

Comparison between measured divertor parameters in ASDEX Upgrade and SOLPS code solutions

A.V. Chankin^{a,*}, D.P. Coster^a, R. Dux^a, Ch. Fuchs^a, G. Haas^a, A. Herrmann^a, L.D. Horton^a, A. Kallenbach^a, M. Kaufmann^a, A.S. Kukushkin^b, K. Lackner^a, H.W. Müller^a, J. Neuhauser^a, R. Pugno^a, M. Tsalias^c, ASDEX Upgrade Team

^a Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany

^b ITER International Team, Garching Joint Working Site, Boltzmannstr. 2, 85748 Garching, Germany

^c NCSR Demokritos, Greece

Abstract

Detailed modelling of the plasma edge of ASDEX Upgrade in Ohmic and H-mode discharges was performed with the SOLPS (B2-EIRENE) code. A tendency of the code solutions to underestimate the divertor T_e and overestimate the plasma density (thus, predicting cooler and denser divertor than in the experiment) has been reliably established. A possible cause of the observed discrepancies is the presence of a significant population of supra-thermal ions and electrons in the SOL and divertor, which cannot be modelled by the fluid plasma code B2.

© 2007 Elsevier B.V. All rights reserved.

PACS: 52.55.Fa; 52.49.Hf; 52.65.-y; 52.25.Fi

Keywords: ASDEX-Upgrade; B2-EIRENE code; Divertor simulation; SOL transport

1. Introduction

ASDEX Upgrade (AUG) has good diagnostic capabilities for measuring edge plasma parameters. Well resolved electron density, n_e , electron temperature, T_e , and ion temperature, T_i , profiles can be obtained at the outer midplane, covering outer core, separatrix and SOL regions. In the modelling described below, these midplane profiles were fitted by adjusting perpendicular transport coefficients using the SOLPS code package, which consists of

the coupled fluid plasma code B2.5 and Monte-Carlo neutral code EIRENE. Comparison between simulated and measured plasma parameters in the *divertor* then enables benchmarking code solutions on the consistency with experiment. This strategy is explained in [1].

Typically, code solutions in the divertor agree within a factor of 2 with experimental measurements [2–4]. However, the tendency of the code solutions to underestimate the divertor T_e and overestimate n_e , especially near the outer strike point position, has often been noticed. The present paper describes a comparison between SOLPS modelling and experiment based on two AUG shots: a

* Corresponding author. Fax: +49 89 32992580.

E-mail address: Alex.Chankin@ipp.mpg.de (A.V. Chankin).

standard AUG Ohmic shot is analysed in detail, while the previously modelled ELMy H-mode shot [1] is mostly reviewed, with only limited new information on further modelling being presented.

2. Modelling of H-mode shot

The results of the quasi-steady-state inter-ELM modelling of low density ($\bar{n}_e = 5.8 \times 10^{19} \text{ m}^{-3}$) H-mode shot with $B_t = 2 \text{ T}$, $I_p = 0.8 \text{ MA}$ and 5 MW of NBI are described in [1]. This modelling revealed a significant discrepancy between simulated and measured parameters in the divertor, especially in the vicinity of the outer strike point (measured and simulated parameters at the inner target have not been compared in detail. The same applies to the Ohmic case described in the next section). The strongest direct indication of the discrepancy was a substantially higher, by factor 2.2, simulated peak H_α radiation from the outer target than in the experiment. The simulated H_α profile was also narrower than in the experiment. Extensive sensitivity studies, by varying input parameters in the code, were conducted. They included variation of: separatrix density within a certain allowable range, ion and electron parallel heat flux limiters, power sharing between ions and electrons, degree of ballooning of transport coefficients (by default, a rather arbitrarily chosen dependence $\sim 1/B$ is used in the modelling as a compromise between zero ballooning and a stronger ballooning, $\sim 1/B^2$, cases), the value of transport coefficients in the SOL and divertor, Helium content, models of the neutral description in the vacuum vessel, chemical sputtering coefficients, and prompt reflection coefficient of neutrals and ions from the target. The main discrepancy in the H_α radiation profiles has not been eliminated.

