Plasma Rotation Induced by Directed Waves in the Ion-Cyclotron Range of Frequencies

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Changes of the toroidal plasma rotation induced by directed waves in the ion-cyclotron range of frequencies (ICRF) have been identified experimentally for the first time on the JET tokamak. The momentum carried by the waves is initially absorbed by fast resonating ions, which subsequently transfer it to the bulk plasma. Thus, the results provide evidence for the influence of ICRF heated fast ions on plasma rotation.

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Plasma rotation can have beneficial effects on the performance of tokamak plasmas. It can increase the stabilizing effect of a resistive wall [1]; and shear in the toroidal velocity component associated with the radial electric field can suppress turbulence and thereby create transport barriers; see, e.g., [2,3]. It is therefore important to investigate mechanisms for plasma rotation.

In present day tokamak experiments, the momentum imparted by neutral beam injection (NBI) heating induces significant toroidal plasma rotation. If NBI is used in a fusion reactor it will require very high injection energies, $E_{\rm inj}$, leading to a fairly modest imparted momentum ($\sim P_{\rm inj}/E_{\rm inj}^{1/2}$). It is therefore of interest to study other methods for generating rotation. One possibility is to use directed (or traveling) waves in the ion-cyclotron range of frequencies (ICRF); see, e.g., Ref. [4]. Such waves provide much less total torque than NBI. Nevertheless, the peak torque density provided by the waves would not necessarily be small since the power deposition tends to be much narrower for ICRF heating than for NBI. Furthermore, the direction and location of the ICRF torque can be varied. The latter is controlled by the frequency since the absorption is concentrated to the vicinity of the cyclotron resonance, $\omega = n\omega_{ci}(R)$ (n is the resonant harmonic number and R is the major radius of the tokamak). Measurements of rotation profiles in plasmas with directed ICRF waves have been reported in [5]. However, the experiments were mainly designed for studying the influence of the cyclotron resonance position on rotation, and far off-axis resonances were used. As a result, only a very weak influence of the propagation direction was observed, and the differences could not be identified as being directly due to the ICRF torque.

In this Letter we present the first experimental evidence, consistent with theoretical expectations, for a direct influence of absorbed ICRF wave momentum on plasma rotation in the JET tokamak. Fast resonating ions act like an intermediary in the process; they first absorb the wave momentum and subsequently transfer it to the bulk plasma via collisions and by being displaced radially. Thus, our results provide evidence for the influence of fast ICRF heated ions on plasma rotation

The theoretical background can be summarized as follows. An ion absorbing a wave quantum changes its energy and toroidal angular momentum by $\Delta E = \hbar\omega$ and $\Delta P_\varphi = \hbar k_\varphi R = \hbar N$, respectively, where N is the toroidal mode number, yielding $\Delta P_\varphi = (N/\omega)\Delta E$ (the equation of motion and Maxwell's equations yield the same result). Thus, the rate at which the waves impart toroidal angular momentum to the plasma is given by $\sum_N (N/\omega)P_{\rm ICRF}(N)$, where $P_{\rm ICRF}(N)$ is the power coupled by the antennas for toroidal mode number N. The fast ions transfer the momentum to the bulk plasma via two mechanisms: collisions and a radial fast ion current. In the latter case, the plasma strives to preserve quasineutrality. Consequently, the fast ion radial current is compensated for by an opposite current in the bulk plasma, resulting in a $\vec{j} \times \vec{B}$ force on the bulk plasma. An outward/inward fast ion current produces a countercurrent/cocurrent torque on the bulk plasma. Cocurrent propagating waves lead to a drift of the turning points of resonating trapped ions towards the equatorial plane [6,7], and many of these ions will eventually detrap into copassing orbits in the potato regime [6,8,9]. The torque on the bulk plasma should then be dominated by collisions with copassing ions in the potato regime and the inward current of fast trapped resonating ions. In contrast, for countercurrent propagating waves, the turning points of resonating trapped fast ions are driven away from the equatorial plane, and the momentum is largely transferred via the associated outward fast ion current.

The JET tokamak is equipped with four ICRF antennas, and each has four current carrying straps. In the experiments reported here the phase difference between the currents in adjacent straps was either $+90°$ or $-90°$; $+90°/-90°$ phasing produces waves propagating predominantly in the cocurrent/countercurrent direction. Typical toroidal mode number spectra can be found in Ref. [10]. The locations of the peaks of these spectra are relatively insensitive to the heating scenario, and appear roughly at $N = \pm 12$ for $\pm 90°$ phasing. Minority heating of ^{3}He in a deuterium plasma, (^{3}He)D ($n_{\rm He}/n_{\rm D} \sim$ 1%–3%) with $f = 37$ MHz was used in the experiments, the current and magnetic field were 1.8 MA and 3.4 T, respectively, locating the ^{3}He cyclotron resonance slightly on the high field side ($\sim$ 20 cm).

