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Development of a computational tool for limiter edge plasma modeling with application to IGNITOR

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Abstract

IGNITOR is the only experiment today designed with the ambitious goal of achieving ignition. During the discharge, the First-Wall Limiter (FWL) will receive about 20 MW [B. Coppi, A. Airoldi, F. Bombarda, et al., Nucl. Fusion 41 (2001) 1253–1257] power, split between conduction/convection and radiation channels. Previous estimates suggested a peak heat flux on the FWL close to 1 MW/m^2. This value should be re-evaluated, accounting for the latest developments in the design of the IGNITOR first wall and changes in the operational scenarios, in order to assess the risk of damages to the FWL deriving from the combination of thermal and mechanical stresses. For this purpose, the development of the ASPOEL code, implementing a 2D model of the edge plasma and including a detailed representation of the FWL, was started at Politecnico di Torino. Here we present the main features of the new code, and illustrate its potential via a preliminary application to IGNITOR.

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Keywords: Power deposition; First wall; Limiter; Edge plasma; Edge modelling

1. Introduction

In IGNITOR [1], the FWL is everywhere close to the main plasma. The design is optimized to allow spreading the plasma heat flux onto a relatively large area, reducing the peak values. This is important, because unfavourable combinations of thermal and mechanical stresses could limit the machine performances.

Estimating accurately the heat load distribution onto the FWL is difficult [2], because the geometry does not allow applying computer codes with magnetic fitted co-ordinates, like SOLPS [3], to cases such as IGNITOR. Moreover, it can be a serious issue also for divertor tokamaks, because the first wall plays always a considerable role in plasma–wall interactions [4]. Furthermore, even divertor tokamaks typically have a limiter start-up

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phase. In the case of ITER, the modelling of the start-up configuration was attempted with magnetic fitted co-ordinates [5], but required strong simplifications, which did not allow a geometrically realistic treatment of the first wall. An interesting attempt at modelling in detail a limiter configuration was presented in [6], which however included only a limited portion of the wall.

Other models were proposed to estimate the heat flux distribution in IGNITOR [7], giving peak values in the range 1–3 MW/m^2 for the reference scenario ($I_p = 11$ MA, $B_T = 13$ T, central temperature ~ 11 keV), with uncertainties deriving from the need to provide the power e-folding length as an input parameter.

In order to tackle these issues more accurately, we have recently started at Politecnico di Torino the development of the ASPOEL code, applying the fluid modelling approach [3] to the IGNITOR edge up to the FWL. ASPOEL implements presently a single-fluid model, neglecting neutrals and impurities. This is a dramatic simplification with respect to more sophisticated models [3], but allows estimating the power distribution onto the FWL, provided an educated guess on the radiated power fraction is given. The inclusion of a more complete physical content obviously requires intensive efforts, but is possible. Here we illustrate the ASPOEL code and the model implemented in it, then we discuss the application to a model FWL geometry, before presenting preliminary results for the case of IGNITOR. Finally, we draw our conclusions, and discuss possible perspectives for future work.

2. Physical model and geometrical considerations

The present ASPOEL version solves the following fluid equations:

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \bar{u}_i) = S^n, \tag{1}$$

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

$$\frac{\partial \Gamma_{\parallel,i}}{\partial t} + \frac{\overline{B}}{B} \cdot \nabla \cdot \left(\overline{\Gamma}_i \bar{u}_i + p_i \widehat{I} + \hat{\pi}_i \right) = S^{\Gamma_\parallel}, \tag{3}$$

