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Evidence for a Wave induced Particle Pinch in the presence of Toroidally Asymmetric ICRF Waves

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ABSTRACT

First experimental observation of a Radio Frequency (RF) wave induced particle pinch has been made in experiments at the Joint European Torus (JET) with nearly on-axis ICRF (Ion Cyclotron Range of Frequencies) heating. Significant differences have been detected in discharges where the waves have been directed in opposite toroidal directions. In particular, fast ion driven Alfvén Eigenmode activity, sawtooth behavior and proton distribution functions have been found to be strongly affected. The analysis of the discharges using numerical 3D simulations of the distribution function of the resonating ions shows that the observed differences are consistent with an ICRF-induced particle pinch predicted by theory.

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Heating with waves in the Ion Cyclotron Range of Frequencies (ICRF) is one of the main methods for auxiliary heating of tokamak plasmas. On JET [1] ICRF is a well established method and its potential for heating of reactor plasmas was demonstrated during the recent deuterium-tritium (DT) campaign [2]. Each of the four ICRF antennae at JET consists of four straps. By applying different phasings to the currents in the straps, it is possible to launch waves not only with a symmetric but also with an asymmetric toroidal mode number spectrum. In this letter we present experimental evidence for a theoretically predicted wave induced particle pinch associated with asymmetric spectra.

The most commonly used asymmetric phasing at JET is obtained by having $+90^o$ or -90^o between the currents in two adjacent straps. For these phasings the toroidal mode number spectrum is asymmetric with a peak around the toroidal mode number $|N| = 16$ (see Fig. 14b in Ref. [3]). Furthermore, the wave propagation is mainly collinear to the toroidal magnetic field and the plasma current for the $+90^o$ phasing (Fig. 1).

Two major effects are predicted by theory in the presence of asymmetric spectra. Firstly, it is possible to produce Minority Current Drive (MCD) [4] which generates an asymmetry in the distribution of passing ions around the cyclotron layer. Experiments with asymmetric spectra and the off-axis cyclotron resonance near the q=1 surface have confirmed that MCD does exist and can be used to stabilize sawteeth [5, 6].

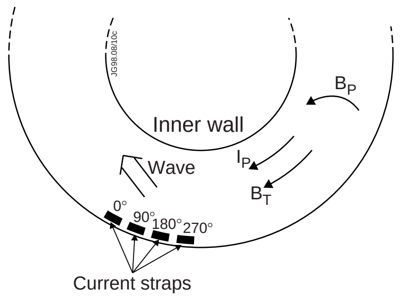


Fig. 1 Schematic view of the JET tokamak seen from above. The directions of the plasma current, I_p, *toroidal field,* B_T, *poloidal field,* B_p, *and the launched wave in the case of* $+90^o$ *phasing are shown.*

Secondly, there should be an inward or outward pinch of resonating trapped ions, depending on the direction of the antenna spectrum (i.e. on the sign of N) [7]. The ICRF-induced particle pinch arises because an ion interacting resonantly with a wave receives a change not only in its energy E but also in its toroidal angular momentum, $P_\varphi = mR\mathrm{v}_{\|}B_\varphi / B + Ze\psi$. Here, m is the mass and Ze is the charge of the resonating ion, R is the major radius, $\mathrm{v}_{\|}$ the particle velocity component parallel to the magnetic field, ψ is the poloidal flux (and a flux surface label), B_φ is the toroidal magnetic field, and B is the total magnetic field.

The wave particle interaction can be viewed as a diffusive process in phase space. Each time an ion crosses a resonance, where the Doppler shifted wave frequency is close to its cyclotron frequency, it receives a change in its energy ΔE_i, with a random sign. Owing to gradients of the ion distribution function in phase space (mainly that the distribution function decreases with energy), the average energy of the resonating ions increases during ICRF heating, i.e. $\sum_i \Delta E_i > 0$. Using Hamiltonian mechanics one can show that the change in P_φ is related to the change in the particle energy as $\Delta P_\varphi = (N/\omega)\ \Delta E$[6]. Thus, the average increase in the energy of the resonating ions leads to a drift in the positive or negative P_φ direction if the wave spectrum is asymmetric.

It is known that interaction with ICRF waves tends to increase the number of trapped ions which have a restricted poloidal movement due magnetic mirrors formed as a result of the poloidal variation of the magnetic field. At the turning point of a trapped ion $\mathrm{v}_{\|} = 0$ and hence the poloidal flux is equal to $P_\varphi/(Ze)$. Therefore, a change in P_φ gives rise to radial transport of trapped ions. Consequently, if the wave spectrum is asymmetric, there is also an inward or outward drift of the turning points of trapped ions. During on-axis (and nearly on-axis) heating the fast ion pressure profile should be more peaked when the drift is inwards, which corresponds to $+90^o$ phasing at JET, as compared to the case where the drift is outwards. Possible applications of this ICRF-induced particle pinch are to influence fusion reactivity [8, 9] and the MHD stability.