A perturbative technique using short diagnostic NBI pulses (200 ms), was used to measure the toroidal rotation profile. It was deduced from the Doppler shift of the active charge exchange spectrum for C^{+6} [11]. By considering only the first spectrum taken after the application of a beam pulse, the NBI perturbation of the rotation should be small [5]. The behavior of the fast resonating ions was diagnosed with the gamma-ray profile monitor installed in JET. It has nine vertical and ten horizontal lines of sight [12], and is especially suited for monitoring reactions produced by fast ^{3}He ions interacting with carbon and beryllium impurities.

An overview of essential discharge parameters is shown for two discharges, $+90°$ and $-90°$ phasing, respectively, in Fig. 1. The applied ICRF power, NBI diagnostic pulses and plasma central density were virtually equal in the two ICRF only discharges. There are small differences in the diamagnetic stored energies and somewhat larger differences in the central electron temperature, consistent with an inward/outward drift of the fast ions during heating with $+90°/-90°$ phasing [6–9]. The stored energy of a reference discharge with $+90°$ phasing where 2 MW ICRF power has been replaced by 2 MW of lower hybrid (LH) heating in the high power phase is also shown in Fig. 1. This discharge has a lower stored energy than the other two, which is the case also when the fast ion energy content, estimated to be 0.2–0.3 MJ (at the lower end for the discharge with LH), is subtracted. This is not unexpected since LH provides direct electron heating and deposes the power further off axis than ICRF heating. The measured toroidal rotation and ion pressure profiles for the three discharges taken at 11 s are shown in Fig. 2 (note that the magnetic

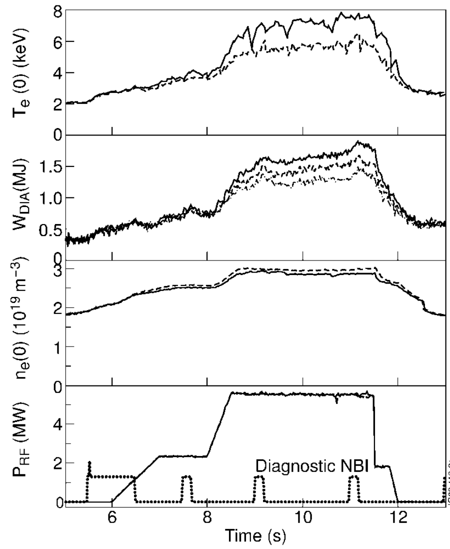

FIG. 1. Overview of two discharges using the (^{3}He)D heating scheme, one with $+90°$ phasing (#57307), (solid line), and the other with $-90°$ (#57303), (dashed line). (a) Electron temperature, (b) diamagnetic stored energy, including for the discharge with 2 MW LH power (#57308), (dot-dashed line, lower trace), (c) central electron density, (d) ICRF power and NBI power for the diagnostic beam.

axis is at $R \approx 3$ m). The profiles show plasma rotation in the cocurrent direction. However, the discharge with $+90°$ phasing rotates significantly faster in the cocurrent direction in most of the plasma than the $-90°$ discharge. Since $+90°$ phasing produces cocurrent propagating waves, this result is qualitatively consistent with an ICRF torque on the plasma. The rotation velocity for the reference discharge with LH heating lies in between the other two. The LH waves are directed, but carry only about 10% of the momentum of the $+90°$ ICRF waves for equal power. The ion pressure profiles for the $+90°$ and $-90°$ discharges are very similar, and the discharge with LH power has somewhat lower ion pressure. From these facts we conclude that the stronger rotation for $+90°$ phasing is not due to a higher stored energy or stronger ion pressure (otherwise the discharge with LH heating should have rotated less than the $-90°$ discharge), cf. [13–15]. Thus, we can be fairly confident that the difference in rotation profiles between the $+90°$ and $-90°$ ICRF only discharges is due to the absorbed wave momentum. The rotation profiles shown in Fig. 2 are those of the carbon impurities and not the main ion species deuterium. An analysis with the method described in Ref. [16] shows that the difference $\Delta\omega = \omega_{\phi \rm D} - \omega_{\phi \rm C}$ is 0.4–0.5 krad/s for $R > 3.2$ m. Most importantly, $|\Delta\omega(+90^\circ) - \Delta\omega(-90^\circ)| < 0.05$ krad/s everywhere; i.e., $\Delta\omega$ has virtually no effect on the difference in rotation between $+90°$ and $-90°$ phasing. Thus, the experimental observations are consistent with an underlying mechanism giving rise to cocurrent rotation, and an overlaid torque from the absorbed wave momentum.

