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2D fluid modeling of the ASDEX upgrade scrape-off layer up to the first wall

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Abstract

We present an application to the full ASDEX upgrade edge plasma of a novel method for 2D fluid modeling, including for the first time a realistic representation of the First Wall. Two independent edge plasma codes are coupled to this purpose: B2 (with a detailed physics content but intrinsic geometrical limitations due to the 5-point computational scheme) for the inner region of the Scrape-Off Layer (the so-called near SOL) and ASPOEL (with simplified physics content but larger geometrical flexibility thanks to the Control Volume Finite Element CVFE scheme) for the outer region (the far SOL). The two codes share information across an interface magnetic surface, representing the outer boundary for B2 and the inner boundary for ASPOEL. An iterative procedure is developed, ensuring the continuity of profiles and fluxes at the interface. The radial profiles of density and temperature computed at the outboard mid-plane across the complete SOL, up to the first wall, are in good agreement with experimental data.

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Keywords: Computational modeling; Tokamak; Scrape-off layer; First wall

1. Introduction

2D fluid modeling is being applied since more than two decades to the study of edge plasma in tokamaks [1] and relies nowadays on a number of well-developed codes, e.g., B2 [2]. The success met by these codes is due to the effectiveness shown in modeling standard plasma configurations, in particular divertor discharges, including however a number of geometrical simplifications. For example, the limitations of the B2 code when applied to first wall/limiter (FWL) geometries were explored in [3]. Other codes, e.g., UEDGE [4] and EDGE2D [5] adopt a 9-point computational molecule, which provides more geometrical flexibility, but are still bound to quadrilateral structured meshes, such that their computational domain is usually not extended up to the first wall (FW).

These geometrical constraints are usually handled by substituting the physical outer wall with a fictitious boundary, coincident with a magnetic surface. As a result, along the outer portion of the plasma only the boundary conditions applied at the divertor plates are justified on a physical basis, while somewhat arbitrary assumptions are needed along the fictitious external boundary. Furthermore, there are situations where the knowledge of the plasma conditions in the far SOL is directly relevant. For example, the plasma density profile in the far SOL is important for the design and optimization of the ICRH antennas adopted for the plasma auxiliary heating [6].

Codes able to overcome the mentioned geometrical limitations were indeed developed in the past, based on Finite Element schemes [7,8], but did not evolve into a production tool. More recently, the ASPOEL code was developed [9], aiming specifically at extending the available 2D plasma modeling techniques to FWL configurations. This problem requires considering numerical schemes more geometrically flexible than the one adopted, for example, by B2. The main difference with respect to the attempts previously mentioned is that the

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ASPOEL code relies on the mixed Control Volume Finite Element (CVFE) numerical discretization scheme [10], which allows extending classical conservative schemes such as presented in [11] to triangular Finite-Element meshes.

In this paper we describe and implement a coupling procedure between the B2 and the ASPOEL codes, aiming at extending the modeling domain of a divertor tokamak up to the FW. The two codes are applied to model the near and far SOL, respectively, using an iterative procedure to guarantee continuity of the plasma parameters across the interface surface. The resulting tool is then applied to a selected discharge from the ASDEX Upgrade Tokamak, to provide a benchmark with experimental data.

2. Physical model

In the current version, ASPOEL is a two-fluid, 2D plasma code, which includes a single ion specie and electrons, as described by the following set of Braginskii-like [12] equations:

