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PIC Simulation of the Electron Energy Distribution Function in a RF Magnetized Plasma Column Connected to a Tilted Electrode

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Abstract : The simple Maxwellian EEDF (Electron Energy Distribution Function) used in collisional plasmas at thermodynamic equilibrium can be distorted when the plasma is close enough to a RF source especially when electrons are well magnetized. This has been verified in our experimental device Aline. During the experiment, negative floating potentials have been found when a Langmuir probe is magnetically connected to the RF electrode, in both direct and capacitive coupling. Floating potentials as low as -40 to -100 V have been measured while the plasma potential remains positive. The large gap between them can be explained by energetic electron beams accelerated in the RF sheath surrounding the electrode. Such acceleration is known as stochastic heating, which is investigated using PIC (Particle in Cells) simulation to demonstrate the importance of the tilting angle of the electrode with respect to the magnetic field direction in the enhancement of these electron beams. Both measurements and PIC simulations show these beams are much stronger at grazing angle, inducing a bi-Maxwellian EEDF with two characteristic temperatures, the highest value explaining the high negative floating potentials.

EXPERIMENTAL FLOATING POTENTIALS

During experimental work on the plasma device Aline [1], in which a tilting electrode allows to change the angle of the active RF surface with respect to the magnetic field, some very negative floating potentials (Fig.1) have been measured [2] in the case of grazing angle with a RF compensated Langmuir probe [3]. After several investigations, it has been found that this phenomenon did not come from a bad compensation of the probe because the RF floating potential component had a very low magnitude (less than 1 V), especially in capacitive coupling where the plasma potential is low (10-20 V) according to the electron temperature (3 eV). It did not come as well from the $\mathbf{E} \times \mathbf{B}$ or diamagnetic drift of electrons in the density gradient region of the plasma which is localized in a thin layer above the RF electrode and all along the magnetic field (Fig. 2).

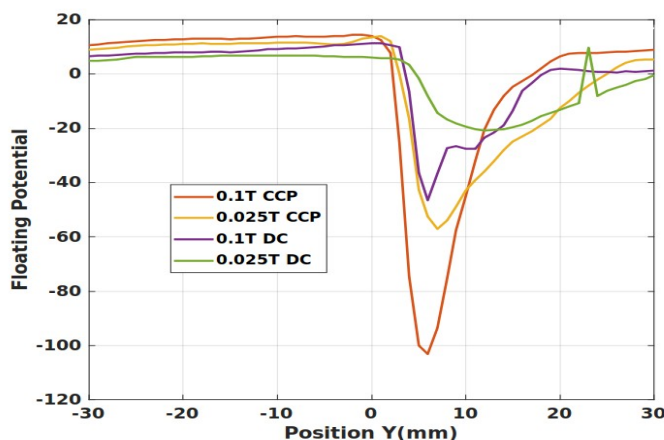


Figure 1. Floating potential at grazing angle for capacitive coupling (CCP) and direct coupling (DC) at $Z=60$ mm from the center of the electrode

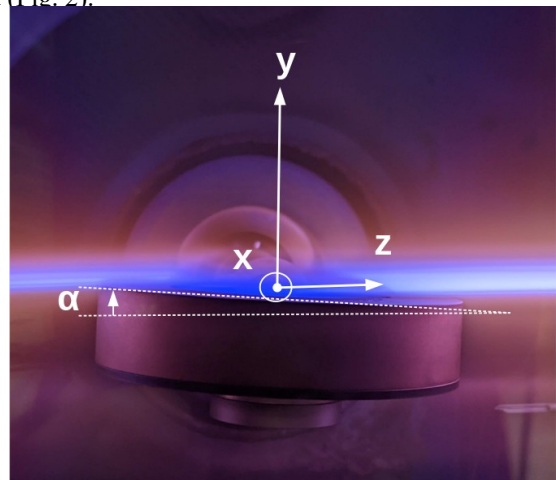


Figure 2. Picture of the plasma layer just above the RF electrode active surface (top). The rest of the electrode is screened by a grounded shield.

