Turbulence and Transport in Simple Magnetized Toroidal Plasmas

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Abstract: We report on recent progress in understanding basic aspects of fluctuations, turbulence and related transport in the simple magnetized plasmas of the TORPEX toroidal device, in which a small vertical magnetic field is superposed on a toroidal magnetic field to form helicoidal magnetic field lines with both ends terminating on the vessel of the device. Similarly to the Scrape-Off Layer (SOL) of toroidal fusion devices, this magnetic configuration features open field lines, ∇B, and magnetic field curvature. Plasmas of different gases are produced by microwaves and are characterized by temperatures T_e~5-20eV and densities $10^{16}m^{-3} \leq n_e \leq 10^{17}m^{-3}$. Plasma turbulence and associated transport are studied via high-resolution measurements of plasma parameters and wave fields throughout the plasma cross-section. Different underlying instabilities are identified for different plasma configurations. Increasing the vertical magnetic field leads to a transition from resistive to pure interchange modes, in agreement with 3D global fluid linear model and nonlinear simulations. A critical pressure gradient needed to drive the ideal interchange instability is observed experimentally. The mechanisms behind the origin and the dynamical properties of filaments or blobs, region of enhanced pressure originating from the nonlinear development of the instabilities, are elucidated. An analytical expression for the blob velocity including cross-field ion polarization currents, parallel sheath currents, and ion-neutral collisions is derived and shows good quantitative agreement with the experimental data. In addition to particles and energy, blobs affect the plasma momentum generation and transport. Two-dimensional structures of plasma toroidal flows, associated with the blob generation and propagation, are measured, indicating that toroidal momentum is transferred from an ideal-interchange mode to density blobs. The influence of turbulence and blobs on supra-thermal ions is also directly investigated using a miniaturized fast ion source and a movable detector.

1. Introduction

The levels of cross-field transport of particles, heat and momentum in magnetically confined plasmas are generally much larger than those induced by collisional processes. This anomalous transport is due to plasma turbulence. At the edge of fusion devices, turbulence is characterized by high relative fluctuation levels, leading to the formation of nonlinear macroscopic structures, referred to as blobs (or filaments, due to their field-aligned character) [1]. Fundamental aspects of the physics of the formation, propagation, and consequences of these structures can be addressed in basic plasma physics devices, which are relatively easily diagnosed throughout the entire plasma volume by a large number of probing channels, allowing for a complete characterization of plasma and wave (turbulence) parameters with adequate spatial and temporal resolution [2]. Furthermore, basic plasma devices allow for well-defined external control parameters, which can influence plasma turbulence. The results obtained in such investigations can then be used to assess and validate theoretical models and numerical codes used for predicting the behaviour of the plasma edge and plasma boundary interactions in fusion experiments [3].

Here, we review recent advances by the Basic Plasma Physics group at CRPP on the simple magnetized toroidal plasma device TORPEX [2] on fundamental aspects of the physics of fluctuations and turbulence, as well as related transport phenomena [4]. The TORPEX device and its main diagnostics are briefly reviewed in Section 2. Investigations on the nature of the instabilities and on the blob dynamical behaviour are discussed in Section 3 and 4, respectively. Section 5 deals with the effects of turbulence on plasma flows and momentum transport, while Section 6 addresses the dynamics of supra-thermal ions. Section 7 concludes the paper and briefly outlines possible future developments.

2. The TORPEX device and diagnostics

TORPEX is a toroidal device (R = 1m, a = 0.2m), in which plasmas are confined by a toroidal magnetic field up to B_ϕ=100mT, and a vertical field, $B_z \ll B_\phi$. Similarly to the SOL of toroidal fusion devices, this magnetic configuration, usually referred to as simple magnetized torus (SMT), features helical open field lines terminating on the vessel wall, ∇B, and magnetic field curvature. Highly reproducible discharges of different gases (H, He, Ar and Ne), with density and electron temperature in the range $n_e \sim 10^{16}$-$10^{17}m^{-3}$ and $T_e \sim$5-20eV, are produced by microwaves at f=2.45GHz (P<50kW), in the electron cyclotron (EC) range of frequencies [5].