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \bar{V}_i) = S_n, \tag{1}$$

$$n_e = n_i, \tag{2}$$

$$\frac{\partial \Gamma_{//,i}}{\partial t} + \hat{e}_{//} \cdot \left[\nabla \cdot (\bar{V}_i \bar{\Gamma}_i + p_i \hat{I} + \hat{\Pi}_i)\right] = S_{\Gamma_{//}}, \tag{3}$$

$$n_i V_{r,i} = -D_r \nabla_r n_i, \tag{4}$$

$$\frac{\partial}{\partial t}\left(\frac{3}{2} n_e T_e\right) + \nabla \cdot \left(\frac{5}{2} n_e T_e \bar{V}_e + \bar{q}_e\right) = -Q_{ei} + S_{Ee}, \tag{5}$$

$$\frac{\partial}{\partial t}\left(\frac{3}{2} n_i T_i\right) + \nabla \cdot \left(\frac{5}{2} n_i T_i \bar{V}_i + \bar{q}_i\right) = Q_{ei} + S_{Ei}, \tag{6}$$

$$\bar{V}_e = \bar{V}_i. \tag{7}$$

In Eqs. (1)–(7) $n_{e(i)}$ is the electron (ion) density, $\bar{V}_{e(i)}$ the electron (ion) fluid velocity, $\bar{\Gamma}_i = m_i n_i \bar{V}_i$ is the ion momentum flux, $\hat{e}_{//}$ the unit vector parallel to the (given) magnetic field B, p_i is the ion pressure (which we assume to be related to the density and temperature by the ideal gas law), $\hat{I}$ is the identity tensor, and $\hat{\Pi}_i$ the ion stress tensor. D_r is the particle diffusion coefficient (the subscript r, whenever it appears, refers to the radial direction, i.e. perpendicular to the magnetic surfaces, while // refers to the direction parallel to the magnetic field), $T_{e(i)}$ is the electron (ion) temperature, $\bar{q}_{e(i)}$ the electron (ion) heat flux and Q_{ei} the collisional energy exchange rate between ions and electrons. S_n, S_Γ, S_{Ee}, and S_{Ei} are the sources of particles, momentum, electron and ion energy, respectively. The parallel components of the heat and momentum fluxes are assumed to be due to collisional processes (classical transport), and the detailed expressions of the transport coefficients can be found in [13]. As for the radial components, it is customary in fluid edge plasma modeling to assume that anomalous transport can be modeled by a diffusive Ansatz (a detailed discussion of this assumption can be found in [2]). Finally, the energy exchange terms are also assumed to be collisional, and are described in [13].

Eq. (1) is the continuity equation, written for the particle density. Eq. (2) is the quasi-neutrality assumption. Eq. (3) is the parallel component of the ion momentum balance, while the radial particle flux is given, in a diffusive approximation, by Eq. (4). Eqs. (5) and (6) are the electron and ion heat equations (neglecting the viscosity contributions), and finally Eq. (7) is the condition of zero net electric current density in the plasma (ambipolar flow). For this study, we assumed deuterium as the only ion species.

Eqs. (1)–(7) describe also a subset of the physical model implemented in the B2 code. Among the most important items considered in B2 but non included in ASPOEL we mention the arbitrary number of charged species (multi-fluid approach), the inclusion of neutrals via the coupling to the EIRENE code [14], the inclusion of drifts and viscosity terms. For the purpose of the study described here, most of these terms were switched off in B2. Since at present no neutral model is implemented in ASPOEL, the source terms appearing in Eqs. (1)–(7), originating from atomic physics processes, were different from zero only in the near SOL.

Concerning the boundary conditions, as previously mentioned, in a B2 stand-alone run they would be applied at the B2 outermost magnetic surface. In the present case, this surface is an internal interface, and the boundary conditions for the complete model should be applied at the physical outer wall (Fig. 1 shows where the interface surface and the wall are located). Most of the plasma–wall transition models developed so far focus on the case of a finite incidence angle between the magnetic field and the wall, while only limited literature is available for the case of very shallow angle (or, at degenerate locations, field–wall tangency) [15]. At the outer wall, for the continuity, momentum, and electron energy equations, we adopt tentatively the same boundary conditions already described in [9], based on [15] and [16]. For the ion energy, which in [9] was considered in the over-simplified form $T_i = T_e$, we adopt a coefficient $\gamma_i = 3$ for the ion energy sheath transmission factor.

