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Simulation of ASDEX Upgrade Plasmas with Internal Transport Barrier

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1. Introduction

Transport simulations have been performed for different operation regimes in the tokamak ASDEX Upgrade with an emphasis made on discharges with improved core confinement [1-3]. The objective was to compare different theory based transport models with the experimental data of ASDEX Upgrade. All transport models used in this comparison have proved their applicability for large machines such as JET, TFTR and JT-60U. Verification of those models against experimental data on smaller devices could give more confidence in extrapolation of the results and make predictions for the next generation tokamaks more reliable. Theoretical models by Weiland-Nordman [4], IFS/PPPL [5], Itoh-Fukuyama [6] and the semi-empirical mixed shear model [7] were used in this study. Various plasma regimes including H and L-mode, both with and without Internal Transport Barrier (ITB) were selected for the comparison.

It was found that the best results for ASDEX Upgrade were provided by the Weiland-Nordman model. Other transport models overestimate transport coefficients and give too low electron and ion temperatures in comparison with the experimental data.

2. Experimental regimes and transport models

Different types of discharges are considered below. Discharges with ITB [2] are obtained by early (at time $t = 0.3$ s) neutral beam (NB) heating during the current and density ramp-up phase. Immediately after switching on the NB, the increase of the electron temperature strongly decelerates the current diffusion. The line average density grows up to $(4 \div 5) \times 10^{19}$ m^{-3} until the plasma current flat top is reached and then is kept constant. The plasma density profile remains peaked during the whole process. During the current ramp-up phase, ion and electron temperatures do not change much and stay approximately equal. At the flat top, the NB power is raised resulting in proportional or even stronger increase in the ion temperature while T_e changes less. Transport barriers are formed for ions and electrons. The highest values of the central ion temperature, 15 keV, were achieved at this phase if L-H transition was avoided by using a limiter configuration. However, the ITBs were of a transient nature, being terminated by (2,1) modes or radiative collapse. In H-mode, the ITB phase was limited only by duration of NB heating [3]. If the additional heating was first applied at the current flat top then ITB did not form. These regimes were also included in considerations.

The experimental results described above were compared with the transport modeling where the radial profiles of n_e, Z_{eff}, radiated power P_{rad} and the toroidal rotation velocity $v_{\rm tor}$ were prescribed as measured in the experiments. The thermal transport of electrons and ions, poloidal field diffusion, NB heating and current drive were calculated in the 1.5D transport code ASTRA employing the theoretical transport models listed above. The ion and electron heat conductivities were taken as a sum of neoclassical and anomalous contributions. In plasmas with $q = 1$ resonance surface present, an MHD oscillation model similar to Kadomtsev's reconnection model was used. This model results in a periodic redistribution of the current density and temperature profiles over the central ($\rho < 0.3$) region.

3. Results of modeling

L-mode. First of all, we describe the results of modeling for a plasma with L-mode edge without ITB. In Fig. 1, the steady state profiles of calculated and measured electron and ion temperatures are shown for the shot No. 7945. This shot is in the plasma density similar to the ITB shot No. 10701 which is discussed later. One can see that the electron temperature is described equally well in all four transport models. All models give also a correct ion heat conductivity in the outer ($\rho_{\rm tor} > 0.5$) part of plasma while the central ion temperature is always underestimated.

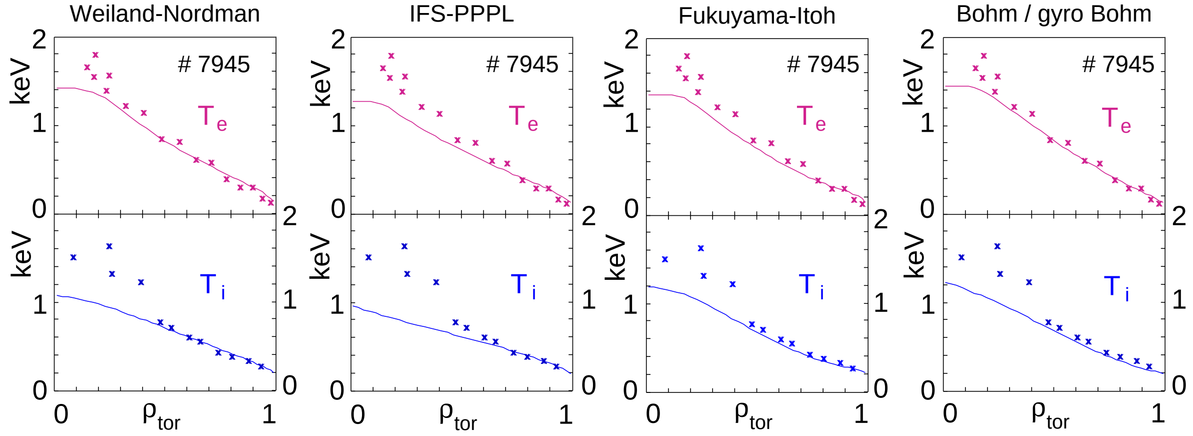

Fig. 1. Radial profiles for the measured and calculated plasma temperatures for the shot No. 7945 ($\bar{n}_e = 5 \times 10^{19}\ m^{-3}$, $P_{NB} = 2.5\ MW$)

