Contamination and radiation losses in post-ELM tokamak plasma

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Abstract. In large tokamaks operating in the ELMy H-mode after each ELM the divertor emits eroded ionized material into SOL and then the impurities may deteriorate the confinement. The repetitive diffusion of carbon impurity into the core and its accumulation during tokamak discharge is simulated with a newly developed self-consistent two-dimensional plasma equilibrium code.

In the H-mode anticipated for the future tokamak ITER, high power repetitive bursts of edge localized modes (ELMs) that may accompany the tokamak discharge will be probably a serious problem. The divertor armour is made of carbon fibre composites (CFC) in the most loaded part at the separatrix strike position (SSP) and of tungsten cover in the other parts. The ELM heat deposition Q in the range about $0.5 - 3$ MJ/m^2 is expected [1]. This causes intense vaporization at the surface, then contamination of the scrape-off layer (SOL) and later the confinement region.

Recent computer simulations of SOL contamination by carbon impurity was carried out with the code FOREV which models propagation in SOL of dumped during ELM hot deuterium-tritium plasma and its impact on the target [2]. Evaporation and ionization of target atoms, radiation transport in the ionized erosion species and its backward propagation into SOL was simulated. For $Q \approx 1$ MJ/m^2, carbon fills SOL of thickness of a few cm for several ms with the density n up to 10^{20} m^{-3}, thus replacing the DT plasma. It is cooled down to a few eV by radiation losses.

The purpose of this study is to simulate numerically the consequent carbon contamination of confined plasma assumed be quiescent. The magnetized rich impurity diffuses across the separatrix. For the SOL carbon temperature $T = 1.5$ eV, the gyro-radius of carbon ions CII in the magnetic field $B \sim 5$ T is of $\rho \sim 10^{-4}$ m and their collision frequency $\nu \sim 3\times10^{6}$ s^{-1}. The diffusion coefficient $D = \rho^2\nu \sim 3\times10^{-2}$ m^2/s and the carbon influx $j_C = \tau n D/d \sim 3\times10^{17}$ m^{-2} thus follows for the SOL thickness 3×10^{-2} m and the carbon presence time $\tau = 3$ ms. This is one order less than the carbon amount in SOL, so that carbon manly returns along the field lines in the divertor where, as we assume, it is completely absorbed until next ELM. Accurate simulation of the whole diffusion is generally very complicated. Below several simplifications are used in order to estimate the core impurity density and consequent radiation losses for plasma tore of poloidal cross-section typical of future tokamak designs. Main ion species deuterium governed by fixed neutral beam fuelling is assumed. Temperature $T(w)$ common for main and impurity ions and electrons as a function of poloidal magnetic flux w is fixed in time being typical for the H-mode. The plasma is described in frame of the Pfirsch-Schlüter theory [3] for arbitrary aspect ratio A however the thermoforce contributions are not taken into account and the diffusion coefficients for main and the impurity species are multiplied by the factors $15A^{3/2}$ and $3A^{3/2}$, respectively, to account for banana orbits and anomalous effects. This establishes the main $n_0(t,w)$ and impurity $n_1(t,w)$ densities in time t. The radiation losses are calculated based on the data [4] for optically thin plasma. The bulk impurity density is assumed small ($Z_1n_1 << Z_0n_0$, with Z_i the ion charge states) therefore impurity influences on plasma currents and the beam are neglected.

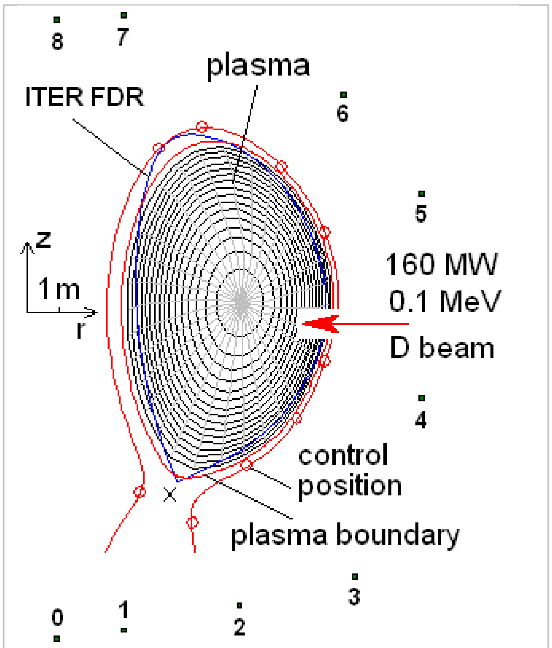

Fig.1 TOKE poloidal cross-section. ¦ - the coils for external poloidal magnetic field, × - the x-point. The arrow shows the beam penetration depth.

