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Localized recycling as a trigger of MARFE

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Abstract

An analytical model taking into account the plasma cooling due to localized hydrogen recycling is proposed to interpret the conditions of the MARFE onset above a critical plasma density in TEXTOR-94. Results of numerical modeling confirm that under conditions of a good plasma contact with the inner wall this mechanism of the MARFE triggering is more important than the usually considered cooling instability on impurity radiation. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

MARFE, a multifaceted axisymmetric radiation from the edge remains still one of the most fascinating and intriguing phenomena in tokamaks. Experimental and theoretical investigations of MARFEs is of importance both from academic and practical points of view because its appearance often leads to a plasma disruption. In numerous MARFE models [1–5] line radiation from light impurities is considered as the most important element for its triggering. Since the radiation intensity increases with decreasing electron temperature, this channel of the energy loss can lead to an instability: the temperature drops, the radiation increases and the plasma cools down further.

Observations on different tokamaks indicate, however, that the processes involving neutral hydrogen also play an important role in the MARFE formation. It has been found [6–8] that the MARFE appearance is accompanied by a significant increase of the H_α-radiation. This manifests a dramatic increase of the plasma particle flow to the wall in the vicinity of the MARFE.

Experiments on TEXTOR-94 support the idea that recycling processes are of importance for the MARFE formation [9–11]. In particular, spectroscopic measurements performed recently allowed to distinguish situations where different plasma constituents make the main contribution to the radiation losses from the MARFE region [11]. Generally, when the plasma has a good contact with the inner wall, the main radiation observed comes from hydrogen (H_α, red light). In experiments with a significant outward shift of the plasma column (4–5 cm) this contact has been weakened essentially and this allowed a record ramp of the plasma density up to two times the Greenwald limit [10]. The MARFE appears in this case also but is located at a large distance from the inner wall. Its radiation is significantly weaker than in the first case and is of a blue color, i.e. generated by carbon ions.

The effect of a strongly localized injection of hydrogen neutral particles has been previously investigated theoretically by one of the authors. As it has been shown in Ref. [12] a homogeneous plasma-wall contact can be unstable if local plasma cooling due to ionization of recycling neutrals becomes too large. In Ref. [13] a possibility of MARFE-like formations near the gas sources has been demonstrated. In this paper a model is

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elaborated and calculations are done which allow to interpret the MARFE development as an effect of a localized plasma recycling on the inner wall.

2. Conditions of MARFE appearance

For a qualitative understanding under which conditions localized recycling can lead to the MARFE formation we consider in this section a simple analytical model. Fig. 1 demonstrates the state with a MARFE in a real toroidal geometry and the plane geometry used in consideration. It is assumed that the penetration depth of neutrals originating from recycling of charged particles on the inner wall determines the dimensions of the MARFE in the radial and poloidal directions. Due to charge-exchange with ions the motion of neutrals in the plasma is diffusive-like with a diffusivity $D_{\mathrm{at}} \approx {v_a}^2 \tau_{\mathrm{cx}}$, where $v_a = (T/m_i)^{1/2}$ is the thermal velocity, $\tau_{\mathrm{cx}} = 1/(k_{\mathrm{cx}} n)$ the time between successive acts of charge-exchange with k_{cx} being the rate coefficient. The life-time of atoms is determined by their ionization by electron impacts: $\tau_{\mathrm{ion}} = 1/(k_{\mathrm{ion}} n)$ and the penetration depth of neutrals is estimated as $\lambda_{\mathrm{at}} \approx (D_{\mathrm{at}} \tau_{\mathrm{ion}})^{1/2} = 1/(n\sigma_{\mathrm{at}})$ [13] with $\sigma_{\mathrm{at}} = (k_{\mathrm{cx}} k_{\mathrm{ion}})^{1/2}/v_a$. Henceforth, we assume $x_{\mathrm{m}} \approx \lambda_{\mathrm{at}}$ for the radial width of the MARFE and $y_{\mathrm{m}} \approx 2\lambda_{\mathrm{at}}$ for the poloidal one.

