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Pair Production of Plasma Vortices

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assumed stationary,

$$\mathbf{v}_i = \mathbf{v}, \tag{9}$$

and Eqs. (3), (4), and (7) yield

$$\rho_i\left(\frac{d\mathbf{v}_i}{dt}\right) + \mathbf{v}_i\left(\frac{d\rho_i}{dt}\right) = \mathbf{J}\times\mathbf{B}, \quad \mathbf{J} = \sum q_s n_s \mathbf{v}_s, \tag{10}$$

$$\frac{d}{dt}\left[\rho_i(\tfrac{1}{2}v_i^2 + \epsilon_i) + \rho_e\epsilon_e\right] - \mathbf{E}\cdot\mathbf{J} + Q = 0,$$
$$Q = \sum Q_s. \tag{11}$$

Expanding Eq. (11) and expressing $d\mathbf{v}_i/dt$ from Eq. (10) and $d\rho_s/dt$ from Eqs. (2) and (8), one finds

$$[\tfrac{3}{2}k(T_e + T_i) + I - \tfrac{1}{2}m_i v_i^2]\Gamma + \tfrac{3}{2}n_i k \frac{d}{dt}(T_e + T_i) + Q - \mathbf{E}^*\cdot\mathbf{J} = 0, \tag{12}$$

where

$$E^* = \mathbf{E} + \mathbf{v}_i \times \mathbf{B}. \tag{13}$$

If it is assumed in Eq. (12) that the temperature gradient and heat loss terms are small, then it can be expressed as

$$\Gamma = \mathbf{J}\cdot\mathbf{E}^*[I + \tfrac{3}{2}k(T_e + T_i) - \tfrac{1}{2}m_i v_i^2]^{-1}. \tag{14}$$

For the case where **E** and **B** are perpendicular, $E^* = 0$, when the ions move with the drift velocity. When Γ is finite, it is seen from Eq. (14) that this drift velocity must be equal to a limiting velocity, v^*, given by

$$\tfrac{1}{2}mv^{*2} = I + \tfrac{3}{2}k(T_e + T_i). \tag{15}$$

On the other hand, when Γ becomes zero, v_i will increase as can be seen from Eq. (10).

During the ionization process, the ion and electron temperatures are expected to be small compared to the ionization potential as a result of the elastic and inelastic collisions between ions and electrons and electrons and neutrals. In such a case,

$$v^* \simeq v_c, \tag{16}$$

which is in agreement with the observations reported by Alfvén[2] and Fahleson.[3]

While Eq. (15) is true regardless of the nature of interactions, further assumptions were needed to obtain Eq. (16). An estimate of the electron and ion temperatures requires consideration of the species energy equations, Eq. (4). As can be seen from these equations, this requires specifying first $(\partial f_s/\partial t)_c$ or the exact nature of interactions among the plasma constituents. With $(\partial f_s/\partial t)_c$ specified, no *a priori* assumptions regarding the relative magnitudes of ion and electron temperatures, as was discussed by Lin[4] and Dobrysheviskii,[5] are necessary as these follow from the results of the calculations. Even for the simplest forms of $(\partial f_s/\partial t)_c$, these calculations have to be carried out numerically. Without such calculations, it is not possible to give a quantitative estimate of the temperatures.

The approximations that led to Eq. (14) are discussed next. They are at least plausible if one shows that the expression calculated for Γ when $v_i = v^*$ is compatible with the expression calculated from Eq. (10). To show this, consider, as an illustration, the homopolar device. In this case, Eq. (14) reduces to

$$\Gamma = J(E - v_{i\theta}B)[I + \tfrac{3}{2}k(T_e + T_i) - \tfrac{1}{2}m_i v_{i\theta}^2]^{-1}. \tag{17}$$

When $v_{i\theta} = E/B = v^*$, L'Hospital's rule, applied to the above equation, yields

$$\Gamma = JB/m_i v^*,$$

which is identical to the result obtained from Eq. (10).

The work of Baker, Hammel, and Ribe[6,7] on Ixion showed that the limiting velocity is many times higher than the critical velocity. In their work, however, the gas was fully ionized. For such gases, other phenomena resulting from the spatial gradients and the heat loss, which were neglected in the above analysis, limit the velocity.

The above analysis does not apply to steady plasma devices like Hall Current Plasma Accelerators. This is because the assumptions introduced here, namely, stationary neutrals and negligible spatial gradients, are not expected to hold in such devices.

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Pair Production of Plasma Vortices

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Image converter photographs of various interfaces between a magnetic field and an accelerated plasma show clearly the production of plasma vortex filaments in pairs. These vortex filaments fall into two classes: those parallel to B_0 (the background magnetic field) and those perpendicular to B_0.

