34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-4.143 (2007)

COLLISIONAL EFFECTS IN QUASI-COLLISIONLESS DRIVEN MAGNETIC RECONNECTION

J. J. Martinell[1] and J. J. Ramos[2]
[1] *Instituto de Ciencias Nucleares, UNAM,*
A. Postal 70-543, Mexico D.F. MEXICO
[2] *Plasma Science and Fusion Center, MIT,*
Cambridge, Massachusetts 02139, USA

I. Introduction

The problem of driven magnetic reconnection is of importance in several physical situations of interest such as fusion plasmas, the solar corona and the earth magnetosphere, where magnetic storms originate. In most of these cases the plasmas are weakly collisional or completely collisionless. These two regimes have been studied in several works for many years considering the importance of the different terms in Ohm's law that may lead to reconnection, besides the collisional resistivity, mainly the electron inertia and the pressure tensor. Also the effect of the Hall term has been studied and it has been found that it is most important when there is no guide field, perpendicular to the reconnecting magnetic field. Analytical studies are normally limited to linear regimes and the nonlinear cases have to be treated by means of numerical computations.

In a previuos work [1] we studied the forced magnetic reconnection of a typical magnetospheric plasma using a collisionless reduced model, given in [2], developed when a guide field is present, which we argue is the relevant case for the magnetosphere. The starting magnetic configuration was a neutral X-point. That model includes also the effect of resistivity and of flow aligned with the guide field that were not deemed to be important in our case of interest. In this work we explore the effects that a small amount of collisions may have on the reconnection process. We follow two different approaches. First, the terms related to the resistivity given in [2] are included in the numerical code, but assuming they are very small. Second, a new computation is made based on a set of equations derived recently by Ramos [3]. As a reference system, we will consider a magnetospheric plasma with the following parameters: $n \sim 10cm^{-3}$, $T \sim 10eV$ and $B \sim 10^{-4}Gauss$, for which the ion-sound gyroradius is $\rho_s \sim 20km$, the electron inertial skin depth is $d_e \sim 1km$, while $\beta \sim 1/4$. Thus relevant range to consider has $\rho_s/d_e > 1$ but $\beta < 1$, which we analyze using the nonlinear equations.

II. Reduced model for weakly collisional evolution

Our configuration consists of a magnetic null X-point in 2D contained in the $x-y$ plane and a guide field in the z direction. The magnetic field is represented by $\mathbf{B} = \hat{z} \times \nabla\psi(x,y,t) + B_z(x,y,t)\hat{z}$. The equilibrium magnetic potential is $\psi_0 = B'_\perp xy$ and is characterized by a scale length defined by $l_0 \equiv B_{z0}/B'_\perp$. The plasma velocity is written in terms of the potential ϕ as $\mathbf{v} = \hat{z} \times \nabla\phi(x,y,t) + v_z(x,y,t)\hat{z}$. The two fluid equations, when the conditions $\beta < 1$ and $l_0/d_i \gg 1$ are assumed, where d_i is the ion skin depth, can be reduced to a set of three equations for the variables ψ, ϕ and the density contained in $\xi \equiv l_0/d_i \log(n/n_0)$, with n_0 the equilibrium density. These equations for a weakly collisional plasma, in the limit $v_z \to \infty$ and cold ions, are [4]:

$$\frac{\partial U}{\partial t} = [U, \phi] + [\psi, \nabla^2\psi] \tag{1}$$

$$\frac{\partial}{\partial t}(\psi - d_e^2\nabla^2\psi) = [\psi - d_e^2\nabla^2\psi, \phi] - \rho_s^2[\psi, \xi] + \eta\nabla^2\psi \tag{2}$$

$$\frac{\partial \xi}{\partial t} = [\xi, \phi] + [\phi, \nabla^2\psi] \tag{3}$$

where $[f, g] = \hat{z} \cdot \nabla f \times \nabla g$, and all variables are normalized according to $\phi \to \phi(\tau_A/l^2)$, $\psi \to \psi/(l^2 B'_\perp)$, the lenghts to the system size l, and the time to the Alfvén time $\tau_A = (4\pi n_0 m_i)^{1/2}/B'_\perp$. The term proportional to ρ_s in (2) is proportional to the electron compressibility and the resistive collisional diffusivity is η.

