Transport studies at ASDEX Upgrade: Cold pulses local or non-local? NBI particle source important or not? Pellet fuelling in or out?

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Magnetic confinement plasmas are usually primarily driven by heat sources, with limited particle sources, particularly in the core. This is also the case of a fusion reactor, where the limited penetration of the neutral particles leads to the requirement of using fuelling pellets. Depending on plasma conditions, the particle source can impact the turbulence and the transport of particles and heat. Here three situations are analyzed with new experimental results from ASDEX Upgrade (AUG), linear and nonlinear simulations with the gyrokinetic code GKW, and integrated modelling with the transport code ASTRA, coupled to the transport model TGLF, the neoclassical transport code NCLASS and the impurity transport code STRAHL.

The first problem is related to the impact of the core particle source produced by neutral beam injection (NBI) on the density profile in present experiments and in planned future reactor plasmas. In a reactor plasma the peaking of the density profile is an essential element to reach required values of the central density, while keeping the edge density below the density limit. In recent AUG experiments [1], a combined density scan from discharge to discharge and an NBI power scan in each discharge, added to a constant background of ICRH power, have been performed starting from conditions of lowest possible density (and thereby collisionality) at the maximum applied NBI power, achieved by the application of edge magnetic perturbations. By such a combined scan, a set of plasma conditions has been investigated covering a range of collisionality and particle source levels from which an extrapolation to reactor conditions can be performed. In addition the experimental results are used for comparison with the predictions of the turbulent transport model TGLF-SAT1 [2]. Plasma conditions close to those of a reactor, in terms of collisionality, electron to ion heat flux ratio, particle to heat flux, normalized flux in gyro-Bohm units, have been reached. In contrast, obviously at the same time the plasma beta and the normalized inverse Larmor radius were much smaller than those expected in a reactor. In order to increase the probability of reaching the lowest possible density, relatively low plasma currents have been obtained (0.8 MA at 2.5 T), leading to edge safety factors around 5, higher than those expected in a reactor. The measured density profiles are compared with the TGLF-SAT1 predictions for three density levels at the same heating power (2MW NBI) in Fig. 1(a), where also the predicted density profiles in simulations in which the NBI particle source has been removed are shown. TGLF-SAT1 provides an excellent prediction of the density profile shapes, and good predictions of the temperature profiles in general, with a clear tendency of under-predicting the heat transport in the peripheral region and over-predicting it in the central region when going to conditions of lower collisionality. The impact of the NBI particle source is found to be completely negligible in the TGLF-SAT1 predictions, consistent with the observed very strong correlation of the measured density peaking with collisionality, and the much weaker correlation of density peaking with the particle source strength. An artificial increase of the particle source in the modelling reveals that increases of the particle source by factors 5 and 10 increase the central density by factors 1.2 and 1.4 respectively. This is consistent with the expected general scaling of the impact of the particle source on the density peaking, proportional to $2000(P/EnV)(a^2/\chi)$ (with P and E the NBI power and injection energy, in MW, kV and 10^{19} m^{-3}, m, s). The correlation with collisionality is demonstrated in both experiment and simulations in Fig. 1(b), where also the predictions for the ITER and DEMO baseline scenarios are presented. We observe that the ITER and DEMO predictions change significantly depending on whether electro-magnetic effects are included or not in the simulations. This strong effect is significantly weaker at the low β ($\beta_N \simeq 1$) of these AUG plasmas, but it becomes important for the expected ITER and DEMO scenarios. This limiting effect, produced by outward convection of passing electron with increasing beta [3], requires more experimental consideration and model validation.

