Possible way of reducing heat and particle loads on divertor plates

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Abstract. The heat and the particle loads on the divertor plates from the plasma in the scrape-off layer (SOL) are studied in edge localized modes (ELM) with high frequency. For this purpose we have performed computer experiments with self-consistent simulation of the neutral particles in the SOL of tokamaks with deuterium plasma assuming different regimes (instant cold and permanent hot gass puffing).

1. Introduction

The goal of the present work is to study the application of PIC simulations for investigation of ELM discharges and to find ways for reducing the heat and the particle loads on the divertor plates.

Here we show results from 1D PIC simulations for various edge conditions and different time and space steps in a simplified tokamak geometry [1]. It has been assumed a diode-like geometry of the SOL with a cross-section $10^{-4}m$ and a length $0.054\,m$. The length of the simulated volume is 880 times less then the real length ($48\,m$ from the inner to the outer target of TCV reactor along the field line within $2\,-\,3mm$ from the separatrix). Plasma injection is supplied in the 'source' with a constant intensity 4×10^{25} computer particles $m^{-3}\,s^{-1}$ (each computer particle consists of 8×10^{8} electron-ion pairs). It adjusts the conditions of TCV experiments with frequent ELM discharges [2]. It has been assumed termalization ($T_e\,=\,T_i$) of the edge plasma in the large time scale of the stationary ELMs.

The following particle collisions are considered:

Coulomb scattering of electrons and D ions [3]

Elastic scattering of electrons and D ions from D atoms [4]

Excitation and effective ionisation of D atoms from electrons [5]

Charge exchange between D ions and atoms [4]

Absorption and electron recycling from target plates [3]

Radiative and collisional recombination [6]

2. Simulation Methods

We used Monte Carlo methods for simulation of particle collisions with collision rate distributions for plasma equilibrium in each grid cell during a short time step (of the order of $10^{-12}\,s$). The number of colliding particles is defined from the current characteristics of the plasma. The type of collision is chosen with Monte Carlo procedures using uniform normalization of all type of collision probabilities [5]. The results from the Monte Carlo procedures are analytically and statistically verified.

For the recombination of the charged particles two extreme cases are considered: radiative (two-body) recombination processes if the electron energy exceeds $0.68eV$; collisional (3-body) recombination if the electron energy is below $0.068eV$. For the remaining interval of energies a Monte Carlo procedure chooses between the 2- and the 3- body processes by splitting the total rate of recombination. This procedure uses the approximation functions for the total recombination rates shown on Fig.1. They are derived according to the predictions of the general theory [7] validated by the compiled experimental data [8]. In Fig.2 we compare the histogram from the number of simulated recombination processes in equal (log scale) temperature intervals for plasma density about $10^{18}\,m^{-3}$ with the corresponding approximation function.

All simulation experiments have been performed with the BIT1-S code [6]. BIT1-S is a new version of the BIT1 code which in turn is based on the XPDP1 code. The present variant of the BIT1-S code performs self-consistent simulation of the neutral component. As in the XPDP1 code only the external magnetic field is considered while the electric field is self-consistently simulated determining current change of particle velocity during a time step $\Delta\,t\,\frac{dV}{dt} = \frac{q}{m}(E + V \times B)$ (V scaled in $\frac{\Delta\,x}{\Delta\,t}$). The space $\Delta\,x$ and time $\Delta\,t$ steps in the grid calculations are chosen within the constrains of λ_D and cyclotron frequency defined for the conditions of a steady state plasma. They remain constants during the code run. Our goal is to check whether such choice of the time and space steps is adequate in the case of turbulent plasma as that in ELM operation scenarios.

3. Simulation Results

We have performed three computer experiments with self-consistent simulation of the neutral component assuming an instant and uniform injection of cold ($0.1\,eV$) deuterium atoms:

The first experiment is for: $B = 0$, time step $3.5\,10^{-12}\,s$, plasma 'source' temperature $80\,eV$. It results in steady state plasma (Figs. 3, 4)

The second experiment: $B = 2.4\,T$, time step $2.8\,10^{-12}\,s$, plasma 'source' temperature $80\,eV$ resulting in steady state plasma (Figs. 5, 6)

Third experiment: $B = 2.4\,T$, time step $3.5\,10^{-12}\,s$, plasma 'source' temperature $80\,eV$ resulting in ELMy plasma (Figs. 7, 8, 9, 10).

