Towards a Comprehensive Approach of Edge and SOL Transport Issues: from Experimental Results to Global Simulations

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Abstract. Bringing answers to the questions still open regarding edge transport issues in ITER requires a comprehensive approach bridging experiments to simulations. We report here about such an effort. We first present results from the Tore Supra (TS) tokamak. Experiments were led to study the dynamics of edge turbulence by correlating various diagnostics. Data evidence the existence of structures aligned on the magnetic field, localized on the low field side with similar dynamics to that observed on other devices. Filaments were also observed in the closed field lines region during detached discharges. Such results obtained in a limiter machine demonstrate that the phenomenology of the edge turbulent transport is little sensitive on the magnetic topology. Another set of experiments was devoted to the measurement of the ion temperature in the edge plasma. Large Ti/Te ratios are found in the Scrape-Off Layer (SOL). In highly radiating scenarios, Ti drops more than Te implying that the energy dissipated through electron radiation losses is supplied mainly via the ions. To back these results, a theory and modelling effort, the ESPOIR project, has been initiated. Global transport aspects have been studied with the SOLEDGE-2D fluid code. In particular, simulations allow us to recover regimes with Ti/Te>1 in the SOL, Ti being more sensitive than Te to an enhanced volumetric sink on the electron channel. In parallel, more fundamental work has been undertaken on the numerical treatment of edge boundary condition leading to a novel method based on penalization techniques. The method offers greater flexibility in the configuration of plasma facing components and allows the use of powerful numerical algorithms. The 3D dynamics of filaments is also analysed with an analytical and numerical model based on parallel front propagation. Finally, first results of a 3D turbulent code (SOLEDGE-3D) are presented. The occurrence of the Kelvin-Helmholtz instability in self-consistent equilibriums is analyzed. An ITER geometry version is also being developed and first simulations dedicated to radiative layers and the associated fronts and instabilities are presented. To conclude, we suggest defining the Mistral Base case from the TS data base. This would provide a means to compare edge fluid and kinetic simulations as achieved with the Cyclone base case for core turbulence.

1. Introduction

The issue of transport in the edge region of tokamak plasmas remains one of the most critical points in explaining current machines results and extrapolating them towards larger scale devices like ITER. It is now accepted that the diffusive ansatz is not sufficient to address the physics governing transport in the edge plasma and that intermittent turbulent events are the dominant contributors to the average fluxes. However, it is also clearer and clearer that the smallest turbulent scales cannot be decoupled from the global equilibrium scale and that the contribution of large scale structures cannot be set aside either. A striking example is the turbulent momentum transport that is believed to be a major contributor to the anomalous rotation of the plasma which, in turn, influences the transport of particles and energy and may have a decisive role in the existence of the H-mode barrier. Bringing answers to the numerous questions still open regarding ITER operation requires a comprehensive approach of edge transport issues bridging experimental data to the most advanced global simulations.

We present in this paper an overview of the results and perspectives of an important collaborative effort initiated in France aiming at getting a better understanding of edge transport issues in sight of ITER. A multi-frontal approach of the problem has been adopted.

From the experimental point of view first, the Tore Supra tokamak has been used to conduct extensive studies about particle and heat transport (Section 2). Correlating measurements from three different diagnostics (fast cameras, Doppler reflectometry and reciprocating probes), a consistent description of particle transport in the edge can be drawn that evidences and quantifies the ballooning character of turbulent transport and solves apparent inconsistencies found previously on Tore Supra and other machines. It is also demonstrated that the phenomenology of edge turbulence in L-mode is similar to that in diverted machines and hence little sensitive to the magnetic topology, such as the presence or not of an X-point. The topic of heat transport was addressed with experiments devoted to the measurement of the ion temperature profiles in the edge plasma. Large Ti / Te ratios are found in the Scrape-Off Layer (SOL), with a strong dependence on the density.

