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THE EFFECT OF ELECTRON THERMAL CONDUCTION ON PLASMA
PRESSURE GRADIENT DURING RECONNECTION OF MAGNETIC FIELD LINES

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THE EFFECT OF ELECTRON THERMAL CONDUCTION ON PLASMA
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ABSTRACT

The interplay of electron cross-field thermal conduction and the reconnection of magnetic field lines around an $m = 1$ magnetic island prior to a sawtooth crash can generate a large pressure gradient in a boundary layer adjacent to the reconnecting surface, leading to an enhanced gradient of poloidal beta to satisfy the threshold condition for ideal MHD modes. This narrow boundary layer and the short onset time of a sawtooth crash can be supported by fine-grained turbulent processes in a tokamak plasma.

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The mechanism that causes a sawtooth crash in a tokamak plasma has been a subject of inquiry since laboratory observations of internal disruptions were reported more than a decade ago [1,2]. Recently, Wesson [3] showed that the experimentally observed crash time (≤ 100 μ sec) is about one order of magnitude shorter than that predicted by Kadomtsev's resistive reconnection model [4], while the threshold of the pressure gradient is several times lower than that predicted by ideal MHD theory of internal kink modes [5]. Furthermore, he and his co-workers [6] pointed out a fundamental conceptual inadequacy of existing theoretical models (including his own) in describing the sudden onset of a crash: because of the short crash time, the incremental change of the safety factor q to trigger the instability during the crash is unacceptably small ($\sim 10^{-5}$). In this paper we show that the interplay of electron cross-field thermal conduction and the resistive reconnection of magnetic field lines around an $m = 1$ magnetic island can result in a large, localized pressure gradient at the boundary of the hot core. The magnitude of this pressure gradient can become sufficient to satisfy the threshold criterion for ideal MHD modes. Based on this mechanism, the instability is thus triggered by an incremental increase in the gradient of poloidal beta, rather than by an incremental drop of q .

The basis of this idea derives from an experimental observation in the PLT tokamak during sawtooth suppression by lower hybrid waves which sustain energetic electrons (≥ 100 keV) as current carriers [7]. The reconnection speed V_r (measured from the rate of growth of the $m = 1$ magnetic island determined from local $2\Omega_{ce}$ emission) decreases with increasing wave power. At 245 kW of wave power the measured V_r is $\sim 2 \times 10^2$ cm/sec, while in the ohmic heating case V_r estimated from Kadomtsev's model is $\sim 10^4$ cm/sec. With the power increased to ~ 400 kW, the island growth essentially stops ($V_r = 0$); the core plasma no longer disrupts during the 150-msec period when wave power is applied and there is only a steady-state $m = 1$ oscillation. In addition, as the reconnection rate decreases, the growth duration of the magnetic island before the crash becomes longer. Thus, the measured island width before a crash occurs increases with wave power, being ≤ 1 cm in the ohmic heating case and extending deeper into the center to ~ 10 cm at 245 kW (in all cases the electron temperature begins to decrease when reconnection starts). We are thus led to perceive that resistive reconnection and internal disruption are two distinct events and that the resistive reconnection triggers the internal disruption. We therefore look for the effects of the speed of reconnection that can cause configurational changes. One such effect is the sharp increase in the local temperature gradient adjacent to the boundary of the reconnecting surface in a well-confined plasma with sufficiently low cross-field thermal conductivity [8].

The existence of a temperature boundary layer can be demonstrated relatively clearly by solving the simplified problem of conductive heat transfer of constant temperature and q gradients on either side of the magnetic island in a slab geometry. For the present purpose, the island width can be assumed to be infinitesimal. Reconnection, as soon as it begins, mixes the temperature of the plasma adjacent to the island on the high-temperature side with that on the low-temperature side. The temperature at the boundary of the core is then constant (and can be set as $T = 0$) during reconnection. The governing differential equation and boundary condition are, respectively,

$$\frac{\partial T}{\partial t} = \frac{\chi_{e1}}{\partial x^2} \frac{\partial^2 T}{\partial x^2} \quad (1)$$

and

$$T = 0 \text{ at } x = x_0 - V_r t \text{ for } t \geq 0, \quad (2)$$

where the cross-field thermal diffusivity χ_{e1} is assumed to be a constant, and $x_0 = r_1$ is the position of the initial boundary with r_1 being the radius of the $q = 1$ surface. The initial temperature profile is relatively unimportant and can be taken as $T = T_0$ for $x \leq x_0$, where T_0 corresponds to the peak amplitude of the temperature sawtooth oscillation. $T_0 = 0.2$ keV and $r_1 = 10$ cm in the PLT experiment.

