Evidence for a Wave-Induced Particle Pinch in the Presence of Toroidally Asymmetric ICRF Waves

L.-G. Eriksson, M. Mantsinen,* D. Borba,† A. Fasoli,‡ R. Heeter,§ S. Sharapov, D. F. H. Start, J. Carlsson,‖ A. Gondhalekar, T. Hellsten,‖ and A. Korotkov

JET Joint Undertaking, Abingdon, Oxfordshire, United Kingdom

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The first experimental observation of a radio frequency (rf) wave-induced particle pinch of trapped ions has been made in experiments at the Joint European Torus with nearly on-axis high power toroidally asymmetric ICRF (ion cyclotron range of frequencies) heating. Significant differences have been detected in discharges when 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 shows that the observed differences are consistent with an ICRF-induced particle pinch predicted by theory. [S0031-9007(98)06753-2]

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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 campaign [2]. Each of the four ICRF antennas 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 $+90°$ or $-90°$ 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. 14(b) in Ref. [3]). Furthermore, the wave propagation is mainly collinear to the toroidal magnetic field and the plasma current for the $+90°$ phasing (Fig. 1).

Several effects are predicted by theory in the presence of toroidally asymmetric wave particle interaction. First, it is possible to produce minority current drive (MCD) [4]. Experiments with asymmetric spectra and the off-axis cyclotron resonance near the $q = 1$ surface have confirmed that MCD exists and can be used to stabilize sawteeth [5,6].

Second, a mechanism for inducing convective radial transport of resonating passing ions, i.e., ions with $v_\parallel \neq 0$ along their orbit, has been suggested [7]. Here $v_\parallel$ is the velocity component parallel to the magnetic field B. Experimental evidence for this effect has been presented [8]. However, in the case of strong ICRF heating, as in the experiments discussed in this Letter, the resonating ions are mainly trapped and the number of energetic passing ions involved in the radial transport described by the mechanism in Ref. [7] is small.

For trapped resonating ions another radial convective transport mechanism has been proposed [9], which depends on the direction of the antenna spectrum (i.e., on the sign of N). This ICRF-induced particle pinch arises because of a fundamental relationship between the change in energy E and toroidal angular momentum $P_\varphi = mRv_\parallel B_\varphi/B + Ze\psi$ an ion receives when it interacts resonantly with a wave. Here m is the mass and Ze is the charge of the resonating ion, R is the major radius, ψ is the poloidal flux (and a flux surface label), and B_φ is the toroidal magnetic field component.

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 f in phase space (mainly that f 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

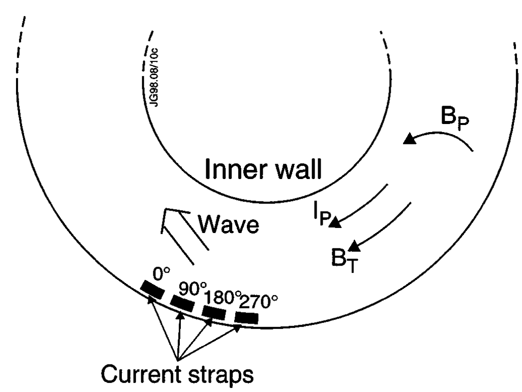

FIG. 1. Schematic view of the JET tokamak seen from above. The directions of the plasma current $I_{\rm P}$, toroidal field $B_{\rm T}$, poloidal field $B_{\rm P}$, and the launched wave in the case of $+90°$ phasing are shown.

the particle energy as $\Delta P_\varphi = (N/\omega)\Delta E$ [9]. 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. At the turning point of a trapped ion $v_\parallel = 0$, and hence $\psi = P_\varphi/(Ze)$. Therefore, a change in P_φ gives rise to radial transport of trapped ions. Consequently, if the wave spectrum is asymmetric, there is 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 $+90°$ phasing at JET, as compared to the case where the drift is outwards. Possible applications of the ICRF-induced particle pinch are to influence fusion reactivity [10,11] and the MHD stability.