Two possible explanations for the discrepancy were considered: some drawbacks (e.g. missing atomic or molecular reactions) of EIRENE which make the neutrals slower than in reality and result in narrow ionisation profiles, and the presence of a significant population of supra-thermal ions or electrons in the SOL and divertor plasma. The latter was related to low plasma collisionality in the SOL: in the code simulation, parameters at the separatrix midplane position were: $n_e = 1.6 \times 10^{19} \text{ m}^{-3}$, $T_e = 105 \text{ eV}$, $T_i = 190 \text{ eV}$. By defining electron and ion collisionality parameters according to [5], Eq. (4.105) as $v_{ee}^* \equiv L/\lambda_{ee} \approx 10^{-16} n_e L/T_e^2$ and $v_{ii}^* \equiv L/\lambda_{ii} \approx 10^{-16} n_e L/T_i^2$, where L is the product $\pi q_{95} R$,

with $q_{95} = 5$ being the safety factor at the surface containing 95% of the poloidal magnetic flux, $R = 1.7 \text{ m}$ – major radius of the plasma, and assuming $Z_{\text{eff}} = 1$, one obtains $v_{ee}^* = 4.5$ and $v_{ii}^* = 1.3$. Hence, ions may be considered as almost collisionless and electrons – marginally collisionless in the SOL.

Since the completion of the sensitivity studies described in [1], other checks have been made in order to assess the sensitivity of the SOLPS solution to assumptions made in EIRENE. Runs with the newer version of EIRENE (dated 1999, compared with the older version of 1996), coupled with B2.5, were performed. The peak H_α radiation was reduced by 20%, while the maximum electron temperature at the outer target, $T_{e,\text{max}}$, only moderately increased from 14.3 to 16.3 eV. The newer EIRENE version includes elastic $D_2 - D^+$ collisions and a crude model to account for vibrational states of D_2 . These reactions, however, could not improve the match with the experiment. Finally, in order to ensure that the perpendicular (across the B-field) mobility of neutrals is not restricted, and avoid their excessive ionisation in a narrow layer close to the strike point, the wall temperature in EIRENE was raised from the usual value of 0.1 eV (1160 K) to 1 eV. As a result, the peak H_α radiation further dropped by 9%. Still, it was concluded that improvements/alterations in the neutral model *alone* could not achieve a significantly better match with the experiment, and kinetic effects related to low plasma collisionality which are not described correctly in the fluid code B2.5, may be important in real plasmas and considerably affect density and temperature distributions in the divertor. To avoid kinetic effects, a higher collisionality, Ohmic shot, was selected for the SOLPS modelling.

3. Modelling of Ohmic shot

A steady-state second phase of a standard AUG Ohmic shot, with higher density, $\bar{n}_e = 3.65 \times 10^{19} \text{ m}^{-3}$, was selected for the SOLPS modelling. The magnetic configuration for this shot with $B_t = 2 \text{ T}$, $I_p = 0.8 \text{ MA}$, $q_{95} = 4$ (the difference in q_{95} with the H-mode shot is mainly due to the smaller size plasma), is shown in Fig. 1, together with the SOLPS numerical grid. The plasma density was maintained by the gas puff of $3 \times 10^{21} \text{ s}^{-1}$ (in terms of D atoms), which was modelled by a poloidally uniform gas puff in EIRENE. The input power into the numerical grid, 0.52 MW, was found by sub-