In order to back these experimental results, a strong theory and modelling effort has been undertaken. We present in section 3 an analysis of the previous sets of experiments with a new edge fluid code, SOLEDGE-2D, which covers both the edge plasma (outer part of the closed field lines region) and the SOL. The code features in particular a novel way of treating Bohm boundary conditions based on penalization techniques, which makes it particular adapted to varying edge configuration as those found in the experiments considered here. SOLEDGE-2D is used to assess the assumptions made in the interpretation of the probes data in the particle transport experiments. Results both validate these assumptions and allow the recovery of the experimentally observed behaviour. An analysis of the interplay between flows in the SOL and the edge of the confined plasma is also proposed. Concerning heat transport experiments, Ti / Te ratios larger than 1 are found in the code in good agreement with experiments, this without requiring the inclusion of electron radiative losses. Parameter scans also exhibit trends similar to experimental ones.

However, the ballooning character of transport evidenced in the experiments often makes it necessary to go one step further in the description of edge transport by considering 3D modelling. Section 4 is devoted to results of such studies. Analytical models dealing with front propagation in the parallel direction are described, allowing for an insight on the implications of the existence of finite $k_{//}$ structures. A numerical effort in that direction has also been initiated with the SOLEDGE-3D code. At the present stage of its development, the code models the parallel shear flow instability, often referred to as the Kelvin-Helmholtz (KH) instability. It is found that most self-consistent equilibrium solutions appear to be stable. In agreement with results derived analytically, conditions under which the equilibrium becomes KH unstable are exhibited, the KH turbulence originating mainly from the limiter tip. To complete the project, a 3D full torus turbulent fluid code with realistic edge geometry of ITER, the ESPOIR code, is being developed. First results are dedicated to radiative layers and the associated fronts and instabilities.

Finally, we draw the first conclusions of these on-going studies in section 5. In particular, the richness of the Tore Supra database makes of it a good candidate as a test bench for edge modelling codes. In the same way as the Cyclone test case was designed to benchmark gyrokinetic and fluid codes in the core plasma, we define the Mistral base case for edge transport simulations.

2. Overview of recent edge transport experimental results on Tore Supra

We first report experimental results from the Tore Supra tokamak. A series of experiments was led to study the dynamics of edge turbulent fluctuations by correlating data from fast camera images, reciprocating Langmuir probes and Doppler reflectometry [1,2]. They show the existence of structures strongly aligned along the magnetic field direction, the so-called filaments, localized on the Low Field Side (LFS) with qualitatively similar dynamics to that observed on other devices (Fig. 1). Doppler back-scattering measurements, in agreement with fast camera data analysis, exhibit poloidal velocity profiles for the filament that reverse across the Last Closed Flux Surface (LCFS): from 1 to 2 km.s^{-1} in the electron diamagnetic direction inside the LCFS, it reverses to a few 100m.s^{-1} in the ion diamagnetic direction in the SOL (Fig. 2). Ion saturation current fluctuations data obtained with reciprocating Langmuir probes is, as commonly observed, characterized by a strongly non Gaussian probability distribution function in the SOL. A phase shift of $\pi/2$ is systematically found between electrostatic potential and density fluctuations, suggesting that the driving mechanism of the filaments is the interchange instability. Filaments were also observed in the closed field lines region during steady detached plasma discharges (Fig. 1 c) and d)). Such results obtained in a limiter machine are of primary importance since they demonstrate that the phenomenology of the edge turbulent transport is little sensitive on the magnetic topology: filaments and their dynamics are neither a consequence of open field lines nor of the presence of an X-point.

