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RF sheath rectification process in presence of transverse RF currents in the Ion Cyclotron Range of Frequencies

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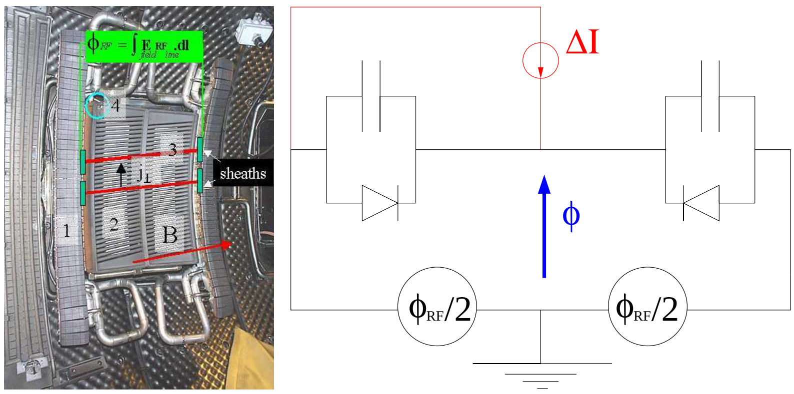
Introduction

Hot spots [1] appearing on the Faraday screen (FS) structure of Ion Cyclotron Range of Frequencies (ICRF) antenna (fig.1(a)) are a limiting factor for long shots in tokamaks, especially for ITER. They result from interactions between the material and ions fluxes accelerated in sheaths and convected by RF-induced DC ExB drifts along iso-potential surfaces [2]. The heat flux attributed to accelerated ions is directly proportional to the DC sheath potential. The purpose here is to calculate a DC potential map resulting from the rectification process due to RF sheaths coupled self-consistently with RF transverse (perpendicular to the magnetic field B_0) currents in front of ICRF antennas. The new and unexpected effect of these RF transverse currents is to increase the DC value of rectified potentials.



(a) ICRF antenna in Tore Supra

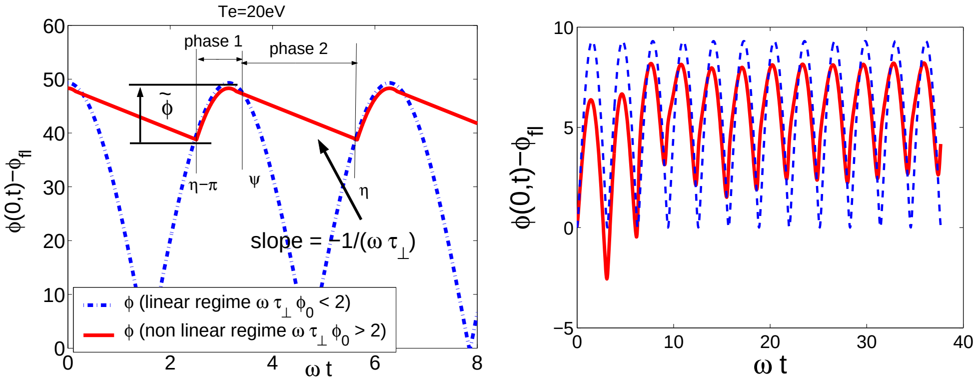
(b) double probe model with transverse current

Figure 1: (a) : ICRF antenna is composed of 2 straps behind the Faraday screen (label 2) and protected by 2 bumpers (label 1) on each side (image CEA). 2 samples of magnetic lines (label 3) connected to the bumpers appear in red and sheaths are at the end of them in a thin layer in front of the material. The hot spot damaged the corner of the antenna (label 4). (b) : Double probe model with transverse current ΔI. Each sheath is represented by a capacity and a resistance in parallel.

Modelling of RF sheaths coupled with transverse RF currents and simulation results

A flute hypothesis was made considering the potential is constant along open magnetic lines connected to bumpers on each side of the antenna, excepted in sheaths (fig. 1(a)). The near electric fields [3] radiated by the antenna are integrated along each flux tube to obtain RF potentials applied to each open magnetic line, and then transverse RF currents resulting from RF transverse gradients and the rectified potential ϕ due to RF sheaths are calculated self-consistently. This rectified potential is normalized to $k_B T_e/e$ with $T_e = 20\,eV$, the typical temperature in the

Scrape off layer. Each flux tube is treated as a double probe driven by an oscillating RF potential ϕ_0, with a transverse current term (fig. 1(b)) which increases or decreases the rectified potential of the flux tube according to the non linear I-V characteristic of sheaths during one period.



