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Applications of SOLEDGE-2D code to complex SOL configurations and analysis of Mach probe measurements

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A series of experiments dedicated to the determination of the ballooning nature of the edge and SOL transport has been achieved on Tore Supra [1,2], proposing a quantitative characterization of the radial flux that enters the SOL. The aim of this paper is to back up the interpretation of these probe flow measurements making use of SOLEDGE-2D code. In particular, this fluid code allows one to study density and parallel momentum transport in a 2D geometry including edge and SOL region. Moreover, thanks to an appropriate numerical technique recently proposed [3,4], SOLEDGE-2D code is also able to deal with a complex geometry of plasma facing components including main and secondary limiters.

1. Introduction

A better understanding of the interplay between edge and SOL plasma is a matter of growing concern. Transport properties in this region of transition from closed to open magnetic flux surfaces have been recently investigated by experimental and numerical means in order to determine, for example, the relationship between the strong asymmetries in the SOL parallel flows and the core plasma rotation [5]. Another related and crucial topic for developing future fusion reactors is the possibility of quantitatively predicting and hopefully controlling the power deposition on the plasma facing components. In this context, we analyse a series of experiments performed on Tore Supra, dedicated to the determination of the ballooning nature of the edge and SOL transport [1,2]. Moreover, we will use SOLEDGE-2D code to perform synthetic numerical experiments and study plasma flows in complex SOL geometries.

The paper is organized as follows: in the next section, the experimental results we consider for analysis are presented. Then the SOLEDGE-2D code used for the comparison with measurements is introduced and simulation results for one-limiter SOL are presented. Finally, the last section deals with the influence of a secondary limiter and the comparison with experimental measurements.

2. Mach probe measurements in the SOL of Tore Supra and estimations of radial flux

The radial flux that enters and propagates into the SOL can be measured by using a reciprocating Mach probe. In Tore Supra, this probe is located at the top of the tokamak (see Fig. 1). It performs radial plunges into the SOL to measure the density and Mach number for a range of radial positions. The coordinates of the measurement points will be noted (r_p, θ_p) . The probe curvilinear abscissa along the field line is noted s_{θ_p} . Assuming total pressure conservation along the field line ($\Pi_t = \text{cst}$) [1], it is possible to deduce from local measurements of density (n_p) and Mach number (M_p) the radial source entering the SOL integrated along a field line at radial position r_p . More precisely, it is possible to determine the source entering between the probe and the limiter, see Eq. (2.1): These source terms will be noted $S_{r_{\text{lim}}}^A$ on the “left” of the probe and $S_{r_{\text{lim}}}^B$ on the “right” of the probe, see Fig. 1. Note that we name source all the transverse flux of particles into a given field line. Since we do not consider volumetric sources due to neutral ionization, the source term accounts for the cross-field particle transport. The total source is $S_{r_{\text{lim}}}^{\text{total}} = S_{r_{\text{lim}}}^A + S_{r_{\text{lim}}}^B$. Within this framework, the definition of the source $S_{r_{\text{lim}}}^A$ is

$$S_{r_{\text{lim}}}^A = \int_0^{s_{\theta_p}} \Gamma_r ds = \frac{1}{c_\theta} \int_0^{\theta_p} \Gamma_r d\theta \quad (2.1)$$

Γ_r is the radial flux and for direct comparison with experiment one introduces $ds = 1/c_\theta \cdot d\theta$ where one assumes $c_\theta = 1/(qR_0)$ where q is the safety factor and R_0 the tokamak major radius [6]. The formulas used to derivate an estimation of the sources from the probe

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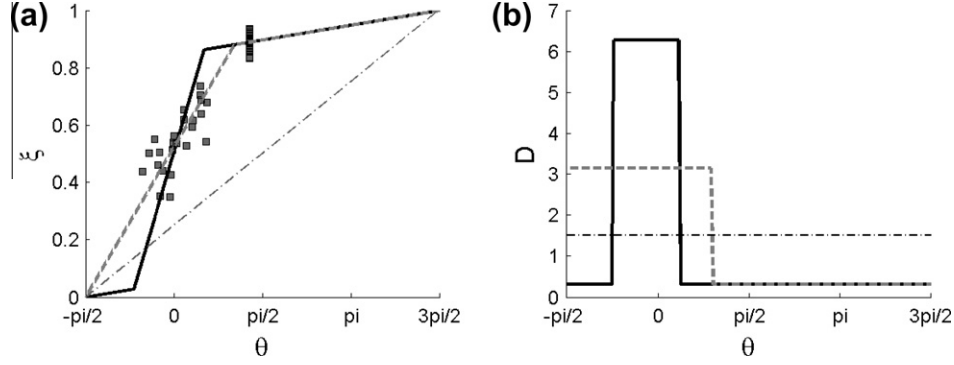


Fig. 3. (a) Experimental data (symbols) from Fedorczak et al. (in press) [2] representing the peaking function $\xi(\theta)$ and linear fits. Homogeneous diffusivity case is represented for comparison (dash-dot line). (b) Corresponding diffusivity profiles: D1, weakly ballooned (grey-dash) – D2, strong ballooned (black-solid) – homogeneous (dash-dot).