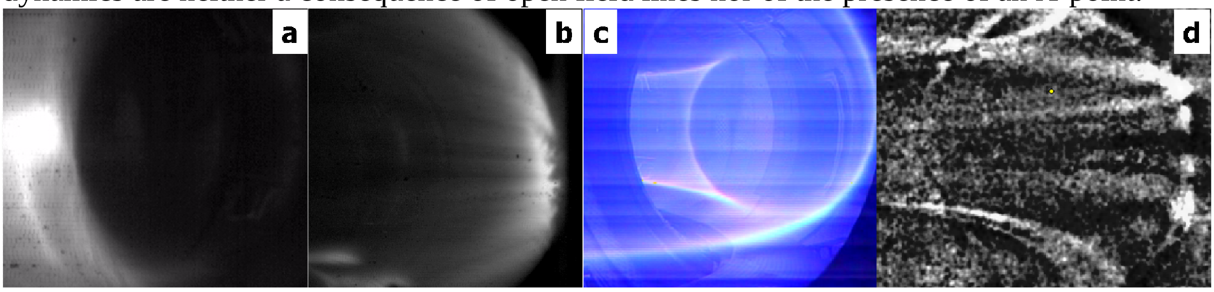


FIG. 1. Pictures from the fast visible imaging on Tore Supra. a) Gas injection performed on the high field side (exposure time of 20µs). The neutral cloud does not reveal any turbulent structures. b) same gas injection performed on the Low Field Side (LFS), revealing field aligned filaments propagating across the Last Closed Flux Surface to the SOL. c) Picture (20ms exposure time) of the emissive ring formed in the confined region of a stationary fully detached plasma. d) 20µs picture of the emissive ring, from which has been subtracted the time averaged frame. The fluctuations reveal field aligned structures only on the LFS, propagating across the emissive ring.

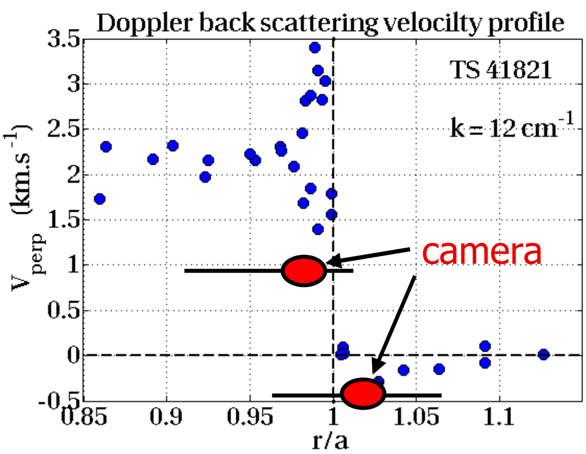


FIG. 2. Poloidal velocity profiles measured by Doppler back scattering with measurements from fast camera images super-imposed (positive velocity is in the electron diamagnetic direction).

