Investigation of the fast particle velocity space by diagnosing poloidal asymmetries of heavy ions at ASDEX Upgrade

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Introduction

Plasma heating in tokamaks can affect the poloidal profile of the high-Z impurities as it was demonstrated at Alcator C-Mod [1]. In the present work, we will investigate the asymmetries caused by fast particles from ion cyclotron resonance heating (ICRH). Despite the significant advances in diagnosing fast ions in the plasma core, the ICRH accelerated hydrogen ions are hardly observable at their birth location, due to their low cross-sections for charge exchange or fusion reactions. Nevertheless, high-Z ions are affected by a poloidal electric field due to these energetic particles, which, provides indirect information about their distribution.

Poloidal asymmetry of the high-Z impurity density

ICRH increas mainly the perpendicular energy of the resonant ions leading to an increase of the temperature anisotropy which is responsible for their enhanced magnetic trapping and accumulation close to the resonance position. The other plasma species are redistributed to maintain the charge neutrality and fulfill the pressure balance. The influence of the perturbation in the electric potential on the profile of the bulk ions, electrons or light impurities is rather small. On the contrary, the effect is amplified for the high-Z impurities because of their charge, resulting in substantial variation of their poloidal density profile. For a high-Z impurity in the trace limit, the relation between the impurity poloidal distribution $n_z(\theta)$ and that of the minority fraction $f_m(\theta) = n_m/n_e$ can be expressed as

$$\ln\left(\frac{n_z(\theta)}{n_z(0)}\right) = -Z_z(f_m(\theta) - f_m(0))\frac{Z_m T_e}{T_i + Z_{\text{eff}} T_e} + \frac{m_z \omega_\phi^2}{2T_i}\left(1 - \frac{Z_z m_i}{m_z}\frac{Z_{\text{eff}} T_e}{T_i + Z_{\text{eff}} T_e}\right)(R^2(\theta) - R^2(0)) \tag{1}$$

where Z_z and m_z are charge and mass of the impurity, Z_m is the charge of the minority, m_i is the mass of the bulk ions, ω_ϕ is the toroidal angular frequency and $\theta = 0$ is located at the low field side. The first term on the right-hand side of the Eq. (1) stands for the electrostatic force produced by the fast ions. The second term represents the centrifugal force. The poloidal profile of the fast ion concentration $f_m(\theta)$ depends on their distribution function at the point of the minimal magnetic field on the flux surface, approximated here by the Dendy's distribution [2].

Experimental results

The tomographic reconstruction of the soft X-ray (SXR) radiation at ASDEX Upgrade (AUG) provides sufficient accuracy to observe a poloidal asymmetry in the tungsten density. The radial profile of the asymmetry was investigated in discharge 30812 at 4.65 s, with $T_i = 6.0\,\text{keV}$, $T_e = 4.1\,\text{keV}$ and $n_e = 4 \cdot 10^{19}\,\text{m}^{-3}$. The plasma was heated by 4.3 MW of ICRH with an outboard side resonance at $\rho_\theta = 0.4$ and 2.5 MW of NBI causing a negligible centrifugal force. The SXR emissivity in Fig. 1a shows apparent accumulation of the tungsten on the inboard side of the plasma. Figure 1b compares the poloidal asymmetry, defined as the first cosine component of the poloidal Fourier expansion of the emissivity, with the model based on the results of TORIC-FFPMOD (TRANSP) and TORIC-SSFPQL [4], where the main differences are the Fokker-Planck solvers and the interface to TORIC.

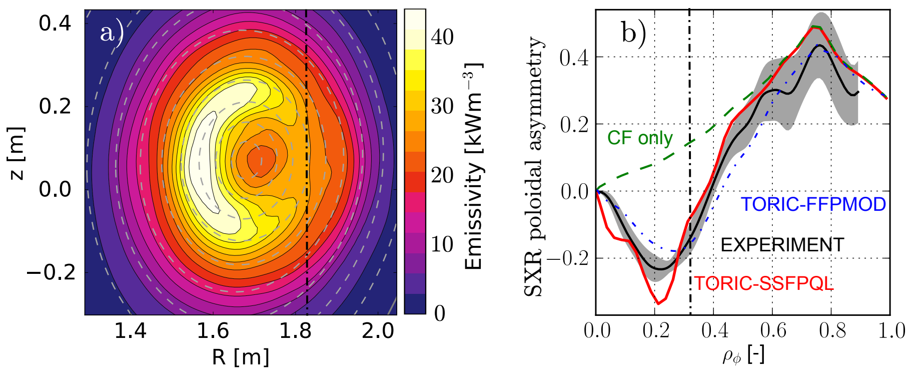

Figure 1: (a) SXR emissivity profile of W from discharge 30812@4.65s with ICRH resonance indicated by the black vertical line. (b) Radial profile of the measured asymmetry (black) compared with the centrifugal asymmetry (CF), TORIC-SSFPQL and TORIC-FFPMOD models.

