

FILAMENTS AND TRANSPORT BARRIERS

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Abstract

We discuss the peculiar temperature profiles observed in certain Electron Cyclotron Resonant Heating (ECRH) experiments. For instance, multi-peaked (filamentary like) temperature profiles and sharp temperature gradients (seemingly due to transport barriers) have been observed in RTP and in TEXT-U. Nonstandard sawtooth traces have been observed in TCV. We present a theoretical model that may account for these experimental findings.

ECRH is type of plasma heating with distinctive properties. The electron cyclotron waves transfer their energy directly to the electrons within a very localized deposition region and on a very fast time scale. Thanks to these properties, and to recent advances in gyrotron technology, record values of deposited power density have been attained. When such a source of auxiliary power is available, one may expect to observe structures of the electron temperature near the heating location. This indeed does happen during time intervals of relative MHD quiescence. However, in sawtoothed plasmas produced by the Dutch tokamak RTP, multiple temperature peaks were observed within the sawtooth mixing region, while sharp temperature gradients were observed just outside this region [2] [1]). These observations were obtained using a double pulse, multi-channel Thompson scattering detector. The RTP team suggested a filamentary process, whereby each temperature peak corresponds to plasma being well confined within a thin and long magnetic flux tube. Also, the sharp temperature gradients were taken as evidence of transport barriers, i.e. region of reduced perpendicular heat diffusion coefficient. In a later publication, it was shown that the individual temperature filaments have an $m/n=1$ periodicity [3].

Similar structures were observed during central ECRH in the Texas tokamak TEXT-U on the basis of an ECE diagnostic [4], which allowed to follow the time evolution of the temperature profile. The TEXT-U team proposed that the observed peaks were part of a common $m/n=1$ magnetic island structure (see, e.g, Fig. 11 of Ref. [4]; see also Ref. [5]). Indeed, the underlying $m/n=1$ magnetic topology does not preclude the formation of separate temperature peaks, for instance near the displaced magnetic axis and the $m/n=1$ island O-point, or more complex structures.

In the TCV tokamak in Lausanne, temperature filaments are not observed during ECRH, perhaps due to limited diagnostic resolution, but also, in our opinion, because the wave beam is not as narrowly focused within the TCV plasma as it was in RTP and TEXT-U. On the other hand, nonstandard sawtooth traces are observed as the location of the deposition region is swept through the plasma (Ref. [6]).

A sensible theoretical model for the evolution of the temperature in ECRH plasmas should be able to explain all these observations, i.e. multiple peaks, sharp gradients and nonstandard sawtooth traces. Such a model was proposed in Ref. [5]. Here, we briefly discuss its essential features. The model considers a transport equation for the

electron temperature, which includes a convection term, a perpendicular diffusion term, and a localized heat source. The electron density is assumed constant for the sake of simplicity. In addition, plasma toroidal rotation and the growth of an $m/n=1$ magnetic island are considered. The effect of rotation is such that, on a poloidal cross section, the heat deposition region is effectively a ring (see Ref. [5]). On account of very large heat parallel diffusion, the deposited heat spreads instantaneously along magnetic flux tubes intersecting the heating ring. Thus, the temperature depends on the $m/n=1$ helical flux function, ψ_* , as well as explicitly on time: $T = T(\psi_*, t)$. A model for ψ_* based on basic reconnection rules (conservation of toroidal and helical flux during the $m/n=1$ reconnection process [7]) was proposed in Ref. [5]. The model assumes the specific $m/n=1$ resistive internal kink convection pattern (see, e.g., Fig. 6.10.3 of Ref. [8]). The stream function contour lines projected on a poloidal cross section consist of two symmetric convection cells, corresponding to a rigid displacement of the plasma core, with a return flow localized near the island separatrix. The helical flux is nearly frozen to the plasma, as the ideal MHD approximation is assumed to hold everywhere except in a narrow region near the island X-point. In a *Lagrangian* frame of reference, i.e. moving with a constant ψ_* magnetic surface, the equation for the evolution of the electron temperature reads