An overview of two JET discharges with $+90^o$ and -90^o phasing is shown in Fig. 2. In both discharges 10 MW of ICRF power was applied at a frequency of 42.4 MHz. Both discharges had about the same hydrogen concentration ($n_H/n_D \approx 1.5\%$), and a plasma current of 2.6MA and a toroidal magnetic field of 2.6 T were used in both discharges. As can be seen in the electron temperature traces in

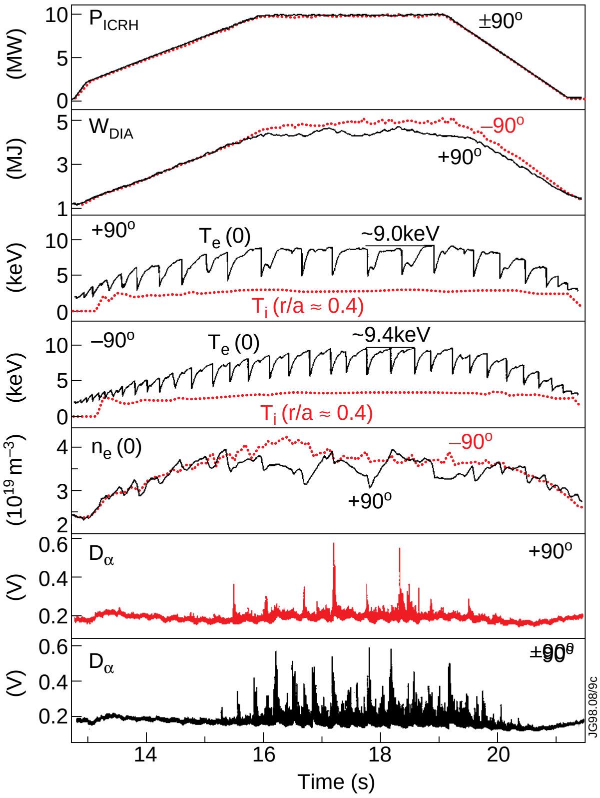
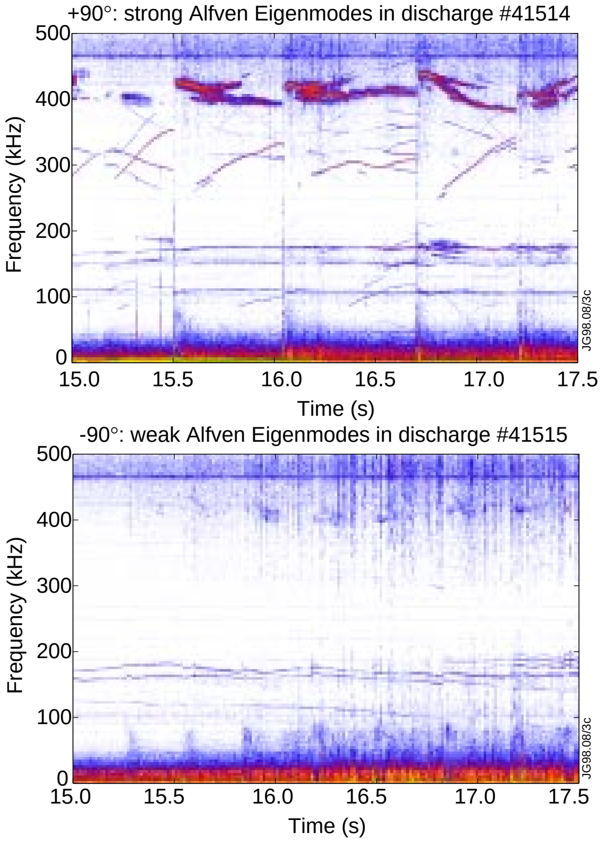


Fig. 2 ICRF power, diamagnetic plasma energy, central electron temperature, ion temperature measured at $r/a \approx 0.4$, *central electron density and* D_α *signal for two 2.6T/2.6MA JET discharges with* $+90^o$ *and* -90^o *phasings (discharges 41514 and 41515).*

Fig. 2, the sawtooth behavior is clearly different throughout the ICRF heating phase. In the case of +90^{o} phasing, the sawtooth period is longer, which is consistent with the stabilizing effect of a higher fast ion pressure in the plasma center [10]. The difference in the sawtooth behavior cannot be explained by MCD, since the fundamental hydrogen resonance was located on the high-field side at a normalized minor radius of $r/a \approx 0.25$, and not around the q=1 surface (sawtooth inversion radius at $r/a \approx 0.5$) as would be required for stabilization with MCD [5].