(a) time amplitude of the rectified gaussian potential ϕ at low frequency

(b) time amplitude of the rectified gaussian potential ϕ at $\omega = 2\Omega_{ci}$

Figure 2: (a) : Qualitative time amplitude of a gaussian RF potential at $\omega < \Omega_{ci}$ (capacitive behaviour). The blue curve is the rectified potential without current effect. (b) : time amplitude of the rectified potential for $\omega > \Omega_{ci}$ in a typical edge plasma $\phi_{RF} = 20$, $T_e = 20\,eV$, $\omega/\Omega_{ci} = 2$, $r_0 = 1\,cm, L_{\parallel} = 50\,cm$

This model solves the current conservation (Eq. 1) along one flux tube and the momentum equation (Eq. 2) from which the displacement current term is extracted. Sheaths are considered as non-collisionnal, electrons follow Botzmann distribution, magnetic lines are perpendicular to the wall (no magnetic presheath) and the RF frequency ω is much lower than the ion plasma frequency ω_{pi}.

$$1 - \exp\left(\phi_0 - \phi\right) = \frac{\Delta I}{2\,j_{isat}} \tag{1}$$

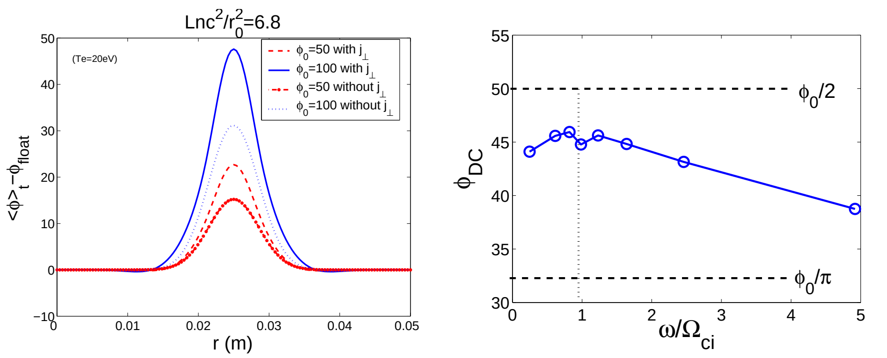
$$\frac{1}{\Omega_{ci}^2}\frac{d^2}{dt^2}\left(\frac{\Delta I}{2\,j_{isat}}\right) + \frac{\Delta I}{2\,j_{isat}} = \frac{L_{\parallel}\rho_{ci}}{2\Omega_{ci}}\frac{d\nabla^2\phi}{dt} \tag{2}$$

$$\phi_0 = \phi_{fl} + \ln\left(\cosh\left(\frac{\phi_{RF}}{2}\sin(\omega t)\exp\left(-\frac{r^2}{r_0^2}\right)\right)\right)$$

ϕ_{fl} the floating potential, r_0 the half width of the Gaussian potential, ΔI is the transverse RF current, j_{isat} the ion saturation current, ϕ_{RF} the amplitude of the RF potential resulting from the integration of electric field along flux tubes, Ω_{ci} the ion cyclotron frequency, $L_{\parallel}$ the length of the flux tube and ρ_{ci} the ion Larmor radius.

A 2D fluid code built from this model is applied to a Gaussian potential structure in a plane perpendicular to the magnetic field B_0 in which occur transverse currents. The fluid model is valid for typical frequencies involved in RF heating (from 20 MHz to 80 MHz) in a deuterium plasma. For $\omega < \Omega_{ci}$ the response of the RF current ΔI in Eq. 2 is capacitive (current behind potential) and for $\omega > \Omega_{ci}$, the response is inductive (current ahead of potential). The figure 2(a) gives the rectified potential for $\omega \ll \Omega_{ci}$ and then reveals a typical capacitive regime with a linear saturated decreasing phase expressing the saturation of transverse current at 2 j_{isat}.

This type of time signal looks like those obtained with a capacitive diode bridge whose the capacity determines the slope of the decreasing phase (phase 2 on the figure 2(a)). An example of the time rectification of the potential for $\omega = 2\Omega_{ci}$ is illustrated on figure 2(b) and reveals a dominating inductive regime, with the same tendency to increase the time average value of the rectified potential. But the main result coming out from fluid simulations is that these potential structures are smoothed only for small spatial scales (width$<$ 1 cm) in a typical edge fusion plasma ($T_e = 20\,eV$, $n_0 = 10^{18}\,m^{-3}$, $B_0 = 2\,T$, $10 < \phi < 100$). On another hand, the DC potential peaks are not smoothed and reduced by RF currents (see fig. 3(a)) but on contrary are increased by 50 % in the worst case. A rigorous analytical treatment has showed that if the DC value of ΔI is 0 the only effect of RF transverse currents is to increase the DC value of potential structures whatever the frequency [4].



