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Effects of fast electrons on the potential of a divertor plate

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Lower-Hybrid Grill (LHG) devices are used in tokamaks for plasma heating and noninductive current drive (CD). A secondary effect of LHGs is the appearance of very energetic, fast electrons, which can move to the divertor plate and dramatically change the plasma parameters there. These fast electrons, which acquire their energy in a narrow layer in front of an LHG, can cause damage to the divertor, the first wall, and the LHG components [1]. Our simulations, which are performed with the 2d3v (two spatial and three velocity dimensions) particle-in-cell (PIC) code XPDP2 [2] with some modifications, are aimed at investigating the effects of these energetic electrons on the potential distribution and the energy dissipation at the divertor plate. For the plasma density and temperature, the magnetostatic field, and other parameters we have chosen values relevant to contemporary LHCD experiments performed at the Tore Supra tokamak [3].

The effect of energetic electrons on the plasma sheath was analytically investigated in [4, 5], where a plasma with two-temperature electrons was considered. In the present work, we also consider a plasma exhibiting two electron fractions with different temperatures, but the minority fraction has a sufficiently large shift velocity relevant to the LHCD experiments.

We simulate a collisionless divertor plasma sheath, neglecting the secondary-electron emission from the wall. The simulation area is perpendicular to the divertor plate and parallel to the toroidal (y) direction (Fig. 1). We neglect the z component of the magnetic field, so that the magnetic field lies within the simulation area. The angle between the magnetic field and the divertor plate is $\psi = 14^0$. Since the fast electrons are created in a very thin layer of radial width $\Delta r = 1 \div 5$ mm, we can estimate the toroidal width of the fast-electon beam at the divertor plate as $\Delta y = \Delta r / \sin\psi \approx 2$ cm.

In our simulation, we consider a subregion of toroidal width $L_y = 8$ mm located in the center of the region hit by the fast-electron beam. Within this subregion, we may assume conditions that are homogeneous in the toroidal direction, i.e., independent of y. This situation is effectively realized in our simulation by choosing homogeneity at the injection or entrance plane ($x = L_x$) and periodicity with respect to the boundaries $y = 0$ and $y = L_y$, which means that all physical quantities have the same values at these boundaries and that a particle crossing one of them will appear at the other end with the same velocity.

According to the problem considered, we assume two types of electrons: Slow electrons with a half maxwellian distribution, fast electrons with a shifted (along the magnetic field) maxwellian distribution, and ions with a shifted (along the magnetic field) maxwellian distribution are injected into the empty system. The plasma particles are injected at the $x = L_x$ (injection or entrance) plane, whereas the divertor plate plane ($x = 0$) is assumed to be perfectly absorbing.

Before discussing the simulations, let us calculate theoretically the potential drop to be expected. At the sheath entrance, the plasma is quasineutral ($n_e^0 = n_{e1}^0 + n_{e2}^0 \approx n_i^0$) and in the stationary state we assume that there is no net current in the normal (to the divertor

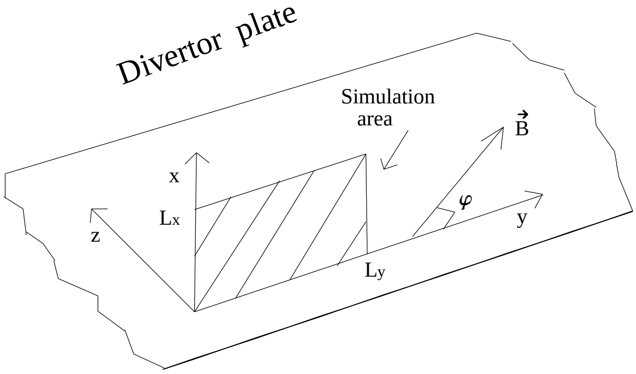

Figure 1: *Simulation region.*

plate) direction, so that the electron and ion fluxes are equal: $F_{ex} = F_{ix}$. Here, n^0_{e1} and n^0_{e2} are the slow- and fast-electron densities, respectively, at the sheath entrance.