For fast reconnection or low thermal diffusivity so that $\chi_{e1}/V_r \ll r_1$, only a layer adjacent to the boundary [9] is cooled. Using the transformation $x' = x - V_r t$ to move with the constant-speed cold front, we find the temperature profile adjacent to the boundary to be $T/T_0 = [1 - \exp(-V_r x'/\chi_{e1})]$. The temperature gradient at the boundary is

$$\left. \frac{\partial T}{\partial x'} \right|_{x' = x_0 - V_r t} = \frac{T_0}{\delta} = \frac{T_0}{\chi_{e1}/V_r}, \quad (3)$$

where $\delta = \chi_{e1}/V_r$ is the thickness of the boundary layer. We can apply the result to the PLT experiment. For a PLT-sized tokamak, $\chi_{e1} \leq 10^4$ cm²/sec in the region of $q = 1$ and decreases monotonically towards the center [10]. In the ohmic heating case, the temperature gradient in the boundary layer is $T_0/\delta = 0.2$ keV/cm (a corresponding boundary layer also exists on the low-temperature side adjacent to the island). This is one order of magnitude higher than that just prior to reconnection, $T_0/r_1 = 0.02$ keV/cm.

The gradient of poloidal θ characterizing the threshold of the instability of ideal MHD modes is defined as $\delta_p' = (2u_0 R^2/r_1^4 B_\theta) \cdot \int_0^{r_1} (-dp/dr) r^2 dr$. When reconnection is taken into account, B_θ is the sum of that of the inner core and the boundary layer. It is approximately a factor

of four higher than that before the reconnection begins. This factor is nearly independent of δ as long as $\chi_{el}/V_r \ll r_1$ is satisfied. The enhanced gradient of poloidal B can satisfy the criterion of the instability threshold without requiring that q at the center be only infinitesimally lower than unity [2]. We note that the actual enhancement of B_p' in a realistic tokamak plasma depends on the profiles of q and T in the vicinity of the $q = 1$ surface. A very large pressure gradient in the boundary layer may also initiate local modes.

For slow reconnection or high thermal conduction so that $\chi_{el}/V_r \geq r_1$, the moving cold boundary cools the entire interior. The characteristic cooling time is $\tau_c = x^2/\chi_{el} = (x_0 - V_r t)^2/\chi_{el}$ and the temperature decreases according to $T/T_0 = \exp[-\chi_{el} t/x_0(x_0 - V_r t)]$. The interior begins to cool when reconnection starts and the cooling rate increases as t approaches x_0/V_r , as in the PLT experiment with lower hybrid waves. The temperature sawtooth crashes when the growing island extends to the deeper interior where local χ_{el} is sufficiently low to provide a pressure gradient satisfying the instability threshold condition; this crash can take place long after the temperature ($m = 0$ mode) begins to decrease due to reconnection. We note that in the PLT experiment, while the measured reconnection speed has decreased by more than one order of magnitude as wave power is increased, the crash time, marked by an abrupt change of the amplitude and phase of the $m = 1$ temperature oscillation, remains ≤ 100 μ sec. This observation supports Wesson's remark on the conceptual inconsistency in using the incremental change of q as the triggering mechanism for the crash. We note also that an internal disruption thus marks the end of the resistive reconnection, rather than its beginning [4]. It is also essential in the present mechanism for a sawtooth crash that an $m = 1$ magnetic island is present and growing [3].

We now discuss conditions required to support the short onset time of a sawtooth crash. The anomalous electron thermal conduction loss in a tokamak plasma is generally regarded as due to turbulence. The minimum thickness of a temperature-gradient layer that can be supported by the turbulence is $\sim 2\pi/k$, and the minimum time required to establish the steep gradient is $\sim 1/2\pi f$, where k and f are, respectively, the characteristic wave number and frequency of the turbulent transport process. Measurement of electrostatic density fluctuation in the ATC and PLT tokamaks [11] (in a region somewhat outside of the $q = 1$ surface) shows that $k \sim 10$ cm^{-1} and $f \sim 100$ kHz. A steep gradient of a few mm thickness can therefore be established in a few μ sec, satisfying the requirements for a sawtooth crash. However, magnetic turbulence having a suitable energy spectrum can also support the required temperature gradient. We note that such swiftness has been primarily responsible for masking both the distinctness of, and the sequential relation between, resistive reconnection and internal disruption, and, indeed, in the difficulty in

defining a sawtooth crash. Finally, based on the present mechanism, we inevitably reach the conclusion that internal disruptions of electron temperature cannot occur in a plasma if its energy loss is not due to a fine-grained transport process, which is essential in establishing the steep temperature gradient. It is a well-known experimental fact that tokamak plasmas with significant global impurity radiation loss from the core region do not exhibit temperature sawtooth oscillations. In those cases, if conditions for resistive reconnection are satisfied, the reconnection of magnetic field lines based on the Kadomtsev model can proceed to completion without displaying a temperature crash.

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