Database study

A database of 10 AUG discharges between years 2011–2016 was build to investigate the parameter dependence of the observed W asymmetries produced by the fast particles. Measurements shortly ($\sim 30\,\text{ms}$) after the start of the ICRH and after sawtooth crashes was excluded, because the fast particles properties were not stationary enough. The centrifugal asymmetry was subtracted using Eq. (1). In the numerical simulations [3], the most important parameters were identified to be P_{ICRH}, n_e, T_e, Z_{eff} and $\langle f_m \rangle$. Since the last two quantities are not routinely measured at AUG, only the dependence on P_{ICRH}, n_e and T_e was considered here.

Figure 2a shows the W asymmetry $\tilde{n}_W$ divided by the total coupled ICRH power as a function of n_e. All discharges are following the trend of the $\propto n_e^{-2}$ scaling. By decreasing n_e, the ICRH power per particle linearly increases and the collisionality decrease as $\propto n_e/T_e^{3/2}$. The dependence of the W asymmetry on T_e, can be obtained by a further normalization with n_e^2 as is shown in Fig. 2b. The normalized asymmetry is scaling with a large uncertainty as $T_e^{3/2}$. The W asymmetry depends additionally on the charge, which is scaling as $\sqrt{T_e}$, but still the minority asymmetry scales roughly linearly with T_e. This is in contradiction with TORIC modeling [3],

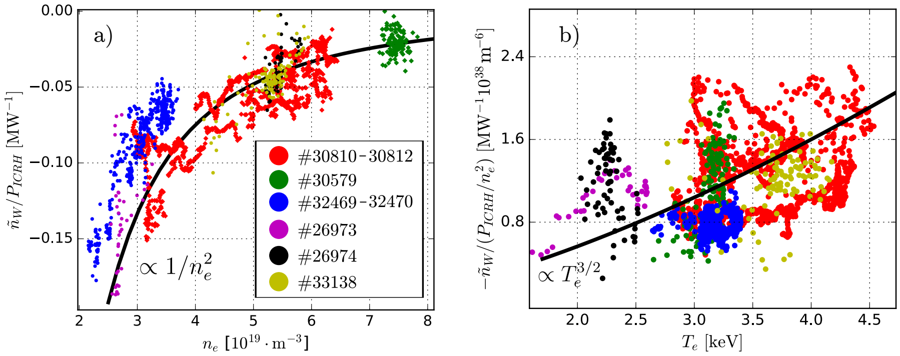

Figure 2: Dependence of the normalized W asymmetry on n_e (a) and T_e (b). The black curve indicate (a) $\propto n_e^{-2}$ and (b) $\propto T_e^{3/2}$ scaling. All quantities were determined at $\rho_\theta = 0.3$ and the colors correspond to the discharges with similar parameters.

where was observed a weak decrease of the temperature anisotropy caused by two mechanisms: higher temperature leads to a broadening of the resonance layer and further, faster deuterium ions are more efficiently absorbing power at the 2nd harmonic.

Fast ions redistribution due to sawtooth crashes

The poloidal asymmetries can also be used as a tool to investigate the transport of fast minority ions during individual sawtooth crashes. In the upper row of Fig. 3 is shown the change in the minority distribution determined from Eq. (1), where each crash is displayed as a line. Further, the lower row in Fig. 3 represents radial profiles of the asymmetry at the first sawtooth crash after turning on the ICRH, corresponding to the blue line in the upper plot. In the first two discharges (30811 and 30812) reduction of 20-30% was observed, while in discharges 32469 and 32470 the change was below 10%. The main difference between these discharges was the sawtooth period and consequently also their magnitude. In the discharges 30811 and 30812, the sawtooth period of 110 ms was sufficient for the grow of significant radial gradients in the fast particles density. In the discharges 32469 and 32470 the sawtooths period of 30 ms has caused a flat fast particles profile, implicating small changes in their density during a crash.