The second problem is related to the impact of a localized particle source as produced by fuelling pellets on the local shape of the density profile and the consequent turbulence and transport that can be destabilized by locally very steep profiles with both positive and negative gradients. A new microinstability with hollow density profiles is identified, and the associated turbulent particle transport is computed by means of non-linear gyrokinetic simulations and shown to be experimentally relevant and consistent with observations [4]. Fig. 2(a) shows the growth rate of the most unstable modes, computed by GKW, as a function of the normalized logarithmic density gradient R/Ln for conditions typical of AUG pellet fuelled plasmas. After the injection of the first pellets, R/Ln is locally measured to decrease to values as low as -10 in the region inside the pellet deposition location. These strongly hollow density profiles are predicted to drive modes which balloon on the high field side (HFS) and which produce inward directed, mostly diffusive, particle fluxes. These modes are caused by the non-adiabatic response of passing particles close to the trapping boundary at the high collisionality of these high density regimes. A reduction of collisionality stabilizes these modes and reduces the consequent inward transport. In contrast, a reduction of collisionality strongly destabilizes the density gradient driven trapped electron mode (TEM), produced by the strongly peaked density profile outside the pellet deposition location. This causes a strong outward, again mostly diffusive, particle flux. HFS ballooning modes driven by negative values of R/Ln (hollow density profiles) can produce a turbulent state, with consequent inward particle fluxes, as demonstrated by nonlinear gyrokinetic simulations with GKW, shown in Fig. 2(b). The GKW predicted inward particle fluxes are consistent with the inward particle flux required in ASTRA modelling to reproduce the dynamics of the observed central density build up in response to pellet fueling at sufficient pellet injection rate [5]. The opposite collisionality dependencies of positive (peaked) and negative (hollow) R/Ln driven modes are unfavorable for a reactor. This further motivates the technical realization of the injection of small pellets (small perturbation) at the highest possible speed (highest penetration).

Finally, the impact of a peripheral source of impurities, like those produced by laser ablation, on the plasma density and temperature profiles is analyzed from new experiments in AUG, which demonstrate the dominant role of the electron to ion heating fraction in determining the plasma response to cold pulses [6]. At the same low density of 1.5 10^{19} m^{-3}, a fast increase of the central electron temperature in response to an edge cooling is only observed in conditions of dominant electron heating, OH or ECRH assisted. In contrast, in the presence of dominant ion heating produced by NBI at reduced voltage, the central electron temperature is not observed to increase. ASTRA modelling with the TGLF-SAT1 [2] model and prescribed evolving density profiles taken from measurements reproduce these experimental observations, as well as the absence of central increase at higher density. Fully consistent with recent experimental and related modelling results in C-Mod [7,8] and DIII-D [9], it is thereby demonstrated that the local reduction of the electron heat conductivity produced by the measured fast density flattening produced by the impurity ablation in the case of TEM turbulence can reproduce the observed very fast central electron temperature increase. More importantly, the still missing element of the modelling of the sudden flattening of the electron density profile has been resolved in this study. Highly integrated ASTRA simulations, which combine turbulent heat and particle transport predicted by TGLF-SAT1, neoclassical transport predicted by NCLASS and impurity penetration modelled with STRAHL, show that in these low density conditions the transient extremely hollow impurity density profile modifies the local turbulence, producing an impurity density gradient driven mode, which causes a very fast inward diffusion of the particles. This turbulent transport is able to reproduce the observation of the sudden flattening of the electron density profile in the modelling, fully consistent with the experimental observations, Fig. 3(a). In trapped electron mode turbulence, this flattening causes a local reduction of the electron heat transport, leading to a fast increase of the central electron temperature, Fig. 3(b). Thereby, the complex and very fast density and temperature responses to a cold pulse can be fully explained by multi-channel interactions within a local model like TGLF-SAT1.

In conclusion, three important studies have been performed on the impact of particle sources on transport and confinement.

1. Experiments and related modelling (ASTRA/TGLF-SAT1 [2]) have demonstrated that the NBI particle source has negligible impact in experimental plasma conditions which approach those expected in a fusion reactor. The observed density peaking is fully sustained by the turbulent pinch (inward convection) arising at low collisionality. Electromagnetic effects at the foreseen high beta of a reactor are predicted to reduce this density peaking [1].