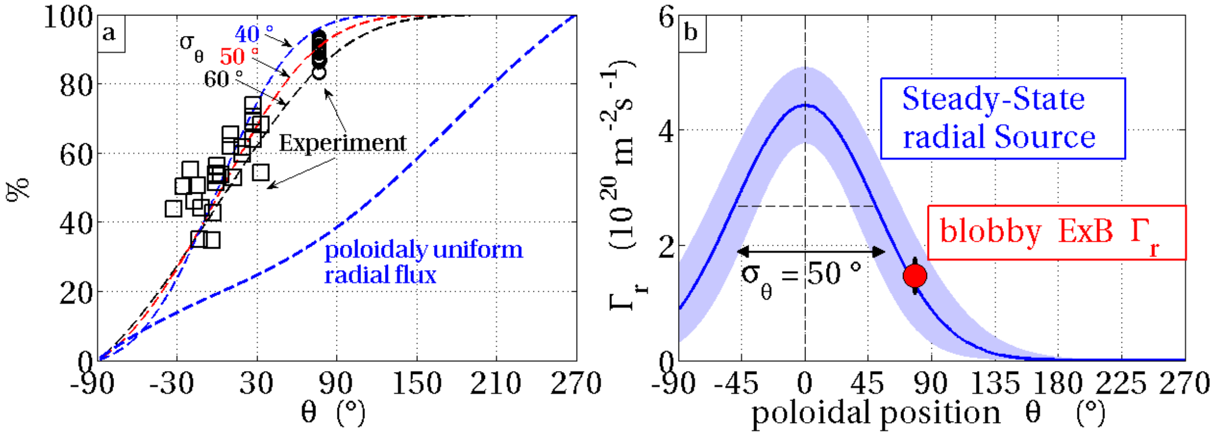


FIG. 3. a) As a function of the poloidal angle is plotted the fraction of the line integrated radial flux counted between that position and the LFS bottom limiter. Circles are obtained on reference experiments (only floor limiter), squares are obtained with the second limiter inserted. The inconsistent case of a purely uniform radial flux is illustrated. Synthetic measurements with Gaussian distribution centred on the outboard midplane are super-imposed. b) Poloidal distribution of the radial flux whose width and amplitude best fit the parallel flow measurements. The local blobby ExB flux is plotted in a red point.

The data gathered in these experiments also allow one to quantify the ballooned nature of the associated particle transport. Using the parallel Mach number as a marker of the distribution of the particle source in the SOL (as done in [3]) and comparing plasmas run with a single floor limiter with plasmas in which a secondary limiter is inserted in the outboard mid-plane, it is possible to estimate the angular distribution of the radial transport in the poloidal direction. This can then be compared to a theoretical Gaussian particle source distribution centred on the outboard mid-plane (as one might expect for interchange driven transport). Results are shown in Fig. 3 a). It is found that a particle source of 50° width fits the best the experimental data, thus quantifying the ballooning character of the particle transport expected in the frame of interchange mechanisms. The comparison with fluctuations data measured locally by the reciprocating probe at the top of the machine shows an excellent quantitative agreement with this radial transport distribution (Fig. 3 b)), demonstrating that the great majority of the particle are convected out in the filaments. Taking into account this non uniform poloidal distribution of the particle exhaust solves the apparent contradiction found between local probe measurements and global particle balance in Tore Supra.

Another set of experiments was devoted to the measurement of the ion temperature (Ti) profiles in the edge plasma using a Retarding Field Analyser (RFA) [4]. Ti is systematically found larger than the electron temperature Te in the SOL, as was observed in the edge plasma in all reported experiments. Density scans have revealed that the Ti/Te ratio is strongly dependent on the average plasma density (Fig. 4). To be more precise, both Te and Ti drop with an increasing density (at constant input power), but Ti drops much faster. This dependence can be attributed to the collisionality of the plasma: as the density rises, electron-ion collisions become more

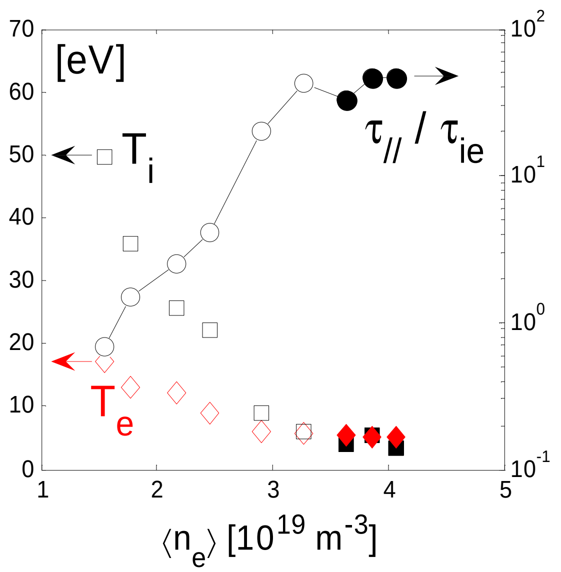


FIG. 4. Ion and electron temperatures measured by Retarding Field Analyser at the LCFS in ohmic density scan in Tore Supra. The ratio of the parallel ion transit time through the SOL to the ion-electron thermalization time evaluated 2-3 cm outside the LCFS indicates the degree of the ion-electron collisional coupling. Full symbols: detached discharges.

frequent leading to a shorter energy exchange time between the two species. Since, in parallel, the parallel transit time of the plasma increases (with the drop of the acoustic velocity), collisions become relatively more effective and the temperatures converge. Note also that evidence of heat transport ballooning was found in SOL temperature profiles [5].

