STRUCTURE FORMATION BY STRONG, LOCALIZED PLASMA HEATING

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The generation and the dynamics of electron vortical structures on fast time scales by strong localized heating is investigated. Strong localized electron heating, like ECRH, leads to perturbations of the electron temperature and causes strong pressure gradients. The nonaligment of the pressure and density gradients generates a magnetic field [1]. This field has a dipolar structure as illustrated in Fig. 1 where we consider a circular heating domain. The density gradient is in the vertical direction and the generated magnetic field is constant along the current flow lines (dotted lines). Such structures may have some relevance to the filamentary profile of the electron temperature observed in the Rijnhuizen Tokamak Project (RTP) [2]. We describe the early stage of their formation using the model of compressible electron magnetohydrodynamics (EMHD) [3, 4], extended to include pressure gradient effects. The dynamics in this model is completely governed by the electrons.

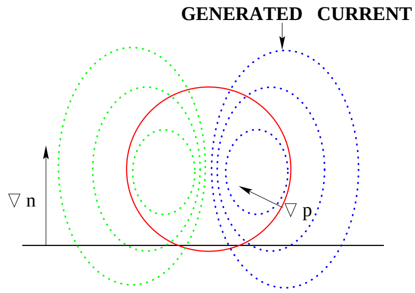


Fig. 1. *Mechanism of dipole generation.*

We restrict ourselves to $2D$ plasma dynamics, and write the magnetic field as $\mathbf{B} = B_0\left[(1+b)\mathbf{e}_z + \nabla\psi\times\mathbf{e}_z\right]$ [4] where, b is the perturbation of the axial magnetic field, $\mathbf{e}_z$ is the unit vector in the ignorable z-direction, B_0 is a large constant, and ψ is the azimuthal flux function. The equilibrium magnetic field forms straight lines under an angle b_y relative to the z-axis. Our EMHD model consists of three coupled equations for the $z-$ component of the generalized potential vorticity $\Omega \equiv b - d_e^2\nabla^2 b - \tilde{n}_e$, the generalized magnetic potential $\Psi \equiv \psi - d_e^2\nabla^2\psi$ and the normalized electron pressure $\beta_\perp = 4\pi p_\perp/B_0^2$,

$$\frac{\partial\Omega}{\partial t} = -\left[b, \Omega - n_{eq}\right] - \left[\psi, \nabla^2\psi\right] + \left[\beta_\perp, n_e/n_0\right], \tag{1}$$

$$\frac{\partial\Psi}{\partial t} = -\left[b, \Psi\right], \tag{2}$$

$$\frac{\partial \beta_\perp}{\partial t} = -\left[b, \beta_\perp\right] + S. \tag{3}$$

Here, the brackets denote the Jacobian $[f, g] \equiv (\partial f/\partial x)(\partial g/\partial y) - (\partial f/\partial y)(\partial g/\partial x)$, time and space coordinates are normalized as: $t \to \omega_{Be} d_e^2\, t$, $(x, y) \to (x/r_0, y/r_0)$ with $d_e = c/(r_0\omega_{pe})$ and r_0 is characteristic width of the heated region, S is the power of the heating source. The normalized electron density is $n_e = n_{eq} + \tilde{n}_e$ where $n_{eq} = 1 - \kappa_n x$ is the equilibrium density gradient, κ_n being the inverse equilibrium density scale length and

$$\tilde{n}_e = \lambda^2 \nabla^2 (b + \beta_\perp), \qquad \lambda^2 = (\omega_{Be}^2/\omega_{pe}^2) d_e^2. \tag{4}$$

Equations (1)–(4) describe coupled electron gradient drift and whistler modes [4].

Assuming proper boundary conditions, our model contains the invariants $\int d\mathbf{r}\,\Omega$, $\int d\mathbf{r}\, f(\Psi)$. In the absence of the heating also $\int d\mathbf{r}\, g(\Psi, \beta_\perp)$ and the energy $E = (1/2)\ \int d\mathbf{r}\,[(b^2 + |\nabla\psi|^2) + d_e^2(|\nabla b|^2 + (\nabla^2\psi)^2) + \lambda^2(|\nabla b|^2 - |\nabla\beta_\perp|^2) + 2\beta_\perp n_{eq}]$ are invariants. Here, f and g are arbitrary functions of their arguments. The evolution equations (1)–(4) can be written in Hamiltonian form if $S = 0$.