In [1] equations (1-3) were numerically solved for $\eta = 0$ when a plasma flow is driven towards the X-point, in order to force the reconnection. It was found that the results agreed with the analytical solutions found for small constant forcing [5], consisting in attaining a constant central current. But a more general case in which the forcing is arbitrarily large and with a finite duration was also considered. Here we include $\eta \neq 0$ to still study driven magnetic reconnection in the so-called Taylor problem, i.e. with a finite-time forcing-flux that increases from zero at $t = 0$; so the boundary conditions are,

$$\phi(\pm 1, y, t) = \frac{1}{4B'_\perp}\frac{df(t)}{dt}\ln(y^2 + \delta^2), \quad \phi(x, \pm 1, t) = -\frac{1}{4B'_\perp}\frac{df(t)}{dt}\ln(x^2 + \delta^2) \tag{4}$$

$$\psi(\pm 1, y, t) = \pm B'_\perp y + f(t), \qquad \psi(x, \pm 1, t) = \pm B'_\perp x + f(t) \tag{5}$$

where $f(t) = v_\infty B_{z0}\tau_d(1 - (1 + t/\tau_d)\exp[-t/\tau_d])$ and the density is constant at the boundaries. The integration domain is $[-1, 1]$ for both x and y. The parameter δ is of the order of ρ_s and is introduced to avoid singularities. The initial conditions are, $\psi(x, y, 0) = B'_\perp xy$, $\phi(x, y, 0) = 0$ and $\xi(x, y, 0) = 0$.

In figure (1) we compare the results for a collisionless and a weakly collisional plasma, when the forcing time is $\tau_d = 5\tau_A$. The reconnected flux, measured by $\psi(x = 0, y = 0, t)$ at the X-point, is larger for the resistive plasma as one would expect, but the asymptotic value is the same. In contrast, the central current shown in Figure (2) is much larger for the collisionless case and it increases up to $t > \tau_d$.

III. Fluid model with pressure variation

Next we take the two-fluid equations developed in [3] for the slow dynamics, in which the flow velocity and time scales are of the order of the diamagnetic velocity and frequency, respectively. Here, the effect of anisotropic pressures for ions and electrons is retained. However, the electron inertial effects are not present, so a completely

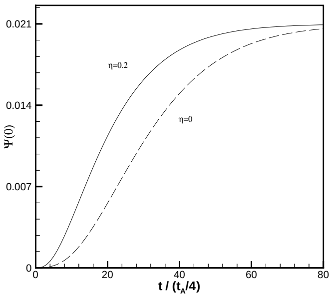

Figure 1: Reconnected flux with (solid) and without (dashed) collisions.

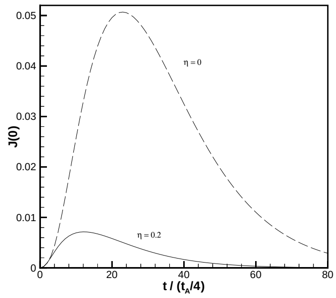

Figure 2: Current at X-point with (solid) and without (dashed) collisions.

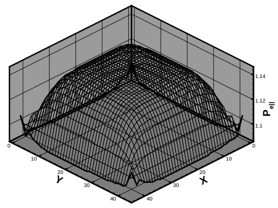

Figure 3: Surface diagram of pressure $p_{e\|}$ for $t = 4\tau_A$ based on Eqs.(6-12)

collisionless reconnection could not be considered. The small, but finite collisionality is what will drive reconnection. When these equations are normalized such that $t \to t/\tau_A$, $x \to x/d_i$, $\phi \to \phi/(d_i^2 B_0/\tau_A)$, $\psi \to \psi/(d_i B_0)$, $n \to n/n_0$, $p \to 8\pi p/(\rho_s B_0/d_i)^2$ and adapted to our cartesian geometry, the reduced model for the seven fields can be cast as,

$$\frac{\partial n}{\partial t} = [n, \phi] \tag{6}$$

$$\frac{\partial p_{e\|}}{\partial t} = [p_{e\|}, \phi] + 2\nu_e (p_{e\|} - p_{e\perp}) \tag{7}$$

$$\frac{\partial p_{i\|}}{\partial t} = [p_{i\|}, \phi] + 2\nu_i (p_{i\|} - p_{i\perp}) \tag{8}$$

$$\frac{\partial p_{e\perp}}{\partial t} = [p_{e\perp}, \phi] - \nu_e (p_{e\|} - p_{e\perp}) + \frac{\rho_s^2}{3n^2}(p_{e\|} - p_{e\perp})[n, p_{e\perp}] \tag{9}$$

$$\frac{\partial p_{i\perp}}{\partial t} = [p_{i\perp}, \phi] - \nu_i (p_{i\|} - p_{i\perp}) - \frac{\rho_s^2}{3n^2}(p_{i\|} - p_{i\perp})[n, p_{i\perp}] \tag{10}$$

$$\frac{\partial \psi}{\partial t} = [\psi, \phi] - \frac{\rho_s^2}{n}[\psi, p_{e\|}] - \frac{\rho_s \epsilon \nu_e}{n}(p_{e\|} + p_{e\perp}) \tag{11}$$

$$\begin{aligned}\frac{\partial U}{\partial t} = {} & [U, \phi] + \frac{1}{2n}[n, |\nabla\phi|^2] + \frac{1}{n}[\psi, \nabla^2\psi] + \frac{\rho_s^2}{n}[\nabla\phi; \nabla p_{i\perp}] \\ & -\rho_s^2 \frac{\partial}{\partial x}(p_{i\|} + p_{i\perp} + p_{e\|} + p_{e\perp})\end{aligned} \tag{12}$$