4. Discussion

The results from the statistical test (Fig. 2) with a steady state plasma confirm that the method of collision simulation and the Monte Carlo procedures are appropriate for SOL simulations.

The comparison of the results from the first and the second experiment (Figs. 3 and 5) shows that the magnetic field has a strong impact on the propagation of the charged particles diminishing the chance for recombination. Correspondingly the ratio between plasma and neutral densities increases in the magnetic field (Figs. 4, 6).

Repeating the simulation from the second experiment but with time step $3.5\,10^{-12}\,s$ in the third experiment ELM-like turbulence appears (Fig. 7). It can be treated as an effect of the uncertainty in the choice of the grid steps. In order to avoid unphysical results we have performed a simulation with the step $2.8\,10^{-12}s$ but increasing the pressure of plasma in the 'source' ($T_e = 100eV$). ELM turbulence mode is obtained with the same relaxation time $3\,\mu\,s$. It is in the order of the time ($5\,\mu\,s$) of ELM recover in a TCV experiment [2]. Qualitative agreement is also obtained for the plasma density and temperature in time intervals excluding plasma crash (Fig. 8). For short time interval of plasma crash too high electron temperature is reached (Fig.

9) which is not seen experimentally. The synchronization of plasma crash with the energy and plasma loads on the divertor target (Fig. 10) indicates to a 'blob'-like transport of plasma [6]. Similar results are obtained in our previous simulations [6]. A special hot gas puffing of D atoms was assumed maintaining time invariant density and temperature profiles of the neutral component. The time of ELM recover in this case was about 50% shorter than that in the present experiment with the instant injection (Fig. 7b). Also, the maintaining of constant neutral density leads to a smaller energy and particle loads on the divertor plates than those shown on Fig.10 for instant gas puffing.

One could conclude that permanent neutral gas puffing leads to more favorable regime for divertor loads. This conclusion should be verified with more precise grid simulations and corresponding assumptions for ELM scenarios in ITER operations. Complex validation of the simulation model and an appropriate study of the grid accuracy are needed to make realistic predictions for ITER.

References

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Figure Captions

FIG. 1: Approximation of the data for the recombination rate in dependence on electron temperature for fixed plasma density.

FIG. 2. Comparison of the histogram of simulated recombination processes with the experimental data from the input file (see Fig.1).

FIG. 3: Time variation of charged (e) *and neutral* (0) *particles in early period* ***(a)*** *and in steady state plasma* ***(b)*** *fromthe simulation with time step* $\Delta t = 3.5 \times 10^{-12} s$, $B = 0T$.

FIG. 4: Density ***(a)*** *and Temperature* ***(b)*** *profiles of charged* (e) *and neutral* (0) *particles in steady state plasma from the simulation with time step* $\Delta t = 3.5 \times 10^{-12} s$, $B = 0T$.

FIG. 5: Time variation of charged (e) *and neutral* (0) *particles in early period* ***(a)*** *and in steady state plasma* ***(b)*** *fromthe simulation with time step* $\Delta t = 2.8 \times 10^{-12} s$, $B = 2.4T$.

FIG. 6: Density ***(a)*** *and Temperature* ***(b)*** *profiles of electrons* (e) *and ions* (i) *in steady state plasma from the simulation with time step* $\Delta t = 2.8 \times 10^{-12} s$, $B = 2.4T$.

FIG. 7: Time variation of charged (e) *and neutral* (0) *particles in early period* ***(a)*** *and in ELMy plasma* ***(b)*** *from the simulation with time step* $\Delta t = 3.5 \times 10^{-12} s$, $B = 2.4T$.

FIG. 8: Density ***(a)*** *and Temperature* ***(b)*** *profiles of electrons* (e) *and ions* (i) *in ELMy plasma from the simulation with time step* $\Delta t = 3.5 \times 10^{-12} s$, $B = 2.4T$ *at* $20.30 \mu s$ *(real time).*

*FIG. 9: Density **(a)** and Temperature **(b)** profiles of electrons* (e) *and ions* (i) *in ELMy plasma from the simulation with time step* $\Delta t = 3.5 \times 10^{-12} s$*,* $B = 2.4T$ *at* $21.00 \mu s$ *(real time).*

FIG. 10: Time variation of the stored energy (up) and plasma flux (down) for the simulation of ELMy plasma with time step $\Delta t = 3.5 \times 10^{-12} s$*,* $B = 2.4T$*.*

