ICRF induced intrinsic plasma rotation in ASDEX Upgrade

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Introduction

Plasma rotation is of very great interest for tokamak plasma confinement and MHD stability. Plasma rotation and velocity shear are important for the formation of internal transport barriers, the transition to H-mode, and the suppression of resistive wall modes in tokamaks [1-3].

The plasma rotation is determined by the net momentum balance. Any sinks or sources of the momentum influence the plasma rotation. Different factors can act as sinks or sources such as, plasma viscosity and inertia, magnetohydrodynamic and kinetic activity, and turbulence. Neutral beam injection (NBI) heating is also a particularly strong source of momentum [4]. There is an effect of electron cyclotron heating (ECH) on the momentum and particle transport and thus, on the toroidal plasma rotation [5]. Ion cyclotron resonance frequency (ICRF) heating can also be a source of momentum in plasmas. There are various mechanisms by which ICRF heating can contribute. In the case of an asymmetry in the $k_{||}$ component of the launched wave in the ion cyclotron range of frequencies the momentum can be transferred to the plasma directly from the wave [6]. However, ICRF can also influence the rotation of the plasma in the case of a symmetrical $k_{||}$ spectrum of the launched wave. In this case the rotation is assumed to be intrinsic as no direct momentum input is applied. The effect of RF heating on intrinsic rotation is of particular interest since in large magnetic confinement devices, like ITER, the external momentum input from NBI will be relatively small.

In this work we investigate the behavior of the plasma in the ASDEX Upgrade tokamak in H minority ICRF heated discharges with symmetrical $k_{||}$ spectra and negligible external momentum input from NBI. Specifically, we investigate the contribution of the omnigenity breaking mechanism [7,8] on rotation profiles in ASDEX Upgrade plasmas, keeping in mind the fact that the rotation profiles in tokamaks can be defined by other mechanisms. For example if a significant portion of the ICRH power is absorbed by electrons intrinsic torque mechanisms similar to those presented in [5] can play a big role.

Experiment description

A series of shots were performed using the ICRF H-minority heating scheme at 36.5MHz with applied power levels between 2 and 5.5MW and a symmetric antenna spectrum, the plasma current, I_p, was 600kA. The purpose of these discharges was to investigate the effect of the ICRF resonance position on the plasma rotation. Three values of the toroidal magnetic field were tested: B_0=2.48T, which corresponds to a central H-resonance position, and two

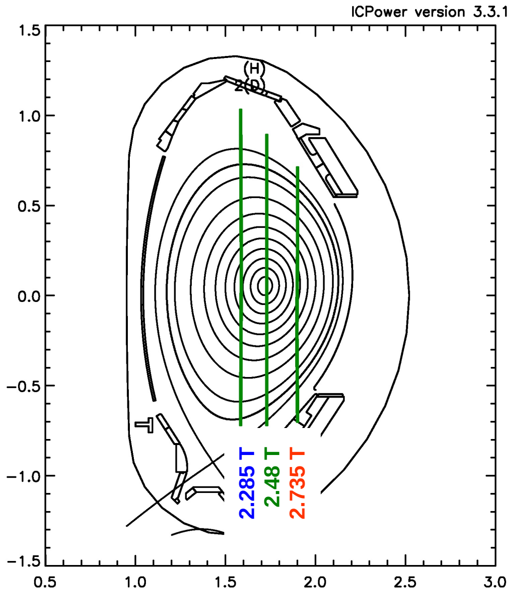

Fig.1. ASDEX Upgrade poloidal cross section with H (or 2nd D) resonance positions for B_0= 2.48, 2.285, and 2.735T

off-axis cases B_0=2.285T and 2.735T. In the two latter cases the resonance position was shifted by ~14cm to the high field side (HFS) and ~19cm to the low field side (LFS) respectively (fig.1). The plasma line averaged core density was n_e=6.0x10^{19}m^{-3} in the discharges with the lowest and middle toroidal magnetic fields and in the discharge with the highest magnetic field, the density was n_e=4.4x10^{19}m^{-3}.

