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Symmetry and evolution of radiative patterns in simulations of the tokamak edge plasma

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Abstract

The heat problem with radiation is investigated and the role of conductive transport in the establishment of radiative patterns is illustrated in two simple situations. In a two-dimensional model of a magnetic surface, a bifurcation scheme made possible by radiation allows coexistence of regions with two different temperatures. These regions are separated by fronts which propagate at a rate which increases with thermal conductivity. The larger diffusivity in the direction along the magnetic field then implies faster propagation in this direction and radiative plumes readily appear on surfaces with rational safety factor. In a closely related three-dimensional problem, we illustrate the role of ballooning of the heat transport which breaks poloidal symmetry and can lead to the formation of radiative regions which reproduces some of the features of the experimentally observed MARFEs.

Heat problem with radiation

We investigate the heat problem with radiation in two and three dimensions, which is of relevance for the formation of patterns in the edge of tokamak plasmas since radiation is classically maximum in this region, according to the equation:

$$\frac{3}{2}n\partial_t T = -\nabla\cdot(Q_\parallel + Q_\perp) - n^2 c_Z L(T) \tag{1}$$

where n is plasma density, T plasma temperature, c_Z the local impurity fraction, $Q_\parallel$ and $Q_\perp$ the heat fluxes parallel and perpendicular to the local magnetic field, and $L(T) = \alpha T^2 \exp -\beta(T - T_r)^2$ models the radiation function. The heat equation if firstly studied in two-dimensions, taking the parallel and perpendicular heat fluxes to be conductive ($Q_\parallel = -\chi_\parallel \nabla_\parallel T$, $Q_\perp = -\chi_\perp \nabla_\perp T$) and retaining the significant anisotropy of transport $\chi_\parallel \gg \chi_\perp$. On a magnetic surface with no local heat source, temperature is maintained by the radial heat flux which is modelled as a heat bath with temperature T_0 and time-constant $\tau_\perp$. Furthermore, assuming that the plasma pressure P_0 is constant in time, with $L(T)/T^2 = F(T)$, Equation 1 can be rewritten

$$\frac{3}{2}\partial_t T = -\nabla\cdot(\chi_\parallel \nabla_\parallel T + \chi_\perp \nabla_\perp T) - P_0 c_Z F(T) - \frac{1 - T_0/T}{\tau_\perp} \tag{2}$$

Radiative bifurcation scheme

It is well recognized that the system described by Equation 2, through the nonlinearity of the radiation function, allows for the existence of bifurcations [2]. The bifurcation scheme is best illustrated by considering the behaviour of points where the heat flux is divergence-free, on which the analysis is simplified by the absence of diffusion, and steady state occurs at the sole condition of balance between radial heat flux and radiation losses. The temperature at those points is then governed by two control parameters, the temperature of the heat bath T_0 and the radiation intensity (relative to the radial heat flux) $P_0 c_Z \tau_\perp$. For large temperature T_0 and large radial heat flux, formally for $P_0 c_Z \tau_\perp$ and T_0 such that $(T_0/T_r - 1)/\tau_\perp > P_0 c_Z F(T_r)$, the heat equation admits the heat bath temperature as unique solution. However, for lower values of the two control parameters, up to three solutions can be found (Figure 1) and bifurcation can occur. One of the solutions is the heat bath temperature, at which radiation is negligible, and a couple of colder, radiative solutions. A linear stability analysis shows that the hottest temperatures T_0 and T_1 are stable, whilst the intermediate temperature T_c, which delimits the respective attraction basins of the hot and cold solutions in the limit of zero diffusivity, is unstable.

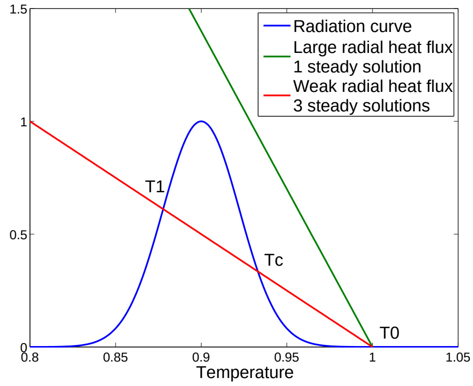

Figure 1: *Number of steady solutions of the problem (intersections of radiation curve with straight lines) as a function of radial heat flux.*

Influence of thermal diffusivities in pattern formation on magnetic flux surface

The bifurcation scheme is illustrated in 2D by introduction of a localized cold perturbation of a homogeneous temperature field at $T = T_0$. Bifurcation can only occur if the perturbation minimum initially lies below the temperature T_c, and must be of even larger amplitude with finite diffusivity in order to overcome the damping effect of thermal conduction. In cases where the perturbation does bifurcate, the temperature field becomes split into two regions, where radiation and radial heat flux are in equilibrium, with temperatures corresponding to the two linearly stable temperatures T_0 and

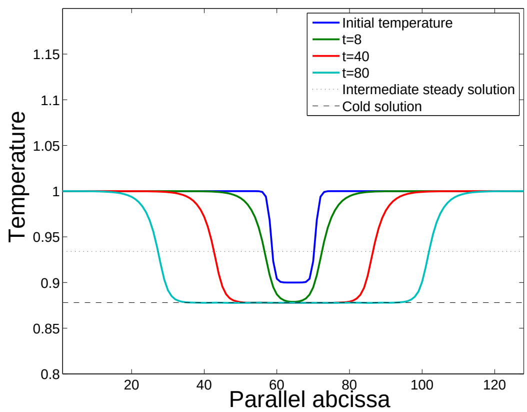

Figure 2: *Parallel cut of the temperature field after introduction of a cold perturbation showing the formation of fronts and their propagation.*

