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ABSTRACT

Recent experiments in JET have provided information on the potential of using majority RF heating schemes in large plasmas. Adopting a wide range of available diagnostics, the plasma behaviour was monitored. The main results of the experiments are that – due to the poor antenna coupling at low frequency, the low (Ohmic) plasma temperature and the reduced RF electric field amplitude near the ion-cyclotron resonance layer of the majority ions - ICRH alone is barely capable of heating the plasma. On the other hand, when preheating the plasma using neutral beam injection, the wave-plasma coupling is noticeably improved and considerable plasma heating, followed by increased neutron yield were observed in several diagnostics. This effect is not only attributed to the lower collisionality of the pre-heated plasma but also to the Doppler-shifted IC absorption of the fast beam ions. By studying the response of the plasma to sudden changes in the RF power level, the experimental power deposition profiles were determined and compared to theoretical predictions. The numerical modelling was done adopting a coupled wave / Fokker-Planck code that enables accounting for the non-Maxwellian distributions of the RF heated particles and the injected beam ions in the wave equation, and for the actual local RF fields in the Fokker-Planck description. The theoretical results confirm the experimental finding that the beam ions do play a crucial role in this heating scheme.

INTRODUCTION

The full-wave code CYRANO [1] has recently been upgraded to compute the complex RF dielectric response of plasma species with general (non-Maxwellian) particle distributions. The computations are based on the numerical evaluation of the residues (anti-Hermitian components) and the Cauchy principal values (Hermitian components) of the orbit-integrals in the constants-of-motion space [2]. Moreover, the CYRANO code has been coupled to the quasi-linear Fokker-Planck code BATCH [3] to allow self-consistent simulations of ICRH scenarios in tokamak plasmas. The integrated numerical procedure consists in looping the WAVE and QLFP codes and systematically updating their respective input data with the particle distributions / RF electric fields obtained in every iteration, until stationary solutions are achieved.

WAVE CODE RESULTS

The fundamental majority ICRH scenario recently investigated at JET [4] is a very convenient scenario from the numerical point of view, because most of the higher poloidal harmonics of the injected RF wave spectrum are evanescent throughout the plasma and short-wave branches are virtually absent.

Another characteristic of this heating scheme is its very low single-pass absorption, related to the fact that the E_+ component of the RF electric field is small close to the cold IC resonance layer, where most of the thermal ions interact with the RF wave [5]. A potential way to increase the absorption efficiency of this type of scenario is the injection of high energy beam particles which, because of their enhanced Doppler-shift $k_{//}v_{//}$, will absorb the RF power far away from the region where E_+ is small. The importance of this effect was noticed during the experiment and was confirmed by the numerical simulations, which have shown that in the case of JET the 130keV beam ions may absorb RF power as far as 0.6m away from their cold IC resonance layer.

In Fig.1 the power absorption profiles per species obtained with the CYRANO code for the D majority ICRH experimental conditions at JET are shown (various lines). The main parameters correspond to pulse #68733 (B_0=3.3T, I_P=2MA, f=25MHz, dipole) and the solution was normalized to a total of P_{RF}=2MW absorbed in the plasma. The adopted radial density profile of the beam is consistent with the PENCIL code results and the velocity distributions of the beam particles at several magnetic surfaces were imported from the BATCH code, where an ion source representing the tangential neutral-beam injection at JET was adopted (see Fig.2a). The percentages in the legend indicate the power fraction absorbed by each plasma species. Note that the RF power deposition of the beam ions is maximum around ρ=0.5m (with the cold IC resonance position near the magnetic axis) and that the beam absorbs about half of the total RF power even at relatively low concentrations ($n_{beam} / n_e \approx 0.08$).

The experimental estimative of the RF power densities absorbed by the electrons (●) and the ions (■) in pulse #68733 are also represented in Fig.1. They were obtained by applying an improved break-in-slope analysis [6] to the ECE and charge-exchange (CX) diagnostic signals, respectively, and were normalized to the same total RF power considered in the simulations (P_{RF}=2MW). Note that the region of maximum power absorption obtained experimentally essentially agrees with the theoretical predictions, indicating that the RF field structure computed by CYRANO is representing well the experimental conditions. Furthermore, one can see the signature of the Doppler-shifted beam heating near ρ=0.5m in the CX profile, also in good agreement with the beam absorption obtained in the simulations. As a matter of fact, such a good agreement between the theoretical and the experimental results is surprising, since the wave modelling was done considering only the dominant toroidal mode (N=-27) and the beam source description in the QLFP code is likely to be over-simplified (δ-function).

QLFP RESULTS

The results of the QLFP simulations indicate that the beam particles indeed absorb a significant amount of the applied RF power in the D majority experiments at JET, although only a small fraction of the injected ions are accelerated to energies beyond the source energy (130keV) for the RF power levels available in the experiment. This effect is illustrated in Fig.2, where the energy densities ($\varepsilon = f_0 \times mv^2/2$) associated to the beam ions for the case of a 'non-heated' beam (a) and an 'RF-heated' beam (b) with P_{RF}=2MW are represented as function of the constants of motion $v = \sqrt{2E/m}$ and $x_n = -\, sign(v_{//})(1 - x / x_{max})$, x being the normalized magnetic moment. The RF fields provided by the CYRANO code were used in the computations of Fig.2b.

It is clear from Fig.2b that the RF-induced energy tail for this case is rather modest (E≤200keV), what is in agreement with the experimental results obtained with the neutral particle analyzer (NPA) and with the neutron diagnostics [4]. This somewhat restricted ion acceleration results from a combination of the low RF power densities available in the experiment and the ‘high’ Deuterium mass.