COLUMNAR plasma vortex filaments[1] parallel to and rotating around the lines of the background magnetic field B_0 (parallel-to-B_0 vortices)

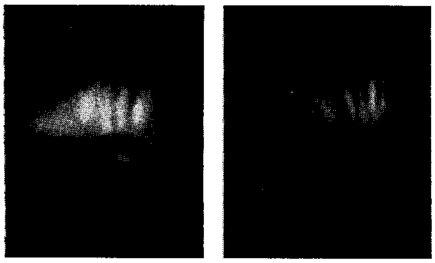

FIG. 1. Image converter photographs (0.1-μsec exposure) of the north polar view of argon plasma flow over a magnetic dipole formed by a 5-cm-diam loop coil (seen as a "shadow"). Argon plasma of density $\sim 5 \times 10^{13}/\text{cm}^3$ flows from the top at a speed of $\sim 3 \times 10^6$ cm/sec for about 8 μsec from a plasma coaxial accelerator located 33 cm from the dipole axis. The magnetic field at the center of the coil is 2.6×10^4 G. The illumination comes from parallel-to-B_0 vortices which are observed to be formed in pairs. The vortices expand rapidly ($\sim 3 \times 10^6$ cm-sec) along the magnetic field and thread the hole in the loop coil. The ion density is concentrated in the vortices, thereby rendering them more luminous than the background. Similar structures have been photographed with hydrogen plasma.

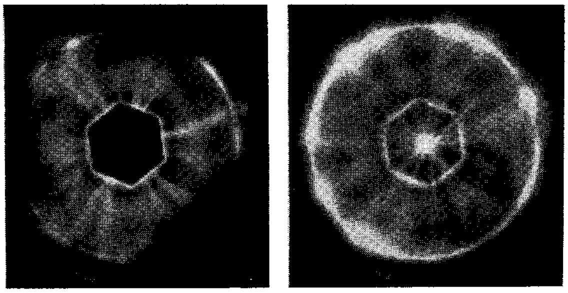

FIG. 2. Image converter photographs, end on, of a plasma coaxial accelerator, o.d. 5 cm, where the center conductor which is 4 cm long, is hexagonal. The accelerator is operated with H_2 gas at a static pressure of 2 mm. The formation of pairs of perpendicular-to-B_0 vortices at each flat side of the hex is striking. The peak current in the accelerator is 150kA, the half-cycle 1.5 μsec. The left photograph is taken 0.8 μsec after the beginning of the current half-cycle; right photograph taken at about 1.0 μsec when the vortices have coalesced in the pinch at the end of the center conductor. The authors suggest that the coming together of these force-free type filaments at the end of the center conductor is analogous to the process which produces solar flares[10] in the solar atmosphere.

have been produced in two-abreast pairs by a small plasma button gun fired across B_0. These two-abreast pairs of vortices are observed with electric-field probes and density probes to proceed across the magnetic field B_0. The generation of plasma vortices in plasma flow over a magnetic dipole has been observed by probes[2,3] and by image converter photographs.[1,4] We now have striking image converter photographs of the formation of parallel-to-B_0 vortices in pairs in plasma flow over a magnetic dipole (see Fig. 1).

Force-free-type plasma vortices where the filamentary axis is perpendicular to the background field B_0 (perpendicular-to-B_0 vortices) have been observed by Wells[5,6] and Small[7] to be produced by the conical theta pinch. Wells and Small have demonstrated experimentally that these vortices have helical, force-free-type magnetic fields. Small has now demonstrated, in addition,[7] that these perpendicular-to-B_0 vortices also have mass flow which is roughly colinear with these helical fields. We now show in Fig. 2 an image converter photograph of a plasma-coaxial accelerator with a hexagonal center conductor in which spectacular radial filaments are observed to occur in pairs on each flat side of the hexagon. We believe that these bright radial filaments represent perpendicular-to-B_0 vortices of the force-free-type which are created in pairs. Measurements of the time derivative of the magnetic field parallel to the axis of each member of a pair of such radial filaments have been made with a coupling loop placed first to obtain the $d\phi/dt$ for one member of the pair, and next to obtain $d\phi/dt$ for the other member of the pair as they pass through the coupling loop. The traces of $d\phi/dt$ given in Fig. 3 show a strong magnetic field ($\cong B_0$ in the coaxial accelerator) and show that these fields are of opposite sign in the two members of the pair, as they should be. One member of the pair should be corotating and left-handed, the other member should be contrarotating and right-handed. Investigations are now proceeding to determine in detail with coupling loops and density flow probes the magnetic and density-flow structure of these filaments.