We have studied the system of equations (1)–(4) numerically with a $2D$ spectral code. The heating power is chosen to be Gaussian distributed. The calculations show that the generated structures are long living and transport the electron heat. Shortly after the onset of heating a dipolar magnetic field is generated with its axis aligned to the density gradient as sketched in Fig. 1. At this stage the perturbations are still linear and, for the cases we are studying $\kappa_n/b_y \geq 1$, they propagate in the y-direction with the electron gradient drift velocity κ_n. The perturbed magnetic field drives a vortical flow $\nabla b \times \mathbf{e}_z$. From Eqs (1)–(4) b is estimated as $b \simeq \kappa_n S_0 t^2$. The vortical flow velocity becomes comparable to the electron gradient drift velocity at times $t_0 \simeq S_0^{-1/2}$. At this time nonlinear effects become important. For incompressible plasma ($\lambda^2 \ll 1$), the generated magnetic pressure inside the negative pole of the vortex equilibrates with the kinetic pressure in a time κ_n^{-1}. Thereafter this pole stays inside the heating region. On the other hand the positive pole propagates out of the heating zone. When $\kappa_n > S_0^{1/2}$, the latter perturbation does not have enough time to develop a sizeable vortical flow. Hence, it remains linear. This is demonstrated in Fig. 2 where plots of the generalized potential vorticity and the normalized electron pressure are given. Due to the smallness of λ and b_y, density perturbations and equilibrium poloidal magnetic field do not play an important role in the dynamics.

Figure 3 shows plots of the generalized potential vorticity and the normalized electron pressure in the case of a weak density gradient $\kappa_n < S_0^{1/2}$. In that case the system stays long enough in the heating region so that it develops sizeable vortical flow. The strong turbulence that appears in the plot of the generalized potential vorticity is due to the influence of the perturbations of ψ which are created by the flow.

Figure 4 shows the same case as Fig. 2 but with large λ so that density perturbations become important. In this case the previous mechanism of equilibration is not dominant anymore. The effect of density perturbations result in rotating the dipole axis over almost $\pi/2$ radians. Both poles of the vortex stay together, get heated and drift slowly along the y-direction. The dipole drifts out of the heating region and a new one is generated in its place. The strong turbulence characterizing the final state of the generalized potential vorticity is due to the density perturbations.

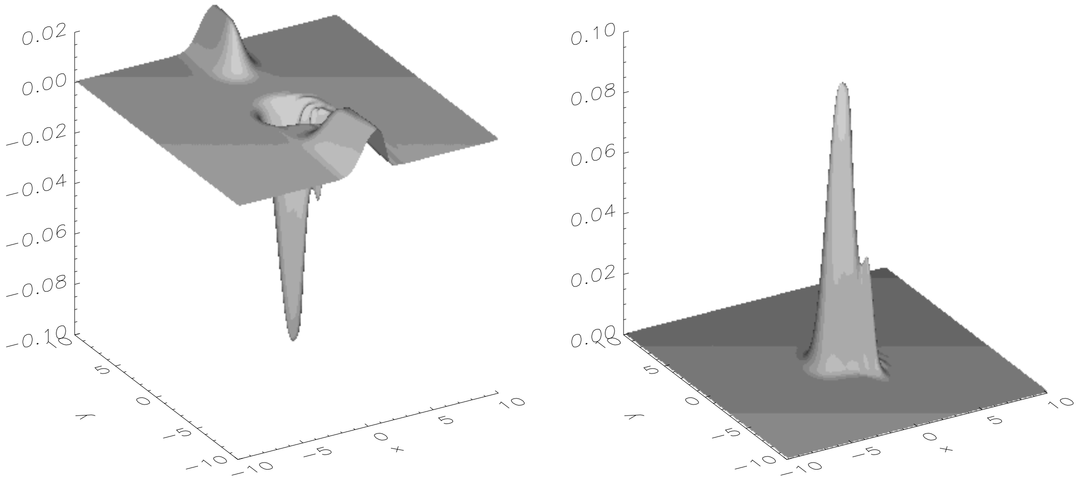


Fig. 2. *Generalized potential vorticity (left) and normalized electron pressure (right) at time* 800*. Plasma parameters:* $d_e = 1.0$, $\lambda = 0.01$, $\kappa_n = 0.1$, $b_y = 0.01$, *source amplitude* $S_0 = 0.001$, *source switched off at time* $t_s = 100$.

