On magnetic field generation in the interpenetrating plasma clouds

S. I. Krasheninnikov

University of California San Diego, La Jolla, CA 92093, USA

Introduction. Spontaneous generation of the magnetic fields is of fundamental physics interest since it plays an important role in many phenomena in both, laboratory and astrophysical environments. A number of different mechanisms for large-scale magnetic field generation have been identified [1]: crossed gradients of plasma density and electron temperature (the $\nabla n \times \nabla T_e$ mechanism) and its kinetic analog for semi-collisional plasma, a mechanism related to the transport of energetic electron beam through a plasma, and mechanisms related to radiation and dynamo effects, etc.

Recently, a new mechanism of spontaneous generation of large-scale magnetic fields for interpenetrating plasma clouds has been proposed in Ref. [2]. It is based on the electron dynamics causing current drive due to the electron collisions with different ion species [3]. Such a mechanism is relevant for understanding the interactions of astrophysical plasma clouds/jets and for simulation of these objects in the laboratory experiments.

However, depending on the plasma parameters, turbulent processes caused by the interactions of the interpenetrating plasma clouds can also contribute to the current drive and, therefore, to the generation of the large-scale magnetic field.

Model. As an illustration we consider the interaction of two plasma streams in the case where ion density of one stream, n_i, is much larger than the ion density of another one, n_b. We will assume that initially ions are almost mono-energetic, while electrons have the temperature T_e. Then, our problem becomes identical to that of the ion beam interaction with the plasma (in our case n_b and n_i can be considered as the ion densities of the beam and plasma, respectively, satisfying inequality $n_i >> n_b$) and we can use a weak turbulence approximation. We will also assume that the relative velocity of the ion streams is smaller than the sound speed, $C_s = \sqrt{T_e / M_i}$, where M_i is the mass of plasma ions. For this case beam-plasma interaction has a 1D character [4] and has the same features as the relaxation of an electron beam.

In the frame where the total momentum of electrons and both ion species, P, is zero, the initial 1V distribution functions of the particles can be sketched as shown in Fig. 1. Since initially, there is no electric current in the streams, the Maxwellian electron distribution function is shifted to account for this. As a result at first we have both, total momentum and electric current density, j, to be zero:

$$P_{in} = P_e + M_i V_i n_i + M_b V_b n_b = 0, \quad (1)$$

$$j_{in} = j_e + eZ_i V_i n_i + eZ_b V_b n_b = 0, \quad (2)$$

where P_e and j_e are the electron contributions to the total momentum and electric current; e is the elementary charge; M_i, Z_i, V_i, and n_i (M_b, Z_b, V_b, and n_b) are the mass, charge number (we assume it is negative for electrons), velocity, and density of the plasma (beam) ions (we will assume that $M_b \sim M_i$ and $Z_b \sim Z_i$).

However, in order to have an anomalous process of the ion beam relaxation, caused by the sound wave turbulence, the growth rate of the sound waves should be positive, which requires that

$$\frac{1}{m}\frac{\partial f_e(v,t)}{\partial v}+\frac{Z_b^2}{M_b}\frac{\partial f_b(v,t)}{\partial v}>0, \tag{3}$$

where m is the electron mass. Inequality (3) sets a low limit on the beam density at which turbulent relaxation is possible. Assuming shifted Maxwellian distribution function for electrons, we have a rough estimate $\partial f_b(v,t)/\partial v \sim n_b/V_b^2$ and $\partial f_e(v,t)/\partial v \sim -n_e V_b/V_{Te}^2$ (where $V_{Te}^2 = T_e/m$ and we neglect a small factor $n_b/n_e \ll 1$). As a result, inequality (3) can be written as follows

$$\frac{n_b}{n_e}>\frac{1}{Z_b^2}\frac{M_b}{m}\left(\frac{V_b}{V_{Te}}\right)^3. \tag{4}$$

Since in our case $V_b \lesssim C_s$, the right hand side of Eq. (4) is $\sim Z_b^{-2}(M_b/M_i)\sqrt{m/M_i} \ll 1$.

Once Eq. (3) is satisfied, the beam relaxation process will flatten the beam distribution function in a way sketched in Fig. 2, so that the averaged beam ion velocity becomes αV_b, where $\alpha \approx 1/2$. In addition, it also will affect the electron distribution function and the velocity of the plasma ions.

