Increased core ion temperatures in high-beta advanced scenarios in AUG: Disentangling ExB-shear and fast ion effects using gyrokinetic simulations

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Introduction. Advanced tokamak (AT) scenarios combine many aspects that are attractive for the operation of future nuclear fusion power plants; Not only do they feature improved stability and confinement, they allow also greatly extended pulse lengths and have even been demonstrated to be able to run completely non-inductively [1]. Additionally, in many AT experiments peaked temperature profiles have been observed, which are associated with a local reduction of turbulent transport.

The mechanisms behind these reductions of transport are as of yet not fully understood. One possible explanation is that turbulent structures are torn apart by sheared flows of the $E \times B$-drift in poloidal direction [2] – similar to how the edge transport barrier is thought to be formed. This $E \times B$-shear $\omega_{E\times B}$ results from gradients in the radial electric field E_r:

$$\omega_{E\times B} = \left| \frac{(RB_\mathrm{pol})^2}{B_\mathrm{tor}} \frac{\partial}{\partial \psi} \left(\frac{E_r}{RB_\mathrm{pol}} \right) \right| \quad ; \quad E_r = v_\mathrm{tor} B_\mathrm{pol} - v_\mathrm{pol} B_\mathrm{tor} + \frac{1}{eZ_\mathrm{imp} n_\mathrm{imp}} \frac{\mathrm{d}p_\mathrm{imp}}{\mathrm{d}r} \tag{1}$$

Another mechanism able to explain the reduction of transport has recently been found with gyrokinetic simulations [3]. According to this, turbulence is suppressed through a non-linear coupling with fast-ion driven modes that siphon away energy from the dominant instability.

To be able to further develop such AT scenarios and extrapolate them to future machines, it is necessary to be able to better understand how much each of these different processes contributes to the formation of locally steepened ion temperature gradients. To this end, an AT experiment has been conducted at the tokamak ASDEX Upgrade, that varies $\omega_{E\times B}$ and p_fast to study their respective importance [4].

Experimental setup. On the left side of figure 1, timetraces of relevant parameters of this discharge can be seen. It has a high value of $\beta_\mathrm{N} = 2.6$ and a good confinement with $H_{98}(y,2) = 1.2$. Including the bootstrap current, almost 90 % of the 800 kA current is driven by non-inductive means. After an initial phase of only NBI and ECRH, 2.5 MW of ICRF are added while keeping β_pol constant via feedback control on the NBI. The resulting reduction of NBI power lowers the torque applied to the plasma, causing a reduction of v_tor, which according to equation 1 leads to a reduction of E_r and therefore $\omega_{E\times B}$ (see figure 1-i). Despite this significant drop, the normalized ion temperature gradient R/LT_i remains constant within uncertainties (see figure 1-h).