3. Analysis of experimental results with the SOLEDGE-2D code

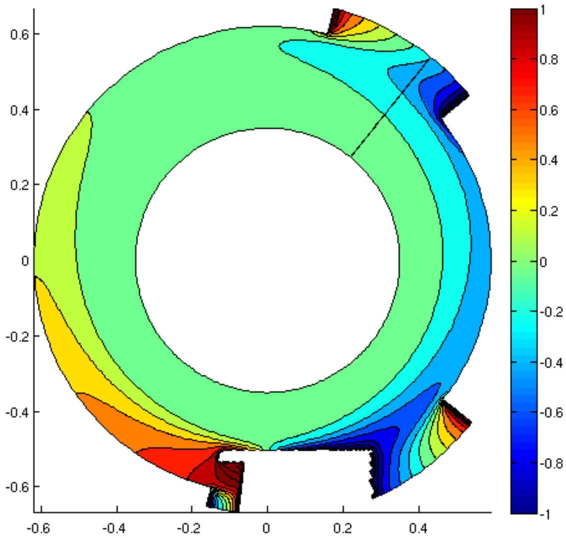


FIG. 5. Poloidal color plot of the parallel velocity (normalized to the sound speed) obtained with the SOLEDGE-2D code in a realistic Tore Supra geometry for polodally uniform transport coefficients.

Previous experiments can be analyzed using the SOLEDGE-2D code. SOLEDGE-2D is a 2D (radial-parallel) transport code which solves fluid balance equations in a region covering both closed and open field lines across the LCFS. Perpendicular transport is considered as diffusive in the current version. An important feature of the code is that it makes use of a novel penalization technique to treat Bohm boundary conditions at plasma-wall interaction surfaces. The method has been validated in steady state as well as during transients [6] and offers great flexibility in the configuration of plasma facing components in the simulation. As an example, Fig. 5 shows a simulation of the parallel flow velocity in a Tore Supra case with uniform transport coefficients, including all the subtleties of the poloidal geometry of the machine. With the penalization method, treating such a complex geometry requires only defining a characteristic function for the localization of plasma facing components. In the frame of the analysis of previous experiments, this was used to model the introduction of a second limiter or of a reciprocating probe.

A first version of the code, relying on isothermal equations, was used to analyse the experiments concerning flows and particle transport [7]. It was checked in particular that the assumption of constant total pressure (kinetic and thermodynamic) along the field lines, necessary for the extrapolation of the radial transport distribution from the parallel velocity measurements described in section 2, is valid under standard plasma conditions in Tore Supra. The perturbation induced by the insertion of the second limiter on the distribution of the radial particle source was also analyzed and shown to be a small correction compared to the observed effect. Figure 6 shows two poloidal maps of the parallel velocity for two different positions of the secondary limiter (in experiments, it is not the limiter that is moved, but the