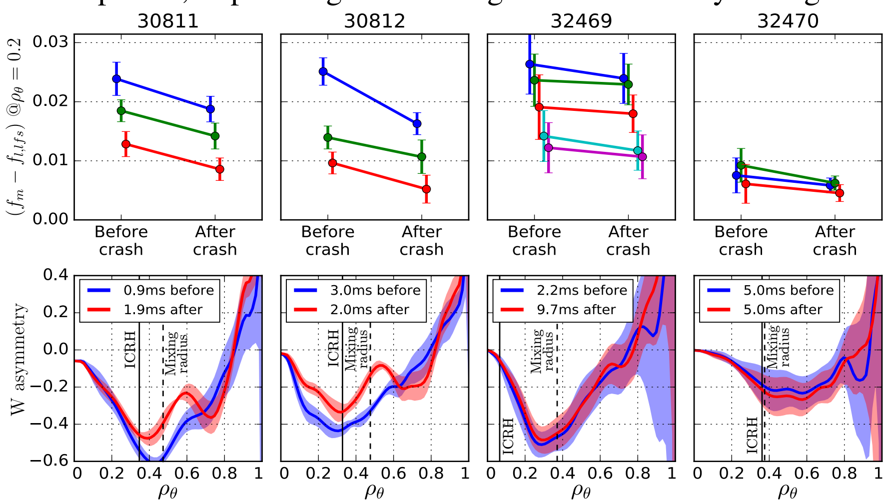

Figure 3: In the upper row is shown a change of the asymmetry for each individual sawtooth crash and in the lower row is radial profile for the first of them (blue).

Unfolding of the distribution function

It is possible to reconstruct the fast particles distribution function from the full poloidal profile of high-Z impurities $n_z(\theta)/n_z(0)$. The angular structure of the poloidal asymmetry contains information about the distribution of the pitch angles of the fast particles. An inversion of this relation allows for determination of $f(\xi)$, where $\xi = v_{||}/v$. This possibility is demonstrated in Fig. 4. The first plot represents the Dendy's distribution function with the temperature anisotropy estimated from the TORIC-SSFPQL. The second plot in Fig. 4b verifies the feasibility of such unfolding. The Dendy's distribution was used to model the poloidal W profile; then a 30% random noise was added, and the regularized inversion was performed. And finally in 4c), the identical procedure was used on the real data from the SXR tomography (Fig. 1). A significant discrepancy in the fast particles density at $\rho_\phi < 0.2$ is probably caused by the low sensitivity of this method close to the axis, where the fraction of trapped particles is going to zero. On the other hand, so-called rabbit ears feature at $\rho_\phi > 0.3$ is robust and was unchanged even during significant variation of the reconstruction parameters.

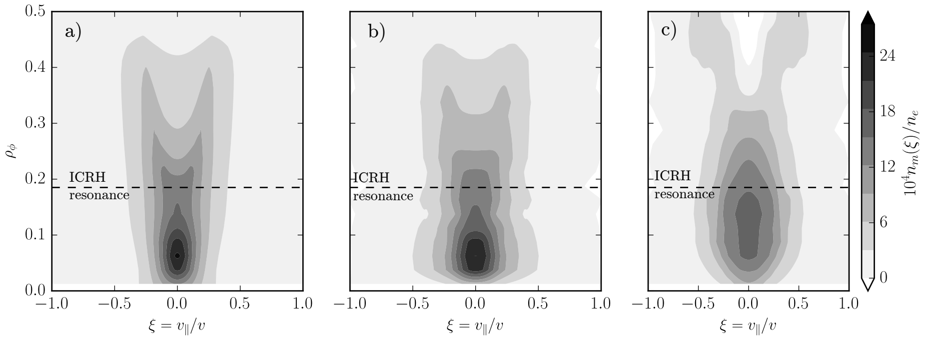

Figure 4: (a) Radial profile of the LFS Dendy's distribution function, (b) result of the unfolding of W profile obtained from (a),(c) unfolding of the distribution function of SXR profile at Fig. 1

Conclusions

We have demonstrated the possibility to determine the fast particle distribution by probing of the high-Z impurity poloidal profile. The database investigation has shown a $P_{ICRH}T_e/n_e^2$ scaling of the ion temperature anisotropy. Additionally, the analysis of sawteeth revealed a clear effect on the fast ions density profile, if their density profile is peaked. And finally, a Dendy's distribution of the fast ions is not inconsistent with the one obtained by unfolding of the poloidal W density profile.

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References

[1] M. Reinke, I. H. Hutchinson, at al. Plasma Phys. Control. Fusion, 54 (2012) 045004

[2] R.O. Dendy, R. J. Hastie, at al. Phys. Plasmas, 2 (1994) 1623

[3] Kazakov, Ye O., et al. Plasma Phys. Control. Fusion, 54 (2012) 045004

[4] Bilato, R., et al. Nuclear Fusion 51.10 (2011): 103034.