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

$$\bar{u}_e = \bar{u}_i, \tag{5}$$

$$\frac{\partial}{\partial t}\left(\frac{3}{2} n_e T_e\right) + \nabla \cdot \left(\frac{5}{2} n_e T_e \bar{u}_e + \bar{q}_e\right) = S_e^E, \tag{6}$$

$$T_i = T_e, \tag{7}$$

with $n_{i(e)}$ the ion (electron) density, $\bar{u}_{i(e)}$ the ion (electron) velocity, $\overline{\Gamma}_i$ the ion momentum, $\overline{B}$ the magnetic field, p_i the ion pressure, $\widehat{I}$ the identity tensor, $\widehat{\pi}_i$ the ion stress tensor, D_r the particle diffusivity, $T_{i(e)}$ the ion (electron) temperature and $\bar{q}_e$ the electron heat flux. Eq. (1) is the ion continuity equation, (2) is the quasi-neutrality condition, (3) is the parallel component of the ion momentum balance, (4) is an ansatz for the radial particle flux, (5) states that zero net current is assumed in the plasma, (6) is the electron energy equation and (7) states that ions and electrons are assumed to have the same temperature. Subscripts $\parallel$ and r refer to the parallel and radial directions, respectively (diamagnetic transport is not yet included). Having neglected neutrals and impurities, the source terms in (1)–(7) vanish. Furthermore, $\overline{B}/B$ in (3) is assumed to be uniform.

We extend the computational domain up to the FWL by adopting a triangular mesh, on which we apply the Control Volume Finite Element (CVFE) technique [8]. We create a number of control volumes (CV) around each mesh node, by joining the midpoints of the element edges with the centres, as shown in Fig. 1. Then we apply the fluid conservation laws (1)–(7) to each CV. The method shares the geometrical flexibility of the classical Finite Elements [9], and is locally conservative thanks to the CV approach. Furthermore, in the simplest cases it produces the same computational molecule as the Finite Volumes method implemented, e.g., in SOLPS. The CVFE method is then an extension of other well-known schemes, already successfully adopted in plasma modelling codes. In order to deal with the transport anisotropy, we align one edge of each element with the magnetic field. Further technical details on the ASPOEL code can be found in [10].

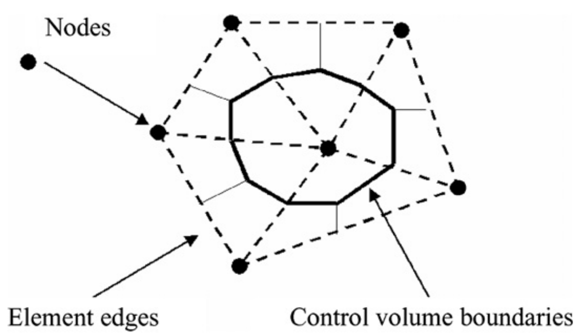

Fig. 1. Structure of a control volume on a triangular mesh. Dashed lines: cell edges. Solid lines: CV boundaries. A particular CV is bolded for easy identification.

3. Applications

We apply ASPOEL first of all to a model tokamak, whose flux surfaces are tori with major radius $R_0 = 1.5$ m. The Last Closed Flux Surface (LCFS) has minor radius $a = 0.5$ m, and the FWL is a torus with minor radius $a_w = 0.51$ m, tangent to the LCFS along the inboard mid-plane. This generates a SOL with a maximum width of $2 \times (a_w - a) = 2$ cm, at the outboard mid-plane. The magnetic pitch is $B_\vartheta/B = 0.1$. We set the radial diffusivities to values similar to what could be expected for IGNITOR, by extrapolating from FTU [11] and assuming $1/B$ proportionality: $D_r = \eta_r = 0.3$ m^2/s, and $\chi_r = 4.5$ m^2/s. At the main plasma boundary (set at 5 mm inside the LCFS) we impose $n_i = 2 \times 10^{20}$ m^{-3} and $T_e = 55$ eV. These conditions were estimated in [7] to be also reasonable for IGNITOR. At the FWL, we assume an electron energy transmission factor $\gamma_e = 5$, sonic parallel flow speed, and the radial flow speed to be a fraction of the ion thermal speed:

