Impact on Divertor Operation of the Pattern of Edge and SOL Flows Induced by Particle Sources and Sinks

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Abstract:
Precise calculation of the particle source recycling is shown to depend on the precise geometry of the plasma facing component. The penalisation technique allows one to introduce such a geometry in a versatile way and thus recover large changes of the particle flow pattern and SOL width with small changes of the limiter position. In the transition from low density to high recycling one finds that the divertor plasma will switch from supersonic to sonic with divertor imbalance governed by the ballooned nature of the particle outflux from the core. Conditions for the distortion of Gas Puff Imaging results are presented using the TOKAM-2D turbulence code coupled to EIRENE. In TOKAM-2D simulations, the SOL width is found to be strongly fluctuating, with fluctuations between zero width and very large width. The mean value is therefore found to be of little relevance.

1 Introduction

The role of divertors in present device operation is multiple, controlling particle sources and sinks and consequently the energy flux channels in the boundary region of magnetically confined plasmas together with providing access to the H-mode with ELM control with resonant magnetic perturbations \cite{1}. While the modelling of neutral particle physics at the plasma boundary includes more and more refinement in the atomic and molecular physics that are taken into account \cite{2}, the plasma modelling effort faces several crucial shortfalls in its capability to reproduce present experimental evidence. The ESPOIR
project [6] has been initiated to develop ab-initio simulations of plasma-wall interaction. The effort is based on a set of fluid codes from 1-D parallel to 3-D micro-turbulence modelling. Key results of this project are presented here.

The design effort of divertors, such as the ITER divertor, is based on a diffusive description of the particle transport such that a well defined particle channel in the SOL appears to divert most of the particle flux into the divertor volume then onto the target plates. However, there is now a large body of theoretical and experimental evidence [4, 5, 7, 8] that demonstrates that particle transport is intermittent, with ballistic propagation of density bursts with characteristic velocities in the range of a few percent of the sound velocity $c_s$, hence expressed in terms of the Mach number, $0.05 \leq M_\perp \leq 0.01$. Given the parallel particle confinement time in the SOL, $\tau_\parallel = L_\parallel/c_s$ ($L_\parallel \approx \pi qR$, q is the safety factor and R the plasma major radius), one then finds that the overdense structures can propagate over radial distances of the order of $\Delta$ before reaching the divertor volume, with $\Delta \approx M_\perp L_\parallel$, and therefore $\Delta/a > 50M_\perp \geq 0.5$ where a is the plasma minor radius. Such distances are significantly larger than the clearance between the plasma and the main chamber wall in most devices. This intermittent transport mechanisms thus drives a complex wetting pattern of the first wall components by the plasma. In long pulse operation, this plasma outflux will gradually generate a neutral particle sources at the wall. The nonlinear interaction between such neutral particle sources and the overdense turbulent burst will in turn contribute to the particle flow pattern. In the framework of such an intermittent SOL transport, it is mandatory to describe the plasma up to all wall components taking into account their specific geometries, Section 2. The impact of the geometry of the particle source on the parallel transport is addressed in Section 3. Further issues related to the intermittent SOL turbulence will be addressed in Section 4.

## 2 Plasma and neutral particle flow pattern

The edge plasma region can be defined as the plasma region with significant ionisation sources. As such, the extent of this region is sensitive to both the plasma screening capability as well as the neutral particle source location at the wall of the device. The geometry of the latter effect thus plays a key role in the particle source, an effect that is machine specific and difficult to incorporate in any scaling effort. Particle transport requires that one addresses the non-adiabatic electron response, a problem that remains very demanding for global gyrokinetic codes. The issue we address here, namely the distribution of particle sources and sinks mediated by plasma turbulence governs most of the complexity of the edge plasma physics.