For the simulation, newly developed two-dimensional plasma-magnetic field equilibrium code TOKE ("Tokamak Equilibrium") is applied. Fig. 1 demonstrates on the poloidal plane (r,z) of the tokamak cylindrical frame, the coils for external poloidal field, the neutral beam and the magnetic flux frame implemented in the code. To calculate these meshes filled with the plasma, for given pressure $p(w)$ and covariant toroidal field component $B_3(w)$, an iterative algorithm for $w(r,z)$ was developed. It uses the Green function for the Grad-Shafranov equation. Plasma currents and the coil currents are calculated and then new magnetic flux frame generated updating the plasma configuration until sufficient convergence. At each time step the pressure profile, the ion influxes and the next magnetic frame are calculated. The code controls the currents in the coils keeping required shape of separatrix. Due to this feedback the plasma boundary keeps at the separatrix with some $w = w_b$. Numerical radial coordinate x is proportional to w as $w/w_b = x/X$, with X the number of mesh layers. After each ELM, $n_1(w_b)$ becomes large for a few ms until given impurity influx j_m. Low plasma parameter β is assumed ($\beta << 1$). In this case radial convective velocity of B_3 can be neglected and the species densities satisfy the equations:

$$\frac{\partial}{\partial t}\left(G_3 n_0\right)=\frac{\partial}{\partial x}\left(G_3 D_0\left(\frac{G_5}{G_3}-\frac{G_3}{G_1}\right)\frac{(2\pi q)^2}{G_1^2}\frac{8\pi}{B_3^2}n_0\frac{\partial}{\partial x}\left(Tn_0\right)\right)+S \quad (1)$$

$$\frac{\partial}{\partial t}\left(G_3 n_1\right)=\frac{\partial}{\partial x}\left(\Lambda_5'\frac{D_1}{Z_1}\frac{m_1\nu_{10}}{m_e\nu_{e0}}\frac{8\pi}{B_3^2}\left(\frac{n_0}{Z_1}\frac{\partial}{\partial x}\left(Tn_1\right)-\frac{n_1}{Z_0}\frac{\partial}{\partial x}\left(Tn_0\right)\right)\right) \quad (2)$$

The coefficients $D_i = f_i c^2/(4\pi\sigma_{||})$, with $f_0 = 15A^{3/2}$, $f_1 = 3A^{3/2}$, the longitudinal conductivity $\sigma_{||} = 2e^2 n_0/(m_e\nu_{e0})$. The speed of light c, electron mass m_e, elementary charge e, safety factor q, and ν_{e0} is Spitzer's electron collision frequency. The impurity ion mass is m_1, and ν_{01} the frequency of impurity ion collisions with main atoms. The ratio $m_1\nu_{01}/(m_e\nu_{e0})$ is of order of $(m_1/m_e)^{1/2}$, which yields enhanced impurity diffusivity.. The term S represents the fuelling obtained based on the data [5]. The geometric factors G_k and Λ'_k are given by the following integrals around the magnetic surface:

$$G_k = \oint r^{k-2}\sqrt{g}\,dy\,, \qquad \Lambda_k' = \oint r^{k-2}B_\zeta^2\left|\mathbf{B}\right|^{-2}\left(g_{22}/\sqrt{g}\right)dy \quad (3)$$

The poloidal coordinate y varies from 0 to the number of radial layers Y. (In Fig. 1 we have $X = 16$ and $Y = 32$.) Given non-negative integers $x < X$ and $y < Y$, $\sqrt{g_{22}}$ is the width along y and $\sqrt{g}$ the area of numerical cell with the diagonal (x,y)–$(x+1,y+1)$.

For the configuration of Fig. 1, stationary layer densities $n_0(x+1/2)$ at integer $x = 0..X-1$ are obtained with a finite-difference form of Eq.(1) for the beam inflow of $J_{\rm nb} = 10^{22}\ {\rm s}^{-1}$. Fig.2 presents $T(a)$ and the obtained profile of n_0 in terms of minor radius $a = (s/\pi)^{1/2}$, with $s(x)$ the poloidal cross-section area. The deuterium radiation power of 25 MW is obtained. Impurity behaviour and radiation losses are simulated solving numerically Eq.(2) only once for single ELM with $j_C = 3\times10^{17}\ {\rm m}^{-2}$.

Fig. 3 demonstrates corresponding evolution of carbon content and carbon radiation loss power. It follows from Fig. 3 that for $f_{\rm ELM} < 100$ Hz the plasma cleaning by next ELM is inefficient. The post-ELM impurity quickly penetrates into the core, n_1 in the pedestal becomes low due to the back diffusion, and the next ELM carries away almost pure plasma.

