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Radiation losses from ITER SOL due to divertor material plasma

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Abstract

Numerical simulation revealed that type I ELMs of ITER typical parameters cause vaporization of CFC targets. Radiation losses due to the divertor target material plasma influx into SOL are estimated to be of the same order of magnitude as total fusion power.

1. Introduction

The tokamak ITER is aimed to demonstrate technological advantages of thermonuclear power production on a full scale, in particular, operating at increased core plasma density, which implies that ITER is going to work in the ELMy H-mode. In this mode the heating power arriving at the divertor plates contains short periodic pulses of the Edge Localized Mode (ELM) of 2-3 orders of magnitude over its averaged value. As expected, each giant ELM of type I will dump deuterium-tritium plasma onto the divertor armour depositing the energy of 1–3 MJ/m^2 at the pulse duration of 0.1-0.5 ms [1]. This heat load causes intense vaporization at the armour surface. Influence of divertor armour material plasma upon the confined DT-plasma is a key issue for fusion technology, because contamination of the core plasma may result in the radiation collapse of the confinement, and intense radiation impact on the first wall – in its damage.

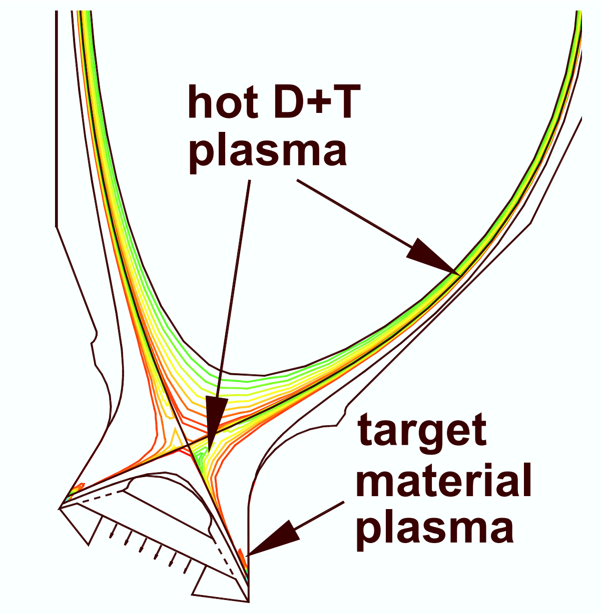

Fig. 1. General view of ITER poloidal cross-section used in FOREV simulations

Experimental estimation of influence of the armour material, vaporized during ITER ELM, on the core plasma, seems now almost impossible on existing tokamaks for the divertor armour does not vaporize during ELMs. This is why simultaneous numerical simulation of the target vaporization, carbon plasma transport along magnetic field into SOL and cooling down of the core plasma by carbon radiation are of a great importance.

In this work such two-dimensional simulation has been performed using radiation magneto-hydrodynamics code FOREV-2D [2]. Created and tested for simulation of disruption-induced core plasma contamination and divertor erosion, it was adjusted to ELM-relevant simulations [3] taking into account the ITER magnetic field topology with the single null of the poloidal field, see Fig. 1.

Self-consistent description of ELMs in tokamak devices is still absent, but experimental measurement of ELM features are numerous (see for example [1,4]). Based on this information, a tentative ELM scenario that takes into account only parameters necessary for estimation of radiation losses has been simulated. The scenario is described in Chapter 2 and the simulation results are explained in Chapter 3.

2. The ELM scenario

The scenario exploits only the parameters of the hot DT plasma that looses from the ITER pedestal region due to sudden increase of confined plasma transport across the magnetic field. Further convective transport of energy and particles as well as heat and radiation transport are described self-consistently by FOREV. In the available version of FOREV the diffusion of both DT plasma and carbon plasma across magnetic field is not taken into account. Instead, it is assumed that hot D-T plasma of the pedestal region merely looses through the separatrix with a loss rate determined by the ELM parameters and then it appears in SOL having equal constant initial temperatures $T_D = T_T = T_e$ and exponential distribution across SOL: $\dot{n} = \dot{n}_{DT} \exp(-x/d(y))$, with $\dot{n}$ the plasma density loss rate, x the coordinate across SOL and y the coordinate along the magnetic field lines. The actual profile thickness $d(y)$ depends on the y-coordinate and it is defined in such a way that in front of the pedestal the loss rate is constant along the magnetic field lines. The thickness changes from d~1cm at the high field side of SOL to d ~10 cm at the x-point region where the magnetic field lines significantly diverge. For the sake of simplicity, during ELM $\dot{n}$ is assumed to be independent on the time t. Densities of deuterium and tritium in the pedestal plasma are assumed equal. The DT plasma so injected into SOL expands along magnetic field lines and heats the divertor armour; in our simulation the armour material is CFC. The simulation is done for the type I ELM with the following parameters: the ELM duration τ= 100 μs, $\Delta n = \dot{n}_{DT}\tau = 5 \cdot 10^{19}\,\mathrm{m}^{-3}$

and the plasma temperature T_e = 3 keV. Hot injected DT plasma mixes with the SOL plasma already existed there and accelerates along magnetic field lines. The influx of DT plasma from pedestal region is stopped at $t = \tau$, but calculation of the transport of DT plasma and of the plasma of evaporated carbon targets continues up to t = 30ms.