The rotation velocity measurements were performed using charge exchange recombination spectroscopy (CXRS), which measures the fully stripped boron population using the B^{4+} CX line at λ=494.467nm. The system can image up to 25 radially distributed points. Recent upgrades to the diagnostic allow measurements to be made with integration times as short as 4ms. Short (16ms) NBI blips, were applied to the ICRH only heated plasmas enabling the CXRS measurement of the toroidal rotation. The increase in plasma rotation caused by the NBI blips is observed to be linear for the first 12-16ms; allowing the intrinsic rotation to be determined by backwards extrapolation of the rotation profiles measured during the NBI blip.

Results

In fig.2 three different rotation profiles for different H-minority resonance positions are shown together with the density and ion and electron temperatures profiles. In all three cases the ICRF heating power, P_{ICRF}, was 5.5MW. Positive (negative) values of the plasma rotation velocity correspond to the co-current (counter-current) rotation direction.

In order to explain the observed behavior of the plasma rotation we consider the rotation mechanism based on the omnigenity breaking of banana-shape trajectories of trapped fast ions suggested by Chang [7,8]. According to this theory the trapped fast ion population can provide counter-current contribution to plasma rotation. No momentum is transferred directly to the plasma from the ICRF wave. The resulting momentum contribution occurs due to differences in the toroidal momentum loss rates for the main and fast resonant ions; thus, we refer to this as intrinsic rotation. We are not discussing here the effect of passing resonant ions and consider a contribution only from fast trapped ions because, according to Chang's theory, in the case of symmetrical $k_{||}$ the contribution of co-passing and counter passing ions compensates and has no influence on the rotation profile.

There are two ways in which ICRF heating affects the trapped fast ion distribution in the plasma in the case of symmetrical $k_{||}$ spectra. First, is the conversion of the passing ions to trapped ones by increasing the perpendicular velocity. Second, is the modification of the fast