We assume that at the sheath entrance the average velocity of each particle is directed along the magnetic field ("perfectly magnetized" plasma). The ions move towards the divertor plate, whereas the electrons, due to the reflection by the negative potential drop across the sheath, move in both directions. Thus, at the sheath entrance the distributions of the particles are cut-off maxwellians:

$$\begin{aligned} f^0_i(v_\parallel, v_\perp) &= 2n^0_i v_\perp \left(v^3_{iT}\pi^{3/2}(1+\mathrm{erf}(v_{i\parallel}/v_{iT}))\right)^{-1} \exp\left(-\left(\left(v^2_\parallel + v_{i\parallel}\right)^2 + v^2_\perp\right)/v^2_{iT}\right)\Theta(-v), \quad (1) \\ f^0_{e1}(v_\parallel, v_\perp) &= 2n^0_{e1} v_\perp \left(v^3_{e1T}\pi^{3/2}(1+\mathrm{erf}(v_c/v_{e1T}))\right)^{-1} \exp\left(-\left(v^2_\parallel + v^2_\perp\right)/v^2_{e1T}\right)\Theta(v_c - v), \\ f^0_{e2}(v_\parallel, v_\perp) &= 2n^0_{e2} v_\perp \left(v^3_{e2T}\pi^{3/2}(1+2\,\mathrm{erf}(v_{e\parallel}/v_{e2T}) + \mathrm{erf}((v_c - v_{e\parallel})/v_{e2T})\right)^{-1} (\exp(-((v_\parallel + v_{e\parallel})^2 + \\ &\quad + v^2_\perp)/v^2_{e2T})\Theta(-v) + \exp(-((v_\parallel - v_{e\parallel})^2 + v^2_\perp)/v^2_{e2T})\Theta(v)\Theta(v_c - v)), \end{aligned}$$

where subscripts i, $e1$ and $e2$ denote the ions, the slow electrons and the fast electrons, respectively, $v_\parallel$ and $v_\perp$ are the particle parallel and perpendicular (to the magnetic field) velocities, $v_{sT} = \sqrt{2T_s/m_s}$ ($s = i, e1, e2$) are the corresponding thermal velocities, $-v_{i\parallel}$ and $-v_{e\parallel}$ are the ion and fast-electron shift velocities, $v_c = \sqrt{2e\,|\Delta\Phi|\,/m_e}$ is the velocity of an electron reflected at the divertor plate with $v = 0_+$, $\Delta\Phi = \Phi(x=0) - \Phi(x=L_x) < 0$ is the total potential drop across the sheath, and $\Theta(v)$ is the step function. Substituting the distribution functions from (1) into the expression for the particle normal fluxes,

$$F_{sx} = 2\pi sin\psi \int_{-\infty}^{+\infty} dv_\parallel \int_0^\infty v_\perp dv_\perp v_\parallel f^0_s(v_\parallel, v_\perp)\ ,\ s = i,\ e,$$

and equating them, we obtain the following equation:

$$\begin{aligned} n^0_i v_{i\parallel} &= n^0_{e1} v_{e1T}\left(2\sqrt{\pi}\right)^{-1} \exp\left(-v^2_c/v^2_{e1T}\right) + n^0_{e2}\left(1 + 2\,\mathrm{erf}(v_{e\parallel}/v_{e2T}) + \mathrm{erf}((v_c - v_{e\parallel})/v_{e2T})\right)^{-1} \times \\ &\quad \left(\frac{1}{\sqrt{\pi}} v_{e2T}\exp(-(v_c - v_{e\parallel})^2/v^2_{e2T}) + v_{e\parallel}(1 - \mathrm{erf}((v_c - v_{e\parallel})/v_{e2T}))\right). \quad (2) \end{aligned}$$

Here we have used the following inequalities [6]: $v_{i\parallel} > v_{iT}$ (this follows from the Bohm-Chodura condition) and $v_c \geq v_c(n^0_{e2} = 0) \approx v_{e1T}\sqrt{\ln(m_i/m_e 2\sqrt{\pi})} > 1.5 v_{e1T}$. In Fig. 2 is plotted the potential drop as a function of the normalized fast-electron density $\zeta = n^0_{e2} v_{e\parallel}/n^0_i v_{i\parallel}$. We see that for realistic plasma parameters even a small fraction of fast electrons can significantly change the potential drop across the sheath.