H-mode. Similar calculations for the H-mode shot No. 11127 are shown in Fig. 2. Here the best description of the experimental results is obtained with the Weiland-Nordman transport model. Although in some cases, IFS-PPPL and Itoh-Fukuyama models give a reasonable representation of ASDEX Upgrade data they have a systematic trend to underestimate both electron and ion temperatures in the plasma center. The same is valid also for the semi-empirical mixed Bohm / gyro-Bohm model. This model could be

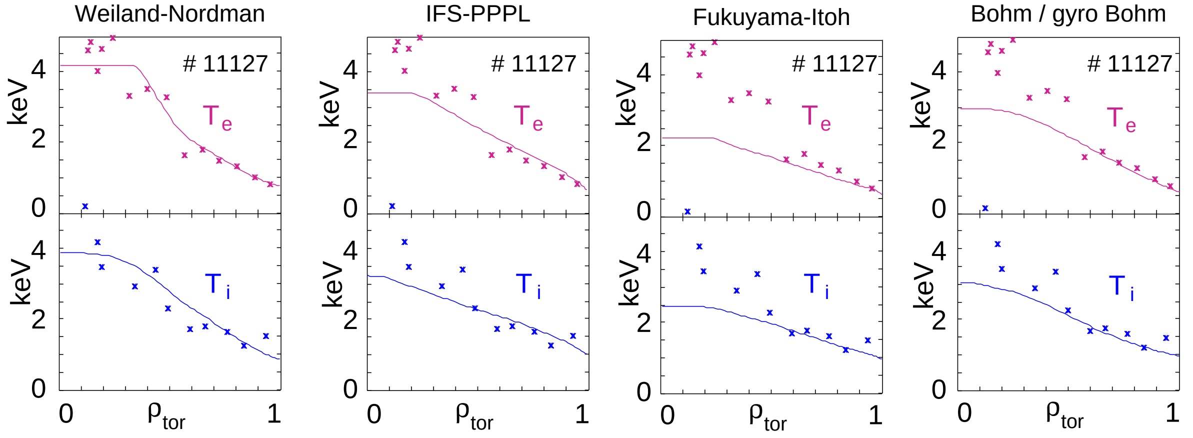

Fig. 2. Temperature profiles for H-mode shot ($\bar{n}_e = 5.1 \times 10^{19}\ m^{-3}$, $P_{NB} = 5\ MW$).

adjusted for ASDEX Upgrade if the fit coefficient in front of the Bohm term would be reduced by a factor $3 \div 4$. However, this would imply a hidden dependence on plasma parameters in the model and restrict its reliability outside the parameter range studied.

As known, the rotational shear, $\omega_{E\times B} = (B_{\rm pol}/B)d(E_r/B_{\rm pol})/dr$, with E_r being $E_r = v_{\rm tor}B_{\rm pol} - v_{\rm pol}B_{\rm tor} + (dp_i/dr)/(en_i)$ reduces the growth rate of unstable modes and thus results in a reduction of the transport coefficients. Unfortunately, only the first and the third terms in the relation for E_r can be derived reliably from the experimental data. The accuracy of $v_{\rm pol}$ measurement in ASDEX Upgrade is so far not in all cases sufficient for a judgement about significance of the correspondent term in E_r. On the other hand, the diamagnetic contribution to E_r is usually small and according to the neoclassical theory the term with $v_{\rm pol}$ has to be of the same order. For this reason, the approximation $E_r \approx v_{\rm tor}B_{\rm pol}$ was used. A relevance of this approach is illustrated by Fig. 3a where the relative values of $v_{\rm tor}$ and $v_{\rm dia}$ are shown. The similar scaling between these terms is also held in L-mode and ITB shots, however, in L-mode, the rotation is at least by a factor of 3 smaller and does not affect the transport noticeably.

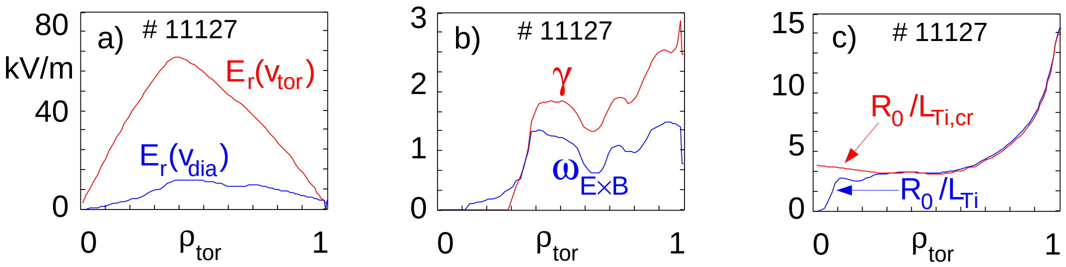

Fig. 3. a) Contributions to the radial electric field due to $v_{\rm tor}$ *and* dp_i/dr. *b) Maximal increment and rotational shear normalized to the drift frequency. c) The critical ion temperature gradient,* $R_0/L_{\rm T_i,cr}$, *and the ion temperature gradient,* $R_0/L_{\rm T_i} = -(R_0/T_i)dT_i/dr$, *obtained in the simulation with the model [5].*

