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# Simulation of Particle Acceleration in Front of a Lower-Hybrid Grill

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## 1 Description of the model

Lower-hybrid (LH) heating and non-inductive current drive are widely used in various tokamaks. A secondary, undesired effect of these operations is the parasitic absorption of LH wave energy by charged particles in the "resonant" layer (which is located just in front of the LH grill mouth). The accelerated particles from the resonant region can reach the divertor, the first wall, and the LH grill components, where they can cause serious damage [1]. In addition, this effect reduces the LH-plasma coupling efficiency. Hence, the investigation and modelling of these parasitic energy absorption processes is an important issue.

Previously it was assumed that these highly energetic particles damaging tokamak components are electrons, but in our previous work [2] we have shown that ions can be accelerated as well and might even be the main source of damage. This conclusion based on the results of simplified one-dimensional particle-in-cell (PIC) simulations.

In the present work we consider particle acceleration in front of the LH gill, using a more realistic two-dimensional model. For this purpose we adapted the 2d3v PIC code XPDP2 from Berkeley to our model [3]. Two different cases have been simulated, corresponding to the CASTOR and Tore Supra tokamaks.

The large size of the plasma region under consideration (more than $10^3$ Debye lengths in the toroidal direction), together with the requirement of long runs (more than $4 \times 10^5$ time steps), does not allow us to simulate real-size systems. Hence, we have simulated systems that are 4 (for CASTOR) and 16 (for Tore Supra) times shorter. In order to have a correct analogy with the real-size systems, we increased the magnetic field and the sources modelling diffusion by the same factors.

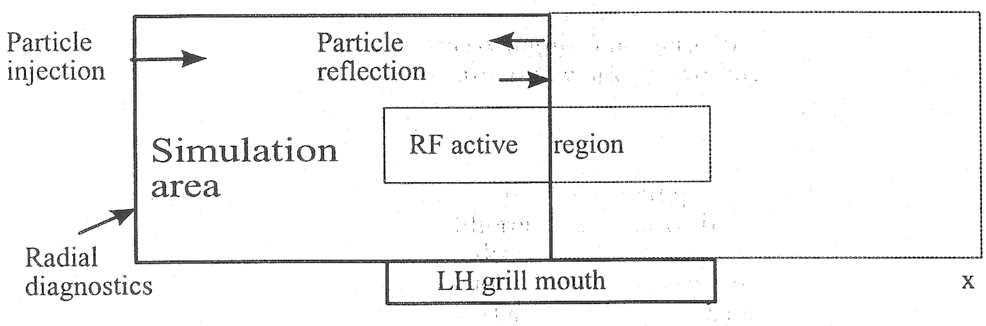


Fig.1 *Simulation geometry*

We consider a two-dimensional plasma slab in front of the LH grill mouth (Fig.1). In our model, the $x$ and $y$ axes correspond to the toroidal and radial directions, respectively. In the radial direction the model is fully periodic: all plasma parameters are equal at the inner ( $y = 0$) and outer ($y = L_y$) boundaries, and particles crossing the inner or the outer boundary are reinjected from the other boundary with the same velocity. In the toroidal direction the model is more complicated. Theoretically we consider the radio-frequency-active (resonant) region, with the toroidal width $2 \times l_{rf.x}$, plus some region with unperturbed plasma, the total width of the system being $2 \times L_x$. However, due to the given symmetry we actually simulate only one half of the system, $x \in [0, L_x]$. An obvious boundary condition for the toroidal electric field is $E_x(x = L_x) = 0$. For the particles we have the following boundary conditions: at $x = L_x$ all particles are reflected, and all particles crossing $x = 0$ are removed. To account for the quasineutral surrounding plasma, we inject Maxwell-distributed particles from the boundary $x = 0$. The electron–wave interaction is modelled by a "ponderomotive" force which acts only on the electrons [2],

$$F_{pond} = -e\partial_x U(x,y)\ , \quad U(x,y) = \frac{U_0}{2}\left(1 + \cos\left(\pi\left(L_x - x\right)/l_{rf.x}\right)\right)\exp\left(-\left|L_y/2 - y\right|/l_{rf.y}\right),$$

where $2l_{rf.y}$ is the radial width of the rf-active region. By contrast with the more realistic LH wave-plasma coupling (PIC) simulations, in which only a very short time scale (a few LH wave periods) is being resolved [4], [5], our simplified model of the electron-wave interaction allows us to investigate long-time-scale processes such as ion acceleration.