2. Strongly hollow density profiles produced by pellet injection transient perturbations are predicted by GK simulations (GKW) to destabilize HFS ballooning turbulence in the region inside the pellet deposition location, leading to inward mostly diffusive turbulent particle fluxes. This turbulence is stabilized at the low collisionality of a reactor, whereas the outward particle diffusion produced by usual density gradient driven TEM turbulence outside the pellet deposition location is destabilized with decreasing collisionality. Inward turbulent fluxes with hollow density profiles are required to explain the observed central density build up in high density pellet fuelled AUG experiments [4,5].

3. Finally, the penetration of a peripheral source of laser ablated impurities, as modelled in coupled ASTRA/STRAHL simulations with TGLF-SAT1 [2] and NCLASS turbulent and neoclassical transport respectively, is shown to transiently lead to the destabilization of strong turbulence producing a fast inward diffusion of particles. With trapped electron mode turbulence, the consequent predicted and observed sudden density flattening, stabilized the turbulence, leading to a fast increase of the central electron temperature. Thereby, the complex and very fast density and temperature responses to a cold pulse can be fully explained by multi-channel interactions within a local model like TGLF [6].

[1] E. Fable et al 2019 Nucl. Fusion **59** 076042. [2] G.M. Staebler et al 2016 Physics of Plasmas **23**, 062518. [3] T. Hein et al 2010 Phys. Plasmas **17** 102309. [4] C. Angioni et al 2017 Nucl. Fusion **57** 116053. [5] G. Tardini et al 2018 APS DPP Conference. [6] C. Angioni et al 2019 Nucl. Fusion submitted. [7] P. Rodriguez-Fernandez et al 2018 Phys. Rev. Lett. **120** 075001. [8] P. Rodriguez-Fernandez et al 2019 Nucl. Fusion **59** 066017. [9] P. Rodriguez-Fernandez et al 2019 Phys. Plasmas **26** 062503.

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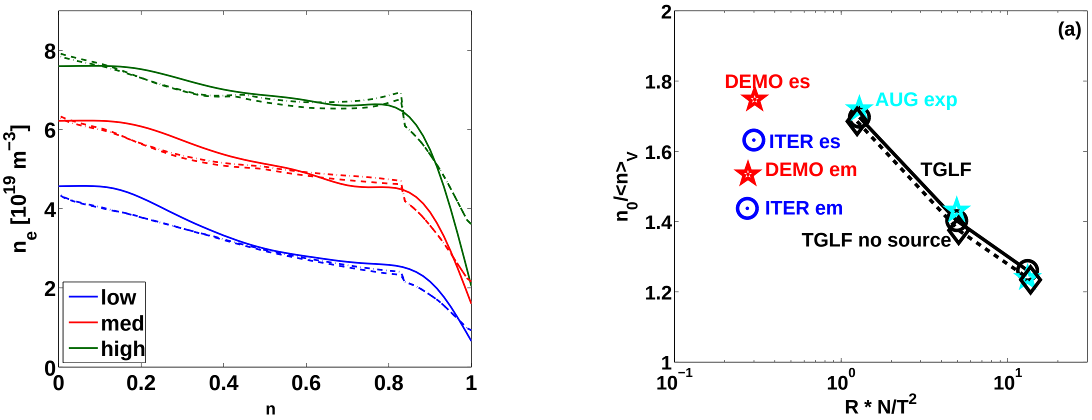

Fig. 1. AUG measured (solid) and TGLF predicted density profiles (a) with (dashed), without (dash-dotted) NBI fuelling. and density peaking (b) in AUG, ITER and DEMO (from [1]).