(a) DC rectifi ed Gaussian potential

(b) rectifi cation impact as a function of frequency

Figure 3: (a) : DC spatial effect of transverse RF currents ΔI on a Gaussian potential structure. (b) : Time average value ϕ_{DC} of the rectified potential as a function of the frequency normalized to Ω_{ci} for $T_e = 20\,eV$, $L_{\|} = 5\,cm$, $r_0 = 1\,cm$.

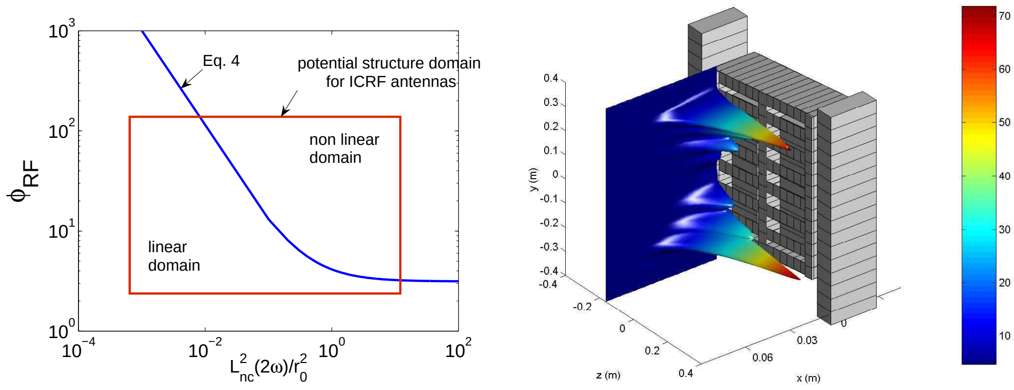
In addition, 2D PIC simulations with the code XOOPIC [5] were performed and confirmed quantitatively the increase of ϕ_{DC} for frequency close to Ω_{ci} (fig. 3(b)). Equation 2 can be linearized around its solution without RF transverse current as long as $\Delta I/2\,jsat \ll 1$. From the linearity condition $\Delta I \ll 2\,j_{isat}$ applied to a gaussian RF potential, we deduce the parameter L_{nc}^2/r_0^2 representing the square characteristic length along which RF currents occur over the square half width of the Gaussian structure. L_{nc} is defined in Eq. 3 and the parameter L_{nc}^2/r_0^2 is used in the peaking criterion (Eq. 4) obtained from the Fourier transform of the linearized system coming from Eq. 1 and 2. This criterion valid at all frequencies determines the importance of the rectification process on the potential structure.

$$L_{nc}^2(2\omega) = \frac{L_{\|}\rho_{ci}}{2}\frac{2\omega/\Omega ci}{1-4(\omega/\Omega_{ci})^2} \tag{3}$$

$$\phi_{RF} < \pi + \frac{r_0^2}{\mid L_{nc}^2(2\omega)\mid} \tag{4}$$

For $\phi_{RF} < \pi + (r_0^2/\mid L_{nc}^2(2\omega)\mid)$ corresponding to linear regime (fig. 4(a)), ϕ_{DC} is higher but close to ϕ_{RF}/π the time average value obtained in previous works [6] without transverse currents. And for $\phi_{RF} > \pi + (r_0^2/\mid L_{nc}^2(2\omega)\mid)$ corresponding to non linear regime (fig. 4(a)), ϕ_{DC}

tends rapidly to reach $\phi_{RF}/2$, which means an increase of 50 % compared to the previous admitted value. Figure 4(a) demonstrates that ICRF antennas work mainly in a non-linear domain and especially for peaks appearing in the upper and lower part of the antenna (fig. 4(b)). These DC potential peaks are due to parallel currents in antenna box [7] and can reach several hundred volts, which enhances acceleration of ions in sheaths and convective effects identified as the main causes of hot spot formation in the corner of antenna.



(a) Peaking criterion fi r ICRF antennas (b) potential map in front of antenna

Figure 4: (a) : Peaking criterion at the summit of the Gaussian potential at different frequencies. (b) : 2D DC potential map obtained in a poloidal plane in front of an ICRF antenna composed of a simplified Faraday screen.

Conclusion

The formation of hot spots resulting from interactions between accelerated and convected ion fluxes in sheath motivated this study about potential maps in front of antenna. The 2D fluid model is now valid for ion cyclotron range of frequency used in tokamaks. The main result concerns the DC value of the rectified potential which can reach $\phi_{RF}/2$ instead of ϕ_{RF}/π as predicted by previous models neglecting transverse currents. This new result has to be taken into account in sheath calculations occurring at RF frequencies and shows that DC potential peaks appearing at the top and the bottom of the ICRF antenna are increased by 50 % compared to previous theories. This result enhances the probability of hot spot formation and deposited power on antenna box should be reevaluated according to this theoretical sheath potential growth with the prospect of the next ITER-like antenna design.

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