An overview of two ICRF only JET discharges with $+90°$ and $-90°$ phasing is shown in Fig. 2. In both discharges 10 MW of ICRF power was applied at a frequency of 42.4 MHz, the hydrogen concentration was about $n_H/n_D \approx 1.5\%$, and a plasma current of 2.6 MA and a toroidal magnetic field of 2.6 T were used. The perpendicular fast ion energy content, estimated by taking the difference between two different measurements of the plasma stored energy [12], was about 1 MJ in the two discharges. This indicates the presence of a substantial population of fast trapped ions.

As can be seen from the electron temperatures in Fig. 2, the sawtooth behavior is clearly different throughout the ICRF heating phase. In the case of $+90°$ phasing, the sawtooth period is longer, which is consistent with the stabilizing effect of a higher fast ion pressure in the plasma center [13]. 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 [14,15] 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 [16]. Much stronger activity is observed in the case of $+90°$ phasing.

Energetic ions can destabilize Alfvén eigenmodes (AE), with the drive being proportional to the radial pressure gradient of the energetic ions, if the product of the toroidal mode number and ion diamagnetic frequency exceeds the mode frequency [16]. The ion diamagnetic frequency is

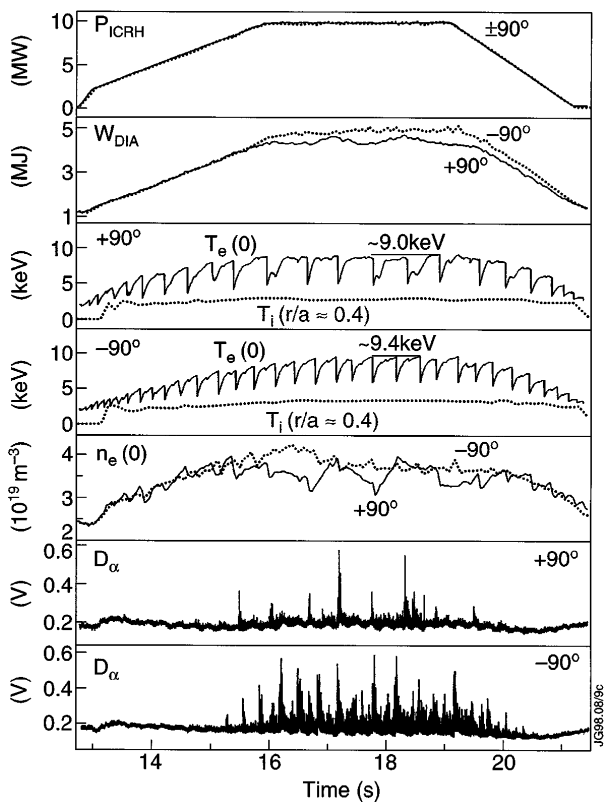

FIG. 2. ICRF power, diamagnetic plasma energy, central electron temperature, ion temperature at $r/a \approx 0.4$, central electron density, and D_α signal for two JET discharges with $+90°$ and $-90°$ phasings (discharges 41 514 and 41 515).

