*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-1.086 (2002)*

Removal of the lower hybrid (LH) frequency time scale in quasi-neutral simulations of LH-induced tokamak plasma edge flow*

V. Fuchs[1], J. P. Gunn[2], M.Goniche[2], and V. Petrzilka[1]

[1]Association EURATOM / IPP.CR , PO Box 17, 18 221 Praha 8, Czech Republic
[2]Association CEA/EURATOM sur la Fusion-Cadarache , F-13108, France

1 Introduction

Frequently observed damage to tokamak wall and/or divertor components during lower hybrid current drive (LHCD) was suggested to be caused by fast electrons generated in front of the LH antenna [1-3]. A theory to explain the origin of the fast electrons has been previously developed on the basis of a Landau [4] and/or Fermi [5] interaction of thermal edge electrons with the LH antenna electric field. However, it was recently pointed out that the ambient ions are coupled to the accelerated electrons via the charge separation electric field**,** which could result in ion acceleration [6]**.** In this work we present quasi-neutral particle in cell (QPIC) simulations of the edge plasma response to absorption of power from a lower hybrid (LH) antenna. Simulations proceed on the ion transit time scale to the wall or divertor target along magnetic field lines, and are therefore computationally very demanding. Standard electrostatic PIC simulations [7,8] combine the electron and ion equations of motion with Poisson's equation for the self-consistent electric field. In situations where the plasma tends to maintain quasi-neutrality, it has been previously shown[9] that the self-consistent electrostatic field can be determined from the conservation of electron fluid momentum rather than from Poisson's equation, thereby removing the fast spatial and temporal scales λ_D and $1/\omega_{pe}$, respectively. However, in LH tokamak edge plasma interactions ω_{pe} is comparable in magnitude to the LH frequency ω_{LH}, so that further efforts are required to make full use of the economy offered by QPIC. In our particular case the interaction of edge electrons with the overlapping part of the LH grill spectrum leads to their diffusing in velocity space and streaming along magnetic field lines in both directions away from the LH grill[4,5]. This allows us to represent the LH grill electric field effect by a Langevin stochastic operator[10] in velocity space, based upon diffusion and friction coefficients derived earlier.[11] The relevant rf time scale is thereby reduced from $1/\omega_{LH}$ to the fast electron transit time across a simulation cell, resulting here in a factor of about ten. The simulations indicate significant plasma expulsion from in front of the grill, giving rise to a deep quasi-neutral density depression and strong parallel pressure gradients at the grill edges.

2 Electron diffusion coefficient and Langevin equation

The quasi-linear diffusion coefficient $D_{ql}(v_{//})$ in front of the LH grill was obtained[11] by integrating the electron Newton equation of motion for the wave-guide fundamental mode

$$\ddot{z} = \frac{dv}{dt} = \grave{u}\ v_q \cos\left[\grave{u}t - \varphi(z) + \varphi_r\right] \qquad (1)$$

along unperturbed electron trajectories $z = v_{//}\, t$. Here φ_r is a random initial phase which distinguishes the individual electrons. Further, $\omega = 2\pi f$, $v_q = eE_0/\omega m_e$ is the electron quiver velocity and d is the (wave-guide + septum) width in the grill. For the Tore Supra (TS) antenna[1,5] $f = 3.7$ GHz, $d = 1.05$ cm, $E_0 \cong 3.5$ kV/cm is the antenna electric field strength, and $\varphi(z)$ signifies the $\pi/2$ phasing between the 32 wave-guides. After integrating and carrying out the required ensemble averages we obtain[11] $D_{ql} = \sin^2(\omega\, d/2v_{//})\, v_q^2\, |v_{//}|/d$. For the given E_0 the grill spectrum modes overlap within the region $|v_{//}|$ $3\mathrm{x}10^7$ m/s. To obtain the diffusion coefficient we average D_{ql} over the resonances and set D=0 outside the region. This gives

$$D = v_q^2\, |v_{//}|/2d \equiv v_{//} F \quad ; \quad F = \mathrm{sign}(v_{//})\, v_q^2/2d \qquad (2)$$

where $v_{//}$ lies in the stochastic region and $F \equiv \partial D/\partial v_{//}$ is the associated friction coefficient. An ensemble of diffusing particles can be described by the Fokker-Planck equation

$$\partial f/\partial t = -\mathrm{div}_v \vec{S} \quad ; \quad \vec{S} = -\vec{\vec{D}} \cdot \mathrm{grad}_v\, f \qquad (3)$$

where f is the distribution function, $\vec{S}$ is the particle flow vector in velocity space, and $\vec{\vec{D}}$ is the diffusion tensor. At TS edge plasma conditions all electron collisions can be neglected on the electron transit time scale so that S includes only the rf-induced flux. For the LH slow wave, the diffusion is parallel to the tokamak magnetic field, so that $\vec{\vec{D}}$ has the single non-zero element $D \equiv D_{//\,//}$. Hence $S_{rf} = -D\ \partial f/\partial v_{//}$. Equation (3) then takes the "standard" form [10]

