Investigation of increased core ion temperatures in high-beta advanced scenarios in ASDEX Upgrade

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Introduction. Standard plasma scenarios for tokamak reactors run in pulsed operation only, increasing the stress on the vessel components. Therefore, it is desirable to (at least partially) drive the toroidal plasma current via non-inductive means such as ECRH and NBI, as well as the intrinsic bootstrap current. Since the externally driven current requires additional recirculating power, it is preferred to have as high a bootstrap-current fraction as possible. Since $j_{\mathrm{BS}} \sim q\nabla p$, it is therefore favourable to have internal transport barriers (ITBs), or regions in which turbulent transport is reduced, which feature large ion temperature gradients. Such regions of reduced transport have been observed in ASDEX Upgrade [1]. In this contribution, first principle mechanisms for transport reduction are investigated.

Effects of ExB-shear. One important parameter that is thought to be linked to the formation of ITBs is the ExB-shear [2]

$$\omega_{\mathrm{ExB}} = \frac{(RB_{\mathrm{pol}})^2}{B}\frac{\partial}{\partial\psi}\left(\frac{E_{\mathrm{r}}}{RB_{\mathrm{pol}}}\right), \tag{1}$$

where the radial electric field E_{r} is given by the force balance

$$E_{\mathrm{r}} = v_{\mathrm{tor}}B_{\mathrm{pol}} - v_{\mathrm{pol}}B_{\mathrm{tor}} + \frac{1}{eZ_{\mathrm{imp}}n_{\mathrm{imp}}}\frac{\mathrm{d}p}{\mathrm{d}r}. \tag{2}$$

In previous studies, ASTRA simulations of ASDEX Upgrade discharges with elevated core T_{i}, using the quasilinear transport model TGLF [3], suggested that the ExB-shear plays an important role in the reduction of turbulent transport and the subsequent peaked ion temperatures [4]. Contrary to that, GENE [5] simulations did not find this dependence. Instead, GENE runs of similar discharges suggest non-linear fast ion effects to be of importance [6].

To test this, dedicated experiments in ASDEX Upgrade have been conducted, that partially replace NBI with ICRF in such scenarios, while keeping β_{pol} constant. This decreases the torque put into the plasma and, therefore, the rotation. According to Eqs. 2 and 1, this ultimately leads to a reduction in ExB-shear. In doing this study, one needs to be careful to account for various

