expanding over the skin thickness $l_1 = 4\pi\sigma v r^2 c^{-2}$. The plasmoid expends energy on Joule heating of the plasma of the cloud and is slowed down over a distance $M/m\, n/n'\, v/\nu_{\text{ei}}$. The fraction of the energy which is converted into energy of the frozen-in magnetic field is $lc^2/4\pi v r^2$. In these expressions, the scale dimension either is determined by the initial transverse dimension of the flux or arises as a result of the instability discussed above; there is, however, a lower limit $c/\omega_p (n/n'\, M/m)^{1/2}$ on this scale dimension. The picture of the process drawn above holds over a distance shorter than the single-particle stopping length of the plasmoid. Because of the entrainment of electrons by ions, ν_{ei} must be understood as

$$\nu_{ei} + \nu'_{ei} - \frac{n}{n'z'}\nu'_{ei}, \quad n = n_i z_i + n'z'.$$

These examples demonstrate the importance of considering the canceling conduction currents which are excited in a medium entered by particle fluxes above the Alfvén limit, as is the case in laser plasmas and in plasmas in space.

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