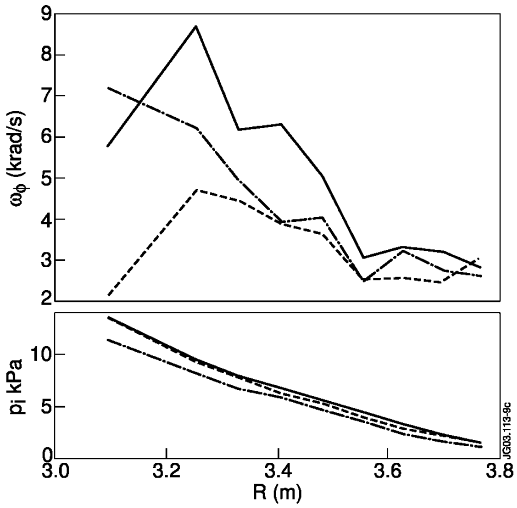

FIG. 2. Carbon impurity rotation profiles and ion pressure profiles for the discharges in Fig. 1: +90° (solid line), −90° (dashed line), and the discharge with 2 MW of LH power (dot-dashed line).

Figures 3(a) and 3(b) show signals from seven vertical lines of sights of the gamma-ray detector for the two discharges with +90° and −90° phasing. The signals are normalized to their highest value, and are shown as functions of the major radius where the sight line crosses the midplane. In the discharge with +90° phasing the emission is slightly displaced towards the low field side of the magnetic axis, and it has an almost symmetrical shape. By contrast, the −90° discharge has a more asymmetrical emission, weighted towards the high field side; cf. [7,9]. The latter is consistent with a strong population of fast trapped ions with turning points on the high field side. Such ions spend most of their time close to their turning points, and their contribution to the emission is therefore strongest on the high field side. On the other hand, because of the symmetrical shape of the emission for the +90° case, one can conjecture that it is dominated by contributions from fast passing ions in the potato regime [17]. The presence of such ions is consistent with theoretical expectations [6,8]. Thus, the theoretical picture discussed above appears to be at least qualitatively correct. The cocurrent torque in the center for +90° heating is mainly transferred to the bulk plasma by collision with fast passing ions in the potato regime and the inward drift of trapped ions. An outward current of trapped ions plays a key role for the countercurrent torque during −90° heating. Note that passing orbits in the potato regime play an important role also in theories [18–20] on rotation in plasmas with little or no external momentum injection.

We have used the SELFO code [21] to assess the quantitative agreement between experiments and theory. It calculates the ICRF power deposition and the distribution function of the resonating ions self-consistently, and returns the fast ion collisional and $R\vec{j} \times \vec{B}$ torques. Owing to a lack of information on the details of the momentum transport in the plasma (likely to be anomalous), we use a simple transport model, $n_i m_i \partial V_\varphi / \partial t = g^{-1/2}(\partial/\partial\rho)[g^{-1/2} n_i m_i D \partial V_\varphi/\partial\rho] + T_f + T_o$, where V_φ is the rotation velocity, m_i and n_i are the masses and densities of the plasma ion species, ρ is a radial coordinate, $g^{-1/2}$ is the Jacobian, T_f is the fast ion torque density, T_o is a torque density of other mechanisms, and D is a momentum diffusion coefficient taken to have the radial dependence used in Ref. [4], i.e., $D = D_0(q(\rho)/q_0)^2$, where q is the safety factor. The value of D_0 is adjusted so that the momentum confinement time is equal to the thermal energy confinement time τ_{Eth}. Here τ_{Eth} has been calculated by subtracting the estimated fast ion energy content (~ 0.3 MJ) from the measured diamagnetic stored energy, resulting in $\tau_{Eth} \approx 0.2s$. Since the momentum diffusion equation is linear, we can write $V_\varphi = V_{\varphi f} + V_{\varphi o}$, i.e., the sum of contributions from T_f and T_o. Inserting the simulated fast ion torque density