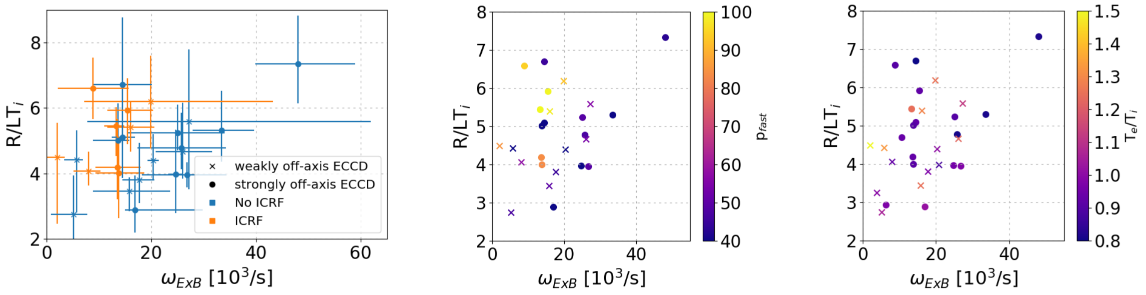


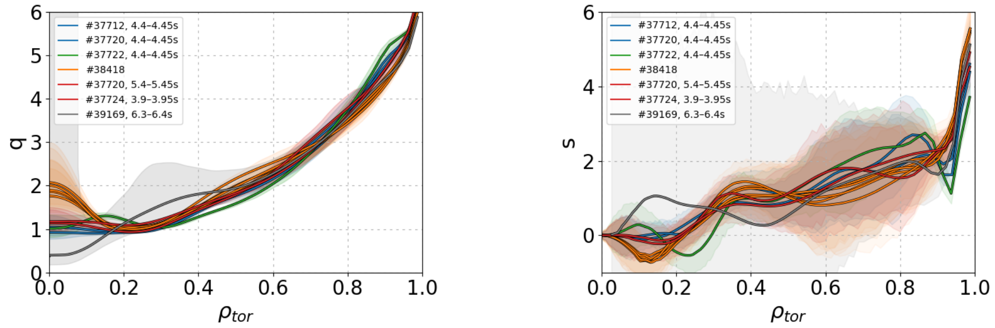
Figure 1: *Maximum R/LT_i vs ω_{ExB} at the same position. Points marked with an 'x' use a weakly off-axis ECCD, points marked with a circle use a more strongly off-axis ECCD. In the left-most subplot, the colors indicate whether ICRF was used, in the other two subplots, the colors indicate the fast ion pressure and T_e/T_i, respectively.*

possible competing effects: For one, by adding ICRF, the fast ion content is greatly increased, which – as mentioned before – might lead to a reduction in turbulence. Secondly, by changing the heating mix, we affect the ratio $T_\mathrm{e}/T_\mathrm{i}$, which affects the critical gradient in ITG dominated plasmas. To disentangle these effects, a wider range of parameter space has been covered, by using different NBI sources and changing the amount of ICRF used. For each distinct flat-top phase of these various discharges, the maximum value of the normalized logarithmic gradient R/LT_i was compared to the ExB-shear at that same position. This comparison can be seen in Fig. 1.

In this plot, each point represents one such flattop-interval. Discharges using different settings for the ECCD are marked separately with an 'x' or a circle. Furthermore, in the leftmost plot, the colors indicate whether or not ICRF was used. There is no clear correlation between the ExB-shear and R/LT_i. Shown in the other two subplots is the same figure, but now with the color representing the fast ion pressure and the $T_\mathrm{e}/T_\mathrm{i}$ ratio. While the temperature ratio does not present a particular trend, there seems to be a tendency that might suggest that a potentially higher transport at lower values of ω_ExB is compensated by the reduced transport associated with higher values of p_fast. However, since there is also a sizable number of points with a lower p_fast, but comparable ω_ExB and R/LT_i, we are confident in ruling this out.

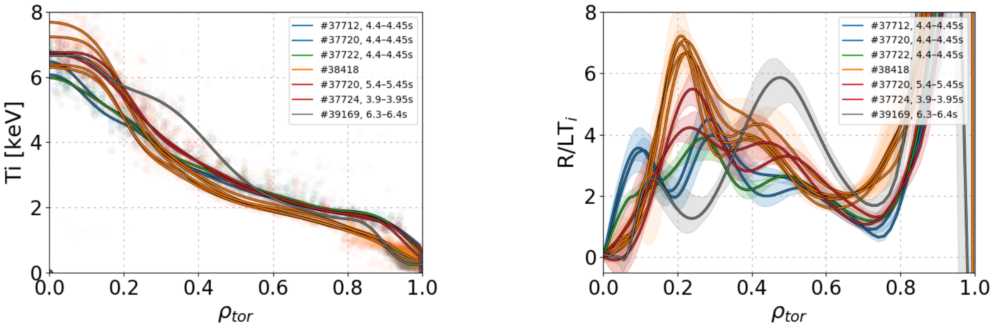
From this, we conclude that the ExB-shear does not play an important role in the formation of regions with reduced transport in the scenarios studied in AUG.

