On the Theory of Improved Confinement due to Stationary Multifaceted Asymmetric Radiation from the Edge

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Abstract. Multifaceted asymmetric radiation from the edge (MARFE's) are toroidally symmetric and poloidally asymmetric radiation bands that occur in tokamaks as a result of a thermal instability, originated by radiation losses. It was observed in TFTR and TEXTOR that they formed as density was increased, and impurities concentrated on the edge. Under certain circumstances, they could evolve into weakly poloidal symmetric structures that cooled the edge of the plasma to a few tens of eV, thus leading to detachment from the limiter. Although non-stationary MARFE's are often precursors of disruptions, the use of a stochastic divertor in TORE-SUPRA, and of feedback controlled gas-puff in HT-7 have proved the existence of stationary MARFE's. Their appearance has been found to depend strongly on the impurity content of the plasma. They trigger internal transport barriers, observed in the electron temperature profiles. The purpose of this work is to review the evidence of the existence of stationary MARFEs, and whether they can actually lead to improved confinement regimes, through non-local mechanisms.

1. Introduction

Multifaceted asymmetric radiation from the edge (MARFE's) are toroidally symmetric and poloidally asymmetric radiation bands that occur in tokamaks as a result of thermal instabilities, originated by radiation losses. Their theory has been extensively explored, and their dependence on the imbalance between input power, and the radiation cooling at the edge has been well established [1-8]. While in limiter tokamaks they form on closed flux surfaces, in divertor devices they can emerge from the divertor region following the occurence of divertor detachment. In this work we shall focus on phenomena occurring in limiter devices. The density at which they occur depends strongly on the Z_{eff} of the plasma. It has been observed that, while they appear at a fraction of the Greenwald limit before wall conditioning, when fresh boronisation or silicosnisation is applied, their onset can be extended to densities above the Greenwald limit. In the past, it was observed in TFTR [9] and TEXTOR, that they formed as density was increased, and impurities concentrated on the edge. Under certain circumstances, they could evolve into weakly poloidal symmetric structures, capable of cooling the edge of the plasma down to a few tens of eV, thus leading to detachment from the limiter. Stacey has provided an explanation for this evolution, based on the dependence of the thermal instability on the poloidal mode number of the edge plasma distribution [4]. In stellerators, MARFE like structures, similar to those found in tokamaks have also been observed [10,11]. In [10] they are found as the density limit is approached, before the plasma is quenched, while in [11] they occur as the divertor plasma detaches, and form at the bottom divertor. In this case, the total radiated power reaches 100% of the input power.

Since non-stationary MARFE's occur when the density limit is approached, they are often precursors of disruptions, and are to be avoided. As a matter of fact it has been well established that the density limit is increased when the Z_{eff} is reduced. However, the use of ergodic divertor in TORE-SUPRA [12], and of feedback controlled gas-puff in HT-7 [13-15], have proved the existence of stationary MARFE's at densities lower than the Greenwald limit. In contrast to previous observations in TFTR and TEXTOR, they do not evolve into symmetric structures, but keep their asymmetric character. Instead of leading to disruptions, they show an improved confinement mode, which manifests itself by a sudden increase of the peaking factor of the electron density profile [13,14]. The electron temperature profile shows the development of an internal transport barrier, at a fraction of the minor radius of the device [15]. Particle confinement time increases 1.9 times, while the energy confinement time is less sensitive, at 1.1-1.2 times.

It must be mentioned that a radiatively improved confinement mode, due to the suppression of ion thermal gradients has been observed in ISX-B, ASDEX, TEXTOR, ASDEX-U, TFTR and DIII-D, and previously studied [16]. However, its relation to the present work is not clear so far.

Concerning the influence of MARFE's on improved confinement there are two intriguing phenomena to understand. First, what are the mechanisms that favour the sustainment of the stationary MARFE's, which prevent them from evolving into weakly symmetric structures. It is clear that, in contrast with Stacey's previous work [4] the system to consider here is driven by a feedback mechanism, and damped by power losses through impurity radiation. This is expected to produce stable structures through the coupling of power gains and losses. Second, and most important, there is an interesting puzzle about the non-local mechanism through which MARFE's may induce the appearance of an internal transport barrier. Two possibilities may exist. One is that it is a boundary condition effect that can be triggered by the presence of the MARFE. The other is that the MARFE may induce a wide shear flow that could reach the inner part of the plasma column. In order to study these problems, an extension of previous theoretical work [2], that takes into account the role of impurity radiation on the plasma dynamics will be used, introducing faithful geometrical and boundary conditions. One of the important things to study is the role of local coupling of the edge plasma with the wall, since an increase in the local flow of the neutrals from the wall may increase the local radiative losses and stabilize the MARFE. Both local gas puffing and the stochastic divertor may produce this effect.

The nature of the transport barriers observed in the experiments is a different puzzle. One possible explanation is that a radial electric field is produced due to impurity ion orbit losses by the edge of the plasma. This may induce a poloidal shear flow that quenches the drift mode turbulence, as predicted in [17].

2. Ergodic Divertors and MARFEs

The ergodic divertor, concept is an alternative to the ubiquitous poloidal magnetic divertor, and would be useful in limiter tokamaks. Although it has been tested in a number of devices, it has been specifically included in the design of Tore Supra. The purpose is to break the edge magnetic field surfaces by means of a weak resonant perturbation. This problem has been studied theoretically by the Tore Supra group, and de Silva et al. [18, 19].

It was experimentally found in [12] that MARFEs could be sustained through the stochastization of the plasma edge, and that neutral penetration could be controlled through the widening of the scrape-off-layer. Further study of the ergodic divertor on low Z impurity transport, has been carried on. De Michelis et al [19], found inner-wall MARFE-like structures, in which the electron density was increased by a strong deuterium gas puff, and the radiation maximum swung eventually inward. More recently, Hogan et al. [20], observed in inner wall limited discharges, that the plasma moved inwards, without trying to increase the density, and remained attached to the inner wall. However, no improvement in the confinement is reported in either case.

3. MARFEs in Continous Gas Puffing Divertor Tokamaks

Although MARFEs are usually associated with disruptions in divertor tokamaks, it must be pointed out that operational regimes have been found, in which they are correlated to H-L transitions, but not necessarily leading to disruptions. Such is the case of [21], in which continuous gas puffing was used during high-confinement discharges, in order to explore the density limit.

4. Conclusions

It has been experimentally established that both gas puffing feedback and ergodic divertors are able to sustain stationary MARFE-like structures, in toroidal limiter systems (both tokamaks and stellerators), which do not lead to disruptions, although in some cases may precede the quenching of the plasma. In divertor systems, the MARFEs may be associated with detachment from the divertor. In any case, these structures radiate excess energy form the plasma. If it is taken into account that we are dealing with open systems away from thermodynamic equilibrium, this fact can be used in order to provide the appropriate feedback, in order to balance this radiation, and lead to an organised structure. However, the experimental evidence is still too feeble to believe that improved confinement can be achieved by these means. The influence of MARFEs on thermal barriers is not understood yet, but there is more evidence that they would trigger their destruction, rather than their creation. However, it should be recognised that there are several kinds ot MARFE structures (at least stationary and non-stationary), which, under different feedback conditions can influence the plasma in different ways. It is necessary to explore further operational parameters, which can clarify this, and develop numerical simulations, in order to back this search.

Acknowledgments
This work is partially supported by DGAPA-UNAM grants IN105100 and IN116200, and CONACyT grant G25427-E.

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