Initially the system is filled with Maxwell-distributed ions and electrons. Due to the ponderomotive force, first electrons and then ions will be pulled out of the rf-active region and the density in this region decreases. The ensuing density gradient should cause strong radial diffusion into the rf-active region, which is modelled by an ambipolar particle source

$$S(x,y) = N_0 \exp\left(\left(x - L_x\right)/l_{rf.x}\right)\exp\left(-\left|L_y/2 - y\right|/l_{rf.y}\right)\ .$$

We run the simulations up to the stationary state. The simulation parameters are as follows:

Case I: CASTOR.

Plasma density $n_0 = 3 \times 10^{17} m^{-3}$, magnetic field strength $B = 3.2T$, temperatures $T_e = 3T_i = 15\ eV$, toroidal and radial dimensions of the simulaiton region $L_x = 1.2\ cm$, $L_y = 0.6\ cm$, size of the rf-active region $2l_{rf.x} = 12\ mm$, $2l_{rf.y} = 0.5\ mm$ (this value corresponds to the experimentally observed radial width of $2\ mm$), number of grids cells $N_x = 256$, $N_y = 128$, amplitude of the ponderomotive potential $U_0 = 200\ V$ [6]. The ambipolar particle source in the rf-active region corresponds to $D = 12\ m^2/s$.

Case II: Tore Supra.

Plasma density $n_0 = 10^{18}\ m^{-3}$, magnetic field strength $B = 48T$, temperatures $T_e = 2T_i = 30\ eV$, toroidal and radial dimensions of the simulation region $L_x = 2\ cm$, $L_y = 0.25\ cm$, size of the rf-active region $2l_{rf.x} = 2\ cm$, $2l_{rf.y} = 0.4\ mm$, number of grids cells $N_x = 512$, $N_y = 64$, amplitude of the ponderomotive potential $U_0 = 1\ kV$. The ambipolar particle source in the rf-active region corresponds to $D = 8\ m^2/s$.

## 2 Simulation results

In both cases we observed accelerated ions as well as electrons. While the electrons are accelerated by the ponderomotive force, the ions are by the electrostatic electric field arising due to the charge separation. In Figs. 2 and 3 are given the radial profiles of the average energy and of the flux of the particles crossing the simulation region (propagating into the plasma). In the region magnetically connected to the rf-active region, the average particle energy for CASTOR is seen to exceed 1.3 times (for electrons) and 3 times (for ions) the thermal value ($2T$). For Tore Supra the corresponding factors are 1.5 (for electrons) and 2 (for ions). Using the average energy and the flux profiles we obtain the particle energy flux from the rf-active region: The CASTOR simulations yield $0.34\ MW/m^2$ for electrons and $0.05\ MW/m^2$ for ions, whereas in the case of Tore Supra these values are $6.6\ MW/m^2$ for electrons and $0.37\ MW/m^2$ for ions. For CASTOR this energy flux is not sufficient to cause any damage of the wall components (this agrees with the experiment). By contrast, for Tore Supra it is sufficiently high.

The radial width of the high-energy electron beam equals the radial width of the rf-active region, while the ion beam is broader by factors of 4 and 1.5 for CASTOR and Tore Supra, respectively. This effect can probably explain the disagreement in the probe and energy-analyzer measurements of the radial width of the energetic particle beams performed in Tore Supra: the probe and the energy analyzer measure the electron-beam and ion-beam widths, respectively.

The energy distributions of the particle fluxes out of the region connected magnetically with the rf-active region are given in Figs. 2e,f and 3e,f. The high-energy tail corresponds to the accelerated particles. The ion distributions exhibit an additional peak at 28 $eV$ for CASTOR, and at 50 $eV$ for Tore Supra.