In order to be able to implement the geometry of the plasma facing components, we have developed a penalisation technique that extends the simulation domain up to all the plasma facing components of interest, fig. 1. This technique has been tested in a series of transport codes using empirical diffusion coefficients to track the mean plasma properties. The usual Bohm surface conditions are then replaced by specific equations that govern plasma termination within the limiters on very short length scales. A mask
function defines the geometry and location of the objects in the boundary plasma, the mask determining where the plasma equations are to be replaced by the equation that allow one to recover the boundary conditions governed by the sheath physics. The penalisation technique initiated for particle and momentum sinks has been extended to the temperatures, penalisation for the electric current is being developed. In the 2D and 3D plasma transport codes, SOLEDGE2D and SOLEDGE3D, we have used the penalisation technique to model several key physics. On fig. 1, the particle source is located in the core plasma and particles diffuse out with a constant diffusion coefficient. The parallel Mach number is very sensitive to the balance of the particle source governed by the cross field transport on each field line. Since its values is bounded to order unity, it also provides a precise and natural criterion to investigate the geometry of the SOL parallel flows as exemplified by fig. 1 where all the secondary SOL regions are well characterised.

FIG. 1: SOLEDGE-2D simulation of the ionisation, left panel, and parallel Mach number, right panel, in the whole volume for the WEST configuration proposed for Tore Supra.

This versatile method to include the plasma facing components has been used for an empirical modelling of the MISTRAL base case [7, 8]. Small changes in the location the interaction point between the plasma and the various limiters, that defines the separatrix, can be investigated. Apart from these geometrical changes, all other parameters are kept constant, in particular the cross-field particle diffusion. To recover the experimental evidence, this diffusion coefficient must be ballooned. This governs the flow reversal that are observed and presented on fig. 2. In these simulations, one recovers the particle flow pattern governed by the ballooned core particle outflux. In conjunction to geometrical effects, such as the distance to neighbouring limiters, one also can observe a modification of the SOL width, with some SOL broadening when the plasma is limited on the high field side compared to the low field side. Such a result, and especially the experimental evidence [8], underlines the weakness of the standard understanding of the SOL width. While including the impact of the divertor, which is machine dependent, in the analysis of the heat deposition width is appropriate and goes in the right direction, the problem and meaning of the SOL width is still open, see Section 4.
3 Variation of the Mach number as a signature of particle and momentum losses and sinks

Divertor physics, by controlling the topology of the magnetic surfaces, is a means to use the parallel transport in order to control plasma-wall interaction. The key physics to be addressed are the loss or gain rates along the field lines for the particle flux, the pressure and the energy flux. Although time dependent fields can be addressed by our formalism [9], one addresses here steady-state balance equations which then leads to parallel variation equations for the parallel particle flux $\Gamma$, the total parallel plasma pressure $\Pi$ (electrons + ions, kinetic + thermal) and the total parallel energy flux $Q$ (electrons + ions, kinetic + thermal). One introduces the fact that a non-linear function $A$ of the parallel Mach number $M_\parallel$ can readily be characterised in terms of the particle and momentum fluxes as well as the sound velocity: $A = 2 M_\parallel \left(1 + M_\parallel^2\right) = 2 m_i c_s / \Pi$. It is important to note that the parameter $A$ is bounded, $-1 \leq A \leq 1$ and that the transition to the supersonic regime occurs at $A^2 = 1$ and therefore at a maximum of $A$. Given the prescribed condition that $M_\parallel^2 \geq 1$ at the sheath, one finds that the variation of $A$ is strongly constrained. In that respect, the increase of the magnitude of particle flux as well as the decrease of the plasma pressure towards the target plates both govern an increase in the magnitude of $A$, hence driving the plasma towards the transition point between supersonic and subsonic regimes. Conversely, the decrease of the sound speed with the temperature towards the target plates will tend to decrease the magnitude of $A$.