The plasma parameters in the MARFE region, temperature T_{m} and density n_{m}, are related to those on the outer board, T_{b} and n_{b} (the electron and ion temperatures are assumed to be equal). To find these relations consider the heat and particle balance in the MARFE. The heat flow $Q_\parallel$ to this region is supplied mainly by the electron heat conduction along the magnetic field. The parallel temperature gradient can be estimated taking into account that the temperature alters from T_{m} and T_{b} along the connection length $\pi q_{\mathrm{b}} R$ with q_{b} being the safety factor at the plasma edge. Thus

$$Q_\parallel \approx \kappa_\parallel \frac{T_{\mathrm{b}} - T_{\mathrm{m}}}{\pi q_{\mathrm{b}} R} \frac{B_\vartheta}{B_\varphi} 2S_{\mathrm{m}}, \tag{1}$$

where $\kappa_\parallel \sim T_{\mathrm{b}}^{5/2}$ is the parallel electron heat conductivity and $S_{\mathrm{m}} = x_{\mathrm{m}} \times 2\pi R$ is the MARFE cross-section in the radial direction; the factor $B_\vartheta/B_\varphi = a/(q_{\mathrm{b}} R)$ takes into account the angle between the toroidal direction and the filed lines. The power supplied to the MARFE is used for ionization of recycling neutrals and lost with generated charged particles when they diffuse out of the plasma through the LCMS

$$Q_{\mathrm{dis}} \approx \left(E_{\mathrm{ion}} \Gamma_{\mathrm{at}} + 5T_{\mathrm{m}} \Gamma_{\mathrm{p}}\right) A_{\mathrm{m}}, \tag{2}$$

where the effective ionization energy $E_{\mathrm{ion}} \approx 25$–$30$ eV takes into account also the losses on the excitation of neutrals, Γ_{at} the influx of atoms due to recycling, Γ_{p} is the outflow of plasma particles through the LCMS with perpendicular diffusion

$$\Gamma_{\mathrm{p}} \approx D_\perp n_{\mathrm{m}}/x_{\mathrm{m}} \tag{3}$$

and $A_{\mathrm{m}} = 2\pi R y_{\mathrm{m}}$ is the MARFE area projected on the LCMS. In a stationary state $\Gamma_{\mathrm{at}} = \Gamma_{\mathrm{p}}$. Complimentary to the above equations the pressure balance along the field lines is assumed for qualitative estimates

$$n_{\mathrm{m}} T_{\mathrm{m}} \approx n_{\mathrm{b}} T_{\mathrm{b}}. \tag{4}$$

Combining Eqs. (1)–(4) we obtain the following equation for T_{m}

$$\frac{\kappa_\parallel}{\pi a D_\perp} \left(\frac{a}{q_{\mathrm{b}} R n_{\mathrm{b}}}\right)^2 \frac{T_{\mathrm{b}} - T_{\mathrm{m}}}{\sigma_{\mathrm{at}}} = \left(\frac{T_{\mathrm{b}}}{T_{\mathrm{m}}}\right)^2 (5T_{\mathrm{m}} + E_{\mathrm{ion}}). \tag{5}$$

The left- and right-hand sides of Eq. (5) are shown in Fig. 2(a) as a function of T_{m} for typical TEXTOR parameters: $a = 46$ cm, $R = 175$ cm, $q_{\mathrm{b}} = 3.8$, $D_\perp = 10^4$ cm^2 s^{-1}, $T_{\mathrm{b}} = 40$ eV, $\kappa_\parallel = 2 \times 10^{23}$ cm^{-1} s^{-1}, $\sigma_{\mathrm{at}} = 10^{-14}$ cm^2 and for different magnitudes of the boundary density n_{b}. There are two stationary states for the density smaller than the critical one, $n_{\mathrm{b}}^{\mathrm{cr}}$, but the state with a lower temperature is unstable. This can be seen easily by considering the effect of a perturbation in T_{m} on the heat balance: if T_{m} decreases the heat supply to the MARFE increases less than the loss in the MARFE and the perturbation grows. Physically, this instability is explained as follows: a local cooling of the plasma by ionization of recycling neutrals leads to an increase of the plasma density through pressure equilibration; this results in a larger outflow of charged particles to the wall with perpendicular diffusion; consequently the influx of recycling neutrals grows up and the plasma cools down further.

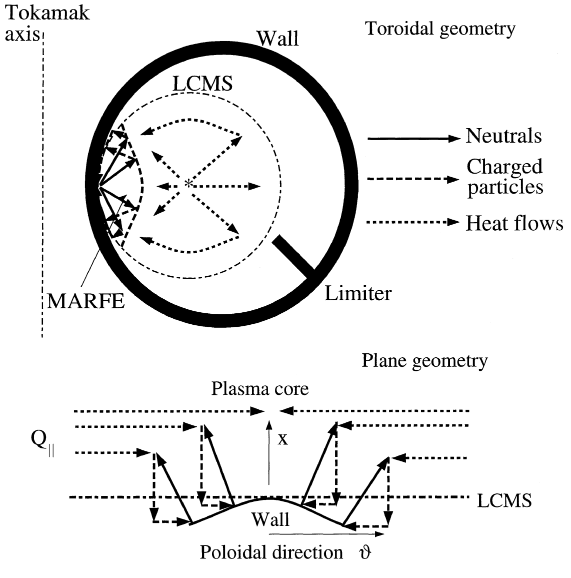

Fig. 1. Schematic view of the plasma poloidal cross-section with a MARFE and the plane geometry assumed in consideration.

