PIC simulations of ELM particle and heat loads to the JET divertor targets

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1. Introduction. It is widely recognized that the type-I Edge Localized Modes (ELMs) represent a serious potential threat for the next generation tokamak, ITER [1, 2]. During the ELM, high temperature plasma penetrates across the separatrix from the pedestal region into the Scrape-of Layer (SOL). In the SOL it propagates along the field lines depositing a large fraction of its energy at the divertor target plates [3, 4]. This energy load can significantly increase erosion, or directly damage the target material, reducing lifetime below acceptable levels. Development of realistic ELMy SOL models has therefore become an important and challenging task requiring kinetic treatment since normalized collisionalities are typically smaller than unity for the type-I ELMs. Due to the complex nature of the SOL, quantitative descriptions are possible only via numerical modeling, except in the simplest cases. At present only 1D3V (1D in space and 3D in velocity) kinetic codes are available for ELMy SOL modeling [5], so that corresponding simulations are restricted to a description of parallel transport in the SOL. This approach is sufficient to study some of the critically important parameters directly related to the target erosion: the peak heat flux, $q_{div.peak}$ and the integral energy deposited on the target in the time interval up to this maximum heat flux, $W_{IR} = \int_0^{\tau_{peak}} q_{div}(t)dt$ [2]. To a first approximation, these two parameters determine the maximum surface temperature reached at the surface (see [6]). If this temperature does not exceed the melting, or ablation threshold, gross erosion will be limited. Using these simulations it is also possible to construct fit functions describing $q_{div.\mathrm{peak}}$(t). These can be used for estimation of energy loads to the ITER divertor targets.

This contribution will report on new simulations of type-I ELM parallel transport in the JET

[*] See the Appendix of M. L.Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA, (2006).

SOL performed using the 1D3v Particle-in-cell (PIC) kinetic code BIT1 [7]. The code self-consistently simulates 1D plasma flow in the SOL, resolving the plasma sheath, including inclined target plates and with higher spatial resolution, than existing models (see [5, 8 and 9]), permitting more realistic simulation of SOL transport.

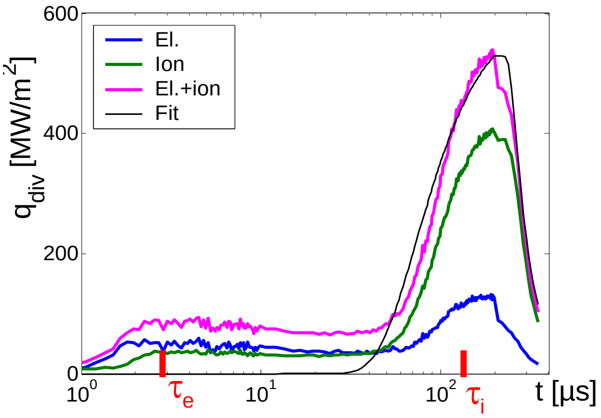

Figure 1. Power loads to the divertor plate during a Type-I ELM with W_{ELM}= 0.4 MJ.

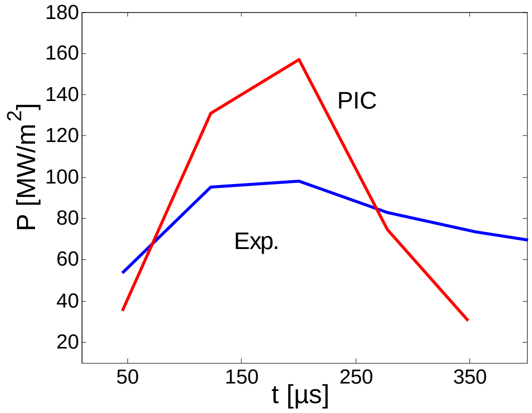

Figure 2. Power flux to the outer divertor from IR measurements (shot 62221) and from PIC simulations averaged over ~50 μs. W_{ELM} ~ 0.45 MJ.

2. Description of the PIC model. The geometry of the simulation corresponds to a 1D magnetic flux tube bounded by the divertor plates. The magnetic field is assumed constant. Over a small region, $L_{pol} = 2.6$ m, in the middle of the tube a plasma source mimicking transport across the separarix is imposed. Plasma parameters correspond to ELMy H-mode discharges at JET. The simulations are done in three steps: the pre-ELM SOL is first established, followed by the ELMy SOL which is simulated by increasing the temperature and strength of the particle source. The ELMy SOL is followed by after-ELM SOL. In order to save computational time, the same pre-ELM SOL is used in all simulations.

A number of ELM simulations have been performed covering a wide range of pedestal parameters: T_{ped} = 0.5, 1.5, 2.5 and 5 keV and n_{ped} =1.5x10^{19}, 5x10^{19} and 1.5x10^{20} m^{-3}. The duration of the ELM pulse is usually fixed at $\tau_{ELM} = 200$ μs. This parameter range covers the following ELM energy and pedestal collisionalities: $W_{ELM} = 0.025 \div 2.5$ MJ and $\nu*_{ped} \approx 2L_{\|}/\lambda = 0.02 \div 2.2$, respectively. Here, $L_{\|} = 40$ m and λ are the connection length and mean free path. The 2.5 MJ is somewhat too high for JET, but corresponds to small size type-I ELM at the ITER. The ELM energy is calculated according to $W_{ELM} = 3SVn_{ped}T_{ped}$, where S and $V = 2\pi R\delta RL_{pol}$ ($R = 3$ m and $\delta R = 10$ cm) are the strength of the plasma source and volume in the SOL, where the ELM deposits its energy after crossing the separatrix. The plasma source has a cosine profile. Motion of plasma particles is fully resolved in time and space. Divertor plates represent absorbing walls, i.e. no plasma recycling has been included in the model. The number of cells in the poloidal direction and simulated particles are $6x10^3$ and up to $5x10^6$, respectively. Further details can be found in [5, 10].