$$\frac{3}{2} \frac{\partial T}{\partial t} = \chi_{\perp} (\langle |\nabla \psi_*|^2 \rangle + \frac{\partial^2 T}{\partial \psi_*^2} + \langle \nabla^2 \psi_* \rangle \frac{\partial T}{\partial \psi_*}) + \langle S \rangle \quad (1)$$

where S is the heat source (divided by the electron density) and the angular brackets indicate flux surface averaging. Note that a constant thermal perpendicular diffusion coefficient has been assumed, so one can safely conclude that if sharp temperature gradients are obtained from the solution of Eq. (1), these are certainly not due to regions of reduced thermal diffusion coefficient. Since the $m/n=1$ convection pattern is known, surfaces of constant ψ_* can be tracked in time and the spatial distribution of the temperature can be reconstructed from the solution of Eq. (1). One of the important points is that flux tubes can merge owing to magnetic reconnection. When two flux tubes merge, the thermal energy in each tube is mixed. Thus, the average temperature of the plasma within a flux tube immediately after reconnection is a volume-weighted average of the temperature in the merging flux tubes.

Simulation results for realistic TEXT-U parameters (in particular, a value of $\chi_{\perp} \approx 0.1 m^2/s$ near the plasma center and a radial ECRH deposition width about 20% of the $q=1$ radius) were presented in Ref. [5]. Typically, four temperature peaks develop within the mixing radius. A fifth peak, more precisely a rim structure, forms around the magnetic island separatrix, where the poloidal return flow is concentrated. However, often one of the four peaks merges with the rim structure. We note that in RTP ECRH experiments, the statistically significant number of observed peaks was around four [3].

Two conditions must be fulfilled in order for multiple peaks and sharp temperature gradients to appear: (1) a localized heat source with a radial width below the island width; (2) small perpendicular heat diffusion, i.e. $\tau_{diff} = r_{mix}^2 / \chi_{\perp} \geq \tau_{saw}$, where τ_{diff} is the characteristic diffusion time, r_{mix} is the mixing radius and τ_{saw} is the sawtooth period. When the first condition is met, the heights of the temperature peaks are no longer directly related to the island width, but rather to the island growth time and to the power source and diffusive terms.

Thus, according to our picture, localized temperature structures correspond to narrow

flux tubes, selectively heated by localized ECRH, which are however part of a macroscopic $m/n=1$ magnetic island structure. These tubes may reconnect in the course of plasma evolution, giving rise to non trivial temperature profiles. Outside the mixing radius, sharp electron temperature gradients develop. These gradients are formed as the specific $m/n=1$ convection pattern advects the heat deposited inside the $q=1$ radius to the separatrix region, where it is then mixed by reconnection, at a rate faster than the heat diffusion rate across field lines. The sharp gradients thus formed, if viewed as evidence of a transport barrier, should not be thought of as localized in regions of reduced perpendicular heat diffusion coefficient, but rather as barriers to convective transport. Indeed, the sharp gradients are localized just outside the radius within which the convection cells are contained.

In the TCV tokamak in Lausanne, when the ECRH power is deposited off axis and near the $q=1$ radius, nonstandard sawtooth traces are produced. This is probably an indication of nonstandard temperature profiles. Unfortunately, the resolution of the Thompson scattering diagnostic in TCV is not high enough to permit a sufficiently accurate determination of the temperature profile. One type of non standard sawtooth, dubbed *humpback* from its characteristic shape, has the peculiarity that the fast drop in the soft X-ray emissivity associated with the crash is followed by a rapid recovery on a time scale significantly shorter than the reheat or the transport time scales. The reader may find examples of humpbacks in Ref. [6].