Fig. 3b shows the influence of the rotational shear on transport according to the Weiland-Nordman model. In this model, the rotational shear rate, $\omega_{E\times B}$, is subtracted from the maximal increment, γ, of all instable modes. As a result, the transport coefficients are strongly reduced in comparison with their values at $E_r = 0$.

Fig. 3c shows the critical ion temperature gradient which is an essential characteristic of the IFS-PPPL model. It is seen, that for the plasma parameters of H-mode the stiffness is very high so that the calculated temperature gradient must follow the critical one. In the case of L-mode shot shown in Fig. 1, the stiffness is not that high and the actual gradient exceeds the critical one by a factor of two at $\rho_{\rm tor} \approx 0.5$ and by four at the plasma edge. Therefore, we can conclude that the IFS-PPPL model either predicts too low ITG threshold or overestimates stiffness for ASDEX Upgrade.

ITB regimes. For ITB plasmas the whole time history of every shot was modeled. It was found that the Weiland-Nordman model was capable to reproduce sufficiently well the most of experimental results. It is the only transport model of all tested ones which has no regular trend to underestimate central values of both electron and ion temperatures. Moreover, in ITB plasmas, this model often gives zero anomalous transport in a wide internal region where $\omega_{E\times B} > \gamma$. For ions the residual neoclassical heat conductivity gives a reasonable description while for electrons the neoclassics results in too steep electron temperature gradients in the central region. For this reason, it was additionally assumed that χ_e does not drop below 0.3 m^2/s. The assumption appears to be not very restrictive and it plays a role in ITB regimes only. Fig. 4 shows the results of modeling for two different time slices at different NB power levels. The observed difference between measured and calculated T_i can be easily attributed to uncertainty in definition of the radial electric field as $E_r = v_{\rm tor}/B_{\rm pol}$. As long as the results are rather sensitive to the rotational shear a further study of this feature is required.

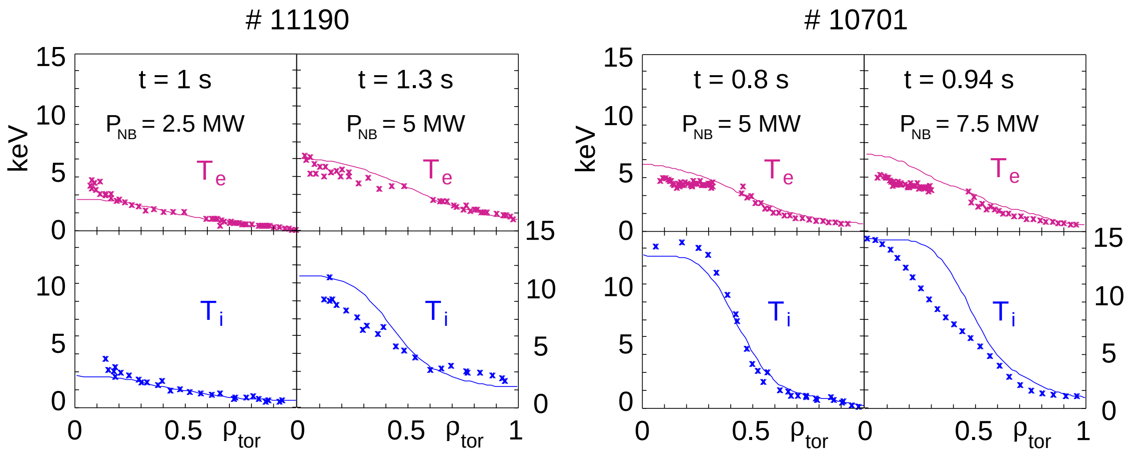

Fig. 4. Radial profiles for T_e and T_i in ITB shots with H-mode (No. 11190) and L-mode (No. 10701) edge. The Weiland-Nordman model was used in the simulations.

4. Summary

Four physics based transport models were tested against a wide range of ASDEX Upgrade experimental data. The Weiland-Nordman model gives the most appropriate fit to the data. Other models predict too high electron and ion heat conductivities. Rotational shear stabilization seems to play an essential part for the anomalous transport in H-mode and ITB regimes. For ASDEX Upgrade a reasonable representation is obtained with the simplifying assumption $E_r = v_{\rm tor}/B_{\rm pol}$. Further study is required to clarify an influence of other terms contributing to E_r. In particular, a self-consistent description for the plasma rotation is needed and will be a subject for further development of the model.

Acknowledgments

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