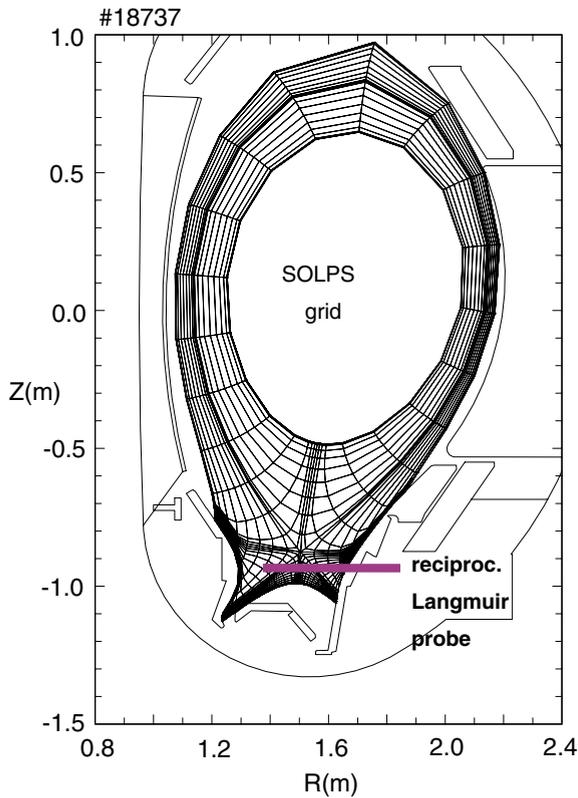


Fig. 1. Magnetic configuration and the SOLPS numerical grid for the standard AUG Ohmic shot #18737, together with the trajectory of the reciprocating Langmuir probe.

tracting radiated power in the core from the input Ohmic power. Within the grid, radiated power of at least 0.175 MW, mostly coming from the SOL and divertor, was to be matched by the modelling. Modelling assumptions are standard and described in [1]. Against original expectations, the consistency between simulated and experimental parameters in the divertor for this Ohmic shot was worse than that for the previously modelled H-mode shot, despite a much higher collisionality in the SOL, as will be shown below. This might be related to the fact that the power balance in the outer divertor is more delicate for plasmas with lower input power.

Measured and simulated upstream density and temperature profiles at the outer midplane position are shown in Fig. 2. Error bars for the experimental n_e data are $\approx 6\%$, almost constant across the profile in the core, separatrix region and stretching up to 2 cm into the SOL region. For the T_e data, error bars are $\approx 15\%$ for the same regions. Transport coefficient profiles across the outer midplane used in the modelling are also presented in Fig. 2, with the rela-

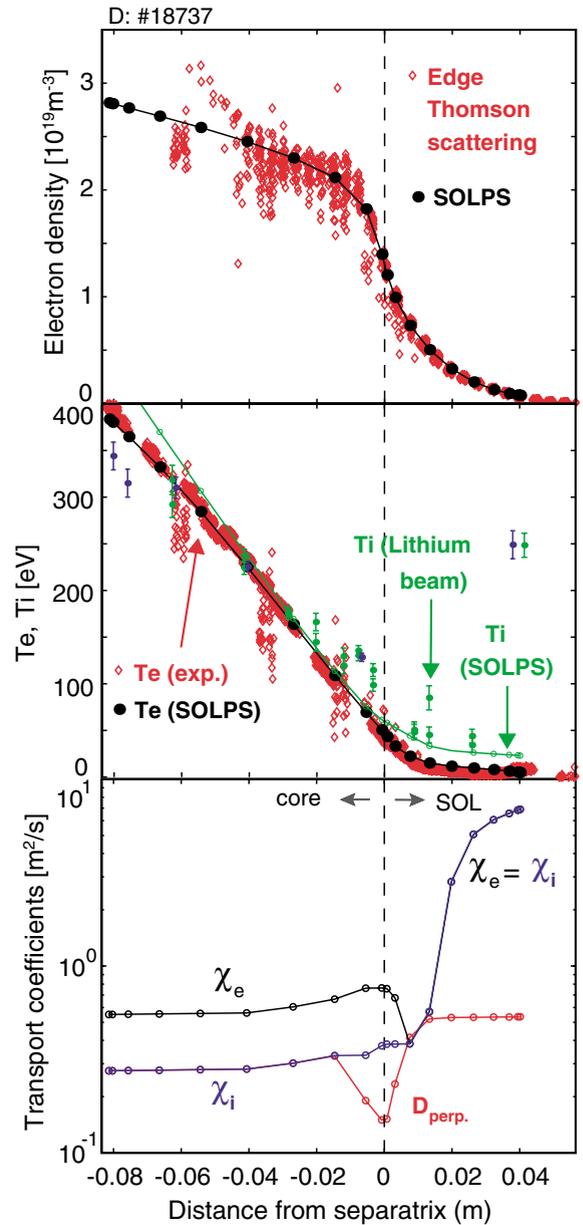


Fig. 2. Measured and simulated density and temperature profiles near the outer midplane and transport coefficients used at the outer midplane, for the standard AUG Ohmic case.