Two issues are addressed briefly here: the occurrence of supersonic flows in the SOL and the divertor imbalance. Regarding the supersonic regimes, let us consider a constant pressure and isothermal plasma so that the variation of $A$ is solely governed by that of the particle flux: $1/A \nabla_\parallel A = 1/\Gamma \nabla_\parallel \Gamma = B/\Gamma \nabla_\parallel (\Gamma / B) + 1/B \nabla_\parallel B = 1/\Gamma \nabla_\perp \Gamma + S / \Gamma + 1/B \nabla_\parallel B$. In this expression $S$ is the volumetric particle source due to ionisation and recombination, $\Gamma_\perp$ is the cross-field particle flux and $B$ the magnitude of the magnetic field. The mirror effect can thus play a role in the variation of $A$ and in
some cases contribute to the transition to supersonic flows \[10\]. A larger contribution will stem from the divergence of the turbulent cross-field transport. It can exhibit a change of sign when the cross-field switches from being a source on a given field line, as in the coupling of the plasma core to the standard SOL, to being a sink, as occurs in the divertor region where cross-field transport will tend to deplete the high density field lines. The impact of such a process strongly depends on the relative magnitude of cross-field versus volumetric particle sources. At low density, and in simulations where the particle source is located in the core region, the cross-field source can be dominant so that at the X-point the parallel flow must bifurcate from the subsonic to the supersonic regime \[11\].

In the high recycling regime, the supersonic regime is achieved at the sheath boundary layer so that one finds the following constraint: \(|A_{HF}| = 2m_i\Gamma_{HF}c_{s,HF}/\Pi_{HF} = |A_{LF}| = 2m_i\Gamma_{LF}c_{s,LF}/\Pi_{LF}\). In this expression \(HF\) stands for the High Field side divertor conditions and conversely \(LF\) for the Low Field side conditions. Let us first consider the case of a constant total plasma pressure along the field line so that one obtains the constraint \(\Gamma_{HF}c_{s,HF} = \Gamma_{LF}c_{s,LF}\). In the low density, isothermal regime, the sound speed is constant so that one finds that the divertors must be characterised by a similar temperature, similar particle flux and consequently similar energy flux. The only imbalance is then associated to the occurrence of supersonic flows that break the above constraint. In the high recycling regime, the temperature at the stagnation point is a function of the parameter \(LQ\), where \(L\) is the parallel connection length. Neglecting radiation and assuming collisional parallel transport, one obtains \(Q_{LF}/Q_{HF} = L_{HF}/L_{LF} = R_L\). For ballooned transport in the Low field midplane one obtains \(R_L > 1\) so that steady state conditions require \(Q_{LF} > Q_{HF}\). Using the Bohm boundary conditions at constant plasma pressure, one finds that \(\Gamma_{div}Q_{div} \propto \Pi_{div}\) so that \(\Gamma_{LF}/\Gamma_{HF} = R_L^{-1}\). The Low Field side particle flux must be larger than the High Field side particle flux. Taking into account the constraint introduced by the parameter \(A\), one then obtains: \(T_{LF}/T_{HF} = R_L^2\) where \(T = T_e + T_i\), the density being characterised by the inverse ratio to maintain the constant total plasma pressure. One can then readily show that pressure imbalance due to momentum transfer from the core plasma will only modify the response of the particle flux, either towards an increase or a decrease of High Field to Low Field particle flux ratio, the energy and temperature imbalance being unaffected.

### 4 Turbulent particle transport, neutral emission imaging and SOL width

The development of the TOKAM turbulence codes \[4, 6\] has stimulated an important effort on synthetic diagnostics to investigate what aspects of the intermittent transport was captured by the diagnostics as well as how could the measurements be affected by the large fluctuation level \[5\]. Gas Puff Imaging \[12\] has provided images of the intermittent SOL turbulence and backed the theoretical results. However, it is important to properly determine the limitation of the diagnostic to evaluate what is measured and what can-
not be measured, an important issue being the radial location of such an intermittent transport. The EIRENE Monte Carlo code [2] describing neutral particles transport has been coupled to SOLEDGE-2D and to the interchange turbulence code TOKAM-2D code [3, 5]. EIRENE takes as input the 2D plasma density maps, and calculates the ionisation source. The latter has been included in the equation for particle conservation solved by the turbulence code. The light emission is proportional to the product of the plasma and the neutral density in this simple isothermal model. Our results on the transport of neutrals in fluctuating plasmas show that Gaz Puff Imaging data can be misleading when the mean free path of neutrals is smaller than the typical size of the turbulent structures [13]. This is related to the ”shadowing effect” [13]. This can be significant, as on fig. ??, where neutrals originate from the right hand side of the simulation box and propagate along the x-axis. The fingers-like structures (left hand side) of the the overdense density structures then appear as blobs, while further upstream the overdense structure are not illuminated. Simulations with TOKAM2D-EIRENE have also shown that the average plasma density response is larger than the fluctuation root mean square: including neutrals appears to reduce the relative fluctuation level [15]. Given these results, one can readily a blinding effect at transport barriers as well as limitations to measure smaller intermittent structures further away from the neutral source.

