# Simplified model for carbon plasma production by ELMs in ITER

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## Abstract

Comprehensive simulations of the ITER divertor armour vaporization under ELMs of different sizes have revealed that production of carbon plasma can be described with the simplified model. The dependence of erosion rate on the ELM heat flux increase rate is calculated.

## Introduction

The type I ELMs in ITER result in the divertor armour vaporization. Calculations of carbon amount vaporized during type I ELMs of several typical for ITER sizes have been done earlier [1] using the FOREV-2D code. These calculations need long time; however, the simplified model which describes the dependence of vaporized carbon amount on the ELM size has been developed basing on the FOREV simulations.

## Carbon plasma production simulation.

FOREV-2D code simulates plasma dynamics and radiation transport in the magnetized plasma taking into account the first wall heating and vaporization, the vapour ionisation and recombination, plasma convection along the magnetic field lines and its diffusion across the magnetic field, electron heat conduction, electromagnetic waves irradiation and absorption in the plasma and the radiation absorption on the first wall. Extensive simulations of the ELM-induced divertor target vaporization and the dynamics of carbon plasma produced out of the vapour have been performed for ELMs of different sizes (the energy release during ELM) but for the same time duration of approximately 500 μs. In these simulations it was assumed that the heat load at the divertor surfaces during ELM is due to temporal increase of the cross diffusion coefficient in pedestal and SOL. The magnitude and the time dependence of enhanced plasma diffusion coefficient $\Delta D_{ped}$ are fitted to reproduce the plasma fluxes anticipated for ITER ELMs and described in [1]. The diffusion coefficient variation along the core and SOL is plotted in Fig. 1. Results of comprehensive FOREV-2D simulations for the divertor targets vaporization and shielding with carbon plasma, which have been done for ELMs of several sizes are shown in Fig. 2. Analysis of the results has revealed that the target vaporization and the incoming heat flux shielding proceeds in the same manner independent of the heat flux amplitude. The heat fluxes at the divertor target produced by ELMs have approximately the same time dependence with initial time delay of 40-50 μs, when the thermonuclear plasma of

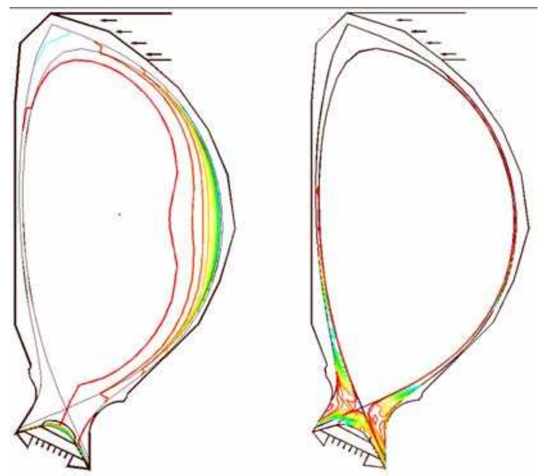

Fig.1. Level lines of $\Delta D_{ped}$ (left) and of the final carbon plasma density in the ITER core and SOL. Red is the minimum and green – the maximum of the values.

the ELM transported from SOL to the divertor targets, linear rise of the flux during 150-200 μs and then the decay of the flux vanishing at ~600 μs. The time dependences of the fluxes at the outer divertor target are shown in Fig. 2. Time dependences of these fluxes differ only slightly, but the amplitudes of the three shown curves are 3 GW/m$^2$, 10 GW/m$^2$ and 45 GW/m$^2$. These fluxes correspond to the peak heat loads of 1.5 MJ/m$^2$, of 3.1 MJ/m$^2$ and of 15.5 MJ/m$^2$ and the average heat loads on the divertor target were 0.84 MJ/m$^2$, 1.84 MJ/m$^2$, and 9.6 MJ/m$^2$.