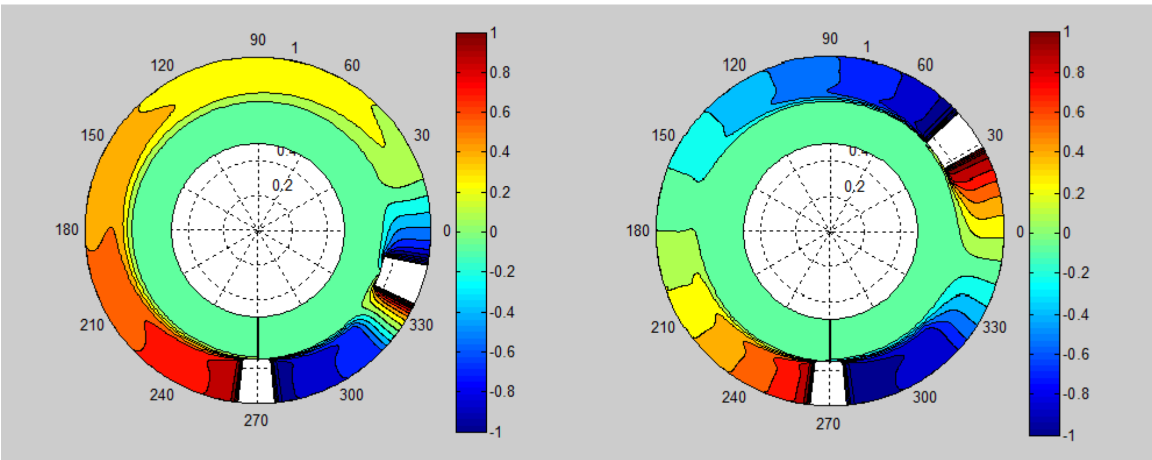


FIG. 6. Poloidal color plot of the parallel velocity (normalized to the sound speed) obtained with the SOLEDGE-2D code for 2 different poloidal positions of the secondary limiter in the LFS, including ballooned transport coefficients in line with experimental findings. Note the flow reversal at the top.

contact point of the plasma with it) in simulations including ballooned transport coefficients suggested by experimental results. Results are consistent with measurements of large parallel Mach numbers at the top, ie the location of the reciprocating probe. Particularly interesting is the reversal of the velocity at the top for a slight change of the plasma-limiter contact point, as was already reported in [3]. Beside the previous results, more theoretical studies on the spreading of SOL flows in the core plasma have been led with SOLEDGE-2D. We refer the interested reader to [8].

For the analysis of ion temperature measurements, a version of the code including energy balances was developed [9]. Simulations run in typical ohmic plasma conditions in Tore Supra allow us to recover regimes with T_i / T_e >1 throughout the SOL (Fig. 7). Ti/Te of the order of 2 to 3 is found in the outer SOL in good agreement with experimental results, and the two temperatures converge further inside the plasma as was also observed in Tore Supra [10]. At this stage of its development, the code does not include electron cooling by radiation. Thus, the modelled divergence of Ti and Te in the SOL is due only to the higher parallel conductivity of the electrons combined with sheath losses. Radiative losses may play a role in experiments but they are not necessary to recover the measured ratios. Parameter scans also demonstrated a higher sensitivity of the ion temperature to a density increase, due to the increase of the ion-electron energy exchange term at larger density, as was reported in Tore Supra.

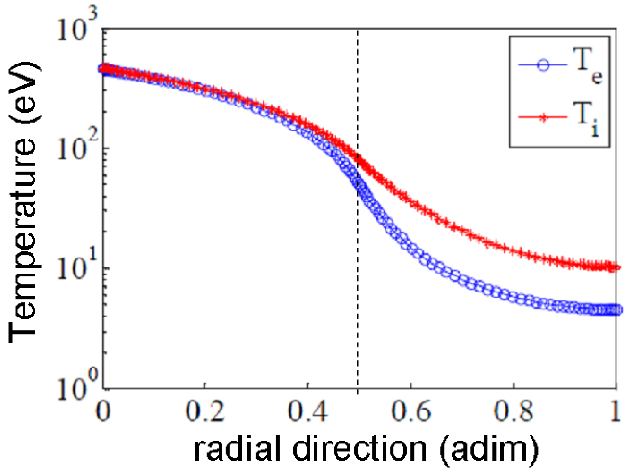


FIG. 7. Poloidaly averaged temperature profiles obtained with the SOLEDGE-2D code for a typical Tore-Supra case. The width of the radial domain is 10cm and the last closed flux surface is at r=0.5 (dashed line).

4. 3D dynamics of turbulent transport

Experiments in Tore Supra combined with SOLEDGE-2D modelling demonstrate the ballooned nature of particle transport in the edge, with evidence that the radial flux is in great majority carried by filaments. 2D models are helpful to analyse measurements and extract the driving physical mechanisms. However, in the absence of a consistent description of the particle transport, extrapolation to future devices is questionable. Two key ingredients of such description stand out of the previously described results: a fully turbulent treatment of transport and the inclusion of parallel dynamics to account for poloidal asymmetries. In this section, we present analytical and numerical work addressing these issues.

