

2-D PIC Simulation of Hot Spot Formation on Target Plates and of Current Flow to Flat Langmuir Probes

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Introduction

In toroidal magnetic fusion devices, such as tokamaks or stellarators, there can be high local power fluxes to limiters or divertor target plates, which lead to high wall temperatures. The observed formation of hot spots and arcs[1] indicates an instability of the plasma-wall transition layer. This effect is studied by 2-D collisional particle simulations of the plasma in front of a thermally emitting wall. Also, the current flow to flat Langmuir probes in divertor target plates is studied by 2-D particle simulations. Langmuir probes flush-mounted into the divertor plates are an important diagnostic in tokamaks with a high power flux into the divertor.

The Particle-in-Cell code

A particle simulation code[2] with full resolution of the gyro motion (variables x, y, v_x, v_y, v_z) is employed for the calculations on a massively parallel computer. The particle motion is calculated in the self-consistent electric field and a homogeneous magnetic field. The Poisson equation is solved on a rectangular grid, and linear interpolation is used for charge deposition and interpolation of the electric field. The simulation area (Fig. 1) is bounded by two walls, and is periodic along the walls. One wall is emitting thermal electrons with an emission coefficient (Richardson law) depending on the wall temperature, which is calculated by solving the 2-d heat conduction equation for the wall with a fixed low temperature at the back side. Coulomb collisions are included by a Monte Carlo solution of the Fokker-Planck equation in each grid cell[3].

Development of hot spots on a target plate and their stability

A part of a plasma-facing wall is in thermal equilibrium when the deposited energy flux of plasma particles hitting the wall is equal to the energy loss of the wall due to heat conduction, thermal radiation, electron emission and sublimation. Electron emission reduces the potential difference between the plasma and the wall; this leads to a higher

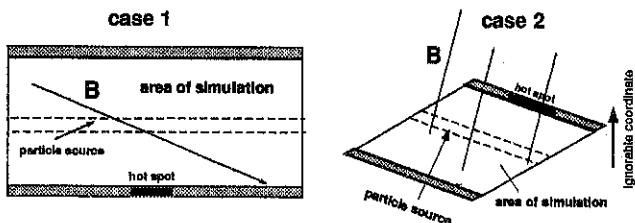


Figure 1: Numerical grids for the PIC simulations

electron flux onto the wall, and more energy is deposited there. Under certain conditions, depending on the plasma temperature and density as well as the wall properties, two stable thermal equilibria exist[4]: one with a low wall temperature, little thermal electron emission and a small energy flux onto the wall; the other one with a high wall temperature, strong emission and a high energy flux. This implies that regions with different wall temperature can exist at the same time (e.g. 'hot spots').

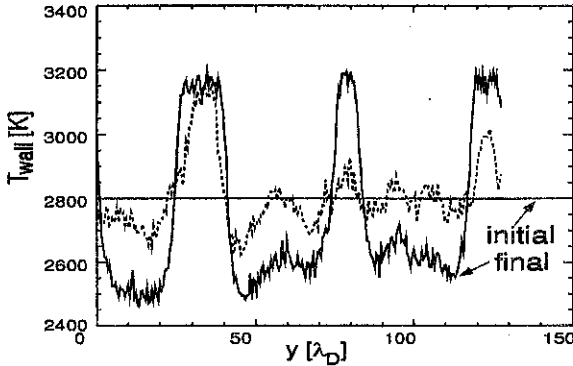


Figure 2: *Spontaneous development of hot spots: evolution of the wall temperature*

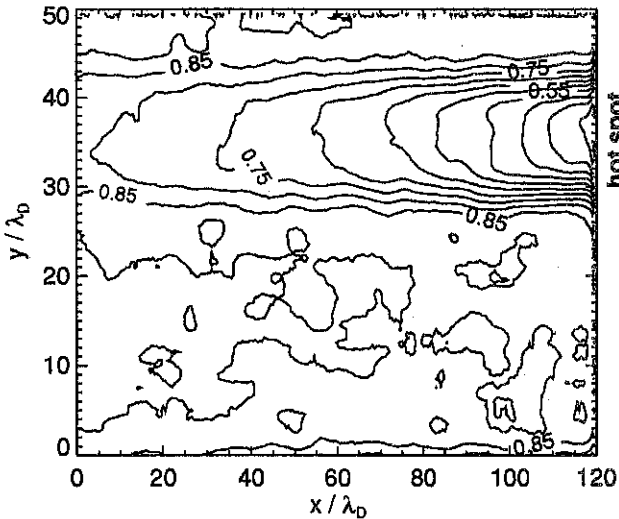


Figure 3: *Contour lines of the electron temperature in front of a hot spot normalized by the source temperature of the PIC simulation. The ion gyro radius is $17\lambda_D$.*

Starting from a wall with homogeneous temperature, we observe in our PIC simulations the development of such spots under the influence of random fluctuations (due to finite number of particles) (Fig. 2), unless the heat conductivity in the wall is too high. These spots are stable with a characteristic size within a small range. The plasma in front of a hot spot is cooler than the plasma in front of the surrounding cold wall because the emitted thermal electrons have a low temperature compared to the plasma temperature (Fig. 3). Hence, heat flows from the surrounding plasma into the region in front of the spot, resulting in additional heating of the hot spot. On the other hand, heat conduction inside the wall leads to a cooling of the hot spot.