The TOKAM-2D code has also been used to analyse the SOL width. We address the problem considering the turbulent flux in the radial direction $\Gamma_r$. The radial profile of the time average flux exhibits an exponential fall-off which readily yields a SOL width $\lambda_{\text{mean}} \approx 122\rho_s$ where $\rho_s$ is the hybrid Larmor radius, typically $\rho_s = 2.10^{-4}m$ so that $\lambda_{\text{mean}}$ is a couple of centimetres. However, the root mean square of the particle flux fluctuation is at least a factor five larger than the mean value, so that the mean profile has little relevance. Two alternative methods have then been used to characterise the SOL width. The points that contribute to determining the SOL width are chosen according to a thresholding process, the threshold being the radial particle flux generated by the particle source $\Gamma_S$. In a first method the SOL width is the mean radial position of the
points such that $\Gamma_r/\Gamma_S \geq 1$. One then obtains a distribution with an exponential tail and large probability for zero SOL width, typically 40% of the maximum probability fig.??.

The mean value of the SOL width $\lambda_n \approx 16\rho_s$, the RMS value being $10\rho_s$. One finds therefore that the SOL width appears as an average between numerous cases where the SOL width is zero and very large values of the SOL width. The mean value of the SOL width then has very little relevance. From the ingeneering point of view, it can be more important to evaluate at what maximum distance from the separatrix can one obtain a particle flux value such that $\Gamma_r/\Gamma_S \geq 1$. The calculation then yields a broad distribution reaching very large values, with mean value $\lambda_n \approx 204\rho_s$ and root mean square $\approx 77\rho_s$ fig.??.

This shows that large events can experience long range transport into the SOL hence broadening the effective particle channel.

5 Discussion and conclusion

The ESPOIR project has been initiated to address the effect of intermittent turbulent transport on plasma wall-interaction [3]. The turbulent plasma transport is found to couple the core plasma to distant wall components in both the main chamber and divertor volume. Due to this strongly intermittent transport, one finds that the SOL width strongly fluctuates so that the mean SOL width is found to be of little relevance since the SOL width fluctuates between zero width and very large values. The idea of the boundary layer being a channel into the divertor can then be misleading. As a consequence of the particle transport pattern, a precise modelling of the wall components is required to recover the appropriate particle source. This is achieved with the very versatile penalisation technique. The SOLEDGE2D code then allows one to recover the key parallel flow pattern reported in the MISTRAL base case [7]. The importance of a precise calculation of the particle source is underlined by the parallel flow into the divertor. In the low
density regime, with negligible ionisation source in the divertor volume, supersonic flows can be obtained. Conversely, in the high recycling regime, a subsonic divertor plasma is recovered. In the latter case, divertor imbalance is readily expected when considering ballooned transport located in the Low Field side midplane. The temperature imbalance between the two divertors can be large enough to drive the divertors legs in different regimes. Finally, the effort towards synthetic diagnostics clearly indicates that precise investigation is required to determine the limitations of present diagnostics. In the case of Gas Puff Imaging, we show that it tends to underestimate the turbulent structures away from the neutral source while modifying the turbulence level. The ESPOIR project is now focused on the integration of present results in a 3D turbulence code of the edge plasma.

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