T_1 evoked above. During the initial transient, the perturbation minimum drops to T_1, after which fronts are formed between the hot and cold regions and their shape rapidly converges to a steady shape. The thickness d of the fronts is directly linked to the diffusivities considered in the problem and scales as $\chi^{1/2}$, as can be expected from a dimensional reasoning since diffusion is the only scale-dependent mechanism in the problem. Subsequent evolution of the temperature field follows from the heat being drawn from the hot region to the cold one, which yields expansion of the radiative region via propagation of the fronts. Thermal dynamics are then restricted to the front region, as is put in evidence by the fact that the size of the radiative region yields no alteration of the velocity at which the fronts propagate.

The thermal diffusivity has a definite role in the establishment of patterns since it determines the propagation velocity of the fronts in the following manner

$$\mathbf{v}_{propagation} = \alpha|\nabla T|^{-1}[\chi_{\parallel}^{1/2}(\nabla_{\parallel}T)\mathbf{e}_{\parallel} + \chi_{\perp}^{1/2}(\nabla_{\perp}T)\mathbf{e}_{\perp}] \tag{3}$$

where $\mathbf{e}_{\parallel}$ and $\mathbf{e}_{\perp}$ are the unit vectors in the direction along and across the magnetic field. The larger parallel diffusivity yields much faster propagation along magnetic field lines, and on surfaces where the safety factor is irrational, the cold perturbation spreads on the whole magnetic flux surface through sheer parallel propagation. On surfaces with rational safety factor however, parallel propagation similarly occurs but the process is interrupted by parallel reconnection and an elongated radiative plume is formed along the field line. At very long times, spreading across the field lines proceeds, leading to overall cooling, but at a much slower rate owing to smaller perpendicular diffusivity so that the plume is long-lived on the timescale of parallel propagation.

Three-dimensional heat problem

In three dimensions, we focus on the appearance of MARFEs (radiative bubbles localized on the high field side of the tokamak) as a result of spatial fluctuations of the thermal conductivity. Influence of radiation, and especially the transition from MARFEs to detached plasmas had already been investigated, principally analytically in [3] and it was remarked that given an appropriate form for the radiation function, the temperature takes the form of islands whose poloidal extent increases with radiative power, allowing transition to a detached plasma state. The presence of a MARFE was assumed from the outset through use of poloidally asymmetric boundary conditions, which is not done in the present simulations. Transport in the radial direction is now assumed to be conductive, the value of the diffusivity being fixed by either turbulence or collisional processes. In the absence of radiation, with Dirichlet boundary conditions on both radial boundaries, the heat problem has a stationary solution that depends only on radius, corresponding to a conservative radial heat flux on which the diffusivity has no influence.

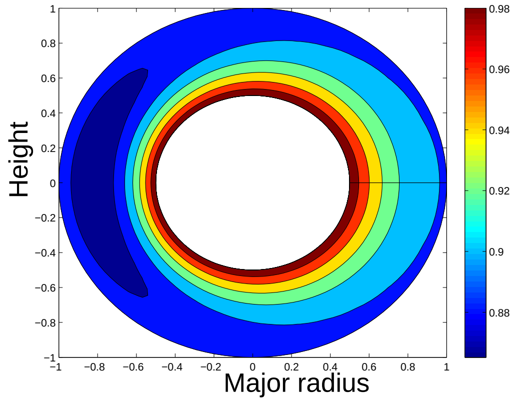

Figure 3: *Temperature field with radiation and ballooned perpendicular heat diffusivity, showing a MARFE-like radiative region on the high field side(left).*

Introduction of radiation in the simulation leads to cooling over the whole domain but thermal diffusion inhibits the growth of poloidally or toroidally varying fluctuations and MARFEs cannot appear, unless a symmetry-breaking mechanism is introduced. Here, the latter consists of ballooning of the perpendicular conductivity with maximum on the low-field side $\chi_\perp = \chi_0[1+(\cos\theta)/2]$. Such a ballooning is expected in tokamaks through the localization of the drive of interchange modes in the outer half of the plasma volume $(-\pi/2 < \theta < \pi/2)$. The heat flux is then larger on the low field side, and in the view of the development presented on the 2D problem, radiative cooling is more likely on the high field side. This statement is confirmed by the appearance of a local minimum of the temperature field in the poloidal cross-section at $\theta = \pi$ with toroidal symmetry, and the radiative region around it is clearly similar in structure to a MARFE (Figure 3).

Conclusions

The role of thermal diffusivity has been investigated in 2D and 3D models of the heat equation with radiation in tokamaks. In the 2D model of a magnetic surface, it is found that the larger parallel anisotropy leads to preferential growth of radiative perturbations in the parallel direction, albeit through non-diffusive propagation of fronts, and formation of field-aligned radiative plumes on surfaces with rational safety factor. In 3D, the influence of spatial inhomogeneities of perpendicular transport is highlighted, showing spontaneous growth of a MARFE-like structure when transport is ballooned of the low field side of the tokamak.

References

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