3. The B2–ASPOEL coupling procedure

In Fig. 1 we show a poloidal cross section of ASDEX Upgrade including the structures of the FW. On the left, we also mark the area occupied by a B2 mesh (96 poloidal × 31 radial nodes, quadrilateral), with the computational domain delimited by the magnetic surfaces labeled as A, D and C, and by a portion of the target plates. The grid is in this case restricted to a limited portion of the whole physical domain because of the near tangency of the C surface with the structures at the upper right. This at the same time forces to use C as an artificial boundary, not corresponding to any physical object. On the right side of Fig. 1 we show a zoom of the top region, including a few cells from both the B2 and ASPOEL mesh (3189 nodes, triangular) which fills the far SOL region (the private region beyond D is not yet included). It is clear that the ASPOEL mesh allows an accurate fitting of the solid structures surrounding the plasma.

The main problem in using two different codes (and physical models) in two regions of the same domain communicating with each other is to guarantee the continuity of the computed solution and fluxes across the interface. Both B2 and ASPOEL

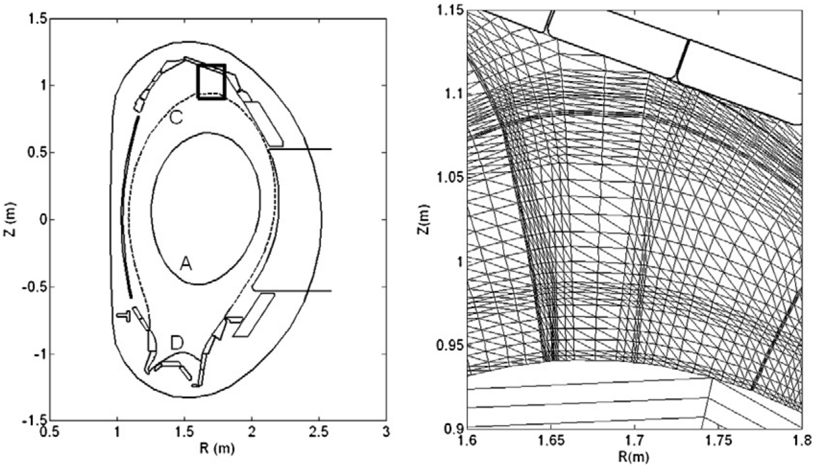

Fig. 1. (Left) Cross-section of the ASDEX upgrade tokamak, showing the internal wall structures and the regions occupied by the B2 and ASPOEL meshes. Line A (solid): The inner boundary of the B2 mesh. Line D (solid): the private region boundary of the B2 mesh. Line C (dashed): the B2–ASPOEL interface surface. (Right) Zoom of the region delimited by a square in the left panel. Also, the B2 (quadrilateral, in the lower region) and the ASPOEL (triangular, in the upper region) meshes are shown.

follow closely the inner/outer iteration scheme described in [11] to find an equilibrium plasma solution; this scheme can be naturally modified to handle together the two coupled codes according to the following strategy:

(i) Start with a B2 outer iteration in the near SOL region, with tentative boundary conditions at the interface;
(ii) Determine the particle, momentum and energy fluxes crossing the interface with the far SOL, and interpolate them on the ASPOEL mesh. Since both codes are conservative, the interpolation must be such as to conserve the total fluxes across that surface;
(iii) Perform an ASPOEL outer iteration, imposing the fluxes interpolated from B2 as the boundary condition at the interface;
(iv) Extract the density, velocity and temperature profiles along the interface surface from ASPOEL, and interpolate them on the B2 mesh. At this point, step (i) should be repeated using these profiles as B2 boundary conditions, to close the loop.

The B2 and ASPOEL coupled codes have been compiled and linked into a single executable, to optimize the speed of the information sharing procedures. With the meshes shown in Fig. 1, about $1/3$ of the needed CPU time is spent in B2, the remaining portion being needed by ASPOEL.