Let us now discass the simulations. At $t = 0$ we start injecting particles into the empty system, with the injection parameters adjusted so as to ensure quasineutrality at the

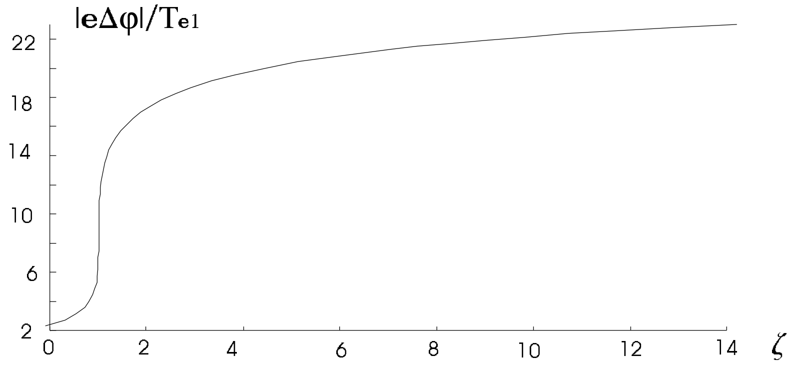

Figure 2: *Potential drop versus normalized fast-electron density,* $\zeta = n^0_{e2}v_{e\parallel}/n^0_i v_{i\parallel}$; $v_{e\parallel} = 7.45 v_{e2T}$, $T_{e1} = 3T_{e2} = 2T_i$.

entrance plane. The system reaches its stationary state after a few ion transit times. The input data and plasma parameters are chosen as follows: $m_i/m_e = 1836$, $n^0_i = 10^{18} m^{-3}$, $T_i = 15\ eV$, $T_{e1} = 30\ eV$, $T_{e2} = 10\ eV$, $v_{i\parallel} = 8.5 \times 10^4\ m/s$, $v_{e\parallel} = 1,4 \times 10^7\ m/s$, the magnetic field strength $B = 3\ T$, (electron cyclotron frequency)/(plasma frequency)= 9.4, system width $L_x = 1\ mm\ = 25\lambda_D$, toroidal system length $L_y = 8\ mm\ = 200\lambda_D$, number of grid cells in the x direction = 50, Number of grid cells in the y direction = 256.

Three different runs are performed.

The first run is performed to obtain basic plasma characteristics (potential drop, particle densities) at the divertor plate in the absence of fast electrons, and to check the numerical code. The potential drop from the system entrance to the divertor plate is found to be $\Delta\Phi = -75\ V$ ($e\Delta\Phi/T_e = -2,5$). This result agrees with the theory and simulation results of other authors (see [6]).

In the second run, a "large" fraction of fast electrons is injected into the system: $n^0_{e2}/n^0_i\ = 0.05$. The potential drop is one order larger than in the previous case, $\Delta\Phi = -630\ V$ ($e\Delta\Phi/T_{e1} = -21$), and agrees (with an accuracy of 3.5%) with the result $\Delta\Phi \approx -653\ V$ obtained theoretically from Eq. (2) at $\zeta \approx 8.24$. All electrons from the slow fraction are reflected halfway to the divertor plate.

In the third run, a small fraction of fast electrons is injected into the system: $n^0_{e2}/n^0_i\ = 0.006$. Also in this case, the potential drop is much larger than in the first case, $\Delta\Phi = -185\ V$ ($e\Delta\Phi/T_{e1} = -6.2$), and agrees (with an accuracy of 1.6%) with the result $\Delta\Phi \approx -188\ V$ obtained from Eq. (2) when $\zeta \approx 0.99$.

We may thus state that the analytical and simulation results are in a good egreement.

The energy dissipated at the divertor plate is significantly enhanced by the presence of the fast electrons originating from the grill. In this case the potential drop across the divertor sheath is much larger than in the absence of fast electrons, so that in traversing the sheath the ions acquire much higher kinetic energy, which is ultimately deposited at the plate and additionally increases the energy dissipation at the divertor plate.