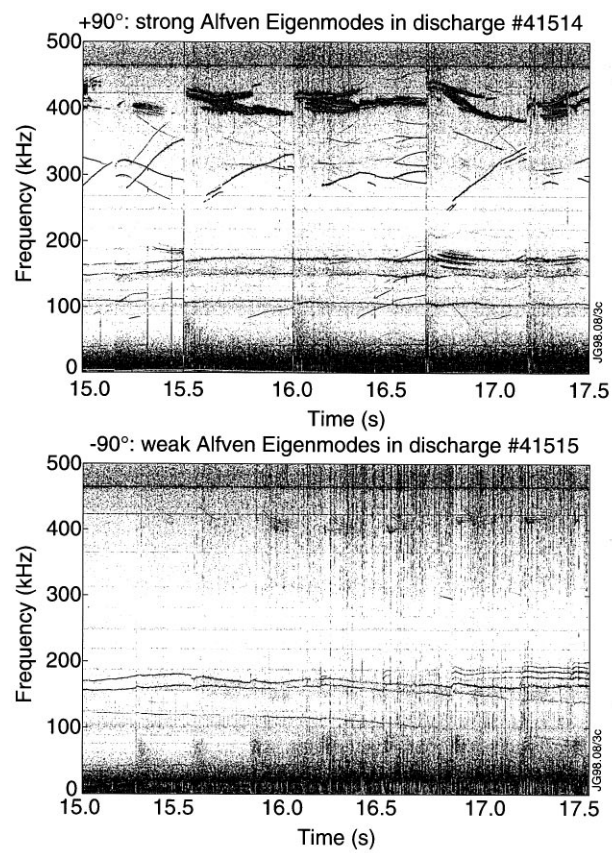

FIG. 3. Spectrograms of MHD activity.

proportional to the radial gradient of the distribution of energetic ions and increases with the tail temperature. This suggests that the $+90°$ phasing generates a more peaked radial pressure profile, and a tail of energetic ions with a higher energy, sufficient to excite AE with high frequencies. The $-90°$ phasing, on the other hand, creates a broader radial distribution of ions with a lower energy.

Earlier it was 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 [14,17]. In the case of $+90°$ phasing a strong AE activity is observed at an ICRF power of 10 MW, while in the case of $-90°$ phasing the AE activity barely appears. This suggests that the AE excitation threshold for $-90°$ 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, the plasma energy content measured using a diamagnetic loop 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 (cf. the D_α signals in Fig. 2) edge localized modes, 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. The stochastic diffusion of fast ions in the case of the observed multiple AE can be of the order of the neoclassical diffusivity [18].

Detailed information on the proton distribution function is also given by the high-energy neutral particle analyzer (NPA) [19]. Figure 4 shows the distribution functions (in the NPA solid angle and integrated along the NPA line of sight) deduced [19] from the NPA measurements for the two discharges. For both discharges a time average over one sawtooth-free period is shown. As can be seen in Fig. 4, there are more fast protons 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. The electron temperature profile for $-90°$ phasing is somewhat broader than for $+90°$ phasing. As the electron density is almost identical in the two discharges at this stage into the heating phase, the data suggest that the heating profile is somewhat broader for the $-90°$ phasing.

Previously, the effects of symmetric ICRF spectra have been studied successfully with models based on a 1D or 2D description of the fast ion velocity distribution function, which do not take into account radial transport of fast ions; see, e.g., Ref. [12]. But because of the associated radial transport, the effects of asymmetric spectra can be studied only with full 3D simulations. We use the ICRF code FIDO [20] for the analysis. FIDO solves the velocity distribution function of resonating ions with a 3D orbit-averaged Fokker-Planck equation [21] $\partial f/\partial t = \langle C(f)\rangle + \langle Q(f)\rangle$ using a Monte Carlo method. Here $\langle\cdots\rangle$ denotes averaging over a drift orbit, C is the collision operator, and Q is a quasilinear rf operator.

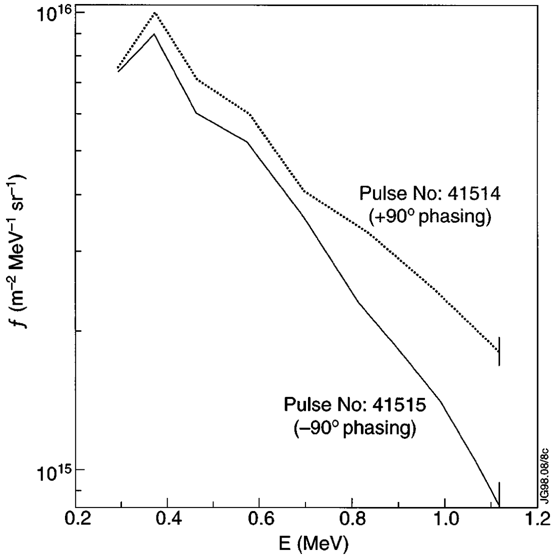

FIG. 4. Proton distribution functions deduced from NPA measurements. The impurity composition is assumed to be identical for both discharges [$n(\mathrm{Be})/n(\mathrm{C}) = 0.4, n(\mathrm{He})/n(\mathrm{C}) = 0.6$].