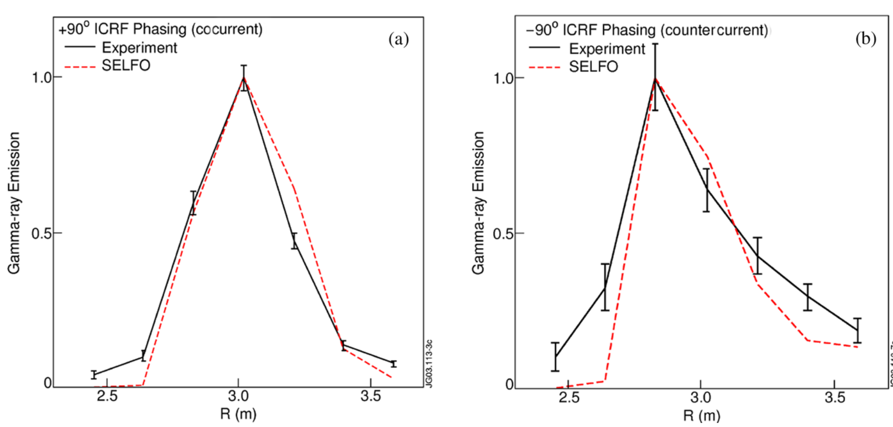

FIG. 3 (color online). Normalized gamma-ray emission from seven central vertical detectors as a function of the major radius where the sight lines intersects the midplane. (a) +90° phasing, (b) −90° phasing, measured (solid line) and simulated (dashed line).

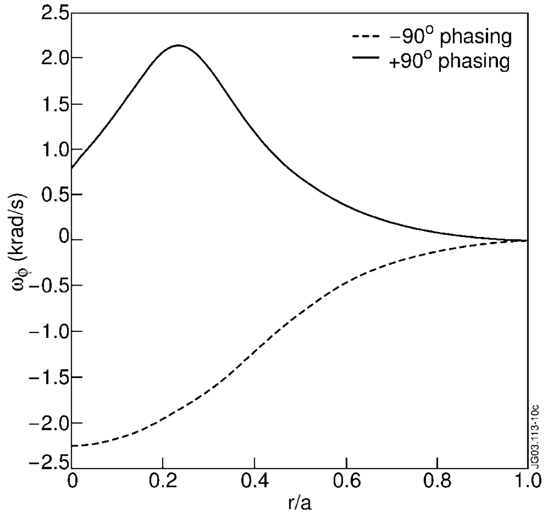

FIG. 4. The rotation profiles, $\omega_{\varphi f} = V_{\varphi f}/R$, resulting from inserting the fast ion torques simulated by the SELFO code in the momentum diffusion equation.

into the momentum diffusion equation gives the rotation frequencies, $\omega_{\varphi f} = V_{\varphi f}/R$, displayed in Fig. 4. The difference is of the order of 4 krad/s at $R = 3.2$ m, in good agreement with the experiment (a finite T_o, similar for the two discharges, is needed to simulate the underlying cocurrent rotation).

The characteristics of the resonating fast ions in the SELFO simulation are also broadly consistent with the experimental gamma-ray emission. The calculated fast ion distribution function has been used to simulate the response of the seven central gamma-ray detectors, the results have been added to Figs. 3(a) and 3(b). The spatial distribution of the measured and calculated gamma rays have very similar features. However, the ratio between the peak emissions for $+90°$ and $-90°$ phasing is roughly four experimentally and two in the simulations. This is probably due to a too low concentration of ^{3}He ions in the center of the plasmas in the $+90°$ simulation, caused by the pump out of resonating ions and a too weak transport of thermal ^{3}He ions (there is no anomalous transport in SELFO). Furthermore, an increase of the ^{3}He concentration in the SELFO simulation for the $-90°$ case brings down the gamma-ray emission to the experimental level with only a very marginal change in the rotation. The calculations show that the peak of the emission on the high field side for $-90°$ phasing is due to resonating trapped ions and that the more symmetric emission for $+90°$ is largely due to cocurrent passing orbits in the potato regime, indicating their importance for the central fast ion cocurrent torque.

In summary, we have presented evidence for the influence of directed ICRF waves on toroidal plasma rotation (and velocity shear) in the JET tokamak. The resonating fast ions play a key role by transferring the absorbed wave momentum to the background plasma, and the experimental results are consistent with the theoretical picture of momentum transfer via collisions and fast ion radial currents induced by the wave absorption. The change in the rotation induced by the waves is found to be overlaid on an underlying mechanism giving rise to cocurrent rotation.

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