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Transport balance of RF-heated impurity ions

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The influence of radio frequency (RF) waves on the transport of seeded impurity ions can be quite significant as was demonstrated on the tokamak TFR [1]. A primary electromagnetic wave launched into a two component (H/D) plasma is known to transform into a quasi-electrostatic wave near the ion-ion hybrid resonance layer whose position is function of the concentration of hydrogen to deuterium n_H/n_D. With the TFR experimental parameters [major radius $R_0 = 98$cm, minor radius $a = 20$cm, on axis magnetic field $B_0 = 5.12$T, plasma current $I_p = 240$kA, antenna frequency $f_{\text{ICRH}} = 60$MHz and a total power launched to the plasma of the order of 550 kW], the hydrogen= resonance layer was located at $R_H = 127$cm i. e., outside the plasma column while the argon impurity has two second harmonic resonances of ionized states of Ar^{16+} and Ar^{15+} inside the plasma: $R_{Ar^{16+}} = 102$cm, $R_{Ar^{15+}} = 96$cm. The concentration ratio n_H/n_D was varied from 0.69 to 0.47. During this scan, the ion-ion hybrid resonance layer position moved from $R_h = 96$cm to $R_h = 101$cm, which is in agreement with our modelling (Fig. 2). The argon was puffed to the plasma during 50 ms which provided the total

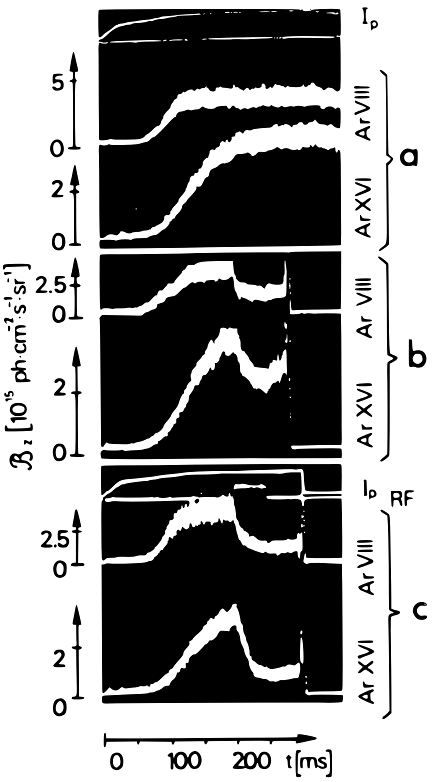

Figure 1: Time evolution of radiance $\mathscr{B}_z$ of Ar^{7+} and Ar^{15+}: a) Ohmic discharge b) RF pulse on $n_H/n_D = 0.685$ c)RF pulse on $n_H/n_D = 0.485$. Data from Ref. [1]

*See the Appendix of J.Pamela et al., Fusion Energy 2004 (Proc. 20th Int. Conf. Vilamoura, 2004) IAEA, Vienna (2004).

argon concentration about 10^{-3} of the electron density. During the RF power modulation the line radiation of Ar^{15+} showed a sudden drop to a low constant value as shown in (Fig. 1). No measurements of the line radiation of Ar^{16+} resonant ions were done due to its emission in the soft X-ray spectral region. Therefore the behaviour of resonant ion was monitored through the evolution of Ar^{15+} line radiation. The typical ionization time for Ar^{15+} being less than a few milliseconds and therefore a decrease in Ar^{16+} content is almost immediately followed by the ionization of Ar^{15+}. Therefore, it is expected that the temporal evolution of Ar^{15+} reflects also the evolution of the Ar^{16+} emission. The relative change in the electron temperature during the RF power modulation was $\Delta T_e/T_e = 0-8\%$ at resonance and $\Delta T_e/T_e = 15-30\%$ far away from the resonance. The electron density did not changed appreciably.

The modelling of TFR experiment

The distinctive feature of the TFR experiment is the antenna location on the high field side (HFS). The presence of the mode conversion layer in the plasma makes essential difference between the launch of fast wave from the HFS and the LFS. The wave exited from the LFS is reflected in the vicinity of evanescence layer where $k_\perp = 0$ and after reflection this wave moves to the plasma periphery. The penetration of this wave through the evanescence layer is exponentially small. The fast wave launched from the HFS propagates to the transformation point where $n_\parallel \approx S$ and then fully transformed to the slow wave. The slow wave transforms further to the electrostatic wave propagating to the point of ion-ion hybrid resonance $S = 0$.