$$u_r = \alpha u_{th,i}, \quad (8)$$

with $\alpha = 0.01$ estimated in [12] for the degenerate case of a surface tangent to $\overline{B}$. Lacking a satisfactory theory for the transition between tangency and finite magnetic incidence angle, we assume (8) is applicable also to the small angles (~1° at most) considered here. We checked the model dependence on α: neither doubling nor halving α produced a strong change in the results. It was observed that the variation of u_r driven by α was partly compensated by a decrease of n_i, which damped the variations of the particle flux. The energy flux depends on α through its proportionality to the particle flux. As a consequence, the energy flux too appeared to be not strongly dependent on α. We found $T \sim 25$ eV at the FWL, which allows estimating a density e-folding length $\lambda_n \sim \sqrt{D_r L/c_s} \sim 1$ cm. Fig. 2 shows the radial density profile computed at the outboard mid-plane, compared with an exponential with decay length λ_n estimated above: the agreement between the two profiles is satisfactory. Spatial convergence was checked computing the total particle flux at the main plasma boundary on successively refined meshes. The error, estimated with the Richardson extrapolation method, was found to be less than 1% on a mesh with 400 nodes, which was used to obtain the results presented in this paper.

We now move to consider the case of IGNITOR. Fig. 3 shows a cross-section of the FWL, with some

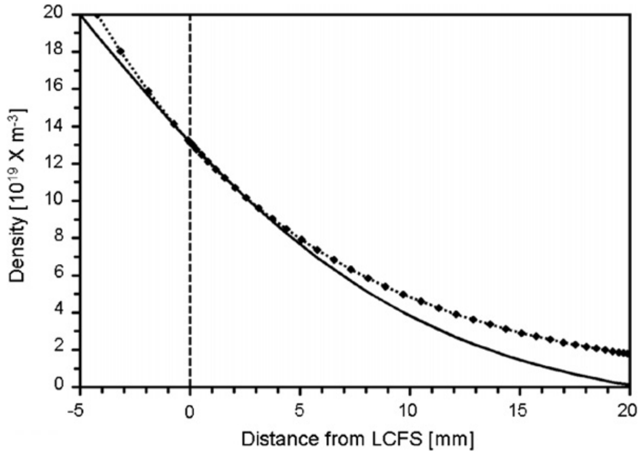

Fig. 2. Radial density profile at the outboard mid-plane (solid), compared with a reference exponential (dotted with square markers). The vertical dashed line marks the LCFS.

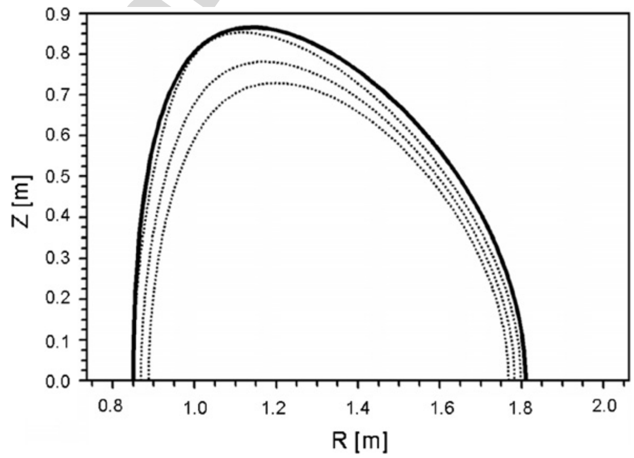

Fig. 3. Poloidal cross-section of the IGNITOR FWL (solid) with some magnetic surfaces (dotted).

flux surfaces. Since the configuration is up–down symmetrical, we show only the upper half. The LCFS touches the FWL at the inboard mid-plane, and approaches it again near the top, dividing the SOL in two main regions: inboard and outboard. Fig. 4 represents the FWL in (θ, ψ) coordinates, with θ the poloidal angle, measured from the outboard mid-plane, and ψ the magnetic flux. It shows the complex structure of the outboard region, divided in a number of nested secondary SOLs. The inset shows a zoom near the inboard mid-plane, with a representation in (θ, ψ) coordinates of the mesh adopted in this case.