tion between χ_i and χ_e replicating that of the earlier modelled H-mode shot [1]. SOLPS profiles shown in Fig. 2 correspond to a case without drifts and impurities. All SOLPS cases displayed mismatch between the simulated and experimental radiated power in the computational domain, with the simulated values always exceeding the experimental value of 0.175 MW due to lower T_e and higher n_e in the divertor than in the experiment (see below). For

the case corresponding to Fig. 2, the power radiated on deuterium along was 0.2 MW. An introduction of chemical sputtering with the sputtering yield of 1.4% (the same as used previously in [1]) raised the total radiated power to 0.3 MW, far above the experimental value. Therefore, to obtain more realistic T_e and n_e at the outer target, chemical sputtering was switched off and pure deuterium plasmas were considered.

Density and temperature profiles at the outer target are shown in Fig. 3 for a case similar to that shown in Fig. 2, with the same separatrix density, but with drifts and a slightly higher input power, 0.56 MW. Upstream profiles around the separatrix position and in the SOL are almost the same for drift and non-drift cases, for the same transport coefficients. However, deviations from the experimental profiles appear near the inner core boundary due to some parasitic fluxes in the present drifts implementation in B2.5. They occur at higher T_e , T_i , a matter to be dealt with in the near future. Typically, drift cases have somewhat higher outer target T_e , however, as can be seen from Fig. 3, still far below the maximal experimental values obtained from the target Langmuir probes. In particular, all SOLPS cases lack the peaking of the experimental T_e profile at ≈ 20 eV. In the previous modelling of the same shot [4], such a peaking could be achieved by running drift cases with fluid neutrals, however, this result was not repeated when running cases with the coupled B2.5-EIRENE code. The simulated

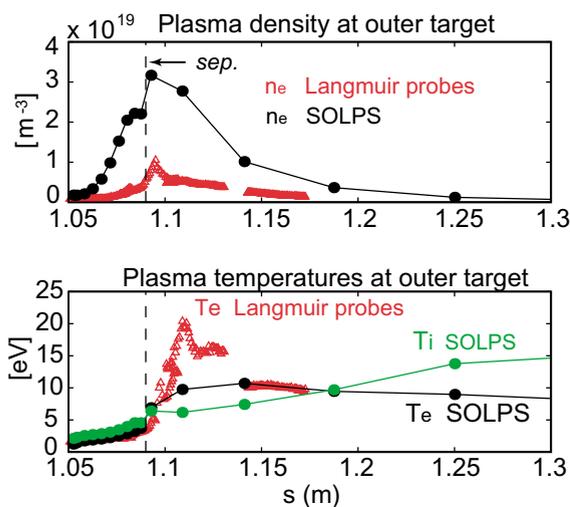


Fig. 3. Experimental and simulated n_e , T_e profiles at the outer target, simulated T_i profile for the standard AUG Ohmic case. The SOLPS case is with drifts, but without impurities, the input power 0.56 MW is slightly higher than in the experiment.

plasma density at the target is much higher compared to that inferred from Langmuir probes. Partly, this must be due to the underestimate of n_e measured by the probes. Probe data in general are not very reliable, partly due to the expected deviations of the electron distribution function from Maxwellian. For the flush-mounted target probes used in AUG there is also some uncertainty about the probes' effective area. That is why an independent assessment of the overestimate of the simulated target n_e is important. It can be established by comparing measured and simulated power and particle fluxes shown in Fig. 4. The integral simulated power flux to the outer target is 0.21 MW, which exceeds the flux calculated from the Langmuir probes as $8n_e c_s T_e$, with c_s being the ion sound speed, only by a factor 1.35. At the same time, the integral simulated particle flux to the outer target is larger than that inferred from the ion saturation current of the Langmuir probes by a much greater factor 2.52, which implies cooler plasma with larger recycling in the divertor in simulations than in the experiment. The simulated sub-divertor neutral pressure