In accordance with the experimental data, the strongest effect of RF on the argon transport was in the case of coincidence of the mode conversion layer (MCL) with the cyclotron resonance layer of argon. To meet this condition, the value of the concentration ratio n_H/n_D has to be approximately 0.47. In this case, the position of ion-ion hybrid resonance is located at 101 cm. Since the position of the mode conversion is expected to be in the vicinity of the hybrid resonance it should also be in the vicinity of the argon resonance. The mode conversion layer move away from the deuterium resonance in the direction of the HFS, while the value of ratio n_H/n_D is increased. The power fraction absorbed by different plasma species has been calculated by the full wave code TORIC [2]. The radial profiles of total absorbed power are displayed in the (Fig. 3). The electron absorbed about 59% in case $n_H/n_D = 0.69$ and 34% for a concentration ratio of $n_H/n_D = 0.47$.

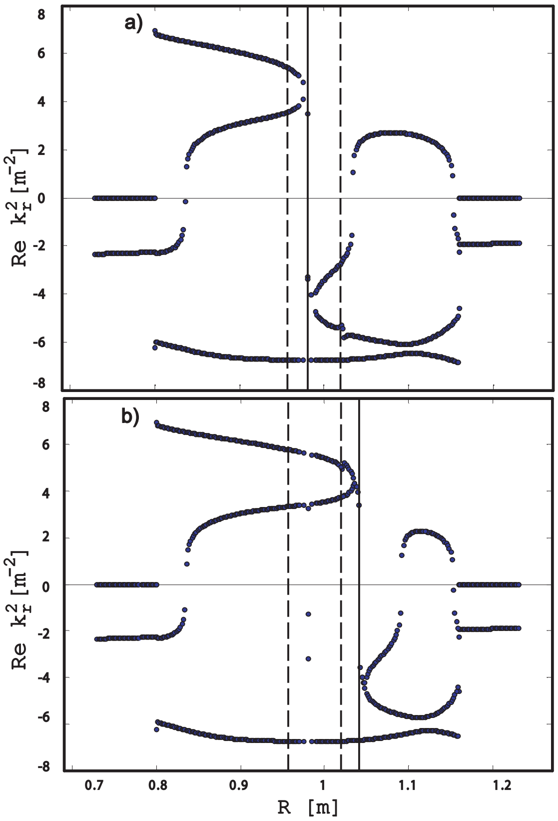

Figure 2: The radial profiles of $k_\perp^2$ for different concentration ratio a) $n_H/n_D = 0.69$, b) $n_H/n_D = 0.47$

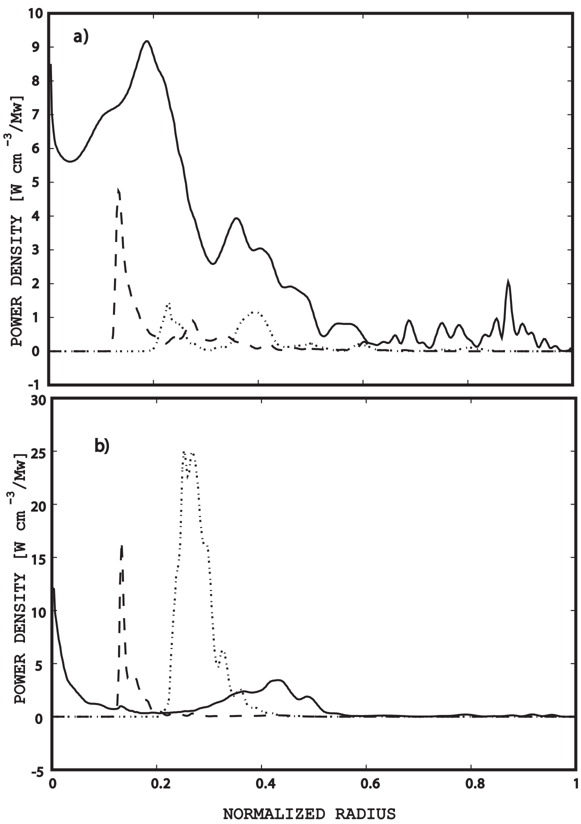

Figure 3: The radial profiles of absorbed power by electrons (solid line), Ar^{15+} (dash line), Ar^{16+} (dot line). Case a) $n_H/n_D = 0.69$, b) $n_H/n_D = 0.47$