Effects of q and s. Another important parameter that is thought to be linked to the formation of ITBs is the magnetic shear $s = \frac{\rho_\mathrm{tor}}{q}\frac{\mathrm{d}q}{\mathrm{d}\rho_\mathrm{tor}}$. It has been observed in the past that the formation of ITBs seems to be connected to minima in q, sometimes also with the additional constraint that it should be located at rational surfaces [7]. To test if this is also the cause for the observed



(a) q-profiles

(b) Magnetic shear



(c) Ion Temperatures

(d) R/LT$_\mathrm{i}$

Figure 2: Overview of various AUG discharges, comparing the relation of the q-profile (a) and magnetic shear (b) to T_i (c) and R/LT_i (d). Note how the error bars for the q-Profile of the grey line are significantly larger than for the other discharges. This is due to the fact that for this discharge it was not possible to obtain usable IMSE data.

turbulence reduction in ASDEX Upgrade, dedicated experiments have been conducted, in which different settings for the ECCD were used to get a variety of different q-profiles, and to observe if this has an effect on T_i.

One particular difficulty of such a study lies in the measurement of the q-profiles. While the standard evaluation for the q-profiles routinely performed in ASDEX Upgrade has proven itself to be very reliable [8], there are some special cases where the current diffusion equation is known to yield incorrect results. To stay on the safe side, constraints from the neoclassical current diffusion are therefore not considered in the determination of the uncertainty of q. As a consequence, we typically encounter rather big uncertainties that are larger than the subtle changes to the q-profiles we were aiming for. To obtain profiles of the required accuracy, measurements using the imaging motional stark effect (IMSE) diagnostic [9] have been used to add additional constraints in the evaluation of q.

In Fig. 2 an overview over a database of discharges, featuring a variety of different q-profiles, can be seen. Looking at the normalized logarithmic ion temperature gradient R/LT_i, it can be seen that the discharges colored in orange show a distinct peak above the fluctuations that can be considered noise. Within the uncertainties, the position of these peaks seems to match the position where the magnetic shear changes sign. Conversely, the shear in the cases depicted in blue does not, or just barely, cross over into the negative. Fittingly, these cases do not feature strong steepened ion temperature gradients. The q-profiles of the cases in red are very similar to the ones in blue, but are slightly shifted upwards; their shear in the core is slightly negative. Here, the match is not quite as clear, but at least one of the two cases features a peak in R/LT_i at the position where the shear crosses into 0. For the second red case, as well as the case in green, the shear crossing 0 does not seem to correlate with a steepened T_i at that position, however. To further test the correlation between the position of the shear becoming 0 and the reduction of turbulence, an additional discharge has been run, with a q-profile that flattens at a radial position further out. In this case, depicted in grey, the ion temperature does indeed steepen at a position where the shear seems to approach 0. Note, however, that for this last discharge, it was not possible to obtain usable IMSE data, resulting in significantly larger uncertainties of the q-profile and shear compared to the other cases.

From this data, we tentatively conclude that the steepening of the ion temperature profiles, or at least the position where this happens, is related to the magnetic shear crossing 0. Preliminary results from an ongoing GENE investigation are in agreement with this finding.

Summary and conclusion. Systematic studies of AUG discharges that feature peaked ion temperature profiles have been conducted to investigate the reasons behind these increased temperature gradients. While the ExB-shear was not found to play a significant role, our data is consistent with the notion that the magnetic shear crossing 0 has an effect.

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References.

[1] A. Bock et al, Nucl. Fusion **57** 126041 (2017)

[2] T. J. J. Tala et al, Plasma Phys. Control. Fusion **43** 507 (2001)

[3] G. M. Staebler et al, Physics of Plasmas **14**, 055909 (2007)

[4] M. Reisner et al, Nucl. Fusion **60**, 082005 (2020)

[5] F. Jenko et al, Physics of Plasmas **7**, 001904 (2000)

[6] A. Di Siena et al, Nucl. Fusion **59** 124001 (2019)

[7] E. Joffrin et al, Nucl. Fusion **43** 1167 (2003)

[8] R. Fischer et al Fusion Sci. Technol. **69** 526 (2016)

[9] O. P. Ford et al, Rev. Sci. Instrum. **87**, 11E537 (2016)