First, the parallel dynamics of density bursts has been analyzed analytically and numerically on the basis of a simple 1D model [11]. The plasma is described by its density and parallel Mach number and is assumed isothermal. As an initial condition, an over-dense region with a finite parallel extent and a step shape is input, supposed to represent a filament with finite $k_{//}$ propagating in the radial direction. Results show that two fronts detach from the initial density step and propagate with a supersonic velocity in the co and counter magnetic field directions. After a short transient, the fronts become independent and the density bursts exhibit a triangular shape very similar to that observed during transients (eg, ELMs) by Langmuir probes at the target plates. The time trace of these fronts at a given location is characteristic of the position, size and amplitude of the initial density burst. It is in particular shown that

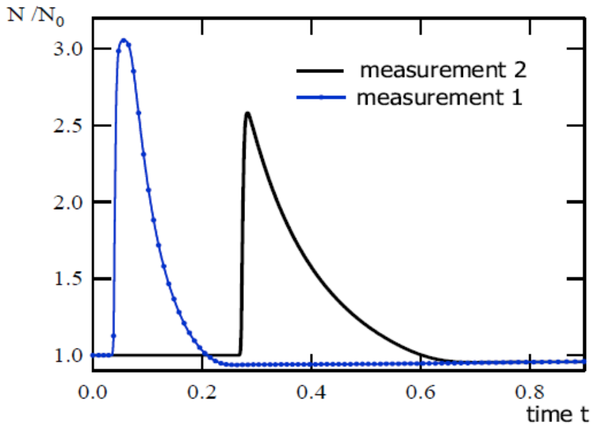
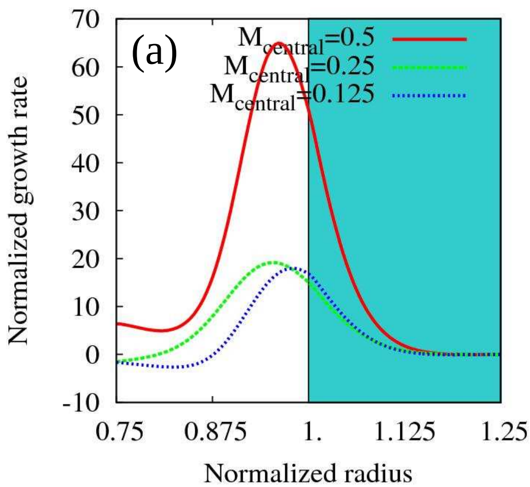


FIG. 8. Time traces of the density recorded at two different measurement points along the parallel direction after the propagation of an initially localized density burst.

measurements of the signal at two different locations (see Fig. 8) are enough to estimate the origin, the extent and the magnitude of the initial density step, suggesting a novel method to analyze the origin of transient density bursts in the edge plasma.

In parallel to that work, a numerical effort has been initiated with the development of a 3D turbulent version of the SOLEDGE code, SOLEDGE-3D. This code aims at modelling plasma fluid turbulence and transport in the edge plasma in a full toroidal geometry and will benefit from numerical advances developed for its 2D version, such as the penalization method. As a first application [12], the code is being used to study the parallel shear flow instability in the presence of a floor toroidal limiter, which was suggested as a possible explanation for experimental observations in Tore Supra [13]. Self-consistent diffusive equilibriums are computed without including non zero toroidal wave numbers. Their linear stability analysis reveals that these equilibriums are stable with respect to the KH instability in most of the available parameter space, which is confirmed by full 3D simulations. However, forcing a central plasma rotation by changing the parallel velocity boundary condition at the inner boundary of the simulated region leads to locally unstable equilibriums as showed in Fig. 9 a). Such a situation is representative of anomalous core rotation. The corresponding full 3D turbulent simulations exhibit the development of density fluctuations in the expected region. These unstable modes remain localized in the vicinity of the tip of the limiter on the LFS, so that they have a finite $k_{//}$ extent. Further work is required for the full characterization of the phenomenon. Close future plans for the development of the SOLEDGE-3D code include the addition of the interchange instability in the solved equations in order to have fully consistent equilibriums.