The code RITM [3] with modification which allows one to calculate the temperature of impurity species and energy exchange between impurity and the main species [4], has been used to investigate the temporal evolution of argon density profiles. It has been assumed that enhancement of particle loss was caused by toroidal ripple. To analyse the consequence of this loss mechanism, it is necessary to modify the transport equations in RITM by adding an extra sink term. With that modification the particles and heat transport equations for the impurity density n_z and impurity temperature T_z read

$$\frac{\partial n}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_z) = S_{z+1} + S_{z-1} - L_z - \frac{n_z}{\tau^*}$$

$$\frac{3}{2}\frac{\partial n_z T_z}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(rq_z) = Q_z + \frac{3}{2}\left[S_{z-1}T_{z-1} + S_{z+1}T_{z+1} - L_z T_z - n_z \sum_\beta \nu^{\varepsilon}_{z\beta}(T_z - T_\beta)\right] - \frac{n_z T_z}{\tau^*}$$

The source terms $S_{z+1,z-1}$ and loss terms L_z are due to ionization and recombination processes. The τ^* represents the characteristic life time of the particles in the ripple loss cone and was calculated by a bounce averaged Fokker Planck code.

Conclusion

The simulations have shown that the selective argon heating, on one hand, leads to the increase of the anomalous pinch velocity and consequently of the total argon concentration. On the other hand, the impurity heating enhance the loss rate due to magnetic ripple. Then, due to the competition of these processes the total concentration of argon was reduced only by a factor of 5 as indicated in (Fig. 4) in the case of a density ratio $n_H/n_D = 0.47$. A possible explanation of the discrepancy in reduction in emissivity could come from a broadening of the heating profile due to finite banana width [5]. A trapped particle in the presence of strong heating could have the banana width large enough to transfer the energy for the large distance from the resonance location leading to the widening of radial profile of losses.

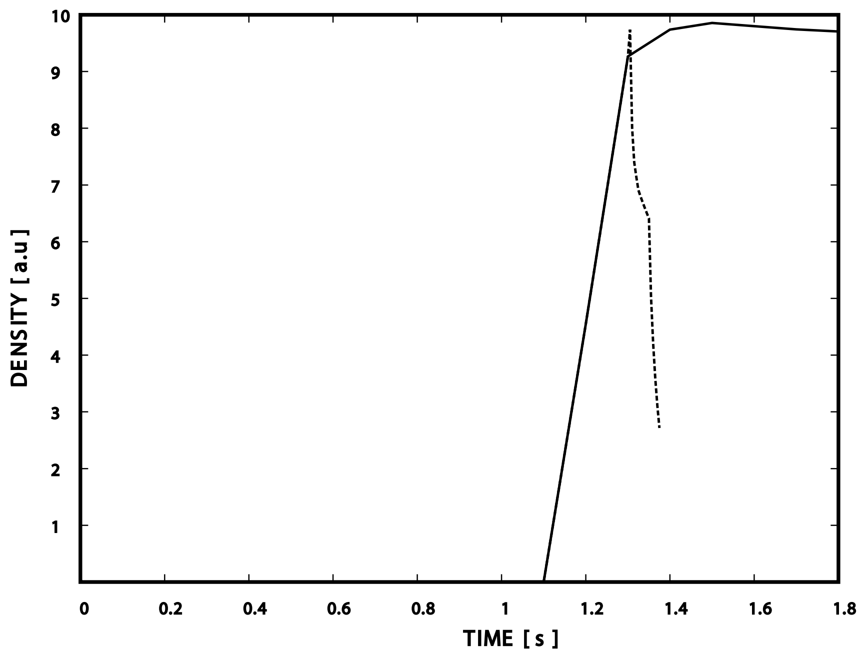

Figure 4: The time evolution of the total argon concentration in case density ratio $n_H/n_D = 0.47$: without ripple losses(solid line), with ripple losses (dash line)

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