$$\partial f/\partial t = -\partial/\partial v_{//}(F\, f) + \partial^2/\partial v_{//}^2 (D\, f) \qquad (4)$$

which is equivalent to the Langevin equation[10]

$$\Delta v_{//} = F\, dt + \sigma \sqrt{2D\, dt} \qquad (5)$$

Here σ is a random process with $\langle\sigma\rangle = 0$ and $\langle\sigma^2\rangle = 1$. The time step dt should be small enough so that $\Delta v_{//} \ll v_{//}$ and $v_{//}\, dt <$ (simulation cell size). In the next section we compare test electron simulations using the full rf-induced trajectories (1) and the Monte-Carlo trajectories (5). The point is that the required dt for solving Eq. (1) is about $0.1/f_{LH}$, whereas for (5) the time step can be about 20 times larger. We then show selected results from QPIC simulations.

3 Test electron and QPIC simulations

The QPIC method assumes that $1/\omega_{pe}$ and λ_D are much smaller, respectively, than the relevant temporal and spatial scales in the problem, so that on these scales quasi-neutrality is established almost instantaneously. The electrostatic electric field is then not calculated from Poisson's equation but from the electron fluid momentum equation. Fluid moments are tabulated at every point on the grid at every time step and used to calculate the ambipolar electric field felt by both ions and electrons. Quasi-neutrality is enforced by substituting the ion density for the electron density in the pressure gradient term of the ambipolar field.[9] A difficulty with applying QPIC in LH tokamak edge plasma interactions is that ω_{pe} is comparable in magnitude to the LH frequency ω_{LH}. In order to apply the QPIC method we therefore replace the rapidly varying rf force (1) by the velocity space Langevin stochastic operator (5). The temporal scale $1/\omega_{LH}$ is thereby replaced by the much larger fast electron transit time through a cell. At every time step we calculate the force on each particle. The electrons in front of the grill are given the small random kick (5) in velocity. In addition they feel the ambipolar electric field that arises in order to balance the pressure gradient and the average rf friction due to the sum of all the small rf kicks. The ions only feel the ambipolar electric field. They do not receive the small rf kicks

The test electron simulation region consists of a 32 wave-guide grill with field-free zones 8 wave-guides long added at each end of the grill. QPIC simulations were done with only 16 wave-guides to avoid numerical problems. The initial conditions are electron (50 eV) and ion (100 eV) edge thermal Maxwellians, with a density of $5x10^{17}$ $1/m^3$. The boundary conditions are thermal Maxwellian influxes from both ends of the simulation region and we recycle the outgoing particles. The grill electric field is described in Section 2. We wrote a 1-dimensional $(z,v_{//})$ code with cell size equal to (wave-guide + septum) width = 1.05 cm. and 2400 particles of each species per cell. Grid quantities are calculated using linear weighting of particle positions and velocities. Figures 1 and 2 compare results of test electron simulations using, respectively, the Newton [Eq.(1)] and Langevin [Eq.(5)] representations for the LH grill electric field. The QPIC results of Figures 3 and 4 then indicate, respectively, a quasi-neutral density depression in the grill region, and an anticipated substantial electron energy gain in the LH grill region. The increase in ion energy appears insignificant.

4 Conclusions

Results from test electron simulations with Newton and Langevin representations of electron dynamics in the LH grill electric field indicate that good accuracy and an approximately 10-fold reduction in simulation time can be achieved with the Langevin representation. QPIC simulations show a significant increase in electron temperature in the grill region, consistent with previous test electron [5,6] and PIC [8] simulations, whereas the ion temperature remains relatively low. As expected, the density depression in the grill region is quasi-neutral.

References

* Supported in part by Czech Republic Grant GA ÈR 202/00/1217

1 M. Goniche, J. Mailloux, Y. Demers, et al., in Proceeding of the 23rd EPS Conference on Controlled Fusion and Plasma Physics, 1996, Kiev (European Physical Society, Petit-Lancy, 1996).

2 J. Mailloux, Y. Demers, V. Fuchs, et al., J. Nucl. Mater. **241-243,** (1997) 745.

3 M. Goniche, J. Gunn, J. Mailloux, et al., Proc. of the 2nd Europhysics Topical Conference on RF heating and current drive in fusion devices, Brussels, European Physical Society, Vol.**22A**, (1998) 129-132.