The third hypothesis is a bi-Maxwellian electron flux [4] received by the probe, which implies that electrons have been highly accelerated by the grazing electrode due to stochastic heating [5]. According to the floating potential formula :

$$V_{fl} = \frac{T_e}{2} \ln \left[\left(2\pi \frac{m_e}{m_i} \right) \left(1 + \frac{T_i}{T_e} \right) \right] \quad \text{Eq. 1}$$

The magnitude of the floating potential measured by the probe is proportional to the electron temperature T_e , assuming a Maxwellian velocity distribution, with m_e and m_i the electron and ion mass respectively and T_i the ion temperature.

PIC SIMULATIONS

To test the last assumptions, some PIC simulations have been run, scanning the RF voltage, the bias DC voltage on the electrode, the plasma density and the tilt angle of the magnetic field with respect to the active RF surface as sketched in figure 3.

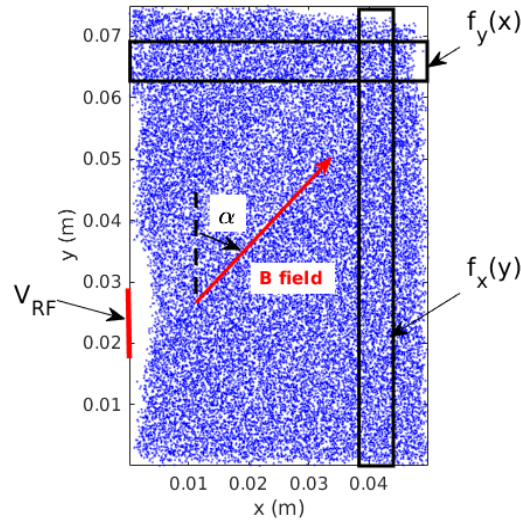


Figure 3. PIC simulation box

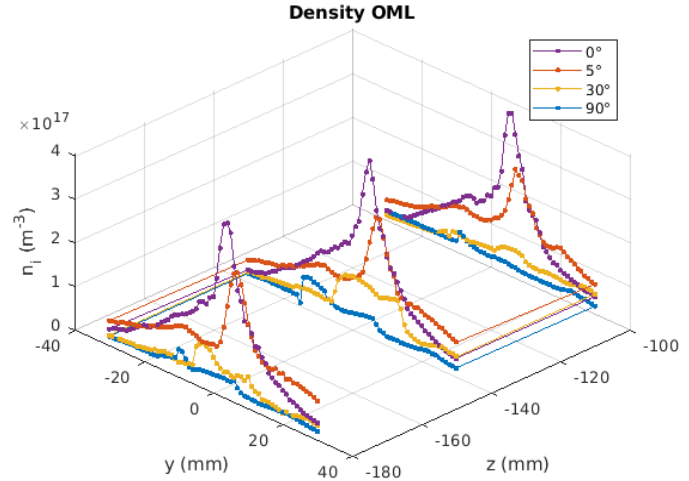


Figure 4. Density profiles at different probe positions (z is the distance between the probe and the electrode center)

The code is based on a Matlab script with specific CUDA functions running on a RTX6000 GPU with 24 GB of memory. It is able to run up to 67 millions super-particles. The code is quite simple, no collision, no ionization, FFT electrostatic solver, Lorentz integrator is a Tajima implicit method, ion or electron numbers can be chosen as constant in the box to allow negative biasing of the plasma. The PIC code has been compared to Xoopic [6] simulations with exactly the same conditions to be validated.

The goal is to be able to simulate large area of magnetized plasma : here 7.5 cm height by 5 cm width. The plasma density is either 10^{15} or 10^{16} m^{-3} , which is lower than the experimental density, measured by a Langmuir probe using Orbital Motion Limit (OML) method [7], in the core plasma (few 10^{17} m^{-3} , see Fig. 4). But at such higher densities in the simulations, electrostatic waves grow inside the box and the whole plasma is heated so that it does not represent the thin plasma layer we observed experimentally. 6 tilt angles are tested (5.7, 11.3, 26.5, 45, 63.4 and 90°). The potential maps appear in figure 5 for a 100 V RF voltage at 25 MHz (same as experiment) and a DC bias voltage of -100 V to simulate the self biasing of the cathode in capacitive coupling.