As it is seen from Fig. 3, after start of these ELMs, first of all the divertor target heated till the vaporization temperature then, after vaporization start and fast transition process the vaporization rate stabilized at approximately constant value. The armour vaporization rate should provide the shielding efficiency, which enough for decreasing of the incoming heat flux to the value needed for maintaining this vaporization rate at constant surface temperature. The process is self-adjusted, so for arbitrary high incoming heat flux shielding of targets can be ensured. At temperatures close to the vaporization temperature of carbon the vaporization rate depends exponentially on temperature, so the target surface temperature always approximately equal to the vaporization temperature. The vaporized carbon is ionized and expanded in ITER vacuum chamber along the magnetic field lines, but the target vaporization provides approximately constant plasma influx needed for the shielding. Heat flux from the ELM fully stopped with carbon plasma shield of a few centimetres thickness and 3-5*10$^{23}$ m$^{-3}$ density. Vaporization of the divertor targets starts at the energy deposition of ~0.8 MJ/m$^2$. For small ELMs shielding of hot electrons is not efficient enough, so a considerable part of the heating energy is transported by electrons. At the energy deposition of 1.5 MJ/m$^2$ the radiation and the hot electrons transport equal amounts of energy

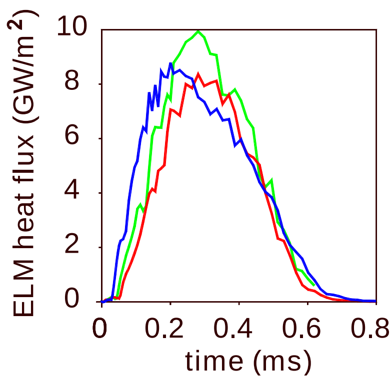


Fig 2. Normalized time dependence of the ELM heat flux to the divertor armour. The amplitudes of these curves are 3 GW/m$^2$, 10 GW/m$^2$ and 45 GW/m$^2$.

to the armour after vaporization start. For these ELMs the maximum of carbon plasma densities close to the armour are less then 3-4*$10^{20}$ $m^{-3}$ and the plasma temperature is of 30-40 eV. But for ELMs with the energy deposition of 1.8 $MJ/m^2$ the hot electrons shielding become perfect and all the heat flux to the armour transferred by radiation after the vaporization start. In this case the maximum of carbon plasma density close to the armour is ~7*$10^{23}$ $m^{-3}$ and the plasma temperature dropped to 2-3 eV.