In a different kind of simulations, where a part of the wall is initially at a higher temperature, but has the same properties as the rest of the wall, induced hot spots are formed if the heated part of the wall exceeds a minimum size, about the ion gyro radius. These spots then grow or shrink towards the characteristic size. If the mean free path length is of order of the ion gyro radius, a large induced spot is split up into two smaller spots. However, stable hot spots do not exist, if the collisionality of the plasma is very high.

Influence of an oblique magnetic field on the hot spots

If an oblique magnetic field \vec{B} is applied, the spots start to move without changing their form. If the magnetic field has a component perpendicular to the simulation plane and another normal to the wall (case 2 in Fig. 1), the hot spots move in the $\vec{E} \times \vec{B}$ direction (Fig. 4 a), where \vec{E} is the electric field in the sheath. In front of the hot spot, the electric field is reversed so that the emitted cold electrons drift in the opposite direction.

If the magnetic field is in the simulation plane (case 1), the hot spots move parallel to

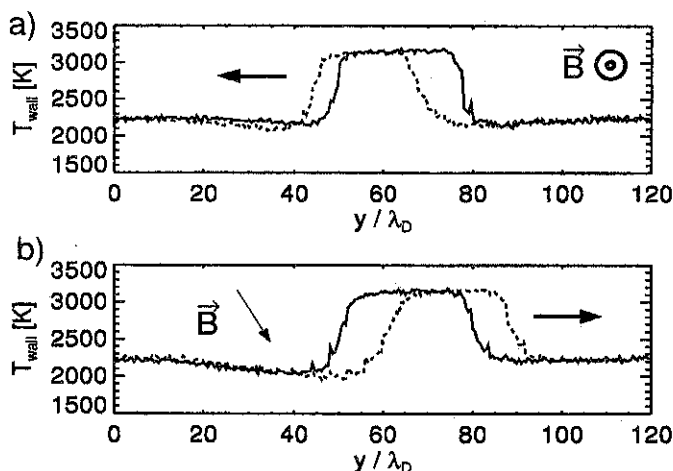


Figure 4: Hot spot in an oblique magnetic field: (a) Motion in $\vec{E} \times \vec{B}$ direction, (b) Motion parallel to the wall (and perpendicular to $\vec{E} \times \vec{B}$ drift).

the wall towards the side with the larger angle between \vec{B} and the wall surface (Fig. 4 b), due to the different motion of the electrons and the ions. Owing to their large gyro radius, ions are focussed onto the right hand side of the hot spot. Hot electrons coming from the plasma, being bound to the fieldlines, travel along \vec{B} towards the wall, while those emitted by the wall mostly have a parallel velocity component directed away from the wall. Hence, more cold electrons hit the left side of the hot spot, whereas more hot electrons hit the other side. These effects lead to a cooling of the left spot side, and a heating of the wall at the right hand side, and a movement of the spot towards the right results.

Current flow to flat Langmuir probes in a divertor plate

The current flow to flat Langmuir probes in a divertor plate which is intersected by a strong magnetic field at a small angle α , was studied by 2-D particle simulations with realistic values of probe size, gyro radius ρ , and angle of incidence α (read 'probe' for 'hot spot' in Fig. 1). The main results are (the details will be presented elsewhere): (i) Extending previous work[2], a new scaling of the ion current non-saturation with the angle of incidence was obtained, which is valid for probes of realistic size and for angles down to 1.5 degree; it can explain the measurements with such probes. (ii) The $\vec{E} \times \vec{B}$ drift in front of a negatively biased probe shifts the ion flux to the probe so that the additional current due to the lateral sheath growth is concentrated on one side. The electron flux to a positively biased probe is reduced by the $\vec{E} \times \vec{B}$ drift. This reduction is considerable for probe sizes below a poloidal gyro radius, $\rho / \sin \alpha$. (iii) The collisionless current flow across the magnetic field back to the wall adjacent to the probe was studied with simulations in which the current flow into the bulk plasma was suppressed. In these simulations, a current of order ion saturation current is drawn by only a part of the probe of a width of about a poloidal gyro radius. In case of grazing incidence, the current returns to the wall behind the probe (viewed along the field line).

Summary

Two-dimensional collisional particle simulations of the plasma in front of a thermally emitting wall have been performed. Fluctuations of the plasma parameters can lead to a stable state where different wall regions have different temperatures. Thus stable hot spots of a characteristic size can evolve. However, a very high collisionality prevents the formation of these spots. An oblique magnetic field causes the hot spots to move in $\vec{E} \times \vec{B}$ direction, as well as parallel to the wall. Also, the current flow to flat Langmuir probes in divertor plates was studied by 2-D particle simulations.

References

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