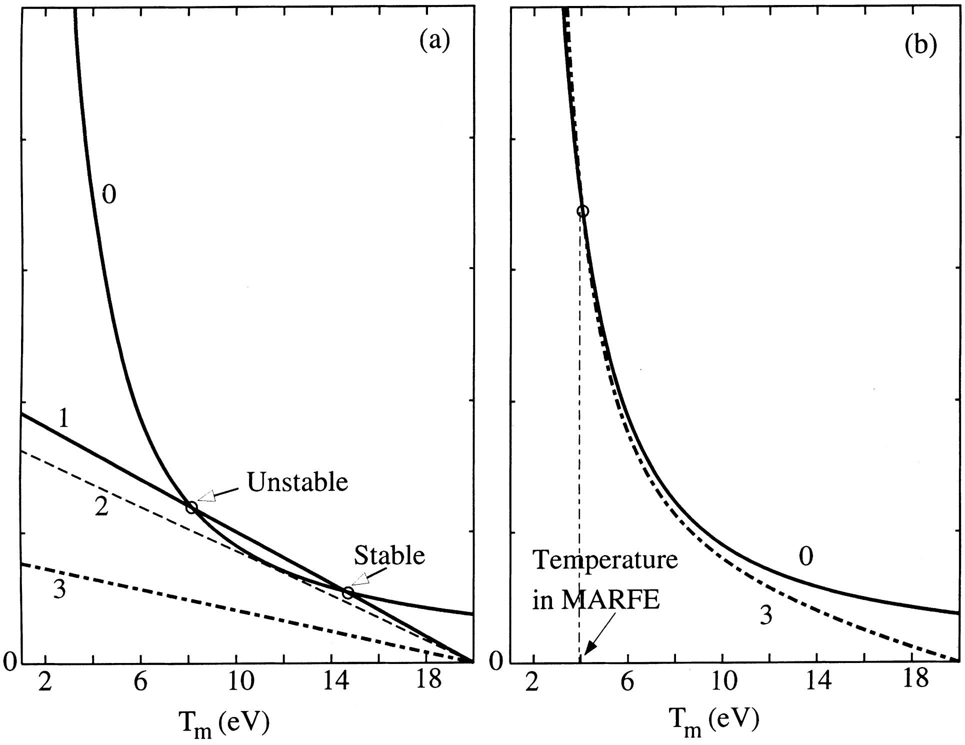

Fig. 2. The dependence of the right (curves 0) and left (curves 1–3) hand sides of Eq. (5) on $T_{\rm m}$ for different magnitudes of the parameter $\langle n\rangle$: 1–2.8, 2–3.0 and 3–4.4 × 10^{13} $\rm cm^{-3}$ and for $\sigma_{\rm at}$ independent (a) and dependent (b) on the temperature.

The critical density can be estimated analytically from the condition that the right-hand side and left-hand side of Eq. (5) as functions of $T_{\rm m}$ touch each other

$$n_{\rm b}^{\rm cr} \approx \frac{1}{q_{\rm b}}\sqrt{\frac{\kappa_{\|}a}{60\pi R^2 D_{\perp}\sigma_{\rm at}}}. \qquad (6)$$

The dependence of $n_{\rm b}^{\rm cr}$ on the safety factor coincides with that given by the Lipschultz criterion for the MARFEs [5], $n_{\rm cr} \propto I_{\rm p}/\pi a^2$, which relates the critical line averaged plasma density and the current (see also [11]). Moreover, Eq. (6) predicts an increase of the critical density with increasing input power which results in higher boundary temperature and larger plasma heat conductivity $\kappa_{\|}$. This tendency has been confirmed in TEXTOR-94 experiments [10].