The formation of pairs of parallel-to-B_0 vortices in the plasma flow over the magnetic dipole can be qualitatively understood to grow out of Rayleigh–Taylor-instability flutes as diagrammed in Fig. 4. The formation of pairs of perpendicular-to-B_0 vortices can be understood qualitatively from the diagram in Fig. 5.

Mather[8] and Kolesnikov *et al.*[9] have photographed similar radial striations in their coaxial plasma accelerators. Mather observes that maximum neutron production occurs under the conditions when these radial striations initially are fairly uniformly distributed around the center conductor, which, in his case, is a cylinder. His neutrons are produced at the moment when the discharge

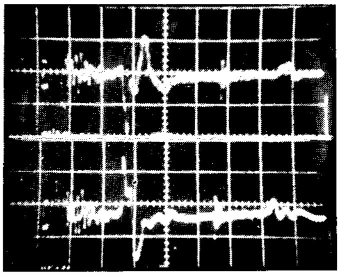

FIG. 3. Oscilloscope traces of $d\phi/dt$ radial in the coax taken for a right-handed and a left-handed member of perpendicular-to-B_0 vortices pairs such as are shown in Fig. 2. The coupling loop is placed approximately half way between the inner and outer conductors. The coupling loop is one turn, 0.34 cm in diameter. The peak magnetic fields measured along the axes of the tourbillons at the position of the loop are about 2500 G.

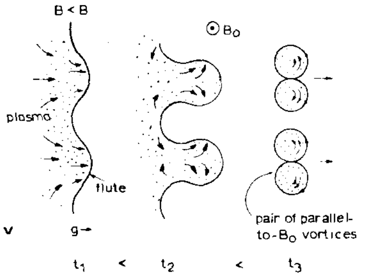

FIG. 4. Diagram showing how parallel-to-B_0 vortices may be expected to develop in pairs out of Rayleigh–Taylor flute instability. **v** is the plasma flow velocity, **g** is the effective "gravitational *g*" felt by the plasma as it is decelerated by the gradient of *B*.

coalesces into a pinch at the end of the center conductor. The right photograph of Fig. 2 shows a bright spot formed by the coming together of the perpendicular-to-B_0 vortex filaments at the end of the hexagonal center conductor. The authors suggest that this process is similar to the production of solar flares in the atmosphere of the sun by the coming together of such structures, as described by Gold and Hoyle.[10] The authors now suggest that the striations observed by Mather and Kolesnikov *et al.* may also be perpendicular-to-B_0 vortices and that these vortices may possibly play a role in the neutron production at the end of the center conductor. The authors also suggest that the striations observed by Kvartskhava[11] in the *Z* pinch and theta pinch and by Bodin[12] in the theta pinch may be the same type of perpendicular-to-B_0 vortices.

A recent preprint received from Kolesnikov and the Filippovas[13] displays streak camera photographs which show their striations being produced in pairs. If these filamentary plasma structures observed by a variety of investigators are really plasma vortices, as the authors suggest they are, the existing theoretical and experimental work on collisionless shocks must be reexamined in the light of these vortices which are so easily produced.

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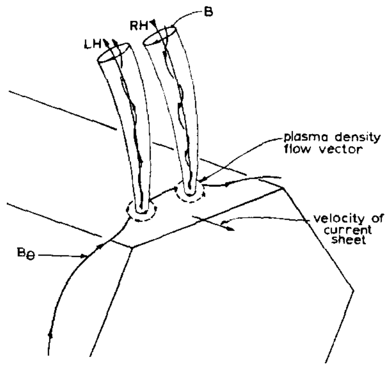

FIG. 5. Diagram showing how perpendicular-to-B_0 vortices may be expected to develop in pairs in the plasma coaxial accelerator with a hexagonal center conductor. The general geometry is somewhat similar to that expected from resistive instabilities in the tearing mode.

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Image Converter Observations of the Development of the Dense Plasma Focus Discharge

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A multiplicity of radial striated light filaments is observed at the back plate of the dense plasma focus coaxial discharge during the early phases of breakdown and current sheath buildup. Later in time, the current sheath appears azimuthally symmetric.

A PHOTOGRAPHIC study of gas breakdown and development of the current sheath buildup in the dense plasma focus coaxial discharge[1] has been made using an image converter camera. During the first microsecond a radial striated light pattern develops across the back plate; for $t > 1$ μsec, the striated structure disappears. A similar striated structure has been obtained by Bostick *et al.*[2] They conclude from their work that the mechanism of neutron production from the dense plasma focus is the coalescing of "paired" filaments (vortices) at the end of the center electrode. The author's evidence does not support this conclusion. What is important to the production of the dense plasma is the uniformity of the initial gas breakdown and