3. Simulation results

For the simulated ELM, the maximum divertor armour heat load at the separatrix strike point Q = 0.8 MJ/m^2 was obtained. For τ = 100 μs this value is larger than the vaporization threshold: the armour vaporization starts at around 20-25 μs at both outer and inner divertor plates. The vapour is being ionised by the hot DT plasma and then expands into SOL, filling it during 10-20 ms. The carbon plasma density n_c in SOL at the position of the separatrix varies from 10^{19} m^{-3} to $2{*}10^{21}$ m^{-3} along the separatrix. The carbon plasma keeps a high temperature T during first 1-2 ms (see Fig. 2), so at that time all ion species contribute to the radiation flux. After 2 ms only CII mainly contributes for the radiation loss.

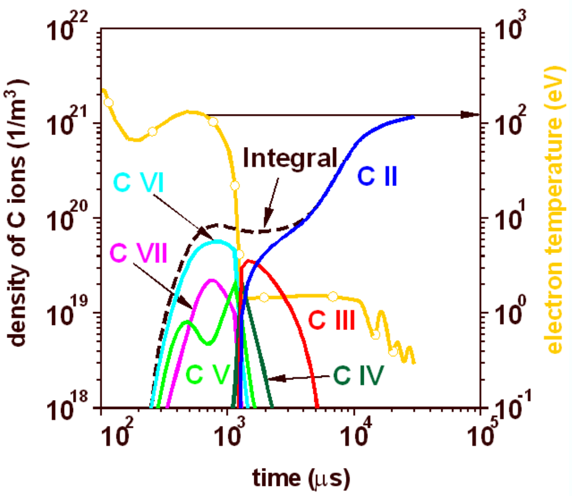

Fig. 2. Time dependence of carbon plasma temperature and the densities of different carbon ions species at the separatrix, 3.8 m from the outer divertor.

Analysis of the radiation spectrum revealed that main contribution to the flux is due to a few strong lines of different C ions. In the opacity tables of FOREV each such line is modelled specially, resolving the central part of the line spectrum. Accurate account for the carbon lines profile is extremely important for the reliable radiation loss calculation. Otherwise, according to our experience, the calculated radiation flux to the wall increases for approximately one order of magnitude. This drastic dependence of the radiation flux on the line shape gives evidence that the radiation is optically thick at the line centres. The line shape meshes corresponding to the transition $2s^2(^1S)2p^2$-$2p^3$ of CII ion are demonstrated in Fig. 3. The shape corresponds to the Voight contour with the central part modelled using 10 groups.

After filling SOL, the carbon plasma diffuses across magnetic field lines into the pedestal and cools down the DT plasma there. Calculation of plasma diffusivity is rather complicated problem, therefore for rough estimation of radiation losses it is assumed that the pedestal DT plasma gradually mixes with the carbon plasma accumulated in SOL during 20 ms. Simulations show that after such mixing the carbon plasma irradiates all the injected power being ~1GW in our calculation and after 0.1-0.2 ms the plasma parameters stabilized. There are two regions of carbon plasma, one with T of 2-3 eV and $n_c > 10^{20}$ m^{-3} reradiates most of the power, and the second one of T of 40-50 eV and $n_c < 10^{20}$ m^{-3} reradiates the power of several orders of magnitude less (see Fig. 4).

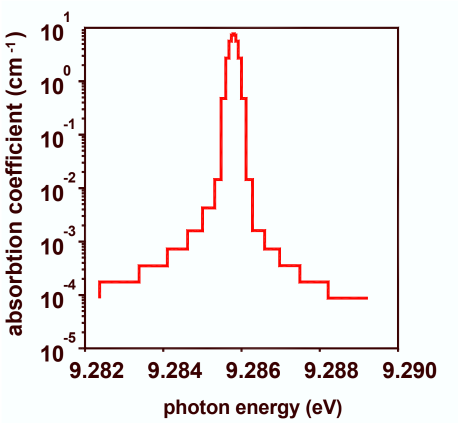

Fig. 3. CII ion line corresponding to the transition $2s^2(^1S)2p^2$-$2p^3$.

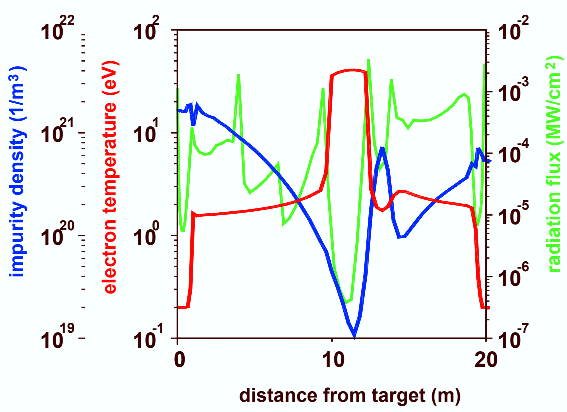

Fig. 4. Temperature, density and radiation flux from the carbon plasma along the separatrix

4. Conclusions

Numerical simulation of SOL contamination by carbon plasma during ITER type I ELM has been performed. Distributions of different carbon ion species inside SOL have been calculated. Analysis of radiation shows that the main contribution to the radiation flux from carbon plasma is due to only few lines of carbon ions. For adequate simulation of radiation transport in carbon plasma the radiation database of FOREV-2D has been improved for more accurate treatment of the radiation lines mainly contributing to the radiation flux. The radiation loss from SOL carbon plasma is of the same magnitude as the total ITER fusion power.

References

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