If the plasma density is larger than the critical one there is no stationary state in the framework of the assumptions above. To analyze what happens in this case one should take into account the temperature dependence of the cross-section of the atom attenuation in the plasma, $\sigma_{\rm at}$. Indeed, $\sigma_{\rm at} \propto \sqrt{k_{\rm ion}} \propto \exp(-I_{\rm ion}/2T)$, with $I_{\rm ion}$ being the hydrogen ionization potential. Thus the approximation used above, $\sigma_{\rm at} = {\rm const}$, is good enough if $T_{\rm m}$ exceeds $I_{\rm ion}$ and it fails for smaller temperatures. Fig. 2(b) demonstrates the effect of the temperature dependence of $\sigma_{\rm at}$. One can see that also in the case $n_{\rm b} > n_{\rm b}^{\rm cr}$ there is a stable solution of Eq. (5) with a small $T_{\rm m}$ which gives the plasma temperature in the MARFE. Physically, the existence of this solution is explained as follows: plasma cooling near the position of the local recycling to a temperature significantly less than $I_{\rm ion}$ leads to an increase of the penetration depth of neutrals, the MARFE width grows, the heat influx into it increases and a further reduction of $T_{\rm m}$ is inhibited.

3. Numerical modeling

To study the dynamics of the MARFE development and its spatial structure a numerical model has been developed for the plasma boundary region where the transport of neutral and charged particles and of heat and momentum along field lines is described by the following set of 2-D equations (toroidal symmetry of the state with a MARFE is taken into account):

$$\frac{\partial n_{\rm at}}{\partial t} - \frac{1}{a^2}\frac{\partial}{\partial\vartheta}\left(D_{\rm at}\frac{\partial n_{\rm at}}{\partial\vartheta}\right) - \frac{\partial}{\partial x}\left(D_{\rm at}\frac{\partial n_{\rm at}}{\partial x}\right) = -k_{\rm ion}nn_{\rm at}, \qquad (7)$$

$$\frac{\partial n}{\partial t} + \frac{1}{q_{\rm b}R}\frac{\partial}{\partial\vartheta}(nV_{\|}) - \zeta(\vartheta)\frac{\partial}{\partial x}\left(D_{\perp}\frac{\partial n}{\partial x}\right) = k_{\rm ion}nn_{\rm at}, \qquad (8)$$

$$3\frac{\partial nT}{\partial t}-\frac{1}{q_b^2R^2}\frac{\partial}{\partial\vartheta}\left(\kappa_\parallel\frac{\partial T}{\partial\vartheta}\right)-\zeta(\vartheta)\frac{\partial}{\partial x}\left(\kappa_\perp\frac{\partial T}{\partial x}\right)$$
$$=-k_{\mathrm{ion}}nn_{\mathrm{at}}E_{\mathrm{ion}},\qquad(9)$$

$$\frac{\partial m_inV_\parallel}{\partial t}+\frac{1}{q_bR}\frac{\partial}{\partial\vartheta}\left(m_inV_\parallel^2+2nT-\frac{\eta_\parallel}{q_bR}\frac{\partial V_\parallel}{\partial\vartheta}\right)$$
$$-\zeta(\vartheta)\frac{\partial}{\partial x}\left(m_iD_\perp\frac{\partial nV_\parallel}{\partial x}\right)=-m_ik_{\mathrm{cx}}nn_{\mathrm{at}}V_\parallel,\qquad(10)$$

where ϑ is the poloidal angle counted from the inner board and related to the length l along a field line as $l=\pi q\vartheta$, $V_\parallel$ is the plasma velocity parallel to the magnetic field, $\kappa_\perp$ is the perpendicular heat conductivity; the factor $\zeta(\vartheta)=(1-\mathrm{d}\Delta/\mathrm{d}x\cos\vartheta)^{-1}$ takes into account the effect of the Shafranov shift $\Delta(x)$ of magnetic surfaces leading to the variation of the radial distance between surfaces with ϑ. In the motion Eq. (10) in addition to the pressure gradient parallel viscosity, momentum transfer across magnetic surfaces with perpendicular diffusion and viscosity and friction of ions with neutrals by charge-exchange are taken into account.

As a first step a 1-D consideration has been performed taking into account only the poloidal dependence of parameters. For this purpose Eqs. (7)–(10) have been integrated over the MARFE width in the radial direction. As a result terms with derivatives respect to x are converted into sources and sinks due to fluxes through the LCMS and the boundary between the edge and core. After this procedure the density of the heat flux from the core comes into play which is proportional to the factor ζ and, thus, is ϑ-dependent. This dependence predefines the location of the MARFE at the inner edge since ζ has its minimum there.