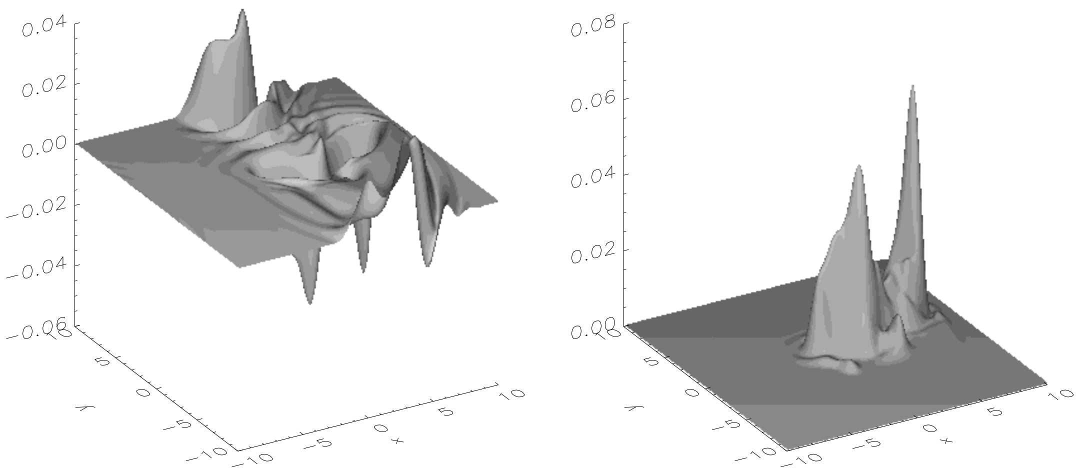
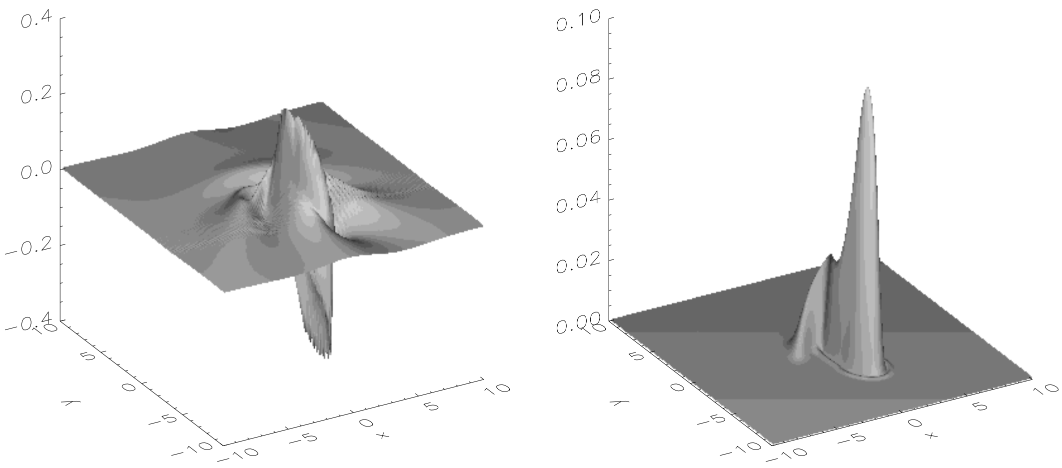


Fig. 3. *Generalized potential vorticity (left) and normalized electron pressure (right) at time 140. Plasma parameters:* $d_e = 1.0$, $\lambda = 0.01$, $\kappa_n = 0.01$, $b_y = 0.01$, *source amplitude* $S_0 = 0.001$, *source switched off at time* $t_s = 100$.

(a)



(b)

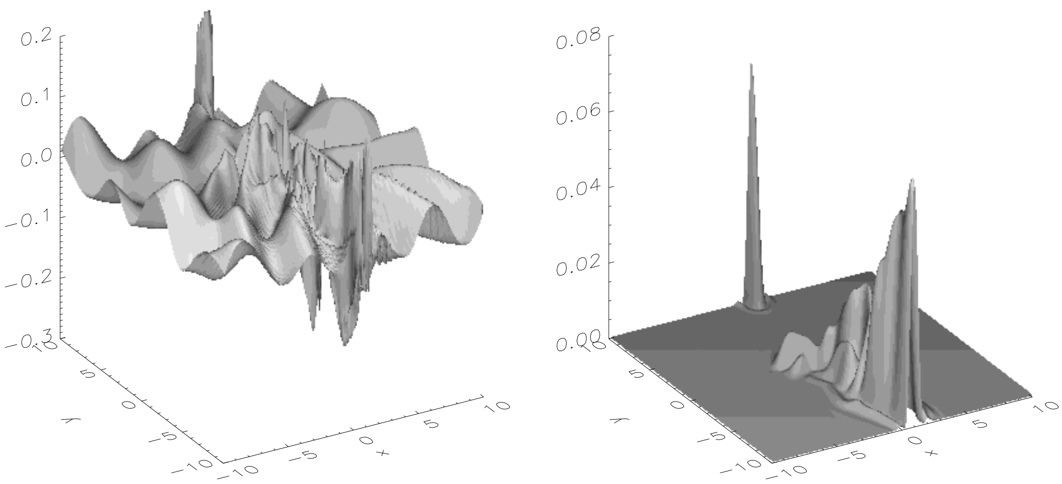


Fig. 4. *Generalized potential vorticity (left) and normalized electron pressure (right) at times (a) 250 and (b) 800. Plasma parameters:* $d_e = 1.0$, $\lambda = 1.0$, $\kappa_n = 0.1$, $b_y = 0.01$, *source amplitude* $S_0 = 0.001$, *source switched off at time* $t_s = 100$.

In conclusion we have shown that strong localized heating of a non uniform plasma generates vortical structures. These structures may capture the heat and transport it across the plasma. When they survive for sufficiently long time, then a filamentary profile of the temperature develop.

References

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