Here we assumed simmetry along the perpendicular z direction and used the simplest approximation for the collisional friction: $F_e^{coll} \sim \nu_e p_e$, $g_\alpha^{coll} \sim \nu_\alpha (p_{\alpha\|} - p_{\alpha\perp})$. The dimensionless constants are $\epsilon = (m_e/2m_i)^{1/2}$, $\nu_\alpha \to \nu_\alpha \tau_A$ and the function U is,

$$U = \frac{1}{n}\left(\nabla \cdot (n\nabla\phi) + \rho_s^2 \nabla^2 p_{i\perp}\right) \tag{13}$$

The characteristic length is the ion skin depth, so the reconnection region must be smaller than this. It is clear that the driving term for reconnection in Eq.(11) is quite small being proportional to ϵ.

Based on Eqs.(6-12) we created a code for the simulation of the reconnection Taylor problem, as described in the previous section. An approximation was made, that

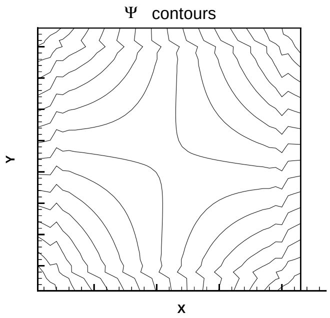

Figure 4: Magnetic field lines at X-point for $t = 6\tau_A$

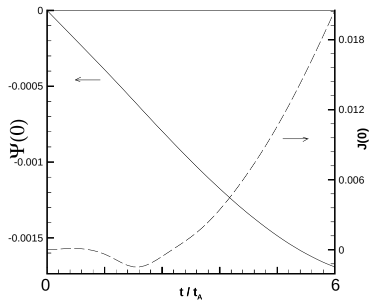

Figure 5: Evolution of $\psi(0)$ and central current

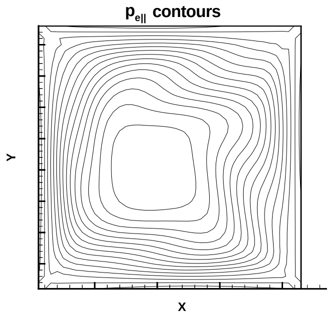

Figure 6: Pressure for high collisionality, $\nu = 0.9$

assumes the density in Eq.(13) is constant, in order to speed up the process of inverting the operator to obtain ϕ. It was checked *a posteriori* that the assumption is indeed satisfied, when n is kept constant at the boundaries. For the pressures, although they have constant boundary values, there is a continuous increment towards the central X-point, as it is shown in Figure (3) for $p_{e\|}$; similar behaviors are observed for the other pressures when $p_{\alpha\|}/p_{\alpha\perp} = 1.1$.

An interesting result, not observed in the zero-pressure case, is that the forcing flow at the border gives rise to an MHD wave that wiggles the magnetic field lines. Figure (4) shows how the originally smooth field lines are twisted as a result of the wave. The reconnected flux can be seen in Fig.(5) and is quite small, for the value $\nu = 0.09$ used. It has opposite sign to that for the collisionless case, since the currents are also negative initially. For higher collisionality, $\nu = 0.9$, the distorting effects are quite large and the reconnected flux does not vary so much (see Fig.(6)).

IV. Conclusions

The collisional contribution to the reconnection rate in a quasi-collisionless plasma were analyzed usind two different approaches. When pressure variations are ignored, the collisionality increases the instantaneous reconnection rate but the asimptotic values of $\psi(o)$ do not change, while the current at the X-point is reduced substantially. With a model that includes anisotropic pressure perturbations the presence of MHD waves is observed and the reconnection rate is very low.

Acknowledgments This work was partially supported by Conacyt project 44324-F and DGAPA-UNAM project IN115205.

References

[1] J.J. Martinell and A. Hernández-García, 33rd EPS Conference on Plasma Physics, ECA **30I**, P2.047 (2006)

[2] B. Kuvshinov, V. Lakhin, F. Pegoraro, T.J. Schep, J. Plasma Phys. **59**, 727 (1998)

[3] J.J. Ramos, Phys. Plasmas **14**, 052506 (2007)

[4] G.L. Delzanno, E. Fable and F. Porcelli, Phys. Plasmas **11**, 5212 (2004)

[5] J.J. Ramos, F. Porcelli and R. Verastegui, Phys. Rev. Lett. **89**, 055002 (2002)