Fig. 3 depicts the steady-state poloidal profiles of the plasma temperature and density corresponding to the TEXTOR parameters with slightly different values of the averaged electron density at the edge taken as a parameter. This picture reproduces nicely the result of the previous section on the threshold of the MARFE formation. Fig. 4 shows the time evolution of the parameters at the MARFE symmetry plane ($\vartheta=0$). A formation time of the MARFE of 0.5 ms is in agreement with the estimate $\tau_\parallel\approx\pi q_b R/c_s$ for a time which particles need to move along magnetic field lines to fill the MARFE region. The profiles in Fig. 4 agree principally with 2-D modeling which will be discussed elsewhere.

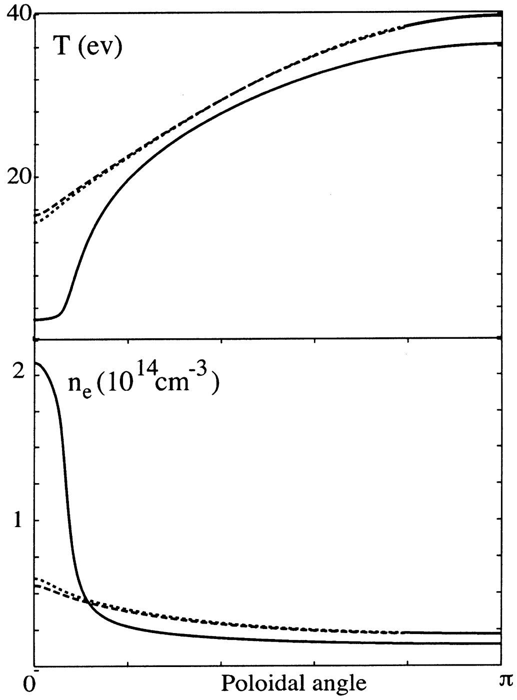

Fig. 3. Poloidal distributions of the plasma temperature and density for different $\langle n\rangle$: - - - 3, · · · 3.1 and —— 3.2×10^{13} cm^{-3}.

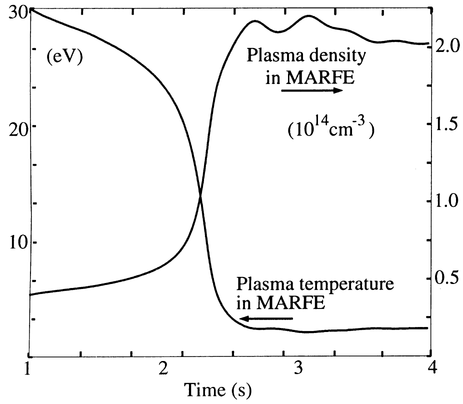

Fig. 4. Time evolution of the plasma parameters at $\vartheta=0$ when the MARFE sets in.

Observations show that the line radiation of C^{2+} ions also increases tremendously as the MARFE develops [11]. Nevertheless, this does not mean that the impurity radiation is the main trigger of the MARFE. For the mechanism proposed here the carbon radiation grows up naturally due to two reasons: first, the reduction of the temperature and increase of the plasma density intensify the recombination of highly ionized impurity ions into strongly radiating low ionized states; second, chemical sputtering of the wall at the position of the local recycling increases significantly the influx of impurities. A cooling instability on impurity radiation [1–5] would be of importance if the recombination would occur faster than the formation of the MARFE due to the effect of hydrogen neutrals. Monte-Carlo modeling of the impurity behavior by the code DORIS [14] indicates that this is not the case. It has been found that the radiation in the MARFE region should grow with a characteristic time of 5 ms i.e. significantly slower than the MARFE develops. Thus in the situation in question the cooling instability on impurity radiation probably can be excluded as the trigger of the MARFE. This conclusion is confirmed by observations which show that the radiation of C^{2+} ions grows much faster and stronger than that of C^{3+} particles. This indicates that the source of C^{2+} ions is predominantly the chemical erosion of the wall but not the recombination from higher charge states.

4. Summary

The present consideration demonstrates that additionally to the conventional mechanism through impurity radiation a localized recycling of the plasma at the inner wall can lead to the development of the MARFE. In this case the heat flux to the MARFE region used for ionization of neutrals and heating of generated charged particles can be provided only if there is a large temperature gradient along the magnetic surfaces. The transition to the state with a MARFE is a result of an instability caused by the local plasma cooling. Critical parameters for the instability are found on the basis of a simple qualitative model confirmed by numerical calculations. Impurity dynamics modeled by Monte-Carlo calculations shows that in the situation in question the cooling instability due to temperature dependence of the impurity radiation is not as important for the MARFE triggering as localized recycling.

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