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# Extension of the B2 code towards the plasma core for a self-consistent simulation of ASDEX upgrade scenarios

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**Abstract**

The new version of the plasma fluid code package B2-SOLPS5.0 is extended to the plasma core and used to simulate self-consistently an L-Mode ASDEX Upgrade discharge. In a first step gas puffing and neutral beam injection are modeled using particle and heat sources. In the second step particle and energy transport, carbon production at the wall, pumping and other processes are fitted to reproduce all relevant diagnostic data. The desired transport coefficients can be used as information on anomalous particle- and energy transport, especially regarding the interplay between diffusive and convective transport. In this way a validated model of an ASDEX UPGRADE L-Mode discharge at a particular time point is achieved with a single code for core and SOL-region. © 2001 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

This paper describes recent enhancements to the multi-species plasma fluid code package B2 [1,2], which allows one to create a detailed model of an experimental discharge.

To describe a fusion plasma as in total, 1D codes simulating the core-region and 2D codes describing the SOL coupled by their boundary conditions have been used in the past (such as COCONUT [3] at JET). Alternatively, the new version of the SOL code B2-SOLPS5.0 (identical to B2.5) can be extended far into the core-region to achieve a detailed simulation of core- and SOL areas using only one code.

In Section 2 of the present work the modifications in the code necessary to extend the simulated region far into the core are described. Gas puffing and neutral beam injection are modeled as particle sources at the boundary and particle and heat sources in the main chamber, respectively.

Section 3 describes how a validated model of a plasma discharge can be achieved with the new B2-SOLPS5.0-code reproducing all important diagnostic data for a particular point in time. Using the ASDEX UPGRADE L-Mode discharge #11277 as an example, particle- and energy transport, carbon production at the wall, pumping, gas puffing and other processes have been modified until there is good agreement with the most important experimental data and profiles. This complex fitting process can be used for all different kinds of discharges to get a detailed overall picture of the physical processes involved. The code is not completely self-consistent as it needs some information from 1D-codes (sources for NBI heating), but it can be seen as a step towards an universal code simulating the whole plasma.

## 2. Extension into the core

The B2 code has been used in the past mainly as a pure SOL–code package. The inner boundary of the grid

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has been set at 5–10 cm inside the separatrix. The influence of the core to the SOL has been incorporated as an inner boundary condition.

There has been ELM-modeling using an extended grid [4], but some modifications of the code necessary for the use in the core region were missing which have been introduced now. To be able to attack the problem of impurity transport from the SOL into the core a necessary prerequisite is the implementation of the complete (neo)classical physics, especially the drift and currents terms [5,6]. Both terms modify the transport in the SOL (e.g., by strongly influencing the in-/out asymmetry) and in the core (e.g., by creating effective inward pinches for impurities on a flux surface).

As an enhancement in the newest version of the B2-SOLPS5.0-code, gas puffing and neutral beam injection have been modeled as particle sources at the boundary, and particle and heat sources in the main chamber. A new interface for B2-SOLPS5.0 takes heat- and particle source profile data for the neutral beam injection received from the 1D-code ASTRA [10], and distributes the right amount in each grid cell. In the core region the 1D sources from ASTRA are distributed equally in each flux surface region, as heat and particle gradients are immediately equilibrated parallel to the magnetic field. Outside the separatrix the sources are distributed locally in the grid cells at the midplane where NBI-heating takes place.

The physics in the core region is mainly 1D. This is why this region is best described by 1D codes like ASTRA. Grid coarsening would enable a transition from a 2D to a quasi-1D code entering the core region from the edge. This is why grid refinement/coarsening will be our next improvement for the B2-SOLPS5.0 code-package. In order to facilitate the implementation of grid refinement/coarsening in the code, the earlier treatment for the momentum equations in the code by using a staggered grid for the velocities has been replaced by a cell-centered treatment [7]. The modifications for the mesh refinement are well under way and first results will be presented elsewhere [8]. Using grid refinement one could also model strong local gradients (like detachment fronts in divertors, etc.) in much more details as now without extending the calculation time.