However, all these modifications of electron and ion distribution functions should be compatible with the well-known conservation of the spatially averaged total momentum, which can be found from the kinetic equations for all species and the Poisson equation:

$$\frac{\partial P}{\partial t}+\frac{\partial}{\partial x}\left(\frac{E^2}{8\pi}+\sum_{e,i,b}\left\langle Mv^2\right\rangle\right)=0, \tag{5}$$

where E is the electric field stress and $\langle ... \rangle$ shows the integration over corresponding distribution function.

Then, taking into account that the electrons practically do not contribute to the momentum balance equation (1) due to their small mass, we find plasma ion velocity $V_i^{\prime}$

$$V_i^{\prime}=-\alpha\frac{n_b}{n_i}\frac{M_b}{M_i}V_b. \tag{6}$$

We notice that in a quasilinear approximation the variation of the background ion velocity is adiabatic.

The electron resonance interactions with the ion acoustic waves cause the flattening of the electron distribution function (see Fig. 2). However, taking into account inequality (4) it is easy to show that it results in a smaller impact on both electric current and energy balance than the effects associated with the relaxation of the ion beam. Therefore, the electron contribution to the electric current can be considered constant. As a result, taking into account Eq. (1, 2, 6) we find the magnitude of the electric current caused by the ion beam relaxation, j_{fin},

$$j_{fin}=-(1-\alpha)eZ_b n_b V_b\left(1-\frac{Z_i}{M_i}\frac{M_b}{Z_b}\right)=-(1-\alpha)eP_b\left(\frac{Z_b}{M_b}-\frac{Z_i}{M_i}\right), \tag{7}$$

where $P_b = M_b n_b V_b$ (recall that from the momentum balance we have $P_b \cong -P_i$)

Thus we see that the quasilinear relaxation of the ion beam can generate an electric current. This effect is particularly strong when the ratios Z/M of background and beam ions are different (see Eq. (7)). But even if they are the same the current generation is still present, although the magnitude of j_{fin} is smaller in comparison with the estimate (Eq. 7). In the latter case to recover the expression for j_{fin} we need to keep the terms, which were omitted while we were deriving Eq. (7).

So far we have considered the current drive associated with the beam relaxation neglecting the effect of large scale-length quasi-stationary electric field, E. Meanwhile, from kinetic equations for plasma species we find

$$\frac{\partial j}{\partial t} + \frac{\partial}{\partial x}\left(\sum_{e,i,b} \left\langle eZv^2 \right\rangle \right) - \left(\frac{\delta j}{\delta t} \right)_{turb} - \frac{\omega_p^2}{4\pi} E = 0, \tag{8}$$

where $\omega_p^2 = 4\pi \sum_{e,i,b} (eZ)^2 n/M \approx \omega_{pe}^2$, $\left(\delta j/\delta t\right)_{turb} = \sum_{e,i,b} (eZ)^2 \left\langle \tilde{n}\tilde{E} \right\rangle /M$ is describing the current drive associated with turbulent processes, $\tilde{E}$ and $\tilde{n}$ are the fluctuating small scale-length parts of electric field and densities and $\left\langle \tilde{n}\tilde{E} \right\rangle$ is the averaged part of their product. As a result, we find the following estimate for the electric field E induced by the turbulent relaxation of the beam

$$E \approx -\frac{4\pi}{\omega_{pe}^2} \left(\frac{\delta j}{\delta t} \right)_{turb}. \tag{9}$$

Taking into account the inhomogeneity of the cloud we have $|\nabla \times \vec{E}| \sim E/a \neq 0$, where a is the scale-length of beam/background plasma. As a result from the Faraday's equation, $\partial \vec{B}/\partial t = -c\nabla \times \vec{E}$ (where c is the light speed), we have the generation of the large scale-length (~a) magnetic field.

The anomalous interactions between the interpenetrating collisionless ion beam and the plasma (or two plasma clouds) caused by ion beam (or two ion streams) instability occurs in a rather narrow region with the width $\delta << a$ [5]. The magnitude of the magnetic field, B_{turb}, which is generated during the time of ion beam and plasma (or two plasma clouds) interactions, $\tau \sim a/|V_b - V_i|$, can be estimated as

$$B_{turb} \sim \frac{c}{|V_b - V_i|} \frac{4\pi}{\omega_{pe}^2} \left(\frac{\delta j}{\delta t} \right)_{turb}. \tag{10}$$

