Stabilization of radiation-condensation instability in tokamaks with beryllium wall.

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1. Introduction

It is well known that high impurity radiation may lead to the Radiation-Condensation Instability (RCI) and to its nonlinear stage the Microfaceted Asymmetric Radiation from the Edge (MARFE) formation [1-2]. Earlier authors of the present paper offered Neon injection in order to suppress RCI development despite of high radiation power close to 100% of the input power in tokamaks with Carbon wall [3]. The nature of the stabilization effect is easy to gasp. The growth rate of the RCI is determined as $\gamma = \frac{2}{5n}(\frac{2Q}{T} - \frac{\partial Q}{\partial T} - k_{\parallel}\kappa_{\parallel})$ [2]. Here n is main plasma density, T its temperature, $Q = nn_I L(T)$ is the impurity radiation rate, $\kappa_{\parallel}$ is the parallel heat conductivity, and $k_{\parallel}$ is the parallel component of the wave vector. One can see that the first term is the destabilizing one while the third one plays the stabilizing role. The most unstable regime corresponds to the case $\partial L / \partial T < 0$. As it has been shown in [3] one can shift this region into higher temperatures with high heat conductivities and prevent the RCI development injecting Neon into plasmas with carbon impurity.

Last years the beryllium wall and tungsten divertor is proposed for ITER. Also in order to improve H-mode confinement and provide reliable radiative cooling at the edge Nitrogen seeding has been used in some experiments with Beryllium wall and Tungsten divertor [4].The present paper is devoted to RCI and MARFE formation in beryllium and tungsten seeded plasmas, the stability of Nitrogen seeded plasmas is studied as well.

2. Mathematical model

Narrow, highly radiating edge plasma layer between pedestal and separatrix is described. Assuming diffusive transport the set of equations for plasma density and temperature can be written as following:

$$\frac{\partial n}{\partial t} - D_{turb}\frac{\partial^2 n}{\partial x^2} = 0 \qquad (2.1)$$

$$3n\frac{\partial T}{\partial t} - n\chi_{turb}\frac{\partial^2 T}{\partial x^2} = -Q_{RAD} \qquad (2.2)$$

Here $n = n_e = n_i$ is the main plasma density, $T = T_e = T_i$ is the plasma temperature. $D_{turb} = D \cdot D_{bohm}, \chi_{turb} = \chi \cdot \chi_{bohm}$, where $D_{bohm} = \chi_{bohm} = \frac{cT}{ZeB}$, D and χ are chosen constants.

$Q_{RAD} = n_e n_I \sum_i \sum_{z=0}^{k} L_z^i(T) y_z^i$ is the radiation losses by the impurity ions, n_I is the total impurity density, $y_z^i = n_z^i / n_I$ is the relative density of certain impurity ion with charge z, and $L_z^i(T_e)$ is it's radiation function.

Boundary conditions on the pedestal side are defined as the density and the heat flows from the core:

$$D_{turb} \frac{\partial n}{\partial x}(x=0) = -\Gamma_0, \qquad n\chi_{turb} \frac{\partial T}{\partial x}(x=0) = -P_{in} \tag{2.3}$$

As for the particles leaving through the separatrix we assume the ballistic model

$$D_{turb} \frac{\partial n}{\partial x}(x=1) = -\alpha \cdot nV_{T_i}, \qquad n\chi_{turb} \frac{\partial T}{\partial x}(x=1) = -\beta \cdot TV_{T_i} \tag{2.4}$$

Where $V_{T_i} = \sqrt{\frac{T}{m_i}}$, α and β are chosen constants.

The coronal equilibrium shifted by the charge-exchange with the hydrogen neutrals is considered for the Beryllium and Nitrogen fractions

$$\frac{\partial y_z}{\partial t} = 0 = y_{z-1} nJ_{z-1} + y_{z+1}(nR_{z+1} + NR_{z+1}^{CX}) - y_z(\text{n}\, J_z + nR_z + NR_z^{CX}) \tag{2.5}$$

Here J_z, R_z, R_z^{CX} are ionization, recombination and charge-exchange rates respectively and N is the neutrals density.

Tungsten radiation is modelled by simple approximation $L_{Tung}(T) = \frac{10^{-15} \exp(\frac{-10}{T^{0.5}})}{T^{0.9}}$ $erg \cdot cm^3 / \text{s}$, that is in a reasonable agreement with the data calculated numerically by Dr. V.E. Zhogolev at the temperature region of interest.

Neutral flow inside is supposed to be equal to the plasma flow outside at the separatrix,

$$\Gamma_N + \Gamma_n = 0, \qquad NV_x - D_{turb} \frac{\partial n}{\partial x}(x=1) = 0 \tag{2.6}$$

Equations (3.1-3.6) are used to determine thermal and density equilibrium profiles, which stability to m=1 n=0 RCI mode is analyzed below.

4. Numerical results

Calculations were performed for DIII-D-like tokamak i.e. major radius R of 175cm, minor one a of 62cm, toroidal magnetic field B of $2 \cdot 10^4$ Gauss, and a safety factor q of 4 at the edge.