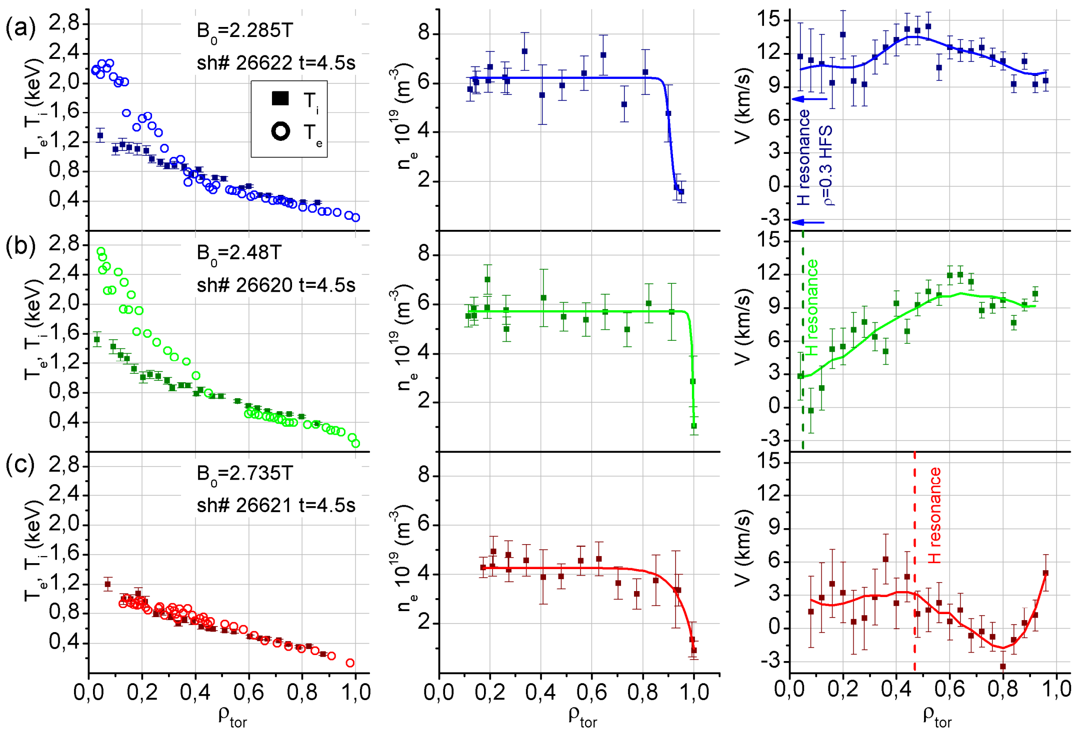

Fig.2. Electron and ion temperature profiles (ECE and CXRS diagnostics), density (Thomson scattering) and toroidal rotation (CXRS) profiles for different B_0 values. I_p=600kA, P_{ICRH}=5.5MW.

ions banana orbits such that all orbits which cross the resonant layer shift the position of their banana tips to the resonant layer. The ions with the banana trajectories that do not cross the resonance are not affected. In this way during the ICRF heating the trapped fast ion population is growing at the LFS near the resonant layer providing a counter-current contribution to the rotation profile. Furthermore, while the resonant layer is shifted to the LFS the absolute quantity of the trapped fast ions is increasing also because more banana-orbits cross the resonant layer.

We can analyze the measured rotation profiles in view of the previously described mechanism. Only the relative changes of the rotation profiles are important for our analysis. It is seen that for cases (a) and (b) in fig.2 there is not much difference at the edge of the plasma consistent with the edge positioned banana trajectories not being affected by the ICRH in both cases. The small negative contribution near the centre of the plasma in case (a) can be explained by the omnigenity breaking of banana trajectories which touch the resonance layer with their tips. However, the quantity of such trajectories is relatively small and the effect observed in the rotation profiles is of the same order of magnitude as the error in the rotation measurements. The hollow profile of rotation in central heating case (b) can be caused by the heating of electrons in the plasma centre [5]. The calculations by the TRANSP code for this shot show that a significant portion of the power is absorbed by electrons. We will not concentrate on this mechanism in this work, however, in the case of central heating it could prevail and define the hollow shape of the rotation profile. The relatively small effect of the omnigenity breaking in this case may be obscured. Thus, additional investigations are needed in order to support the assumption of the omnigenity breaking mechanism effect in cases (a) and (b), and discriminate this mechanism from other processes which define the rotation profile. Going from profile (b) to (c) one sees a change in the edge of the rotation profile which could be interpreted as a contribution to the rotation by the omnigenity breaking mechanism driven by the edge banana trajectories. This leads to a stronger reduction of the plasma rotation at the right side of the resonance position, which is consistent with the theory under discussion. The core rotation in case (c) stays nearly the same as in case (b). Thus, by shifting the resonance layer from the HFS to the LFS we are smoothly changing from a situation in which the central effect from the fast ions is not so prominent because there are fewer trapped particles and other rotation mechanisms may be dominant to a situation with a much stronger effect at the edge where the effect from the trapped fast ion population is supposed to be considerably larger.

Conclusions

First results of the plasma rotation measurements with pure ICRF heating shows qualitative agreement with the rotation mechanism proposed by Chang [7,8]. The counter-current contribution observed at the LFS of the resonant layer is presumably caused by the omnigenity braking mechanism as it is consistent with the theory. However, additional investigations are necessary in order to prove the effectiveness of the described mechanism and to separate this effect from other probably even more determinative mechanisms. The experiments with inverted direction of the toroidal magnetic field, B, and plasma current, I_p, are planned for the near future. This should help to indicate the role of the omnigenity breaking mechanism in plasma rotation and separate this mechanism from other mechanisms responsible for the plasma rotation. Also, additional investigations of the fast ion population are planned using the sample activation technique [9]. This will provide spatially and angle resolved time integrated measurements of escaping fast ions. A comprehensive analysis of the measured data will be done using Maxwell and quasilinear Fokker-Plank solvers and transport codes. Calculations of the magnitude of this effect are also planned in order to compare it with the measurements quantitatively.

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