the order of 80 m. The SOL density decay length is chosen to be about 2 cm when diffusivity is minimum which gives as mentioned before a minimum diffusivity $D_{\min} = 0.31 \text{ m}^2 \text{ s}^{-1}$. The size of the domain simulated in the perpendicular direction is chosen to be $L_r = 30 \text{ cm}$. The dimensionless density gradient is set to 1 at the edge boundary, hence, the characteristic density n_0 is linked with the flux entering from the core region by the relation $\Gamma_r^{\text{in}}(\theta) = D(\theta) \cdot n_0 / L_r$. In Eq. (3.2), $A = L_{\parallel} / L_r$, is the aspect ratio ($A = 50$), Pe is the Peclet number defined as $Pe = L_r C_s / D$ and $Sc = \nu / D$ is the Schmidt number. Given the poloidal diffusivity profiles plotted on Fig. 3, the Peclet number is found to vary between 4000 and 80000.

The penalization technique allows one to add an obstacle of any shape in the domain. The obstacle is defined through a mask function χ equals to one in the region where the obstacle is located and zero elsewhere. In this case, the mask function represents a toroidal limiter with poloidal extent $\pi/15$. The penalization technique consists in forcing the solution to a selected value in a region of the domain. In the case of a limiter immersed in a tokamak plasma, for example, the density is forced to be zero in the limiter region. The momentum equation is also penalized, as shown in Eq. (3.2). In the region where the mask function is equal to zero, one recovers the transport equations for density and momentum as described by the Eq. (3.1), [3].

On Fig. 4, one has plotted the 2D contours of Mach number for the diffusivity profile D1. One notices that the stagnation point is located on the outer midplane where the radial transport is maximum. Under the assumption of conservation of pressure, the stagnation point is located where the peaking factor ξ is equal to 1/2. The values of Mach number on the limiter are in good agreement with Bohm conditions.

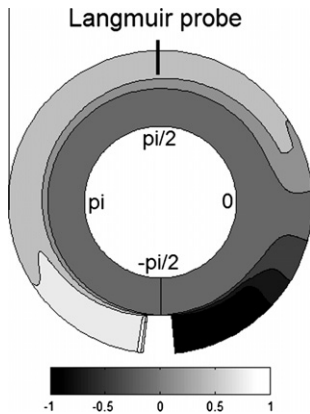


Fig. 4. Mach number contour plot. Simulation results with diffusivity profile D2.

4. Synthetic Langmuir probe measurements

In order to validate the approximation made in the experiment, a synthetic Langmuir probe experience is carried out in the simulated field of density and velocity at the poloidal position $\theta = \pi/2$. Following the experimental data processing, see Table 1, one obtains the radial sources. Then, this *synthetic* source is compared to the *actual* source values computed with the full simulation data. With the diffusivity profile labeled D2, the probe gives a *synthetic* peaking-factor of 0.813 on the LFS whereas the *actual* value is 0.799. With the diffusivity profile D1, the *synthetic* value of ξ is 0.836 whereas the *actual* value is 0.807. In both case, the error is of a few percents which is well below the experimental error bars. More precisely, one notices that the total pressure exhibits a parallel relative variations of 15% at the LCFS where the momentum gradients are the strongest. However, the radial integration leads to a compensation of this pressure variation effect. This property is related to momentum conservation so that the assumption leading to expressions of Table 1 weakly depart from simulation data.

5. Simulation of 2-limiters SOL

A secondary limiter is introduced in the domain using the penalization technique. This limiter is also $\pi/15$ wide in the poloidal direction and its position can be adjusted from $\theta = -\pi/5$ to $\theta = \pi/5$ to reproduce the experiment carried out in Tore Supra. In the present analysis the two limiters have the same radial extent, see Fig. 5.

The experiment consists in measuring the radial flux on one side of this secondary limiter and compare it with the total flux entering the SOL. In the experimental data processing, we assume that the secondary limiter does not change the value of the radial source entering at the LCFS. Hence we consider that the measurement of the total source made without the secondary limiter is such that $S_{r1\text{lim}}^{\text{total}} \approx S_{r2\text{lim}}^{\text{total}}$. Consistent with $S_{r2\text{lim}}^* \approx 0$ giving $S_r^{\text{total}} = S_r^A + S_r^B + S_r^* \approx S_r^A + S_r^B$, the ξ function can thus be evaluated with Eq. (5.1).

$$\xi^{\text{actual}}(\theta_{2\text{lim}}) = \frac{S_{r2\text{lim}}^A}{S_{r2\text{lim}}^A + S_{r2\text{lim}}^B} = 1 - \frac{S_{r2\text{lim}}^B}{S_{r2\text{lim}}^A + S_{r2\text{lim}}^B} \quad (5.1)$$

$$\begin{aligned} \xi^{\text{synthetic}}(\theta_{2\text{lim}}) &= 1 - \frac{S_{r2\text{lim}}^B}{S_{r1\text{lim}}^{\text{total}}} \approx 1 - \frac{S_{r2\text{lim}}^B}{S_{r2\text{lim}}^A + S_{r2\text{lim}}^B + S_{r2\text{lim}}^*} \\ &\approx \xi^{\text{actual}}(\theta_{2\text{lim}}) + \frac{S_{r2\text{lim}}^B \cdot S_{r2\text{lim}}^*}{(S_{r2\text{lim}}^A + S_{r2\text{lim}}^B)^2} \end{aligned} \quad (5.2)$$