In the second step of this work anomalous particle transport coefficients have been taken as a first guess from Hempel [9], but have been modified in the further progress to fit experimental data such as the electron density or temperature profiles in the midplane. The same has been done in the case of heat conduction where coefficients resulting from the 1D-code ASTRA have been used as a start. This complex fitting process will be described in detail in the next section.

## 3. Self-consistent simulation of L-Mode ASDEX UPGRADE discharge #11277

The aim of this work has been an (almost) self-consistent simulation of an ASDEX UPGRADE discharge at a special time point. This means that **main diagnostic results** of the experiment should be reproduced by the code, as the following:

- $n_e$ profile from DCN interferometry and lithium beam diagnostic,
- $T_e$ profile from ECE diagnostic,
- $n_{C6+}$ profile from charge–exchange recombination spectrometry,
- $Z_{eff}$,
- CII- and CIII-line emission signals,
- 2D profiles of total radiation (bolometer camera pictures).

Electron density- and temperature profiles give information about the main plasma state in the midplane. Together with the profile for carbon – the main impurity in most ASDEX UPGRADE discharges obtained from charge–exchange recombination spectrometry (CER) and the $Z_{eff}$ value for the overall impurity content, the plasma state in the core region and in the midplane area of the SOL are well defined. Information on the divertor state comes from 2D bolometer deconvolution and CII/CIII line emission.

The **simulation process** consists of two phases:

1. **Modeling** of all **external** particle and heat sources.
2. **Fitting** of all **internal** transport parameters which are not given by theory.

The goal of this process is to reproduce all experimental data cited above and thereby to get a detailed overall simulation of the discharge. Discrepancies of up to 10% between measured and simulated data are allowed as the fitting is made by hand and the main interest lies in a complete overall physical picture and a complete reproduction of the full set of diagnostic results. In the future, generalized fit routines could be applied to get more accurate results [11].

The fitting results can e.g., be used for:

- validation of theoretical models: By comparing coefficients resulting from the fitting process with different theoretical models one can investigate which model best describes the discharge,
- gaining information about regions which are not accessible to diagnostics,
- checking the results of a specific diagnostic that is not as reliable as the profiles and data used for the fitting process.

The modeling of external particle- and heat sources with the B2-SOLPS5.0 code has been described in Section 2 for the example of NBI heating. This is the only point where the code package still depends on 1D core codes like ASTRA, a fact that makes the results not completely self-consistent. In future developments this influence will be reduced as a universal 2D plasma code with a quasi-1D region in the core further developed [8].

In order to fit the particle transport of hydrogen ions perpendicular to the magnetic field lines in the case of the ASDEX UPGRADE L-Mode discharge #11277 at the time point of 3.5 s, the transport study of Hempel [9] already mentioned earlier has been used as a first guess. Anomalous diffusion coefficients and convective inward drift velocities have then been fitted to achieve a midplane electron density profile close to the one given by DCN and the lithium beam diagnostic (see Fig. 1).

Besides diffusion, gas puffing and hydrogen pumping at the wall also influence the electron density profile. Together with the dependency on the electron temperature profile, the fitting process becomes quite complex and time consuming. For the L-Mode discharge #11277 at 3.5 s we find an anomalous diffusion coefficient for hydrogen in the core region close to the values given by Hempel (see Table 1).

From a value of 0.5 $m^2/s$ in the inner region, the diffusion coefficient first increases to 1.5 $m^2/s$ at 10 cm inside the separatrix, then decreases to 0.7 $m^2/s$ at the separatrix and finally stays about constant outside the separatrix. Compared to the results in the work of Hempel [9] we get a smaller diffusion coefficient close to the separatrix (1.5 instead of 3 $m^2/s$ for an L-Mode shot). The resulting convective drift velocity is zero in the center, increases almost linearly up to 10 m/s (direction inward) close to the separatrix, reaches a value of 2 m/s at the separatrix and vanishes outside the separatrix. These values are identical to data from Hempel [9].