Important information on the fast ion distribution in the two discharges is provided by the MHD activity. Magnetic fluctuation spectrograms measured using an array of Mirnov coils at the plasma edge [11, 12] show $|\delta B|$ versus time and frequency in the frequency range of 0 to 500 kHz (Fig. 3). The high frequency activity at 400 kHz is identified as elliptical Alfvén eigenmodes excited by the ICRF-driven ions [13]. Much stronger activity is observed in the case of +90^{o} phasing.

A population of energetic ions can destabilize Alfvén eigenmodes (AE) if the product of the toroidal mode number and ion diamagnetic frequency exceeds the mode frequency [13]. The ion diamagnetic frequency is proportional to the radial gradient of the distribution of energetic ions and increases with the tail temperature. This suggests that the +90^{o} phasing generates a tail of energetic ions with a higher energy, and with a more peaked radial pressure profile, sufficient to excite Alfvén eigenmodes with high frequencies. The –90^{o} phasing, on the other hand, seems to create a broader radial distribution of ions with a lower energy.


+90°: strong Alfven Eigenmodes in discharge #41514

-90°: weak Alfven Eigenmodes in discharge #41515

Fig. 3 Spectrograms of MHD activity.

Earlier it has been established that for a symmetric toroidal mode number spectrum the AE excitation has a threshold at the ICRF power of about 4 MW at JET [11, 18]. In the case of +90^{o} phasing a strong AE activity is observed at an ICRF power of 10 MW, while in the case of –90^{o} phasing the AE activity barely appears. This suggests that the AE excitation threshold for –90^{o} phasing is much higher, about 10 MW, than the usual power threshold in the case of a symmetric spectrum.

The observed differences in the sawtooth behavior and the AE mode activity cannot be due to differences in the heating efficiency. In fact, measurements of the plasma stored energy using a diamagnetic loop indicate that the plasma energy content is somewhat higher and the energy confinement is somewhat better for –90° phasing (Fig. 2). This can be due to the fact that more frequent sawteeth with –90° phasing trigger more often (as can be seen from the D$_\alpha$ signals in Fig. 2) edge localized modes (ELMs), which are associated with improved confinement. It is also possible that the observed high frequency MHD activity in the case of +90° phasing affects the confinement of the thermal plasma and/or of the resonating fast ions.

Detailed information on the hydrogen minority distribution function is also given by the high-energy neutral particle analyzer (NPA) [14]. Figure 4 shows the proton distribution functions (in the NPA solid angle and integrated along the NPA line of sight) deduced from the NPA measurements for the two discharges, using the method outlined in Ref. [14]. For both discharges a time average over one sawtooth-free period is shown. As can be seen in Fig. 4, there are more fast ions in the range of 0.3–1.1 MeV in the case of +90° phasing.

Figure 5 displays the electron temperature profiles for the two discharges at t = 18.68 s when both discharges have reached a steady state after a sawtooth crash. As can be seen, the electron temperature profile in the case of –90° phasing is somewhat broader than in the +90° phasing case, but both have about the same central temperature. As the electron density is almost identical in the two discharges at this stage into the heating phase, the data suggests that the heating profile is somewhat broader for the –90° phasing.

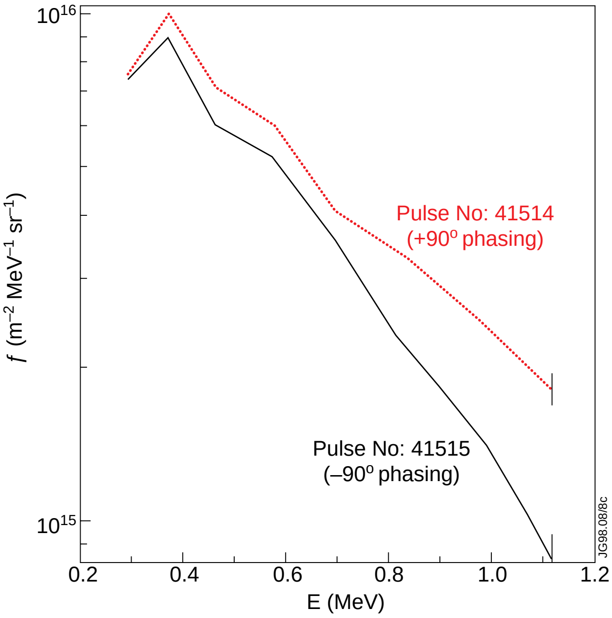


Fig. 4 Proton minority distribution functions deduced from NPA measurements using the method outlined in Ref. [14]. The impurity composition is assumed to be identical for both discharges [n(Be)/n(C)=0.4, n(He)/n(C)=0.6].