Fig. 5 shows the distribution of the power conducted/convected onto the FWL, split into the parallel (dashed) and radial (dotted) contributions. Parallel power deposition follows approximately a

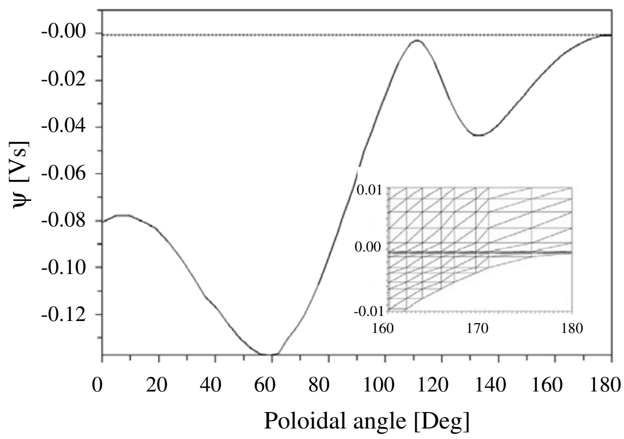

Fig. 4. Cross-section of the IGNITOR FWL represented in the (θ, ψ) space. The horizontal line is the LCFS. The inset shows a zoom of the inboard mid-plane region, with a typical ASPOEL mesh, also represented in the (θ, ψ) space.

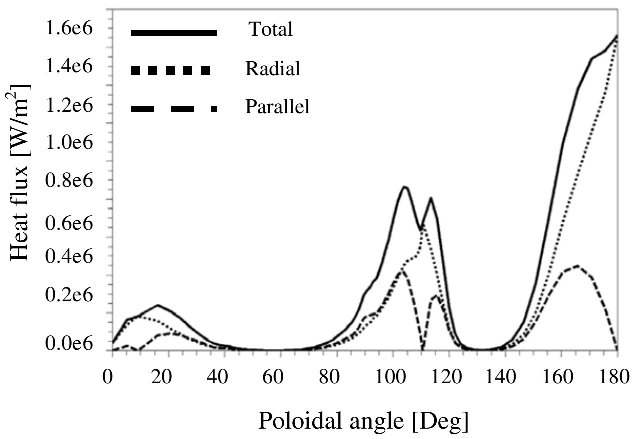

Fig. 5. Heat flux distribution onto the IGNITOR FWL.

cosine-law distribution, driven by the variation of the magnetic incidence angle onto the wall. In particular, it vanishes where the wall runs parallel to the magnetic surfaces. The IGNITOR equilibrium is such that those points correspond closely to the points of minimum (maximum) distance between the wall and the LCFS. Two such minimum distance points are located at $\sim 110°$ (and obviously 180°), see Fig. 4. The radial contribution has a maximum at the same locations, due to the small distance from the main plasma.

Evaluating the actual importance of the radial flux contribution to the FWL heat load is obviously relevant for IGNITOR operation, and this preliminary analysis should be further confirmed. We can mention that experimental observations from DITE and TFTR do report significant fluxes onto the wall at locations where the parallel contribution cancels, due to the geometrical cosine factor [13,14]; however the ability of the ASPOEL code to reproduce such a phenomenology still has to be validated in the future.

Finally, we observe that, even if a detailed comparison is difficult considering the differences in the physical models implemented, the peak heat flux estimated here for IGNITOR is roughly in the same range as obtained elsewhere [7].

4. Conclusions

We have presented the ASPOEL code, and a first application to the modelling of the heat flux distribution onto the IGNITOR FWL. The conservative CVFE method allows adopting triangular meshes, and extending the modelled domain up to the first wall. This improves the geometrical capabilities compared to other computational tools already available today, which, on the other hand, implement more accurate physical models. This increased flexibility is necessary for modelling plasma-wall interactions in IGNITOR (as well as any other limiter tokamak), but could also be relevant for addressing specific issues of divertor tokamaks like ITER, e.g., the load onto the first wall during ELM transients [4] or during the start-up (limiter) phase.

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