Other simulations have been performed for $V(t)=-200+200.\sin(\omega t)$, and in direct coupling : $V(t)=100.\sin(\omega t)$ and

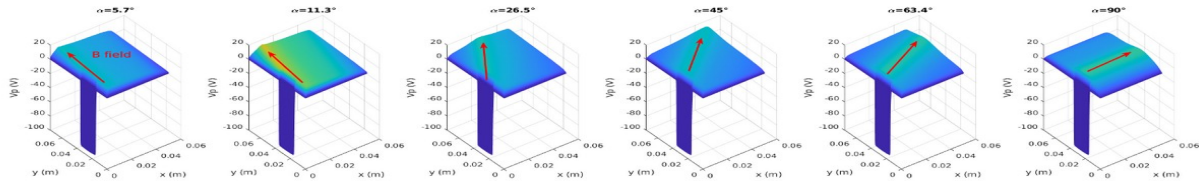


Figure 5. 2D maps of the plasma potential at 6 different angles between magnetic field and y direction

$V(t)=200.\sin(\omega t)$. Only the case $V(t)=-100+100.\sin(\omega t)$ is presented at a density of 10^{16} m^{-3} . The Electron Velocity Distribution is shown in figure 6, which is representative of what happens for the different angles under RF excitation.

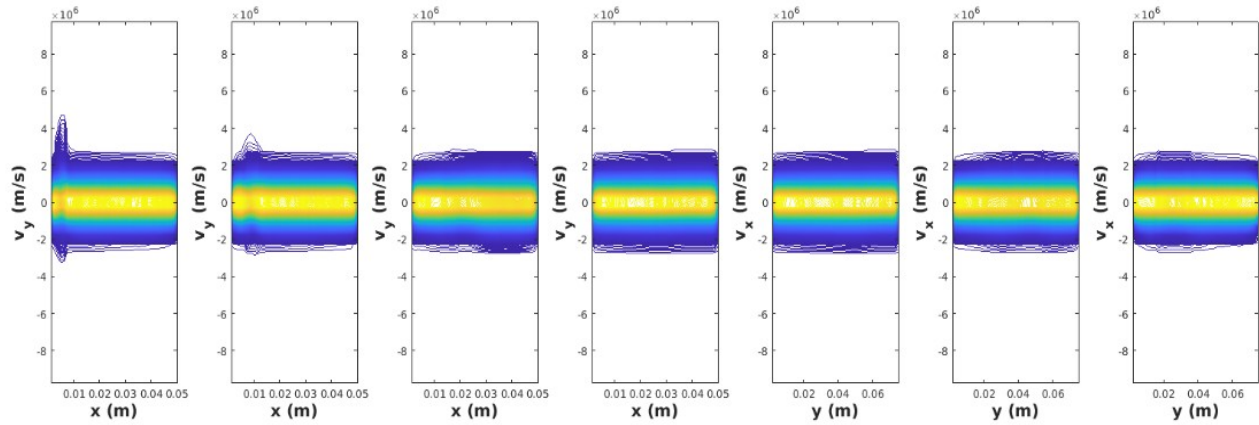


Figure 6. Electron velocity distribution at 6 different angles

It can be seen that the initial Maxwellian distribution of V_y , crossing the horizontal rectangular box in which the distribution is diagnosed (see fig 3), is only disturbed at low angles (5.7° and 11.3°) while, at 26.5° and 45° , it remains mainly Maxwellian at the same temperature. The 3 last sub-figures are plots of V_x as a function of y and are diagnosed in the vertical rectangular box in figure 3. A small perturbation appears at 90° angle but is much lower than at 5.7° , meaning the acceleration process through stochastic heating is much more efficient at low angles. The 0° angle has not been tested in the PIC code to avoid the effect of the grounded wall because the RF electrode is aligned with the wall. The consequence of this electron acceleration is an increase of the flux and then an increase of the floating potential magnitude measured by the probe placed on the beam trajectory imposed by the magnetic field angle.