Figures

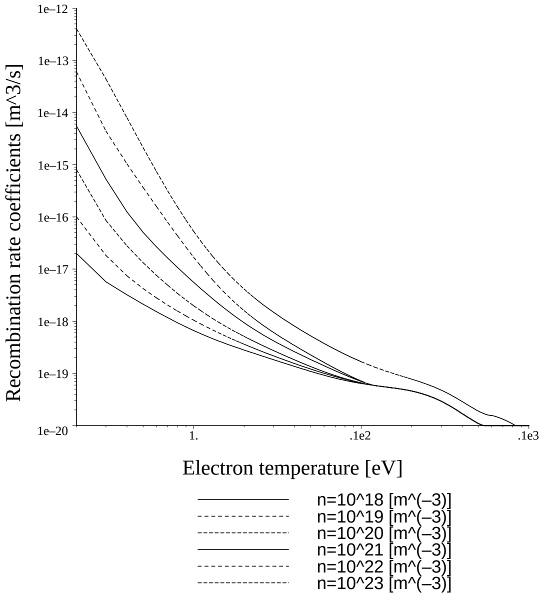


FIG. 1.

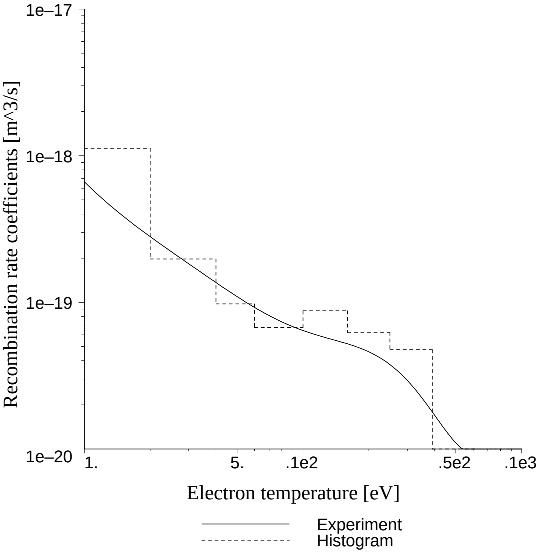


FIG. 2.

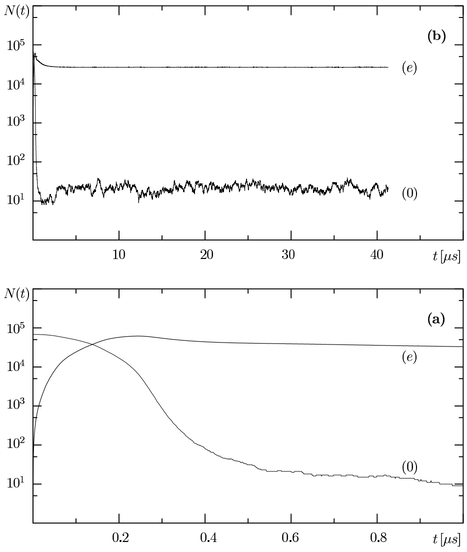
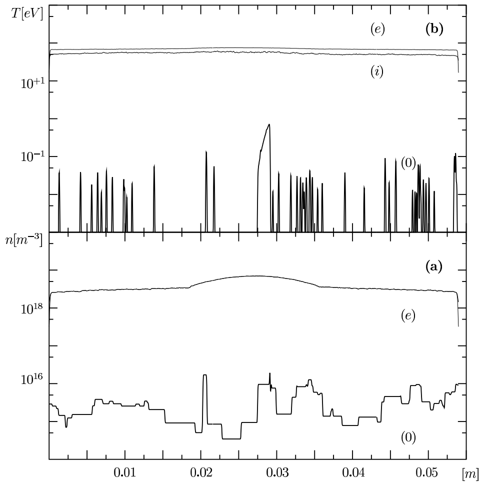


FIG. 3.



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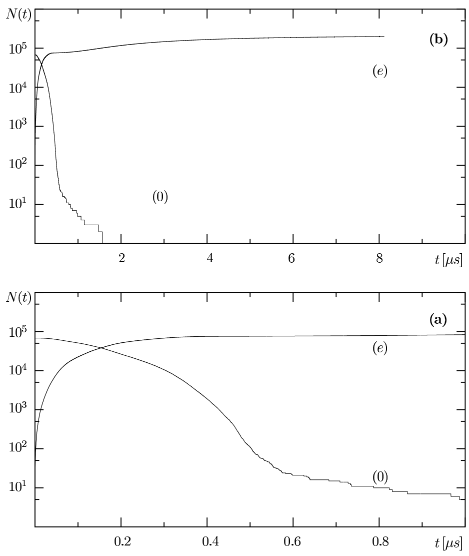

FIG. 5.