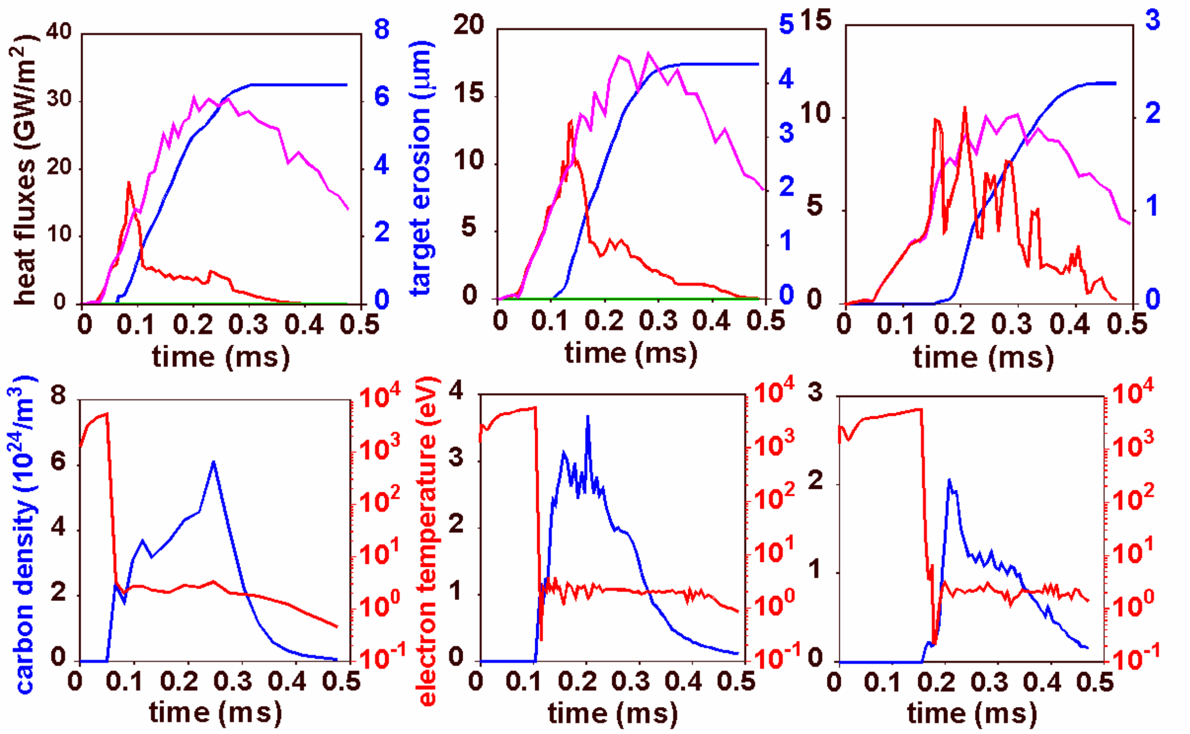


Fig. 3. Time dependences for the heat flux to the divertor armour without shielding, for the shielded heat flux and for the erosion, shown in the upper panel. Corresponding time dependences for carbon plasma density and temperature close to the armour are in the lower panel. The three columns correspond for the heat flux increase rate $\dot{G}$=220GW/$m^2$/ms, $\dot{G}$=106GW/$m^2$/ms and $\dot{G}$=52GW/$m^2$/ms.

Considering the ELMs with perfect shielding of electron heat flux one can note that the vaporization rates become constant after start of vaporization and short transition period, then it remain almost constant during 150-180 µs and then drops to zero. As it is seen from the simulations, the vaporization rate depends only on the heat flux increase rate $\dot{G}$ at the leading front of ELM. The dependence is shown in Fig. 4. Corresponding carbon plasma density close to the divertor armour remains approximately constant during the constant vaporization rate also and is shown in the same figure. Total erosion during ELMs of 0.5 ms time duration is stabilised at approximately 6.5 µm with growing ELM energy deposition. Final carbon plasma distribution along the SOL at 1 ms after the ELM start is illustrated in Fig. 1.

## Conclusions.

Comprehensive simulations of carbon vapour production under ELM induced divertor armour heating and the armour shielding with the carbon plasma have been performed. Analysis of the simulations has revealed common features of this process for ELMs of various energy contents. It has been found that production of carbon plasma during the ELMs can be described with the same scenario independent of the ELM size. The model proposed uses simplifications arising from the fact that the carbon plasma shields, which convert the hot DT plasma heat flux into the radiation flux very close to the divertor targets, have the same temperature of 2-3 eV independent of the incoming plasma flux. This temperature determined by the existence of so called ‘radiation barrier’ at 6-8 eV, which restricts the temperature close to vaporized target. Being converted into radiation the heat flux to the divertor drastically reduced due to its redistribution over much larger surfaces of the divertor and the main chamber.

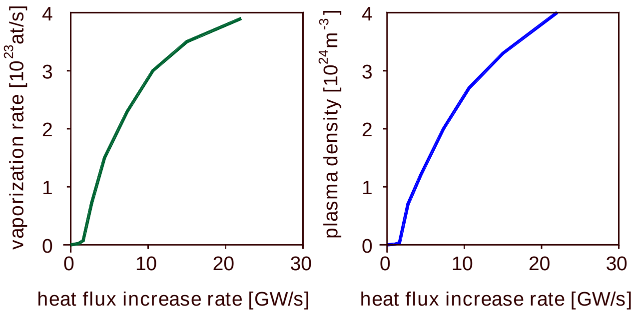


Fig. 4. Carbon vaporization rate and the plasma shield density dependence on the heat flux increase rate $\dot{G}$ for the ELMs of 0.5 ms.

From the simulations it follows that the carbon plasma production depends on the incoming heat flux increase rate $\dot{G}$. The armour vaporization stopped at the time when the incoming heat flux reached its maximum and the carbon plasma production does not depend on the decaying tail of the flux time dependence. Erosion rate and erosion dependence on the heat flux increase rate are calculated. Armour erosion starts at $\dot{G} \approx 10 GW/m^2/ms$, which corresponds to the local energy deposition of 0.8 $MJ/m^2$ per ELM, and saturates at ~6.5µm for ELMs with $\dot{G} \geq 200\text{-}350 GW/m^2/ms$ and the energy deposition of 10-15 $MJ/m^2$ per ELM.

## References

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