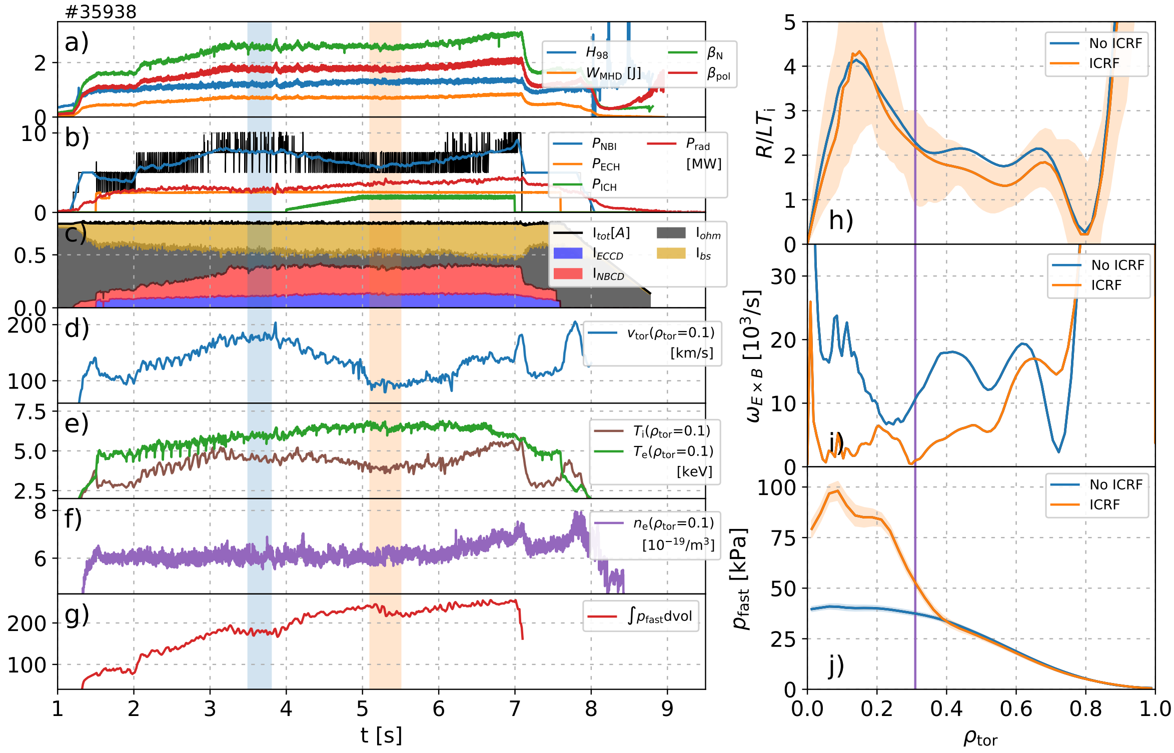

Figure 1: Timetraces of key parameters of the AUG discharge #35938 (a-g). Highlighted in blue and orange are two time intervals without and with ICRF, for which radial profiles of R/LT_i, $\omega_{E\times B}$ and p_{fast} are shown in subfigures (h-j). In those profiles, also the radial position at which GENE simulations have been performed is indicated.

This would indicate that the $E\times B$-shear does not play a significant role in the increase of R/LT_i. However, by the addition of ICRF to the heating mix, also a strong increase in p_{fast} can be observed (see figure 1-j). This is owed to the fact that ICRF strongly heats the hydrogen minority species, and further accelerates the energetic particles introduced with NBI heating. To rule out the possibility that the effects from the reduction in $\omega_{E\times B}$ and the increase in p_{fast} happen to compensate each other, nonlinear simulations with the gyrokinetic code GENE [5] have been performed.

GENE simulations. The general approach with these simulations is to vary these potentially competing parameters separately, to study their effects independently. The radial position at which the simulations have been performed, was chosen to be $\rho_{\text{tor}} = 0.31$ (indicated in figure 1), which is at the edge of the region where the ion temperature gradient is increased. Further towards the core, the magnetic shear s becomes close to 0; as GENE scales the radial box-size with $1/s$, picking a position at a smaller ρ_{tor} would make the simulations more complicated to perform. For the time-interval with ICRF, electron scale turbulence already starts to play a significant role. To describe this properly, a higher wave-number resolution would be necessary. As the resources necessary for such multiscale simulations exceed what was available for this study, the electron heat flux Q_e is significantly overestimated in that case. But for studying relative effects from variations in individual input parameters, a good match for Q_i should suffice.