Then, for the case of two plasma clouds assuming $n_b \sim n_i$ and $Z_b/M_b \sim Z_i/M_i$, (which implies that the growth-rate of the instability is $\sim \omega_{pi}$, where we are not making distinction between the plasma frequencies of different ions) and estimating $(\delta j/\delta t)_{turb} \sim \omega_{pi} j_{fin}$ we find

$$B_{turb} \sim \frac{c}{|V_b - V_i|} \frac{4\pi\omega_{pi}}{\omega_{pe}^2} eP_b \left| \frac{Z_b}{M_b} - \frac{Z_i}{M_i} \right|. \tag{11}$$

This estimate also can be re-casted as follows

$$\Omega_{Be}(B_{turb}) \sim \omega_{pi} \frac{\Delta(Z/M)}{Z/M}, \tag{11'}$$

where $\Delta(Z/M) = |Z_b/M_b - Z_i/M_i|$ and $\Omega_{Be}(B)$ is the electron cyclotron frequency for the magnetic field stress B. We notice that the collisional current drive mechanism [2] gives the following estimate for the magnetic field strength, B_{coll}, generated during interactions of two plasma clouds

$$\Omega_{Be}(B_{coll}) \sim \nu_{ei} \frac{\Delta(Z)}{Z}, \tag{12}$$

where ν_{ei} is the electron-ion collision frequency and $\Delta(Z) = |Z_b - Z_i|$.

Comparing the expressions (11) and (12) one finds that for $\omega_{pi} >> \nu_{ei}$ turbulent processes can be much more efficient in the large scale-length magnetic field generation.

Conclusions. We demonstrated that the turbulent interactions of two plasma clouds can generate large scale-length magnetic field. This process becomes more pronounced when the ions in the interaction clouds have different Z/M ratios. In order to get more accurate estimates of B_{turb} and to account for other possible effects (e.g. the Weibel instability, which is also observed during the plasma clouds interactions [6]), more detailed studies, including numerical simulations are needed.

Acknowledgements. The author acknowledges useful discussions with M. A. Malkov, D. D. Ryutov, R. Z. Sagdeev, and A. I. Smolyakov. This work is supported by USDOE grant DE-FG02-04ER54739 at the UCSD.

References

[1] J. A. Stamper, Laser and Particle Beams, **9** (1991) 841; J. A. Stamper, et al., Phys. Rev. Lett. **26** (1971) 1012; R. J. Kingham and A. R. Bell, Phys. Rev. Lett. **88** (2002) 045004; A. R. Bell, J. R. Davies, and S. M. Guerin, Phys. Rev. E **58** (1998) 2471

[2] D. D. Ryutov, et al., Phys. Plasmas **18** (2011) 104504

[3] T. Ohkawa, Nucl. Fusion **10** (1970) 185

[4] A. A. Ivanov, S. I. Krasheninnikov, T. K. Soboleva, and P. N. Yushmanov, Fiz. Plasmy, **1** (1975) 753 (in Russian)

[5] R. Z. Sagdeev and C. F. Kennel Sci. Am. **264** (1991) 106; T. N. Kato and H. Takabe, Phys. Plasmas **17** (2010) 032114; X. Liu, et al., New J. Phys. **13** (2011) 093001; Y. Kuramitsu, ey al., Phys. Rev. Lett. **106** (2011) 175002

[6] H. Takabe, et al., and J. Zhang Plasma Phys. Contr. Fus. **50** (2008) 124057

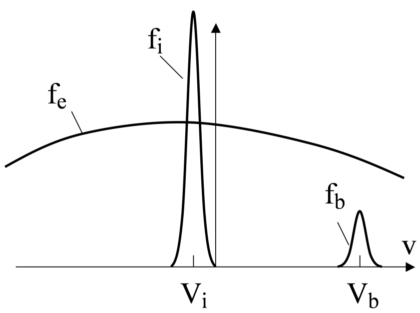

Fig. 1. Initial distribution functions of electrons, $f_e(v)$, and two ion species ($f_i(v)$ and $f_b(v)$).

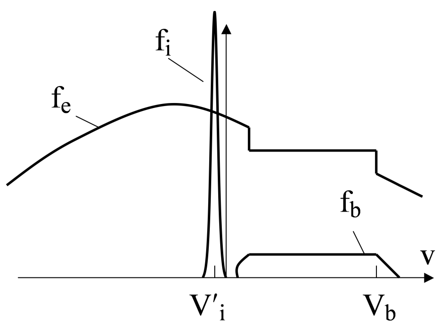

Fig. 2. Final distribution functions of electrons and ions.