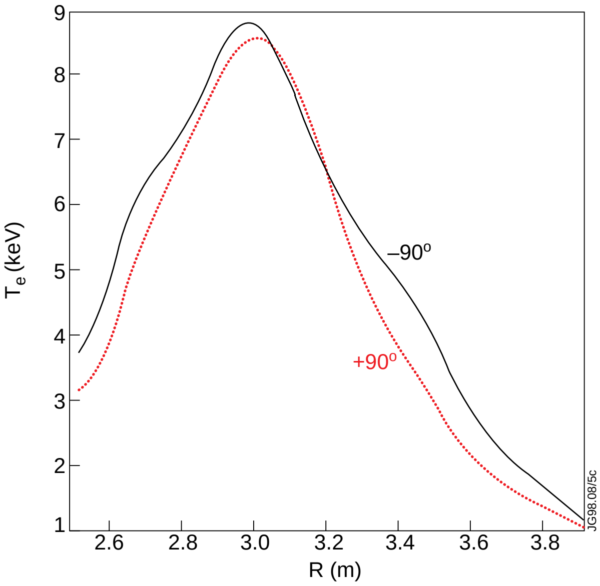


Fig. 5 Electron temperature profiles at t *= 18.68 s when both discharge are in a steady state after a sawtooth crash.*

Previously, the effects of symmetric ICRF spectra have been studied successfully with models based on 1D or 2D description of the fast ion velocity distribution function, which do not take into account radial transport of fast ions, see for example Ref. [15]. But because of the associated radial transport, the effects of asymmetric spectra can only be studied with full 3D simulations. We use the ICRF code FIDO [16] for the analysis. FIDO solves the velocity distribution function of resonating ions, f, with a 3D orbit-averaged Fokker-Planck equation [17] $\partial f/\partial t = \langle C(f)\rangle + \langle Q(f)\rangle$ using a Monte Carlo method. Here, <⋯> denotes averaging over a drift orbit, f is a function of three invariants of the unperturbed motion, C is the collision operator, and Q is a quasi-linear RF-operator.

The analysis has been done taking the input data from the JET experimental data base at t = 18.7 s for both discharges, and evolving the distribution function for 0.6 s (approximately for one sawtooth period in the case of $+90^o$ phasing). As can be seen in Fig. 6, the calculated fast ion pressure profile is more peaked in the case of the inward pinch ($+90^o$ phasing), which is consistent with the sawtooth and the AE behavior. The calculated fast ion energy content inside r/a = 0.5 is 0.45MJ and 0.9MJ in the case of outward and inward pinch, respectively. Furthermore, at the peak of the fast ion pressure the average energy reaches about 850 keV in the case of the inward pinch, but is only about 350 keV when the pinch is outwards. As the AE resonance with trapped fast ions can typically occur at ion energies of about 500 keV [18], the pressure gradient and the energy of fast ions in the inward drift case are large enough to excite AE modes, while in the outward drift case they are low and barely approach the values needed for the AE mode excitation.

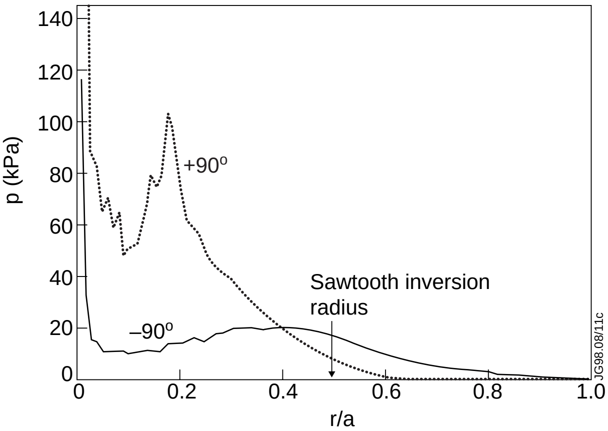


Fig. 6 Simulated fast ion pressure profiles.

To summarize, significant differences between ICRF-only heated discharges with $+90^o$ and -90^o phasing of the ICRF antennae have been observed during nearly on-axis hydrogen minority heating at the JET tokamak. These observations of the sawtooth behavior and AE modes are consistent with a theoretically predicted particle pinch which arises because of a fundamental relationship between the change in energy and toroidal angular momentum in an axisymmetric system. The results presented here clearly show that 3D modeling of the distribution function, taking into account effects of the theoretically predicted ICRF-induced particle pinch, is essential for simulating experiments with asymmetric spectra. Simulations with the 3D ICRF Monte-Carlo code FIDO show that the experimental differences are consistent with the theoretically predicted ICRF-induced particle pinch.

It is a pleasure to thank our colleagues at JET who have operated the tokamak, the heating systems and the diagnostics during these experiments.

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