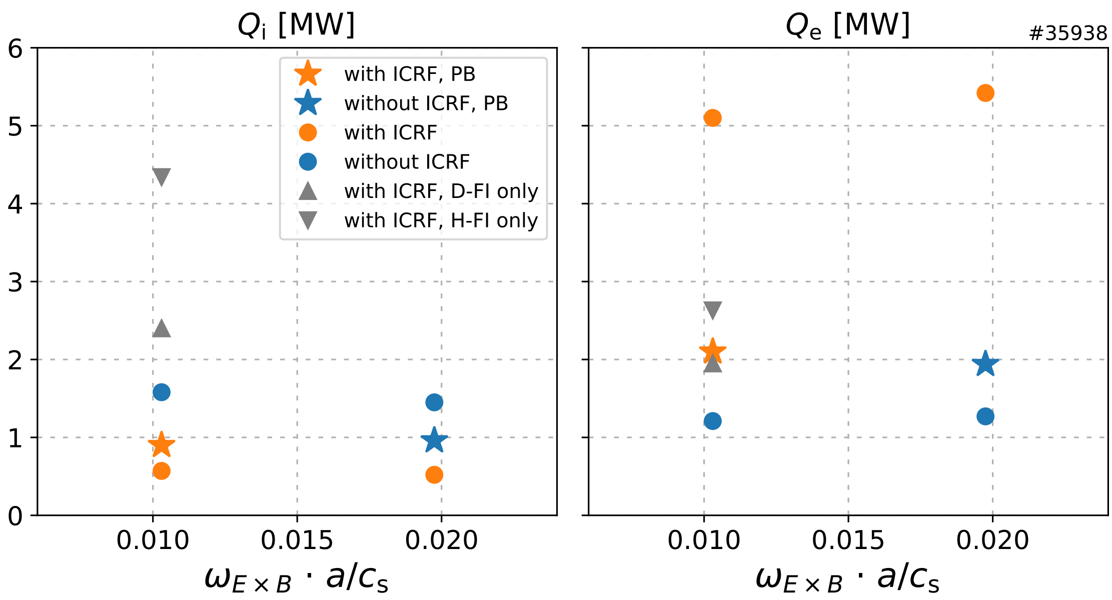

Figure 2: Relation between heat fluxes and $\omega_{E\times B}$ of AUG discharge #35938, according to nonlinear GENE simulations. Stars indicate the power-balance values from ASTRA simulations, circles the results from GENE simulations. In both cases, the colours correspond to the time-intervals with and without additional ICRF indicated in figure 1. For both intervals, simulations with two values of $\omega_{E\times B}$ have been performed. The markers in grey indicate simulations of time-intervals with ICRF, but taking each only one of the two fast ion species into account.

For the time-interval with ICRF, a further complication arises: Besides the electrons, main ions and deuterium fast ions, a fourth species needs to be considered – the hydrogen minority fast ions. Since this makes the simulations computationally more expensive, initial attempts have been conducted using only three species – omitting either the hydrogen or deuterium fast ions. These simulations were however not able to reproduce the experimental ion heat fluxes (see figure 2, grey triangles). Additionally, even simulations using all four species converged only when more realistic, bi-maxwellian distribution functions were used:

$$F_0 = \frac{n_0}{\pi^{3/2} v_{\mathrm{th},\parallel} v_{\mathrm{th},\perp}^2} \exp\left(-\frac{v_\parallel^2}{v_{\mathrm{th},\parallel}^2} - \frac{\mu B_0}{T_\perp}\right) \tag{2}$$

This suggests that the full inclusion and correct treatment of the fast ions is very important in the simulation of such AT scenarios. This important point has been made possible only recently, through an extension in the GENE code [6]. In equation 2, $v_{\mathrm{th},\parallel/\perp} = \sqrt{2T_{\parallel/\perp}/m}$ are the parallel and perpendicular thermal velocity.

The temperature components parallel and perpendicular to the magnetic field, $T_{\parallel}$ and $T_{\perp}$, were calculated with Toric, coupled to SSFPQL[7] for the case of the hydrogen fast ions, and with TRANSP coupling both NUBEAM and Toric for the deuterium fast ions.

After achieving a good match between experimental and simulated ion heat fluxes, one can now investigate the effects of varying $\omega_{E\times B}$, while keeping other parameters such as p_{fast} or $T_{\mathrm{e}}/T_{\mathrm{i}}$ fixed. This is done by repeating the two GENE runs matching the power-balance values for both cases, but with the values for $\omega_{E\times B}$ of the respective other case. If indeed the $E\times B$-shear had an effect that is masked by other competing effects, then these simulations should result in a significant deviation from the power-balance and the simulation done with the nominal $\omega_{E\times B}$.

As can be seen in figure 2, the heat fluxes do not change when varying the $E\times B$-shear, indicating that it does not contribute to the reduction of turbulent transport in the scenarios under investigation here. This result is consistent with the findings of [8], simulating JET experiments.

Summary and Conclusion. GENE simulations have been performed of an AT scenario designed to study the effects of $\omega_{E\times B}$ on R/LT_{i}. With these simulations, potentially competing effects could be disentangled, confirming that the $E\times B$-shear does not seem to play a role in the increased core ion temperatures observed in these AT scenarios. To achieve a good match with the experiment, it was necessary to include a realistic description of the fast ion populations.

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