The numerical code developed to study filaments and transport barriers can also be used to simulate line integrated soft X-ray signals in the case of non standard sawtooth behavior. Our simulations indicate that the fast recovery time scale is a resistive MHD time scale, more specifically it is associated with the growth time of the $m/n=1$ magnetic island. For reasons of limited space, we cannot present simulation results in this paper, however preliminary results were shown in Ref. [9] (a detailed report is in preparation). Here, we can outline the main idea. We believe that humpback sawteeth result from temperature profiles, before the onset of the $m=1$ magnetic island, having a value on axis, T_0 , comparable with the value at $q=1$, T_1 , but significantly larger than that at the sawtooth mixing radius, T_{mix} (according to Kadomtsev model, $r_{mix} = \sqrt{2}r_1$ for a parabolic q profile). When the island starts to grow, assuming a growth time shorter than the perpendicular diffusion time, the plasma in the region surrounding the island O-point maintains a temperature comparable to T_1 , while the plasma in the region surrounding the displaced magnetic axis maintains a temperature comparable to T_0 . Thus, in this case, we have a hot-core, hot-island situation. However, because of reconnection mixing, the plasma near the inner island separatrix must be at a lower temperature, intermediate between T_1 and T_{mix} . Thus, the temperature profile on a section through the island X and O-points exhibits two comparable peaks (T_0 and T_1) separated by a relatively deep valley, which is advected through the plasma central region at a rate corresponding to the island growth rate. Our simulations indicates that the fast drop and rise of the X-ray signal is due to the passage of this valley through the viewing X-ray chords. This is the idea, although things are complicated by plasma rotation and line integration (both taken into account in our code).

In conclusion, we find that a simple transport model for the electron temperature in the presence of a localized heat source, which includes the effects of convection and the presence of a macroscopic magnetic island, may account for the multi-peaked temperature

structures and sharp temperature gradients observed in RTP and TEXT-U experiments, at least from a qualitative point of view. We have shown that these features can be obtained with a constant diffusion coefficient. The role of convection and of magnetic reconnection is thus emphasized. The model is also able to reproduce non standard sawtooth traces observed in TCV during intense ECRH. The peculiar signature of humpback sawteeth, i.e. the fast drop and rise of the soft X-ray emissivity in time, is interpreted as due to the passage of a minimum in the electron temperature profile across the central plasma region, located near the $m=1$ magnetic island separatrix [9].

Our model considers transport in the presence of localized electron heating and a macroscopic $m/n=1$ magnetic island. In principle, similar results can be expected for macroscopic magnetic islands with different helicities, although in practice only low (m,n) numbers produce islands of significant size. We may speculate that qualitatively similar results would be obtained, for instance, in the case of a non monotonic q profile with two $q=2$ magnetic surfaces, which becomes unstable to a double tearing $m=2, n=1$ mode. The convection cells associated with this mode would extend between the two $q=2$ surfaces, so a macroscopic region in the plasma could be affected by convective transport. In this case, significant temperature gradients could be obtained just outside the outer $q=2$ surface. Minor structures in the temperature may also occur near rational q surfaces where macroscopic, low (m,n) magnetic islands may develop.

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References

- [1] N. J. Lopes Cardoso et al, *Plasma Phys. Contr. Fusion* **39**, B303 (1997).
- [2] N. J. Lopes Cardoso et al, *Phys. Rev. Lett.* **73**, 256 (1994).
- [3] M. Beurskens, *Filamentation of tokamak plasmas*, PhD. Thesis, Technische Universiteit Eindhoven, 1999; M. Beurskens et al, submitted to *Nuclear Fusion*.
- [4] G. Cima et al, *Plasma Phys. Contr. Fusion* **40**, 1149 (1998).
- [5] F. Porcelli, E. Rossi, G. Cima and A. Wootton, *Phys. Rev. Lett.* **82**, 1458 (1999).
- [6] A. Pietrzyk et al, *Nuclear Fusion*, to appear (June 1999).
- [7] B. B. Kadomtsev, *Fizika Plazmy* **1**, 710 (1975) [*Sov. J. Plasma Physics* **1**, 389 (1975)].
- [8] J. Wesson, *Tokamaks*, 2nd ed. (Clarendon Press, Oxford, 1997).
- [9] A. Pochelon et al, in proc. of the 17th IAEA Fusion Energy Conference, Yokohama, Japan, 19-24 October, paper IAEA-F1-CN-69/EX8/3.