4. Results and discussion

As an example application, we illustrate here the main results of the analysis of the ASDEX Upgrade discharge 11437, at $t = 4.7$ s. It is an Ohmic shot, which we chose because a sufficient amount of good quality experimental data is available for our purposes.

Figs. 2–4 show the measured [17] and the computed electron density, and electron and ion temperature profiles at the outer mid-plane location across the near and far SOL. In Fig. 4, we added for reference purposes an inset showing the interface region between the near and far SOL. We added a further line in the inset, showing the result of a B2 stand-alone run.

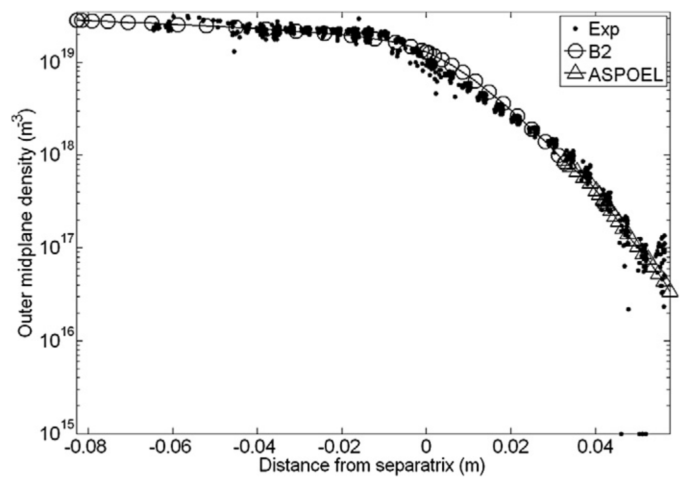

Fig. 2. Experimental and computed radial density profiles at the outboard mid-plane of ASDEX upgrade.

The comparison with experimental data is excellent for the electron density. The computed profiles are compatible with the measured data also for the electron temperature. However, the latter shows a large spread in the far SOL region, which makes it difficult to draw a definite conclusion on the accuracy of the numerical model. The comparison with the ion temperature data seems acceptable in the near SOL, considering the limited number of data points, but there are no data in the far SOL.

Fig. 4 also shows that the difference between the solution computed at the interface from a B2 stand-alone run and a B2–ASPOEL coupled run extends into the near SOL for about 1 cm at the outer mid-plane, i.e. roughly $1/3$ of the distance from the near-far SOL interface to the separatrix.

Fig. 5 shows a profile of the electron mean free path λ_e taken across the outer mid-plane. It can be seen that λ_e is at most of a few meters, which makes the fluid approximation adopted

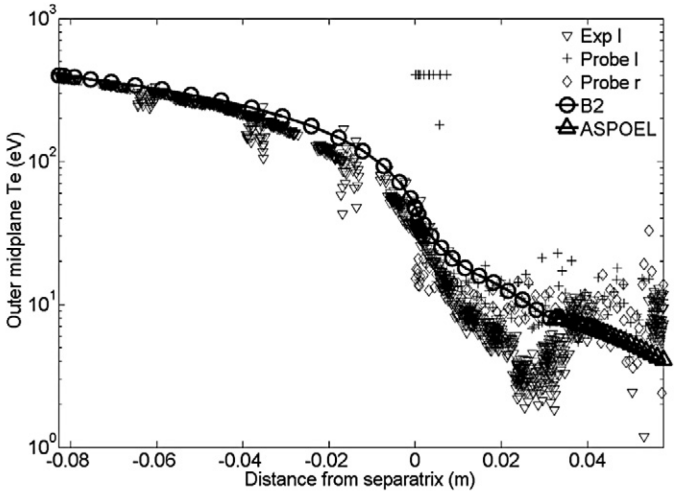

Fig. 3. Experimental and computed electron radial temperature profiles at the outboard mid-plane of ASDEX upgrade.