Initial efforts to link the energy densities obtained with the coupled CYRANO/BATCH package with experimental data at JET are under way. Preliminary comparisons with the NPA results for shot #68733 indicate good qualitative agreement on the fast ion tail formation during the RF heating phase, but the fraction of the fast ions (E>130keV) for the ‘non-heated’ beam case obtained in the simulations seems underestimated. As mentioned, a first candidate to explain this difference is the highly idealized description of the beam source in the QLFP model (delta function). A more realistic numerical representation of the beam source is planned. Nevertheless, it is clear that many other ingredients have to be taken into account to allow a quantitative comparison between the modelling results and the experimental data, such as the line-of-sight of the measurements, the cross-sections of the reactions involved, the (x,v)−response of the diagnostics, etc.

CONCLUSIONS & DISCUSSION

The results of integrated full-wave / quasi-linear Fokker-Planck simulations have shown that due to their enhanced Doppler-shifts, the fast beam ions injected during combined NBI+ICRH experiments absorb RF power considerably far away from their cold ion-cyclotron resonance layer. This feature inspires special attention to the analysis of ICRH schemes where the beam species have a cold IC resonance layer inside the plasma, even if located far off-axis (e.g. ^{3}He minority ICRH).

For the Deuterium majority experiments recently performed at JET, in particular, the wave simulations using the beam distributions provided by the QLFP code indicate that the maximum beam absorption occurs roughly 0.5m off-axis (the cold IC resonance layer being roughly central) and that even at relatively small populations, the beam ions play a crucial role in improving the low absorption efficiency of this type of ICRH scenario. These results are in good agreement with the experimental observations. The QLFP simulations have shown that, for the RF power level available in the experiments (P_{RF}≤2MW), the RF-induced energy tail of the beam particles is restricted to E<200keV, corroborating the modest number of counts obtained by the neutral-particle analyzer and the neutron diagnostics above the beam source energy (130keV). Further efforts to allow a quantitative link between the modelling and the diagnostic results are under way.

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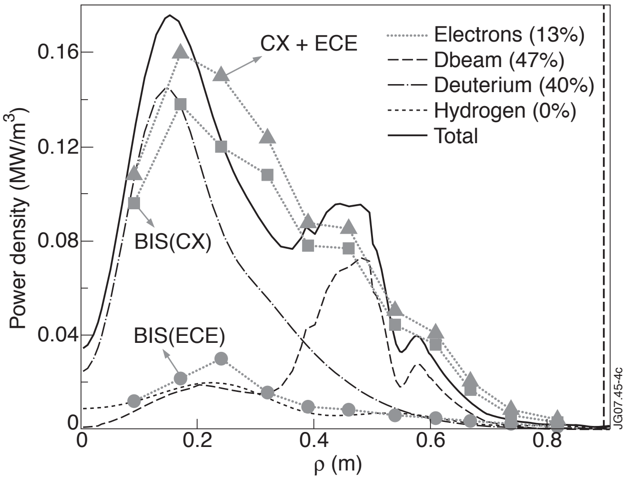

FIGURE 1: Power absorption profiles obtained with the CYRANO code for the fundamental D heating scenario in JET (#68733) together with the experimental power deposition profiles obtained by 'break-in-slope' analysis of the ECE (●) and CX (■) signals [6]. The beam distributions at various surfaces were imported from the QLFP BATCH code.

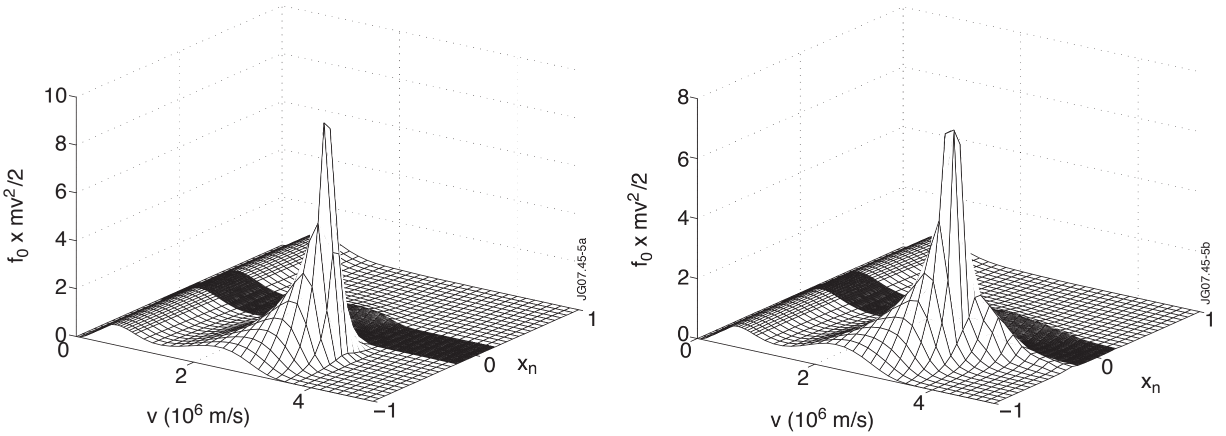

FIGURE 2: Energy distributions of the beam particles at ρ=0.4m obtained with the BATCH code for a 'non-heated' beam (a) and an 'RF-heated' beam (b) with P_{RF}=2MW. The beam source is at (130keV, 45°), roughly representing tangential neutral beam injection at JET.