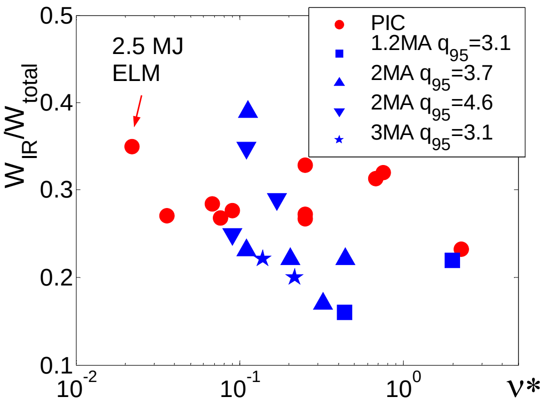

Figure 3. Collisionality dependence of the integral energy to peak for experiment and PIC simulations.

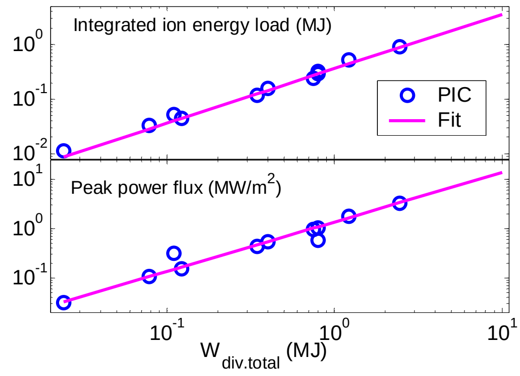

Figure 4. Ion energy and peak power loads to the divertor plates. Solid lines correspond to the scaling described in the text.

3. Discussion of results. An example of the code output for the time variation of the power load to the divertor plates is given in Fig. 1. Two important features can be seen immediately from these plots: (i) there are two peaks corresponding to the electron ($\tau_e = L_{\|} / V_{Te}$) and ion ($\tau_i = L_{\|} / C_s$) timescales, and (ii) most of electron energy (> 95%) is deposited on the ion timescale. Here, $V_{Te} = \sqrt{T_{ped} / m_e}$ and $C_s = \sqrt{2T_{ped} / M_i}$ are respectively the electron thermal velocity and ion sound speed. There are two mechanisms responsible for this showed feature: charge separation forces and the plasma sheath at the divertor target. When the ELM burst penetrates into the SOL it consists of hot electrons and ions having practically the same temperature. Due to their low mass the fastest electrons promptly leave the ELM burst. This results in a negative charge deficit in the leading front of this burst preventing further escape of electrons and forcing the bulk of the electron population to propagate on the ion timescale. The loss of prompt fast electrons from the ELM burst has a further consequence: the potential drop across the target sheath increases as these electrons are absorbed, limiting any further increase of the electron power load until the main ELM burst arrives. This increased potential drop in turn accelerates the thermal ions in front of the plates, resulting in is a small peaking of the ion power load on the electron timescale.

Fig. 2 compares the time variation of power loads from the PIC and experimental measurement, indicating reasonable quantitative agreement. For this comparison we have (i) subtracted 50% from PIC results, which corresponds to the energy losses to the outer wall observed for this particular shot, and (ii) take into account the experimentally observed radial profile of the power loads to the target. The normalized integral energy to plates plotted in Fig. 3, provides a more robust comparison with the experiment, since it involves only a ratio of energies and not an explicit time dependent power. An important conclusion to be drawn from Fig. 3 is the finding that $W_{IR} < 0.4 W_{div.total}$ for a wide range of pedestal collisionalities. In Fig. 4 are plotted the ion energy and the peaking value of the total power as a function of total energy load at the divertor plates, indicating two important scaling laws: (i) The ions curry ~70% of the total energy deposited to the target, and (ii) the peaking value of the power load scales linearly with the total energy deposited at the target $q_{div.peak} \approx 2.5 W_{div.total} / S_{div}$, where S_{div} is the wetted area of the divertor. From the experiment it is known that $W_{div.total} = \alpha W_{ELM}$, $\alpha \sim 0.5 \div 1$ [3]. Hence, $q_{div.peak}$ is independent of particular values on τ_{ELM}, n_{ped}, T_{ped} and depends only on their linear combination $\tau_{ELM} n_{ped} T_{ped} \sim W_{ELM}$.

In conclusion we present an analytic expression for the power load to the divertor plates during the Type-I ELM, fitting PIC results with a high accuracy (see Fig. 1):

$$q_{div}(t) \approx 2.5\alpha \frac{W_{ELM}}{S_{div}} \left\{ H(t < \tau_{ELM}) \exp\left(-\frac{\tau_i^2}{2t^2}\right) + H(t \geq \tau_{ELM}) \left[1 - \exp\left(-\frac{\tau_i^2}{2t^2}\right)\right] \right\} \quad (1)$$

For derivation if this expression we use the analytic approach developed in [11] for propagation of initially Maxwellian wave package.

Acknowledgments. This work is carried out under the European Fusion Development Agreement and supported by the European Communities. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The first author acknowledges support by the projects P19235-N16 and GNSF-69/07.

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