The analysis has been done taking the input data from the JET experimental database 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 $+90°$ phasing). The profile of the wave electric field has been adjusted so that the ICRF power deposition profile is consistent with the PION code [12]. As can be seen in Fig. 6, the calculated fast ion pressure profile is more peaked in the case of the inward pinch ($+90°$ phasing), which is consistent with the sawtooth and the

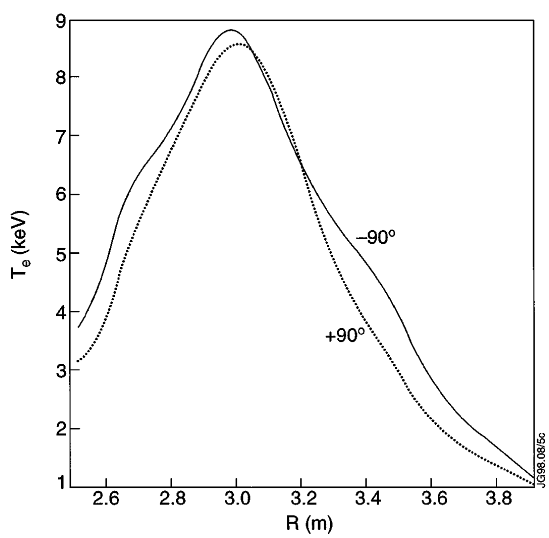

FIG. 5. Electron temperature profiles at $t = 18.68$ s when both discharges are in a steady state after a sawtooth crash.

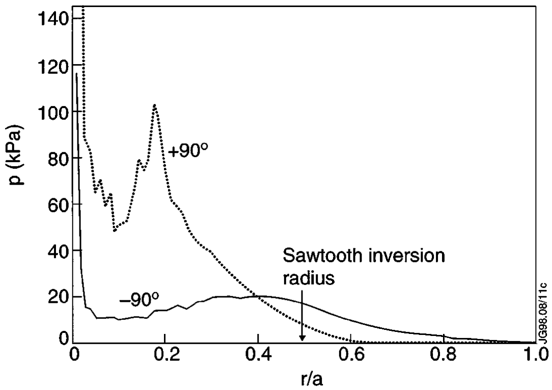

FIG. 6. Simulated fast ion pressure profiles.

AE behavior. The calculated fast ion energy content inside $r/a = 0.5$ is 0.45 and 0.9 MJ 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 [17], 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.

It should be noted that differences in the calculated fast ion pressure profiles between $+90°$ and symmetric phasing are much smaller than compared to $-90°$, which is consistent with experimental findings. The main reason is that for $+90°$ and symmetric phasings most of the fast ions have wide nonstandard orbits which pass near the plasma center, whereas for $-90°$ phasing standard banana orbits which do not pass near the plasma center dominate.

To summarize, significant differences between ICRF-only heated discharges with $+90°$ and $-90°$ phasing of the ICRF antennas have been observed during nearly on-axis hydrogen minority heating at the JET tokamak. The observations 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.

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*Also at Association Euratom-TEKES, Helsinki University of Technology, Espoo, Finland.
†Also at Association EURATOM/IST, Lisbon, Portugal.
‡Also at CRPP-EPFL, Association Euratom-Swiss Confederation, Lausanne, Switzerland.
Present address: MIT, Cambridge, MA 02139.
§Also at Princeton Plasma Physics Laboratory, Princeton, NJ 08543.
‖Permanent address: Royal Institute of Technology, Stockholm, Sweden.

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