Table 1
Transport coefficients resulting from the fitting process in the simulation of discharge #11277

| Distance from separatrix (m) | −0.4 | −0.2 | −0.1 | 0.0 | 0.05 |
|---|---|---|---|---|---|
| Anomolous diffusion ($m^2/s$) | 0.5 | 1.0 | 1.5 | 0.7 | 0.6 |
| Convective drift velocity (m/s) | 0 | −6.0 | −10. | −2.0 | 0.0 |
| Heat conduction coeff. ($m^2/s$) | 0.3 | 1.0 | 5.0 | 3.0 | 2.0 |

To reproduce the experimental electron temperature profile (see Fig. 2), heat conduction coefficients were initially taken from results of 1D-simulations of the core-code ASTRA, but later modified throughout the fitting process. For the heat conduction coefficient the fitting procedure results in 0.3 $m^2/s$ in the central region (40 cm inside the separatrix in the midplane), the heat conduction coefficient increases linearly up to 1 $m^2/s$ 20 cm inside the separatrix. There is a peak value

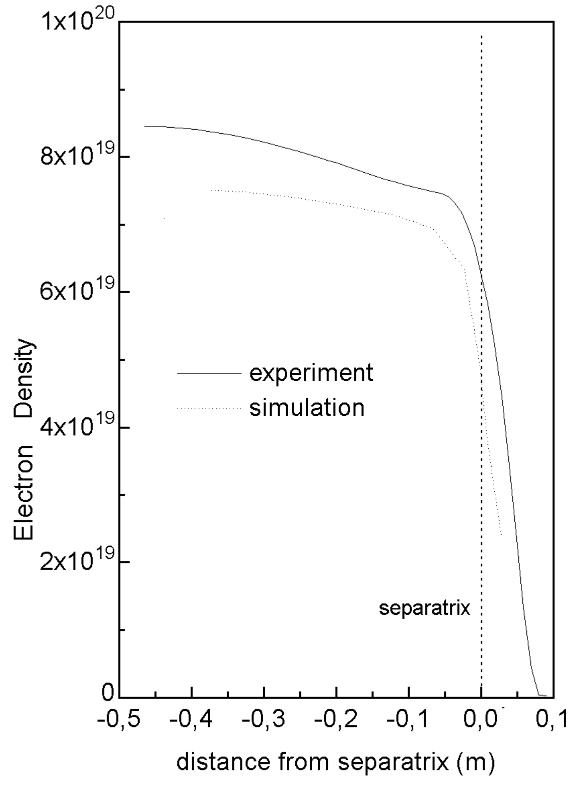

Fig. 1. Comparison of measured and simulated electron density ($m^{-3}$) for ASDEX UPGRADE discharge #11277.

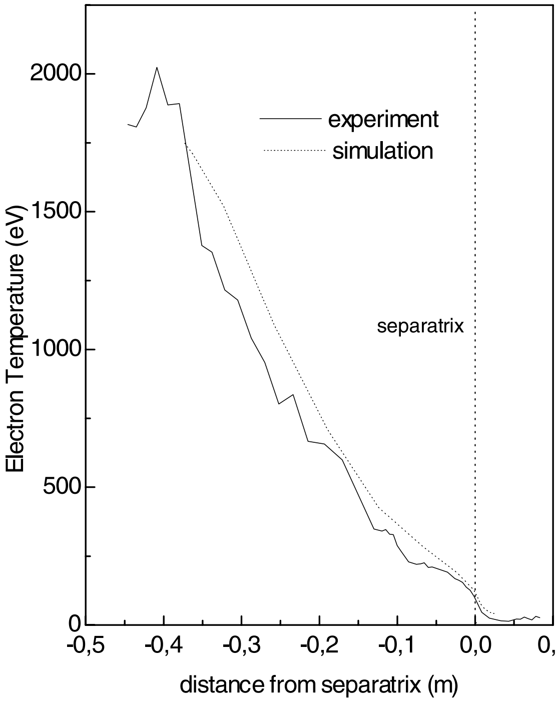

Fig. 2. Comparison of measured and simulated electron temperature profiles for ASDEX UPGRADE discharge #11277.