First, the RC stability of Beryllium-Tungsten mixture was investigated. Fig. 1 plots critical density of Beryllium for plasma temperature profile to remain marginally stable as a function of Tungsten density. Fig. 2 shows the ratio of radiation losses to the input power for the marginal stability of the mixture as a function of the Tungsten-Beryllium density ratio. One can see that the presence of Tungsten ions influences the RCI threshold significantly if its concentration is about $10^{-4} \div 10^{-3}$ of the main plasma density. Such Tungsten concentration is unlikely high in the tokamak-reactor because the Tungsten radiation from the core would be unacceptable.

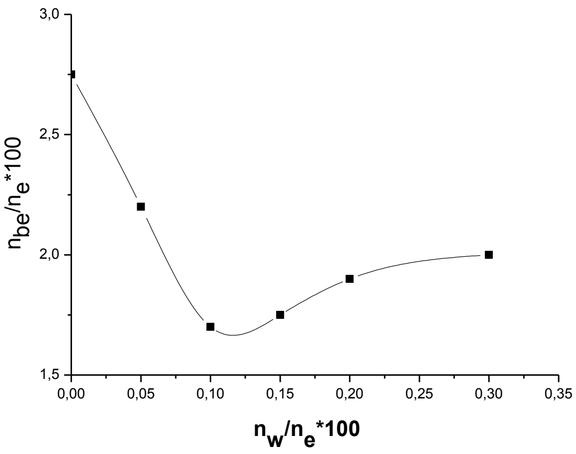

Fig 1. Critical Beryllium concentration as a function of the Tungsten to the main plasma density ratio

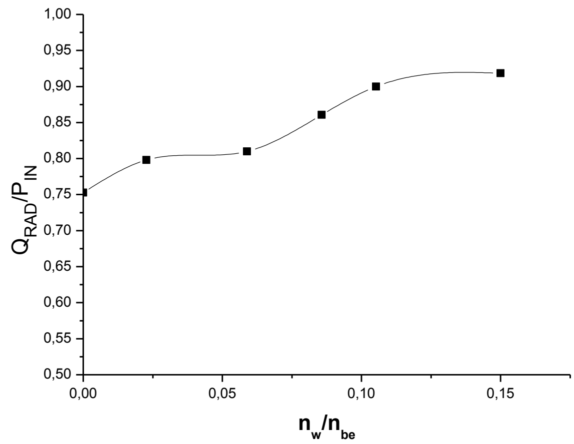

Fig 2. Ratio of radiation losses to the input power for marginally stable mixtures as a function of the relative Tungsten to the Beryllium density.

Similar Figures (3,4) are provided for Beryllium-Nitrogen mixture. One can see that small (in respect to the critical Beryllium density) portions of Nitrogen injected don't influence the value $-\frac{\partial L}{\partial T}$ of the mixture significantly. At the same time they increase the radiation losses, making destabilizing term $\frac{2L}{T}$ grow. It results in the initial decrease of critical Beryllium density. The Nitrogen one goes up. As the Nitrogen density reaches a certain value the stabilizing effect overbalances the radiation increase. Critical Beryllium density starts to grow with the increase of the Nitrogen concentration. Fig. 4 shows that with the addition of Nitrogen it is possible to reradiate up to 90-92% of the power incoming into the edge layer without a thread of noticeable reduction of the RCI threshold.

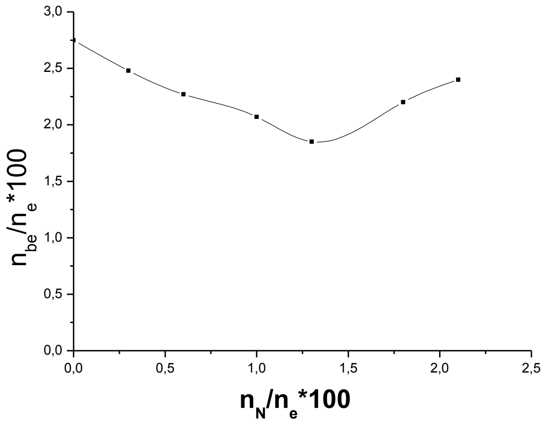

Fig 3. Critical Beryllium concentration as a function of the Nitrogen to the main plasma density ratio

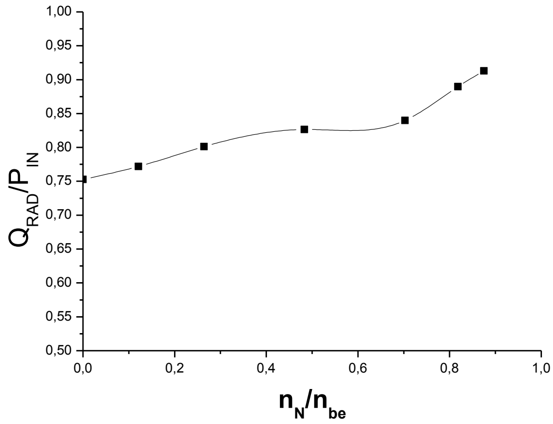

Fig 4. Ratio of radiation losses to the input power for marginally stable mixtures as a function of the relative Nitrogen to the Beryllium density.

5. Conclusion

Radiative Condensation Instability threshold for Beryllium, Tungsten, and Nitrogen seeded plasmas was examined. Calculation shows that the Tungsten influences RCI threshold significantly only if its concentration exceeds limit values supposed for the present tokamaks. Nitrogen on the other hand proves itself worthy in order to decrease the thermal loads on the divertor plates by the means of re-radiation while its influence on the RCI threshold is not critical.

5. Acknowledgements

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6. References

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