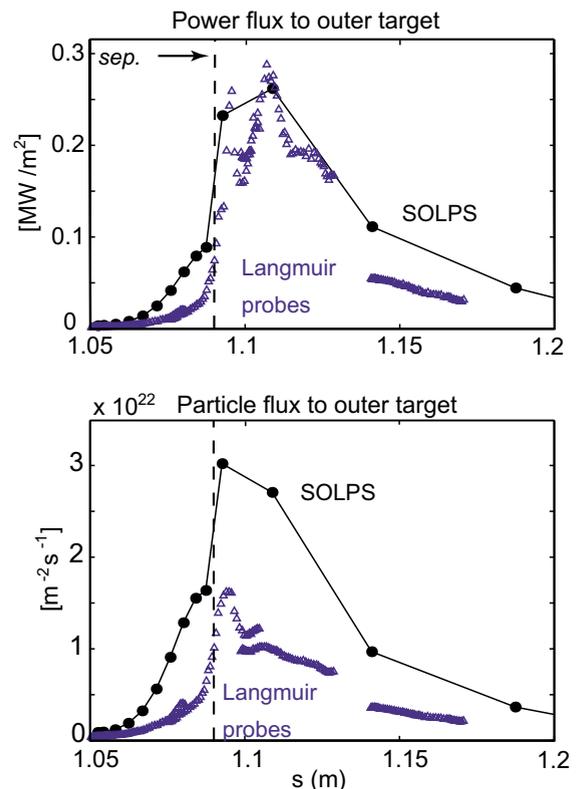


Fig. 4. Experimental and simulated power and particle fluxes to the outer target, for the standard AUG Ohmic shot.

exceeded the measured value by factor 2, consistent with the larger simulated target particle flux.

4. Discussion

Midplane separatrix parameters for the drift Ohmic case described above are: $n_e = 1.3 \times 10^{19} \text{ m}^{-3}$, $T_e = 47 \text{ eV}$, $T_i = 62 \text{ eV}$. Using similar collisionality parameters as in the previous section, gives $v_{ec}^* = 14.6$ and $v_{ii}^* = 7.9$. The SOL plasma is therefore much more collisional than in the H-mode case. However, for the electrons with energies of $3\text{--}5T_e$, which are responsible for the bulk of the heat flux, the effective collisionality is much lower. Taking e.g. $4T_e$ as a characteristic value, one obtains $v_{ec_{4T_e}}^* = 0.9$. Therefore, the heat-carrying electrons are only marginally collisional, indicating a possible impact of kinetic effects on divertor conditions.

The upstream plasma collisionalities in the Ohmic case are typical for the AUG operation, they can only be increased substantially in higher density plasmas with detachment, which however itself presents considerable problems for the modelling. They are also not far from those expected in ITER. According to [6], the expected separatrix T_e in ITER is 150 eV , and $n_e = 4 \times 10^{19} \text{ m}^{-3}$. Taking into account the larger size of ITER (major radius $R = 6.3 \text{ m}$ compared to 1.7 m in AUG) and lower q_{95} (3 compared with 4), one obtains $v_{ec}^* = 12.3$, which is very close to that of the modelled AUG Ohmic case ($v_{ec}^* = 14.6$).

The concrete mechanism by which supra-thermal electrons or ions might raise plasma temperatures in the divertor and reduce its density is not clear at present. It is possible that a large fraction of supra-thermal particles in the divertor originating from the ‘hot’ SOL will raise the effective heat conduction, leading eventually to higher heat deposition onto the targets for the same upstream pressure. Under such circumstances, the application of ‘flux limits’ to parallel transport coefficients would be erroneous, and one should instead introduce ‘flux enhancement factors’, as was concluded in the kinetic simulations in [7]. Within the strategy of the edge modelling adopted in this paper, it would allow one to shift the position of the separatrix more outward (towards positive distances from the separatrix in Fig. 2). The separatrix position is poorly defined in experiment, with the uncertainty of $\approx 1 \text{ cm}$ in AUG due mainly to the poor accuracy of its determination by the equilibrium code used in the grid generation. However, the relation between