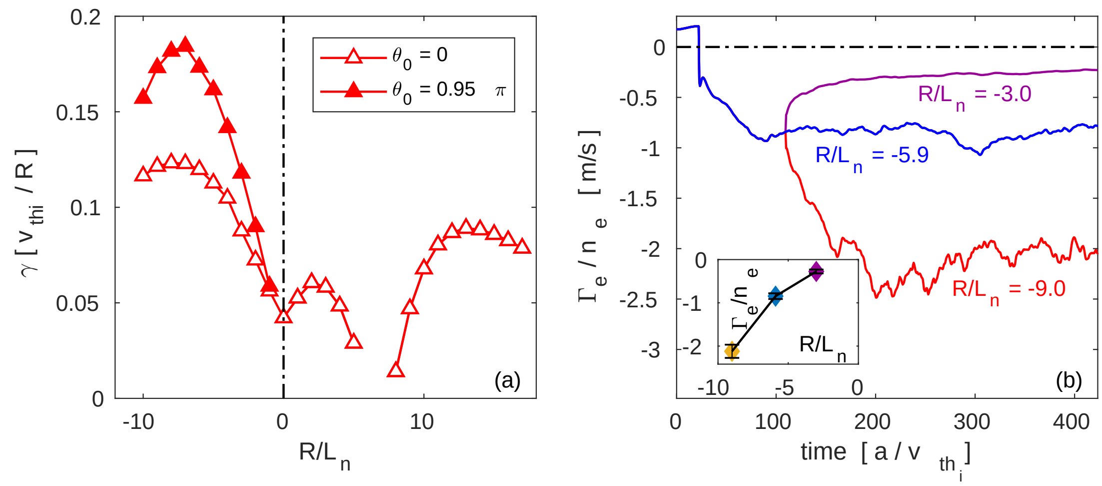

Fig. 2. GKW growth rate dependence on R/L_n for AUG pellet fuelled core parameters (a) and time evolution of nonlinear GKW particle fluxes with different values of R/L_n (b) (from [4]).

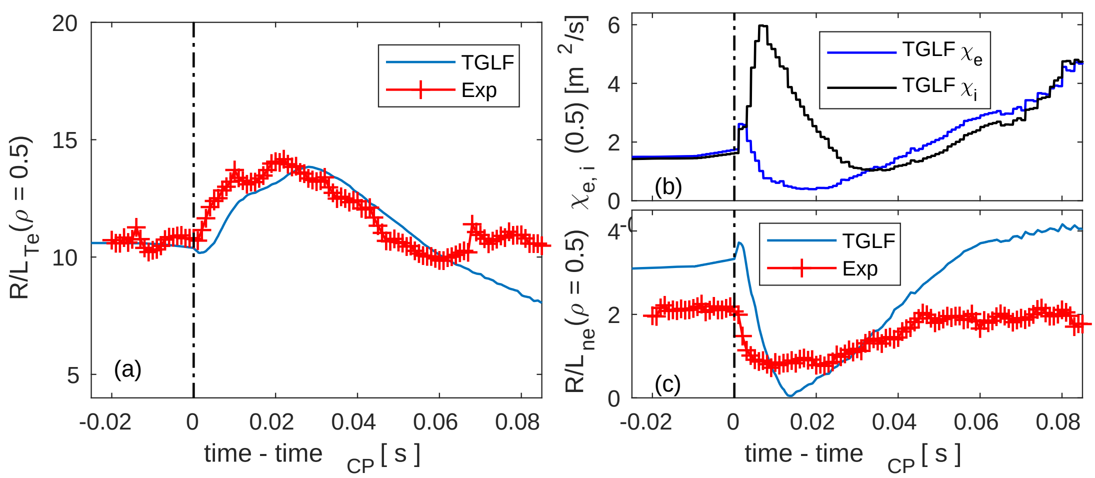

Fig. 3 Time evolution of measured and ASTRA/TGLF predicted R/L_{Te} (a), R/L_{ne} (c) and corresponding χ_i and χ_e (b) with a cold pulse (from [6]).