Since at fixed $n_0(a)$ and $T(a)$ Eq.(2) is a linear equation in regard to n_1, and n_1 is a factor in the local radiation sink, the following results for multiple ELMs are obtained composing them of that of Fig. 3 for linearly increasing ELM onset times. The deposition energy Q relates with the whole ELMs energy $E = 3T(X)N_{\rm ELM}$ as $E = QS_d$, with $N_{\rm ELM}$

number of main species ions the ELM dumps into SOL and S_d effective divertor area. We assume for distinctness a half of plasma outflow into SOL via ELMs (ELMs do not influence substantially the impurity diffusion outflow from the core).

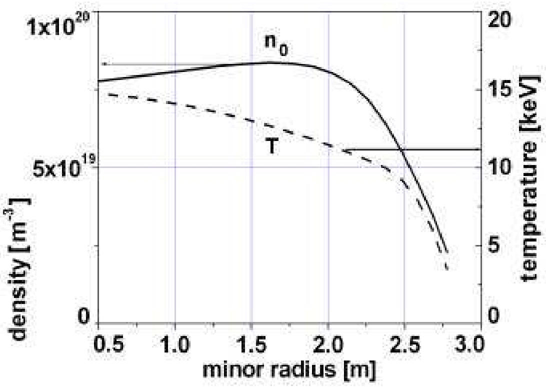

Fig. 2 Stationary profiles of $n_0(a)$ and $T(a)$ as functions of minor radius a

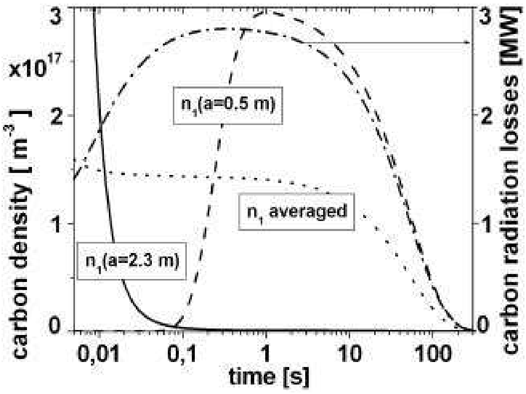

Fig.3 Carbon density and radiation after single ELM of $j_C = 3\times10^{17}$ m^{-2}

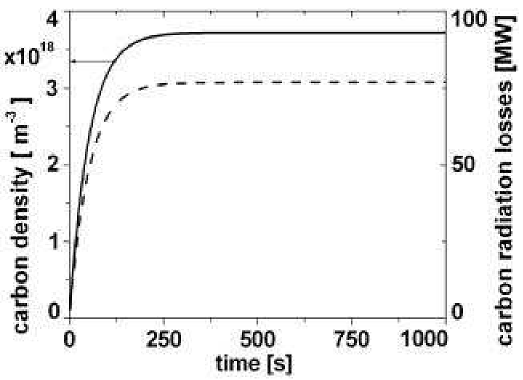

Fig. 4 Multi-ELM regime: $j_C = 3\times10^{17}$ m^{-2} and $f_{ELM} = 0.5$ Hz

Typical values of $S_d = 20$ m^2 and $T(X) = 4$ keV yield $N_{\mathrm{ELM}} = 10^{22}$ at $Q = 1$ MJ/m^2, and then $f_{\mathrm{ELM}} = 0.5$ Hz follows at $J_{nb} = 10^{22}$ s^{-1}. The whole particle number is $N_0 \approx 2\times10^{23}$, so that 5% of plasma is dumped at each ELM. Fig. 4 shows evolution of radiation losses and impurity density in the core for this regime. The radiation losses of 75 MW are of factor 2 less than the neutral beam power. The condition $Z_0 n_0 > 3Z_1 n_1$ at $x = 0$ is fulfilled, however at its margin. We concluded from these results that the maximal tolerable ELM size Q_t for $f_{\mathrm{ELM}} = 0.5$ Hz is about 1 MJ/m^2. Unfortunately, the dependence $j_C(Q)$ is not yet available therefore the dependence $Q_t(f_{\mathrm{ELM}})$ also. Several rather uncertain implications have been mentioned, for instance the plasma fraction dumped out in ELM burst. In future those parameters of ELMy H-mode are going to be clarified.

References: 1: Federici et al., Journ. Nucl. Mat. 313-316 (2003) 11. **2**: S. Pestchanyi B. Bazylev, I. Landman. "Radiation losses from ITER SOL due to divertor material plasma", http://130.246.71.128/pdf/P1_135.pdf: 31st EPS, London, June 2004, ECA V.**28G**, P-1.135. **3**: F.L. Hinton, R.D. Hazeltine, Rev. Mod. Phys. 48 (1976) 239. **4**: D.E. Post et al., Atomic Data and Nuclear Data Tables, 20 (1977) 397. **5**: J. Wesson, "Tokamaks", Clarendon Press (1997) 223.