The power W_d deposited at the divertor plate is equal to the x component of the plasma energy flux at the sheath entrance [6]:

$$W_d = 2\pi \sin\psi \sum \frac{m_s}{2} \int_{-\infty}^{+\infty} dv_\parallel \int_0^\infty v_\perp dv_\perp v_\parallel \left(v_\parallel^2 + v_\perp^2\right) f^0_s\left(v_\parallel, v_\perp\right), \quad s = i, e1, e2; \qquad (3)$$

Substituing the distribution functions from (1) in Eq. (3) we find after simple but lengthy calculations:

$$\begin{aligned} W_d &= \sin\psi(v_{i\parallel} n_i^0 (m_i v_{i\parallel}{}^2/2 + 5T_i/2) + \frac{n_{e1}^0 v_{e1T}}{2\sqrt{\pi}} \exp\left(-e\left|\Delta\Phi\right|/T_{e1}\right)(2T_{e1} + e\left|\Delta\Phi\right|) + \\ & n_{e2}^0(1 + 2\,\mathrm{erf}\,(v_{e\parallel}/v_{e2T}) + \mathrm{erf}(\sqrt{e\left|\Delta\Phi\right|/T_{e2}} - v_{e\parallel}/v_{e2T}))^{-1}(v_{e\parallel}(T_{e2}(5/2 - \frac{3}{2}\,\mathrm{erf}(v_{e\parallel}/v_{e2T}) - \\ & -4\,\mathrm{erf}(\sqrt{e\left|\Delta\Phi\right|/T_{e2}} - v_{e\parallel}/v_{e2T})) + \frac{1}{2} m_e v_{e\parallel}^2 (1 - \mathrm{erf}(\sqrt{e\left|\Delta\Phi\right|/T_{e2}} - v_{e\parallel}/v_{e2T}))) - \qquad (4) \\ & -\frac{v_{e2T}}{\sqrt{\pi}}(2T_{e2} + m_e v_{e\parallel}^2/2 + e\left|\Delta\Phi\right| + \sqrt{e\left|\Delta\Phi\right| m_e v_{e\parallel}^2/2})\exp(-(\sqrt{e\left|\Delta\Phi\right|/T_{e2}} - v_{e\parallel}/v_{e2T})^2))). \end{aligned}$$

From this equation we obtain for run 1 (without fast electrons) $W_d \approx 0.7$ MW/m^2, for run 2 ("large" fraction of fast electrons) $W_d \approx 5.0$ MW/m^2, and for run 3 (small fraction of fast electrons) $W_d \approx 2.0$ MW/m^2. These results indicate strong enhancement of the energy dissipation due to the presence of even a very low-density electron beam.

The main result of our simulation is in the following: Even a very small fraction (0.6%) of fast electrons can cause a significant rise of the potential drop across the sheath and of the energy flux to the divertor plate. For the plasma parameters relevant to the Tore Supra Tokamak in the case $n_{e2}^0/n_i^0 = 0.006$, these values increase by factors of 2.5 and 3, respectively. If the fast-electron fraction is "sufficiently" large (5% in our case), the potential drop at the divertor plate is one order larger than without energetic electrons. Due to this potential barrier, all electrons of the slow fraction are reflected and cannot reach the divertor plate. This increased potential drop enhances the energy deposition at the divertor plate by a factor of 7 (in the case $n_{e2}^0/n_i^0 = 0.05$). Of course, we are talking about the local energy deposition in the region where the fast electrons are hitting the divertor plate.

The good agreement of the simulation and analytical results show that Eq. (2) is accurate and can be used for calculation of the potential drop across the sheath in the presence of an energetic electron beam, assuming that the net current to the target is zero.

Finaly, it should be noted that our model is a simplified one and does not account for the following effects:
a) Secondary-electron emission of electrons from the divertor plate;
b) Local net current to the plate. In the region of fast-electron incidence, a nonzero current can flow out of the plate and a current with the same magnitude, but directed into the plate can flow outside this region, so that the total curent to the plate will be zero.

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