Finally, a longer term project has been launched aiming at the construction of a 3D full torus turbulent fluid code with realistic edge geometry of ITER, the ESPOIR code [14]. This work is still in the earlier stage of its development but first results have already been obtained



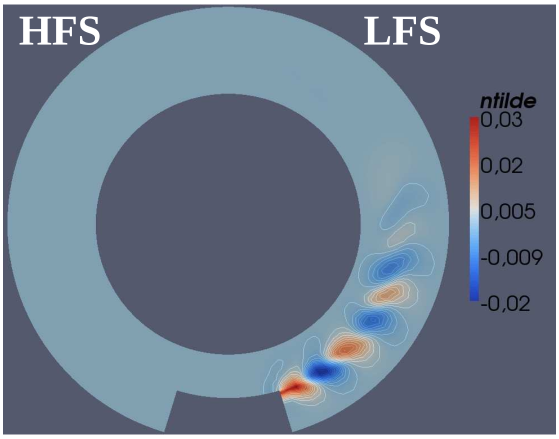


FIG. 9. a) radial profile of the normalized growth rate of the parallel shear flow instability in the most unstable region, ie just on the LFS of the floor limiter. Profiles for 3 different core rotations are plotted. r=1 corresponds to the LCFS. b) colour map of the density (equilibrium subtracted) showing the development of the instability at the tip of the limiter on the LFS.

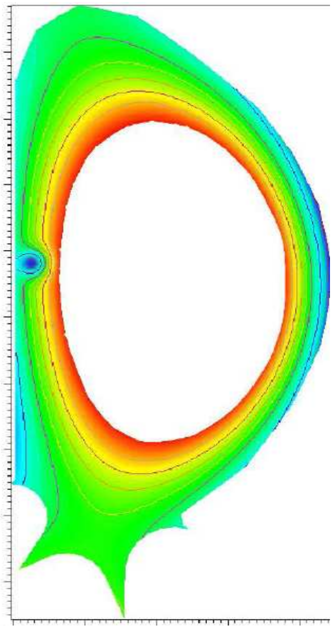


FIG. 10. Colour map of the electron temperature obtained with the ESPOIR code after seeding of a cold radiative spot in the HFS.

concerning the dynamics of radiative layers, thus validating choices made for the numerical discretization of the ITER geometry. It was shown in particular that the seeding of a cold layer or a cold spot in the plasma leads to dynamics very dependent on the exact initial conditions (Fig. 10). According to whether a full ring of plasma starts radiating or only a localized spot, and in the later case according to the poloidal location of this spot, an inward or outward propagation of the radiative region may be found. In the former case, the plasma reaches a new colder equilibrium, while in the later case the cold region is evacuated from the plasma and the initial equilibrium is retrieved.

5. Conclusion: the MISTRAL base case or Tore Supra as a test bench for edge codes

We have presented in this paper the first results of a collaborative effort aiming at giving a consistent picture of edge transport issues in tokamaks. A large part of the modelling work has been led with strong links to experiments in the Tore Supra tokamak and, as the numerical tools presented here are developed, effort will be made towards constant benchmarking with experimental data. The Tore Supra data base constitutes a precious input for edge models for three main reasons: 1- it contains an extensive set of measurements from various edge diagnostics in reliable ohmic plasmas, including numerous parameter scans; 2- experiments have shown an extreme sensitivity of plasma parameters to minimal changes of geometry [3], thus making a demanding test bench for codes; 3- the Tore Supra simple quasi-circular geometry makes it simpler to model without reducing the generality of the physics at play since L-mode transport dynamics was shown to be similar as in diverted machines. This way, the Tore Supra data base has been used to define the Mistral Base case [15] which is intended to be used for the benchmarking of codes against standardized experimental conditions. This will also provide a means to compare fluid and kinetic simulations as achieved with the Cyclone base case for core turbulence.

Acknowledgements
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