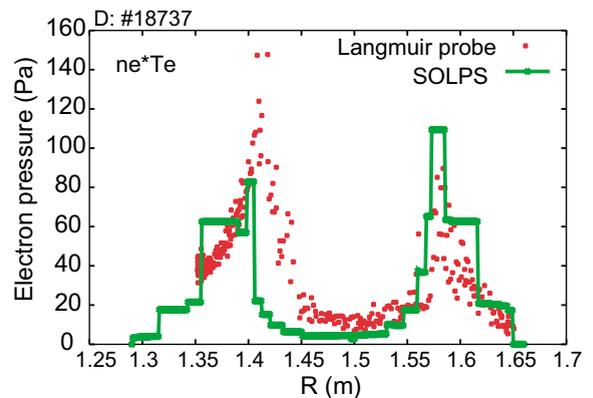


Fig. 5. Electron pressures from SOLPS and the reciprocating probe introduced below the X-point, as shown in Fig. 1.

midplane n_e and T_e is reliable, as both quantities come from the same laser diagnostic. So, if for lower upstream parameters (namely electron pressure $n_e \times T_e$) it was possible to transfer more heat flux onto the target, one could select lower separatrix n_e and still satisfy the power balance (the amount of power conducted to the target). The reduction in the separatrix n_e might then result in a ‘hotter’ divertor solution, with higher T_e , T_i and lower n_e at the target (within the range of $n_s = 0.6\text{--}1.3 \times 10^{19} \text{ m}^{-3}$ for the midplane separatrix density, the maximum simulated target T_e was found to vary roughly according to $n_s^{-1.5}$, for the same transport coefficients). Further modelling work, with the implementation of kinetic calculations into the present-day fluid codes, is required to test these ideas. It is, however, clear from Fig. 5 that there indeed may be a scope for some reduction in the upstream separatrix n_e in the modelling. This figure presents the comparison between electron pressures from the SOLPS simulation and from the reciprocating probe introduced below the X-point, as shown in Fig. 1. Further reduction in the separatrix n_e in the simulations would not contradict the experiment, since the outer peak of the simulated electron pressure profile is clearly above the corresponding experimental values.

5. Summary

A detailed comparison between simulated and experimental divertor parameters of the ASDEX Upgrade Ohmic and H-mode discharges was performed with the SOLPS (B2-EIRENE) code. It was established that the code tends to underestimate

the divertor T_e and overestimate the plasma density, thus, predicting cooler and denser divertor than in the experiment. Sensitivity checks, by changing internal input parameters of SOLPS, were made in an attempt to reach better agreement with the experiment. At present, it seems unlikely that the discrepancies could be caused by either deficiencies of the neutral Monte-Carlo package EIRENE, or its improper implementation in the cases analysed. An alternative explanation via kinetic effects capable of increasing parallel heat fluxes seems more plausible. It is important to point out that for most of the AUG plasmas heat carrying electrons near the separatrix in the main SOL (far away from the divertor) with energies of $\sim 4T_e$ are only weakly collisional. The same conclusion applies to the expected operational conditions of ITER. Hence, proper implementation of kinetic effects in today's fluid codes becomes an urgent task.

References

- [1] A.V. Chankin, D.P. Coster, R. Dux, et al., Plasma Phys. Contr. Fusion 48 (2006) 839.
- [2] R. Schneider, D.P. Coster, A. Kallenbach, et al., in: Proceedings of the 17th International Conference on Plasma Physics and Controlled Fusion Research, 1998, IAEA, Vienna, F1-CN-69/THP2/05.
- [3] R. Schneider, D.P. Coster, J. Neuhauser, et al., in: Proceedings of 22nd EPS Conference on Controlled Fusion and Plasma Physics, Bournemouth, 3–7th July 1995, vol. IV, p. 285.
- [4] D.P. Coster, A.V. Chankin, G.D. Conway, et al., in: Proceedings of 32nd EPS Conference on Plasma Physics, Tarragona, 27 June–1 July 2005, ECA, vol. 29C, 2005, P-1.008.
- [5] P.C. Stangeby, in: The Boundary of Magnetic Fusion Devices, IOP Publishing, Bristol, 2000, p. 56.
- [6] A.S. Kukushkin, H.D. Pacher, G.W. Pacher, G. Janeschitz, D. Coster, A. Loarte, D. Reiter, Nucl. Fusion 43 (2003) 716.
- [7] A.S. Kukushkin, A.M. Runov, Contrib. Plasma Phys. 34 (2/3) (1994) 204.