FAST RECONNECTION DUE TO TRIGGERED MICROTURBULENCE

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In earlier papers [1, 2], we have shown how fast reconnection of the m = 1, n = 1 sawtooth instability in tokamaks can occur as a result of a localized sharp increase in the plasma resistivity in the narrow reconnection layer. This work was carried out using the 3-D resistive MHD code MERCURY [3] for a periodic cylinder, and where the anomalous resistivity was triggered when the electron drift velocity associated with the current exceeded a critical threshold value, this mimicking the triggering of, for example, ion acoustic turbulence.

The present paper builds on the results of the simulations to construct an analytic model of fast reconnection based on a modification of the Sweet-Parker [4, 5] model, later developed by Kadomtsev [6] to explain the sawtooth collapse in tokamaks. However, using the Spitzer resistivity leads to a collapse time some 100 times longer than found in tokamak plasmas e.g. JET [7]. In our simulations we could not employ a realistic magnetic Lundqvist number S of 10^9 to 10^{10} and had to use a lower value of 2.7 x 10^7. This restriction is removed in our analytic treatment, and so correspondingly we can have narrower reconnecting layers with larger localized current densities, these begin the trigger for the local microturbulence and anomalous resistivity. Thus the model provides a sudden trigger (the onset of anomalous resistivity) for the fast reconnection and, as a corollary, the sudden halt when the conditions for microturbulence cease, thus leading to partial reconnection.

Analytic model

The essential feature of our analytic model is the introduction of localized microturbulence in the reconnecting layer, such that the current density J_z here is limited to the value

$$|J_z| \leq \alpha n_e e c_s \tag{1}$$

where c_s is the ion sound speed $\sqrt{(ZkT_e/m_i)}$, n_e the electron density and α is a dimensionless number determined by the microturbulence itself. α lies between $(m_i/Zm_e)^{1/4}$ and $(m_i/Zm_e)^{1/2}$ for ion acoustic turbulence [8, 9], depending on whether $ZT_e >> T_i$ or $ZT_e \sim T_i$ respectively.

Ampère's law then relates the reconnection magnetic field B_0 with J_z for a layer of thickness δ,

$$J_z = \frac{2B_0}{\delta\mu_0} \tag{2}$$

Finally, taking the slow inward velocity of magnetic flux towards the reconnecting layer as V_x over a length L, continuity of mass, together with incompressibility yields

$$V_x L = V_y \delta \tag{3}$$

where, with $L >> \delta$, V_y is much larger than V_x but limited to the Alfvén velocity defined by

$$\frac{1}{2}\rho V_y^2 = \frac{B_0^2}{2\mu_0} \tag{4}$$

B_0 is given by the projection of the poloidal magnetic field, B_p, in the helical surface to give

$$B_0 = (1 - q_0) B_p \tag{5}$$

The anomalous reconnection time τ_c* is simply the radius of the m = 1, n = 1 (q = 1) singular surface r_s divided by the velocity component V_x. On employing Eq. (3) and then Eqs. (2), (4) and (1) we obtain, for $L = r_s$

$$\tau_c^* = \frac{r_s}{V_x} = \frac{r_s}{V_y}\frac{L}{\delta} = \frac{\alpha r_s^2 \mu_0^{3/2} e n_e^{3/2} (kT_e)^{1/2}}{2B_0^2} \tag{6}$$

This is independent of resistivity. Taking values relevant to JET, B_0 (from Eq. 5) = 0.175T, α = 60.6, r_s = 0.375m, n_e = 4 x $10^{19} m^{-3}$ and T_e = 1keV we obtain δ = 3.3mm, and a value of τ_c* = 100μs, close to the collapse time observed.

Comparison to other theories

Wesson [10] proposed that the inclusion of electron inertia into Ohm's law would lead to a faster reconnection and furthermore prevent the electron drift velocity from becoming relativistic. The convective inertial term is $(m_e V_x J_z)/(n_e e^2 \delta)$, but we find that in the presence of the anomalous resistivity, η_{anom}, implied by our model, the ratio of the inertial term to $\eta_{anom} J_z$ is $c^2/(\omega_{pe}^2 \delta^2)$ which for the above numerical example in JET is 0.065.

Similarly in comparing electron viscosity effects in Ohm's law in the theory proposed by Yu [11] for fast reconnection, even assuming no flux limited value for the stress tensor, both parallel and perpendicular electron viscosity effects are negligible in the presence of an anomalous collision frequency. In the case of electron viscosity effects parallel to the magnetic field we take $\nabla_{||} = (2\pi R)^{-1}$ and find that the ratio of the parallel electron stress term to $\eta_{anom} J_z$ is $\mu_{anom} \nabla_{||}^2 (J_z / n_e e) / (n_e e \eta_{anom} J_z)$ where μ_{anom} is p_e/ν_{anom} and η_{anom} is $m_e \nu_{anom}/(n_e e^2)$, ν_{anom} being the anomalous collision frequency. For our numerical example the ratio is 6.4 x 10^{-3}. We note that we have employed the same anomalous collision frequency for both viscosity and resistivity, and the enhancement of resistivity is accompanied by a corresponding decrease in parallel viscosity. In contrast perpendicular viscosity increases with collision frequency so long as the effective Hall parameter $(B/(\eta_{anom} n_e e)$ is greater that one. Taking $\nabla_\perp$ to be δ^{-1} the ratio $\mu_{\perp anom} \nabla_\perp^2 (J_\perp / n_e) / (n_e e \eta_{anom} J_z)$ is $(a_e/\delta)^2$ where a_e is the electron

Larmor radius. This ratio, for our example, is 5.8 x 10 $^{-5}$ and perpendicular viscous effects are hence also negligible.

Discussion

The ratio of the anomalous resistivity to the Spitzer parallel resistivity is given by

$$\frac{\eta_{anom}}{\eta_{\|}} = \frac{\tau_c^2}{\tau_c^{*2}} \tag{7}$$

where τ_c is the Kadomtsev collapse time, $r_s(\mu_0 L/(\eta_{\|} V_y))^{1/2}$. For our example this is 300.

The anomalous collision frequency, ν_{anom}, can similarly be found to give

$$\upsilon_{anom} = \frac{\omega_A}{\beta_p}(1-q_0)^3 \frac{m_i}{Zm_e\alpha^2} \tag{8}$$

where ω_A is the Alfvén frequency defined by B_p and the singular radius r_s, B_p is the ratio of $n_e kT_e$ to B_p^2/μ_0. We note that strongly non-linear $(1 - q_0)^3$ driving factor which might lead to a faster collapse after a long sawtooth period when $(1 - q_0)$ will have developed to a larger value.

This model has the ability to explain the sudden triggering of reconnection events purely as a result of the rapid switch-on of microturbulence at a critical value of the electron drift velocity which generally would strongly peak in the reconnection layer. As a corollary there can be a sudden switch-off of fast reconnection when the drift velocity relaxes below the critical value.

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