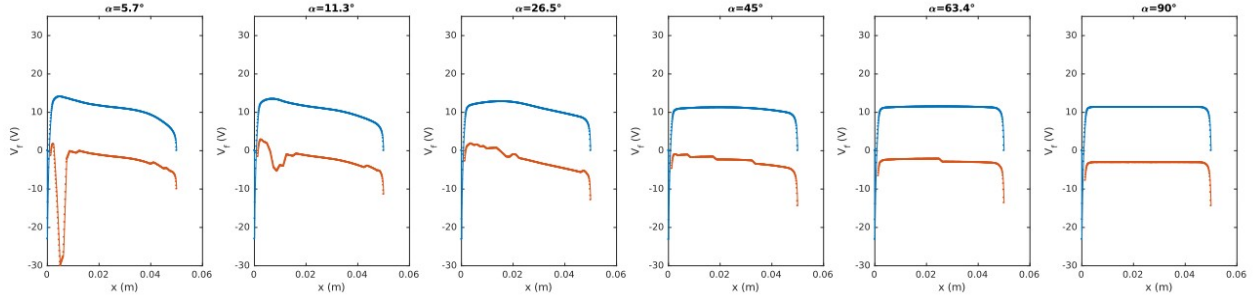


Figure 7. Plasma (blue) and floating (red) potential profiles at 6 different angles

Both plasma and floating potential are plotted in figure 7. The floating potential as it is measured by a virtual probe, can be calculated from $G_e = G_i$ with G_e the electron flux and G_i the ion flux. The last one is given by $G_i = n \cdot C_s$ with C_s the acoustic ion speed and n the plasma density at the entrance of the sheath, as provided by the Bohm criterion. A limit velocity v_0 can next be deduced from the electron velocity distribution calculated by the PIC code as follows :

$$\Gamma_i = \int_{v_0}^{\infty} v f(v) dv \quad \text{Eq. 2}$$

And the floating potential can be calculated from $V_f = m_e \cdot v_0^2 / (2e)$. At 5.7° , one can see the floating potential is strongly negative (-30 V) due to high electron flux in the region connected to the RF electrode. This floating potential can be as negative as -180 V for the case $V(t) = 200 + 200 \cdot \sin(\omega t)$ at low density (10^{15} m^{-3}) as shown in figure 8. A higher density means thinner RF sheath and lower volume for stochastic heating. The velocity distribution also reveals that at 90° angles, significant perturbations can be seen at the edge of the biased flux tube. The heating, in that case, occurs in the strong perpendicular potential gradient region.

But the most spurious consequence of the electron acceleration at grazing angle is the possible generation of a hot spot on surfaces connected the active RF surfaces. Such hot spots are observed on the structure of ICRH antenna, either due to their own power or to ECRH antenna output magnetically connected to them in fusion devices. If this high energy flux hit a floating surface (not grounded) the negative biasing can again accelerate the ions to balance the current and finally induce hot spot, sputtering and impurity generation.

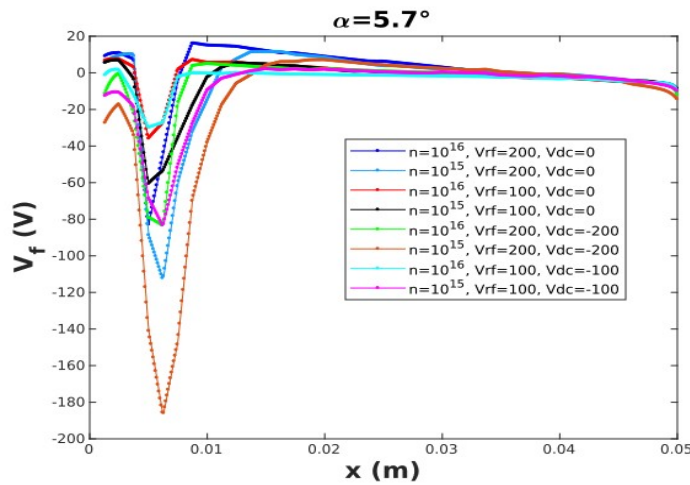


Figure 8. Floating potential at different RF and DC potentials and densities

CONCLUSION

The angle α between the magnetic field and the boundary surface of the wall or RF electrode is a key parameter to deduce the local floating potential. In the case of a RF electrode, it appears that the electrons are much highly accelerated at grazing angle (0-10°), which can result in high energy electron beams able to bias the connected wall or probe at strong negative potentials. This negative biasing can next result in the acceleration of ions in the local electric field, leading to high energy ion fluxes and local hot spots as it can be seen on the structure of the ICRH antenna in Tokamaks. The study of these EEDF in front of an RF biased electrode shows that only grazing angles induce such localized energetic electrons (up to the RF magnitude in eV) which are accelerated within the RF sheath mainly in the magnetic field directions. The energy gain and the floating potential are higher at lower density (larger sheath), higher RF potential and larger negative DC self-biasing of the electrode.

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