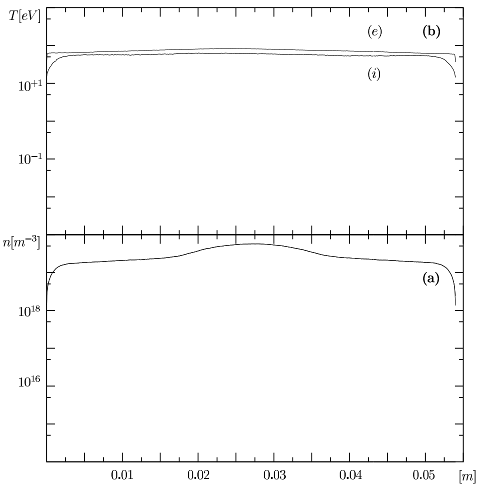

FIG. 6.

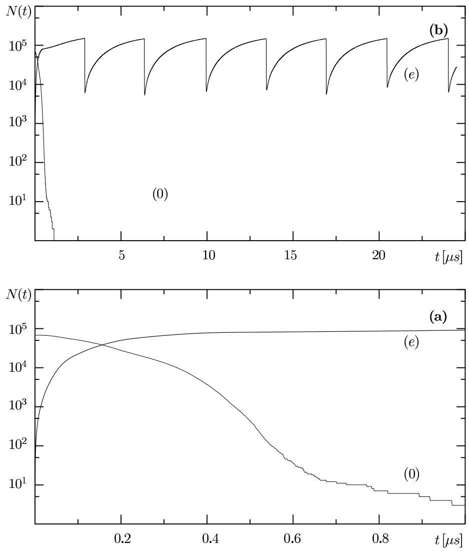

FIG. 7.

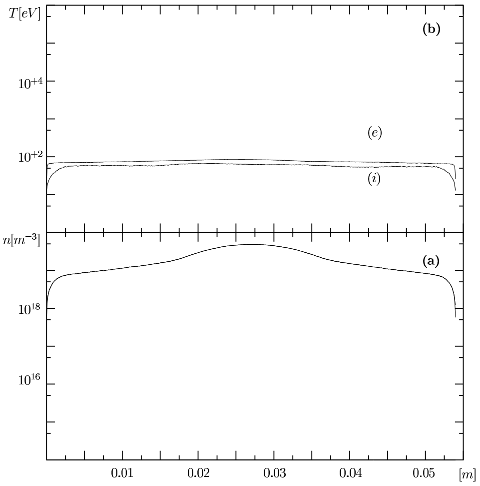

FIG. 8.

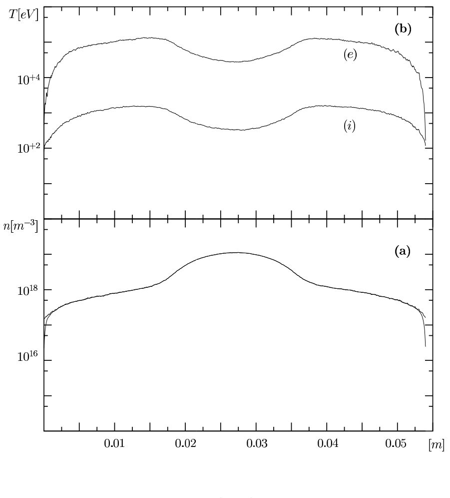

FIG. 9.

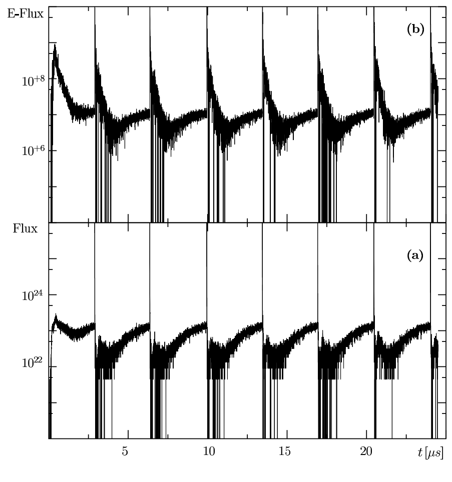

FIG. 10.