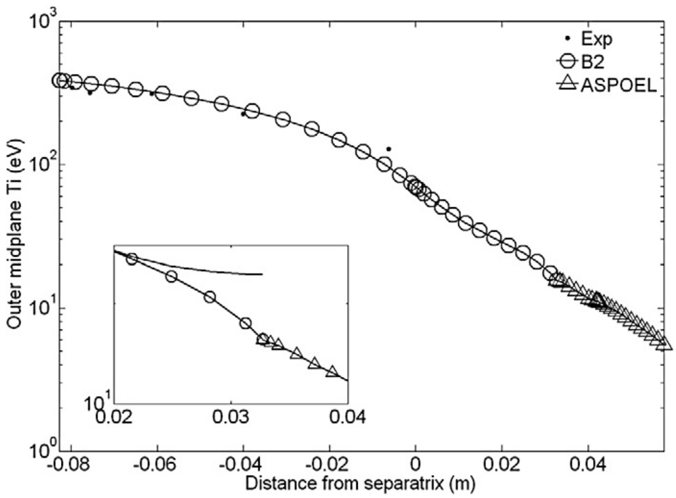

Fig. 4. Experimental and computed ion radial temperature profiles at the outboard mid-plane of ASDEX upgrade. The inset shows: a zoom of the interface region with an additional profile from a stand-alone B2 run.

by our model acceptable, since we can assume a connection length of the order of 10 m and the resulting Knudsen number is less than 1. However, global results of the fluid model across the whole far SOL should be evaluated with care, because λ_e can be significantly larger in some regions of limited, but not completely negligible, extent. For example, in the present case we estimate $\lambda_e > 30$ m over about 10% of the total far SOL volume, while the more extreme condition $\lambda_e > 100$ m is still met over about 5% of the far SOL.

5. Conclusions and perspective

We have presented the coupling of the B2 and the ASPOEL codes, to extend the fluid modeling capability of edge plasma codes into the far SOL up to the first wall, and discussed its first application to the analysis of an ASDEX upgrade discharge. Computed results agree well with the available experimental data.

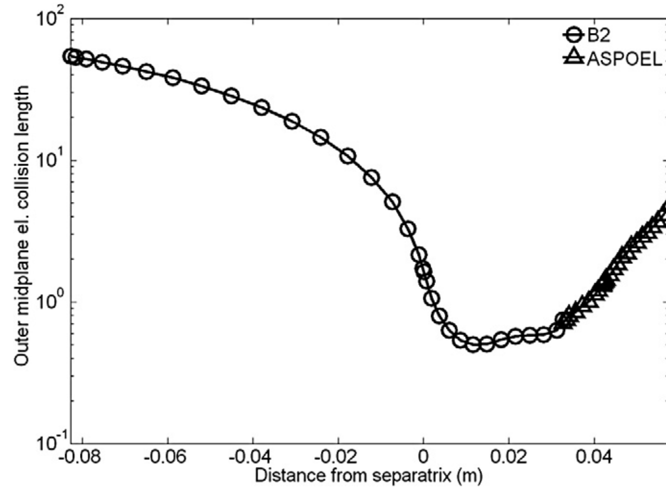

Fig. 5. Computed radial outboard mid-plane profile of the electron collision length.

The possibility of extending the plasma fluid models up to the FW opens the door to a number of interesting applications. For example, the availability of accurate predictions of the plasma density profiles in the far SOL is important for the accurate design of auxiliary heating devices such as ICRH antennas. Also, it makes possible the analysis of limiter plasmas, which is expected to be important for the start-up phase of ITER discharges as well as interesting for both present-day limiter machines like FTU or Tore Supra and other projects like IGNITOR. Finally, the coupled model allows setting the wall boundary conditions on a solid (as opposed to a magnetic) surface. These issues shall be the subject of future work.

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