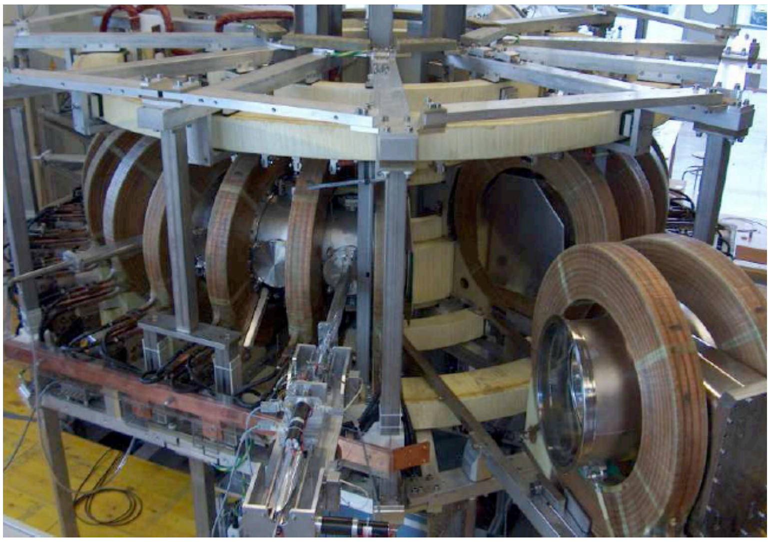

FIG. 1. The TORPEX device, with a mobile sector taken out

A picture of the device is shown in Fig. 1, which highlights one of the mobile sectors that can be slid in and out on a rail system, designed to increase the flexibility of the experiment. Measurements of plasma parameters and of electrostatic fluctuations are done using a large number of Langmuir probes, in different configurations (single, double and triple setup, and Mach probe configuration), disposed at different toroidal locations and covering almost the entire plasma poloidal cross-section. At one toroidal location, an 86-tip probe array (with a probe tip spacing of 3.5cm), named HEXTIP [6], provides high temporal resolution (250kHz) imaging of the ion saturation current and floating potential dynamical evolution.

3. Nature of instabilities and phase space diagram

The SMT configuration provides a drive for both drift and interchange instabilities. Global three-dimensional fluid models of the TORPEX configuration have been developed, based on the drift-reduced Braginskii equations, which have provided a new theoretical understanding of turbulence in the SMT [7]. The simulations are able to follow the plasma dynamics in the full TORPEX domain, which results from the combined effects of the plasma source, parallel losses, and turbulence driven by plasma gradients and magnetic curvature, without separating fluctuation and equilibrium quantities.

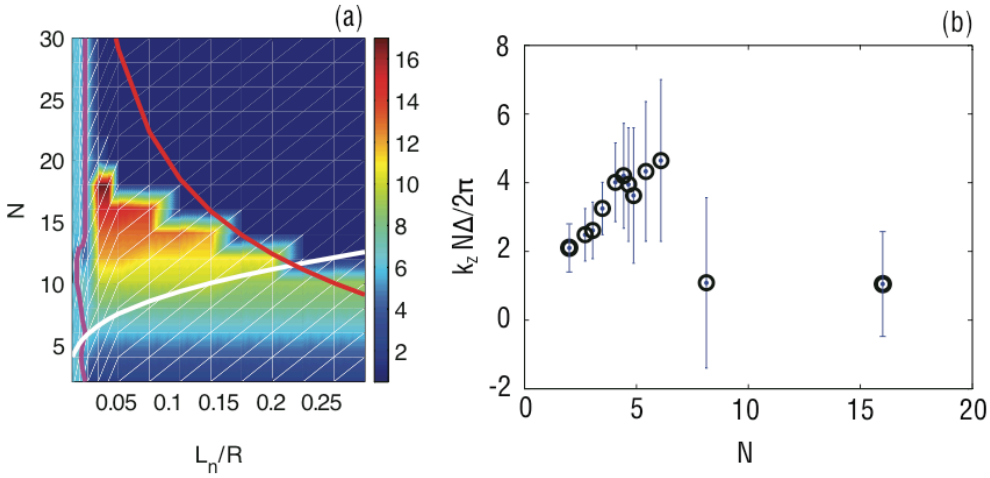

FIG. 2. (a) Instability phase space diagram for the TORPEX device from linear global simulations. The color coding corresponds to the value of the normalised vertical wavenumber, $k_z N\Delta/2\pi$, for the fastest growing mode. The lines represent the boundaries beyond which one particular kind of instabvility dominates, in the sense of having the largest linear growth rate: the white line defines the boundary for the resistive interchange mode (which dominates below it), the red line for the ideal interchange (which dominates above it), and the purple line for the drift wave (which dominates to the left of it). The horizontal axis is the normalised density gradient, where $L_n=n/\nabla n$. (b) Experimentally measured values of the vertical mode number as a function of the number of field lines turns N in the toroidal direction.