of 5 $m^2/s$ just inside the separatrix and a value of 2 $m^2/s$ outside (see Table 1). These values differ from the ASTRA results mainly close to the separatrix where we receive smaller values. This discrepancy is due to the fact that radiation losses are modeled separately in B2 while they are included into the 'heat conduction coefficients' in ASTRA. The resulting simulated temperature profile together with the experimental profile measured by ECE diagnostics is plotted in Fig. 2.

The impurity content experimentally measured as a $Z_{eff}$ value and $C^{6+}$ density profile has been reproduced by fitting the sputter coefficient at the walls and the anomalous transport of the impurities.

The sputter coefficients used in the code are effective coefficients describing both the sputtering- and the redeposition processes as one effective value due to the use of a fluid model for the neutral carbon where it enters in the boundary conditions. This effective value is due to strong (direct) redeposition of carbon (or methane which is the dominant sputter product) much smaller than the normal sputter coefficients (as can be checked with a complete kinetic model such as EIRENE including the full methane chain). To achieve the same impurity density as in the experiment represented by the $C^{6+}$ density profile and the $Z_{eff}$ value, the user of the B2-SOLPS5.0 code package has to set a very small sputter coefficient to get the right carbon production at the wall. Thereby the sputter coefficient in the code must be seen as a tuner for impurity production and cannot be compared with an experimentally derived sputter coefficient.

The anomalous carbon ion transport coefficients are assumed to be the same as for hydrogen, but since the similarity between measured and simulated ion carbon density is still not perfect some more fine-tuning could be done with this parameter. The $Z_{eff}$ value is about 1.15 from both simulation and experiment.

By adjusting the heat- and particle transport from the core into the SOL and the sputter coefficients, the experimental divertor state can be closely matched. The outer divertor for discharge #11277 at the time point of 3.5 s is detached and the CIII-signal of the DIV diagnostic shows detachment between the sightlines Lambda 1–9 and Lambda 1–11. In the simulation the calculated CIII-signal shows a jump between Lambda 1–11 and 12, so there is quite good agreement between the simulation and experiment. The inner divertor is almost completely detached in simulation and experiment (between sightlines Lambda 2–8 and 9).

The result of this complex fitting process consists of 2D plots for all important data like electron temperature, the various ion densities, line radiation, etc. available by the B2-SOLPS5.0-code package. This is giving information about the discharge which reaches far beyond the diagnostic information of the experiment.

## 4. Conclusions

Enhancements to the multi-species plasma fluid code package B2 have been presented which allow to derive a validated model of an ASDEX UPGRADE L-Mode discharge at a particular point in time reproducing all important diagnostic data. The new version B2-SOLPS5.0 has been extended far into the core region to achieve a detailed simulation of core- and SOL area of an ASDEX UPGRADE-shot, using one single code.

In a complex fitting procedure particle- and energy transport, carbon production at the wall, pumping, gas puffing and other processes have been modified until there is good agreement with the main and most accurate experimental data and profiles. The desired data can be used as information on anomalous particle- and energy transport, especially on the interplay between diffusive and convective transport. The method is not completely self-consistent as it needs some information from 1D-codes (sources for NBI-heating), but it can be seen as a step towards an universal code simulating the plasma in total.

In view to a further code optimization, all equations are now solved on cell centers, allowing an optimized gridding (especially grid coarsening for the quasi-1D region of the core) in the near future.

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