Let us finally note that the strong radial electric fields observed in the rf-active region, $2 \times 10^4$ $V/m$ for CASTOR, and $7 \times 10^3$ $V/m$ for Tore Supra, can cause poloidal rotation of the plasma.

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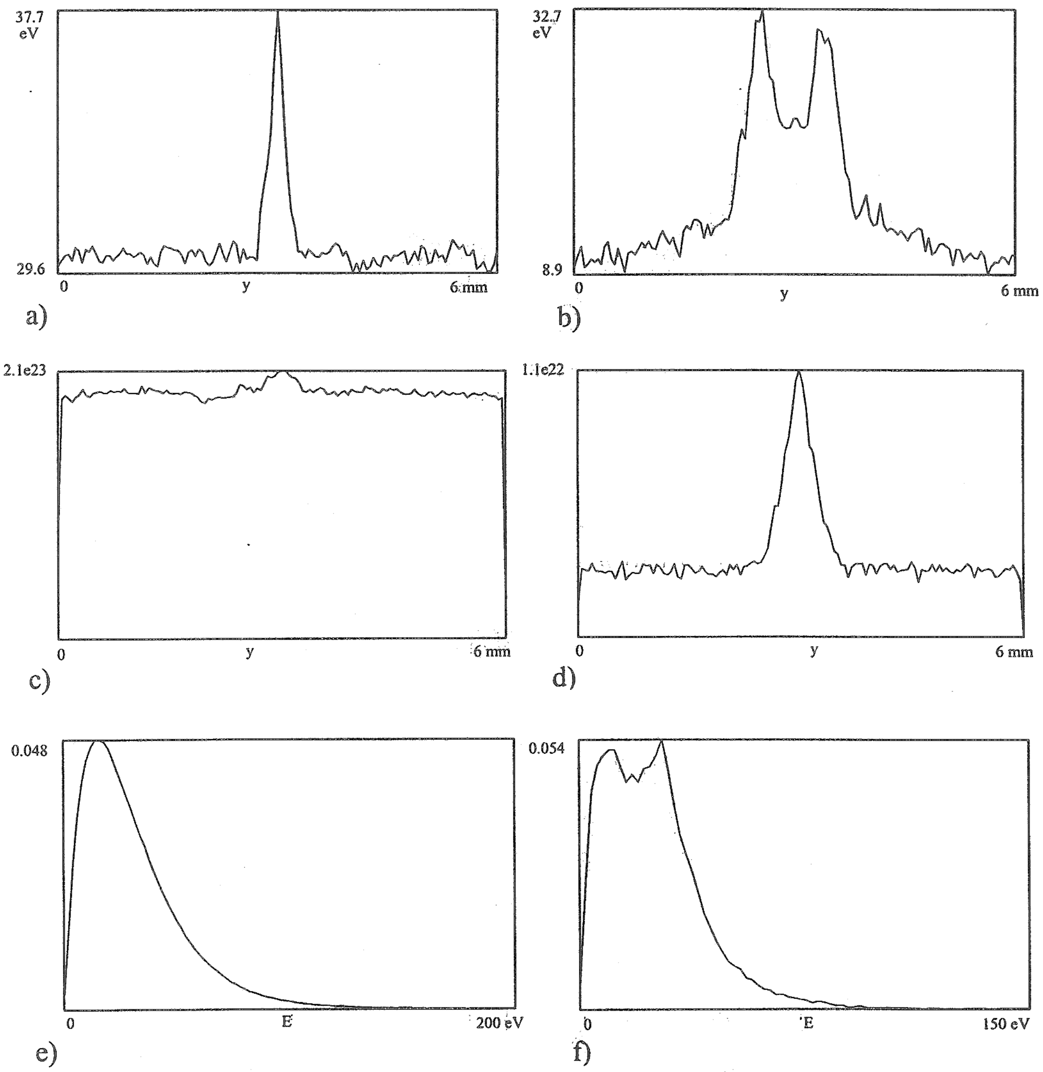


Fig.2 *Simulation results for CASTOR: Radial profiles of the electron (a) and ion (b) average energies. Radial profiles of the electron (c) and ion (d) outfluxes. Energy distributions of the electron (e) and ion (d) outfluxes from the rf-active region.*