Depending on the plasma resistivity, on the number of magnetic field line turns in the device, $N=L_v B_\phi/(2\pi R B_z)$ (L_v is the height of the vessel), and on plasma density (or pressure) gradient, the simulations reveal three regimes of turbulence in TORPEX, each driven by a distinct plasma instability: an ideal interchange mode regime, a previously undiscovered resistive interchange mode regime, and a driftwave (DW) regime [8]. The DW regime, previously assumed to dominate the SMT plasmas as N is increased [9], is found to be achievable only at very low plasma collisionalities. In the high N configuration, the instability spectrum is instead dominated by resistive interchange modes [8,4]. Resistive interchange modes are very similar to resistive ballooning instabilities, which are believed to control plasma transport in the tokamak SOL [10]. The most obvious difference between ideal interchange turbulence and turbulence driven by either resistive interchange or DW instabilities is the wavenumber along the magnetic field. In the former case $k_{//}=0$, while $k_{//}\neq 0$ in the latter. In TORPEX, the transition from $k_{//}=0$ ideal interchange-dominated turbulence to a finite $k_{//}\neq 0$ state is clearly observed as the pitch of the field lines is decreased [9]. In Fig. 2(b), the measured normalised vertical wavenumber is plotted as a function of N. The $k_{//}=0$ regime, is observed for N <~ 7. The dominant toroidal mode number in this case is n=1, as expected, given $k_{//}=0$ and $k_z N\Delta/2\pi=\Delta$ (i.e. $\lambda_z=\Delta$). Around N=7, the turbulence transitions to a state dominated by $\lambda_z=N\Delta$ fluctuations (one wavelength in the vertical direction from bottom to top), corresponding to a small but finite $k_{//}\sim 1/(RN)$. The dominant toroidal mode number in this regime is n=0, that is the turbulence becomes toroidally symmetric. As can be seen in Fig. 2(a), this agrees with the prediction of linear theory, and is confirmed by the nonlinear TORPEX simulations [8]. The existence of a critical pressure gradient for the stabilization of the ideal interchange modes was predicted theoretically and demonstrated experimentally [11]. In the experiment, the critical gradient is reached during a scan of the neutral gas pressure. Around the critical value, a small increase in the neutral gas pressure stabilises the interchange mode or reduces its amplitude by at least two orders of magnitude. In the rest of the paper, we will concentrate on the pure interchange dominated regime, with a relatively large vertical field, and slab-like average density and temperature profiles.

4. Blob dynamics and scaling law

In the ideal interchange dominated turbulent regime, which shows similarities with the SOL of fusion devices, we observe the propagation of blobs, which are generated from ideal interchange waves through a strong ExB shear flow [12].