4 V. Fuchs, M. Goniche, et al., Phys. Plasmas **3**, 4023 (1996).

5 M. Goniche, D. Guilhem, P. Bibet, et al., Nucl. Fusion **38,** (1998) 919.

6 V. Petrzilka, D. Tskhakaya, et al., Czech. J. Phys. **S3**, 127 (1999).

7 C. K. Birdsall and A. B. Langdon, *Plasma Physics via Computer Simulation* (Hilger, Bristol, 1991).

8 K. Rantamaki, T. J. H. Pattikangas, et al., Nucl. Fusion, 40, 1477 (2000).

9 G. Joyce, M. Lampe, et al., J. Comput. Phys. 138, 540 (1997).

10 H. Risken, The Fokker-Planck Equation (Springer-Verlag, Berlin, 1984).
11 V. Fuchs, V. Petrzilka, J. P. Gunn, and M. Goniche, in Proceeding of the 28th EPS Conference on Controlled Fusion and Plasma Physics, 2001, Funchal (European Physical Society, Petit-Lancy, 2001).

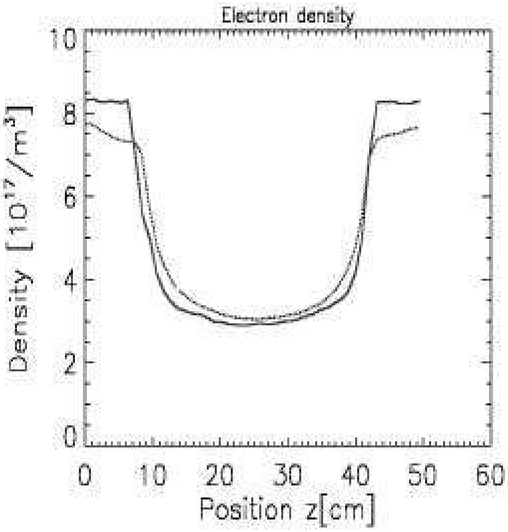

Fig.1 Electron density from Newton [Eq.(1 and Langevin [Eq.(5)] test electron simulations.

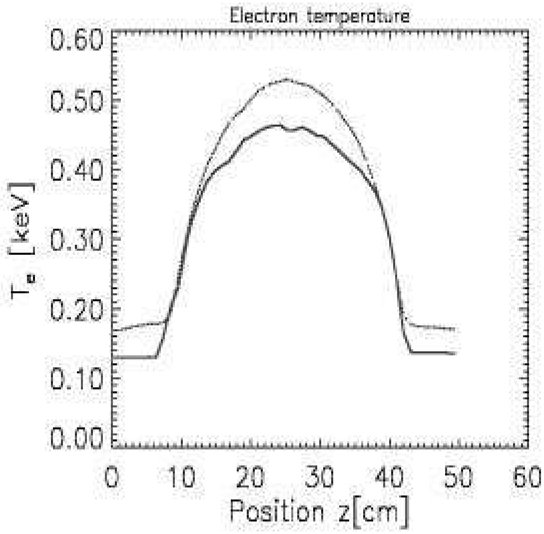

Fig.2 Electron temperature from Newton [Eq.(1)] and Langevin [Eq.(5)] test electron simulations.

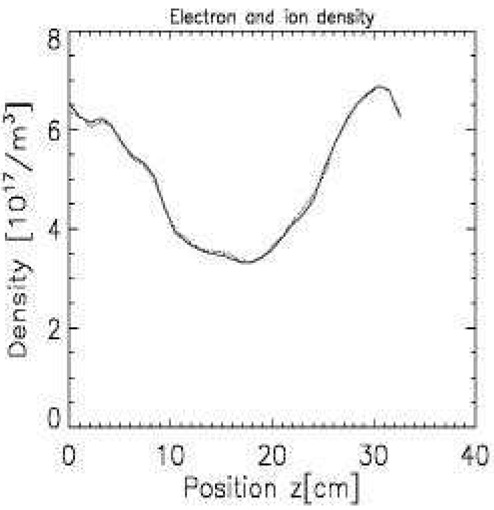

Fig.3 Electron (full line) and ion (dashed line density from QPIC simulations with Langev [Eq.(5)] electron dynamics

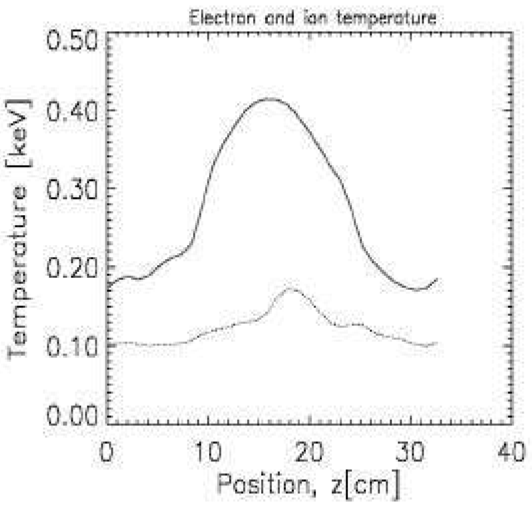

Fig.4 Electron (full) and ion (dashed) temperature from QPIC simulations with Langevin [Eq.(5)] electron dynamics.