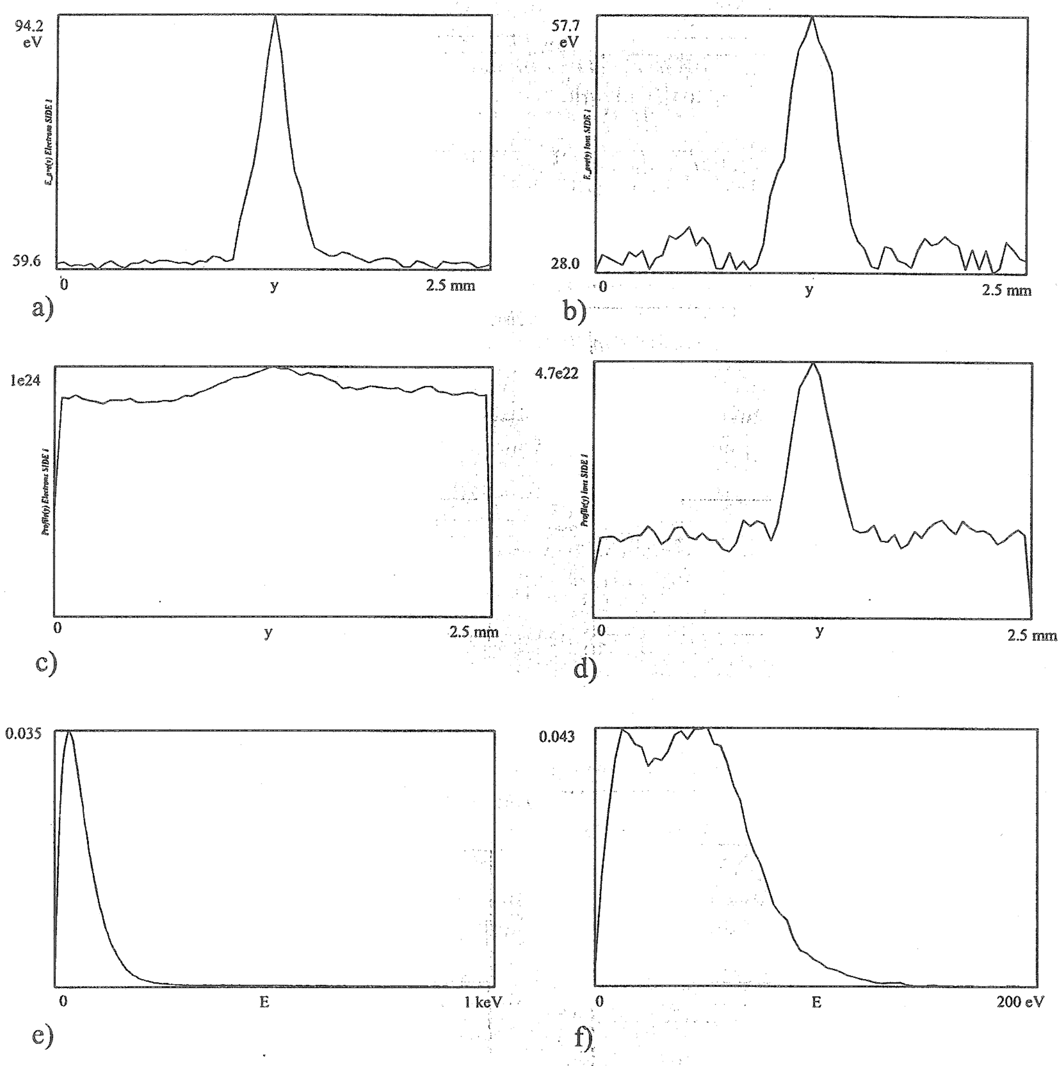


Fig.3 *Simulation results for Tore Supra: Radial profiles of the electron (a) and ion (b) average energies. Radial profiles of the electron (c) and ion (d) outfluxes. Energy distributions of the electron (e) and ion (d) outfluxes from the rf-active region.*

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