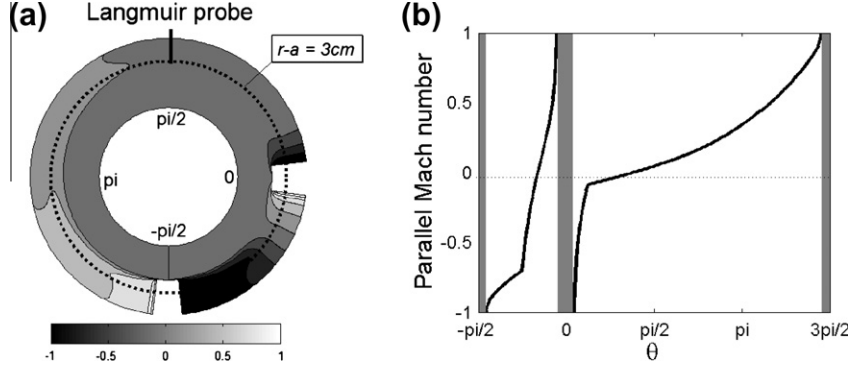


Fig. 5. (a) Mach number contour plot. Simulation results for diffusivity profile D2. The main limiter is at the bottom. The secondary limiter is on the LFS (right, $\theta_{2lim} = 0$). (b) Mach number poloidal profile for $r = a + 3$ cm.

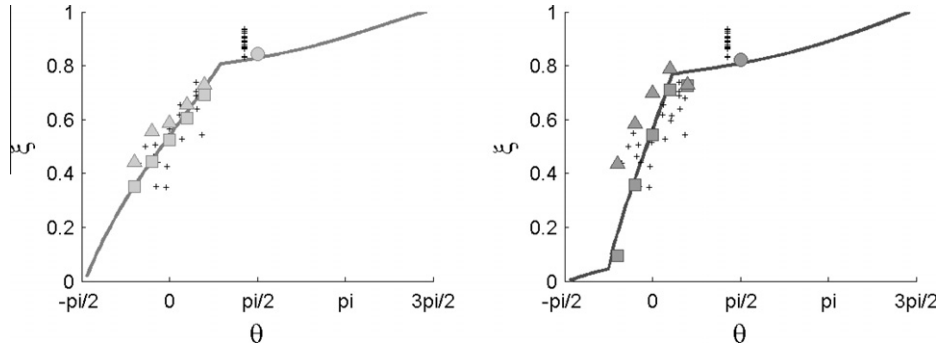


Fig. 6. Weakly ballooned diffusivity case D1 (Left) and strong ballooned diffusivity case D2 (Right) – Lines: ξ functions computed in unperturbed one-limiter SOL. Symbols: Circle (synthetic): Langmuir probe measurements in simple SOL configuration; squares (actual): estimation of ξ in the two limiters configuration; triangles (synthetic) and crosses (experimental): estimation of ξ in the two limiters configuration.

The effective source $S_{r_{2lim}}^A$ and $S_{r_{2lim}}^B$ are calculated as well as $\xi = S_{r_{2lim}}^A / (S_{r_{2lim}}^A + S_{r_{2lim}}^B)$ for five secondary limiter positions in the vicinity of the midplane. The data representing the *actual* values of the peaking factor at $\theta = \theta_{2lim}$ are plotted on Fig. 6 with full squares. On the same Figure are plotted with triangles the *synthetic* values. One can notice that the experimental data processing leads one to overestimate the peaking factor by neglecting the source that enters radially into the limiter S_r^* , see Eq. (5.2). This problem would be overcome by using two Langmuir probes, one measuring $S_{r_{2lim}}^A$ and the other measuring $S_{r_{2lim}}^B$. Finally, on Fig. 6 one also plots the peaking factor ξ calculated without the secondary limiter (solid line). One can notice that there is a weak departure between the single and two limiters cases. Consequently, the presence of a secondary limiter does not appear to modify drastically the localization of the sources.

6. Conclusions

Complex SOL geometries with two limiters have been simulated in the fluid code SOLEDGE-2D by using penalization technique. Synthetic Langmuir probe experiments have been performed with different ballooned cross-field transport properties. These simulation results have been compared with experimental measurements performed on Tore Supra and show a good agreement. Besides, if the experimental data processing assumes total pressure conservation along the field line, the simulations show that pressure

variations effect is weak and only induces an error of a few percents on the peaking factor value. In that sense, it backs up the experimental analysis. The experimental data processing also neglects the particle flux entering radially into the limiter. In Tore Supra's experimental setup, neglecting this flux results in a systematic overestimation of the peaking factor. The simulations make possible to evaluate this up-shift and thus give a better estimation of the radial transport ballooning.

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