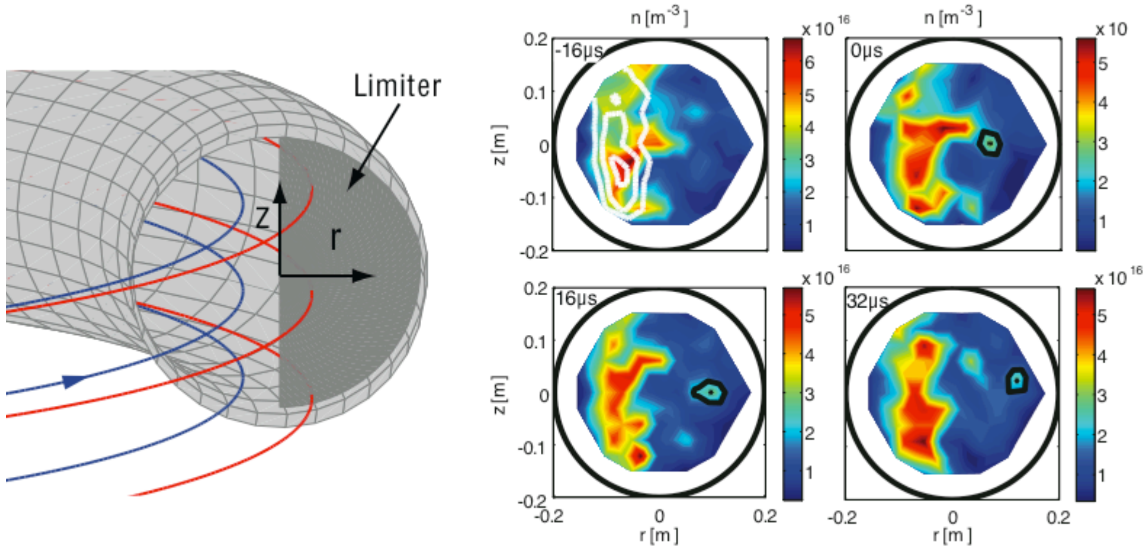

FIG. 3. (Left) Sketch of the experimental setup, with two examples of helical magnetic field lines. The thick blue line lies in the main plasma region and does ~3 turns before intercepting the vacuum vessel. The thin red line lies in the blob region and intercepts the limiter plate after one turn. (Right) Snapshots of electron density in a He plasma, showing the propagation of a blob on the low field side. The time-averaged profiles are indicated by white contours in the top left frame.

An example of a radially propagating blob is shown in Fig. 3(right), based on HEXTIP data in a helium plasma. Here, the blob dynamics subsequent to its birth is studied using a novel spatiotemporal pattern recognition method, which allows the determination of statistical observables, such as blob size and speed [13]. For this study, we have inserted a steel limiter into the blob propagation region, as shown in Fig. 3(left). This leads to a simple boundary condition, where the magnetic field lines are connected to the material surface almost perpendicularly. Previous theoretical studies on blob motion [14] suggest that the curvature-driven polarization of the blob, which causes its propagation, can be damped by cross-field or parallel currents. The relative importance of these terms depends on the normalized blob size ã, which can be varied in the TORPEX experiment by changing the ion mass. We investigate the scaling of the cross-field blob velocity with blob size, connection length and neutral gas pressure for different gases. An analytical expression for the blob velocity including cross-field ion polarization currents, parallel currents to the sheath, and ion-neutral collisions is derived [15]:

$$\tilde{v}_{blob} = \frac{\sqrt{2\tilde{a}}}{1+\sqrt{2}\tilde{a}^{5/2}+\tilde{\eta}\sqrt{\tilde{a}}}\frac{\delta n}{n}$$

Here the normalization of velocity, size and resistivity is similar to the usual convention [14]. By varying the ion mass, the dimensionless vertical blob scale ã is varied from ã <1 to ã >1. The experimental data are compared with the new scaling in Fig. 4(right), showing good quantitative agreement. Consistently with previous theoretical studies, this shows that for ã <1 the blob velocity is limited by cross-field ion polarization currents, while for ã >1 it is limited by parallel currents to the sheath.

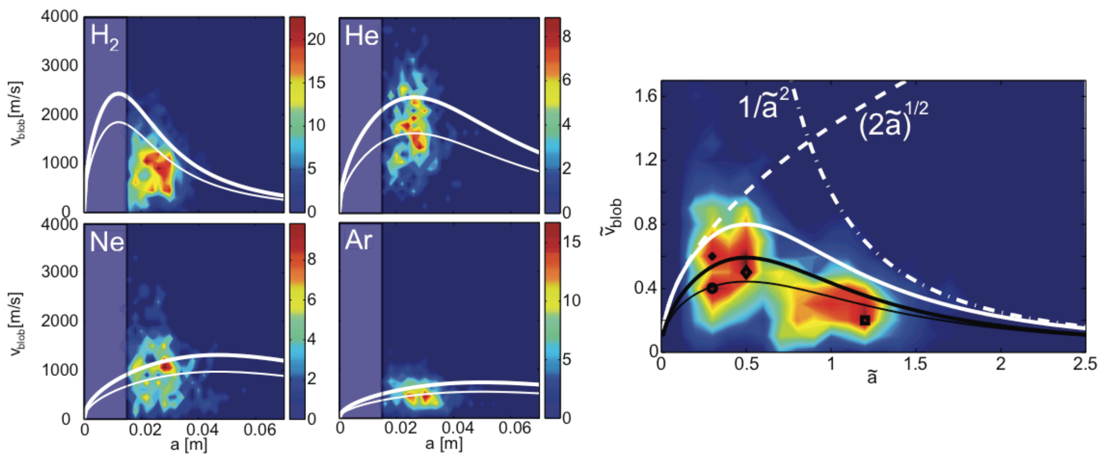

FIG. 4. (Left) Joint probabilities of measured radial blob velocity versus vertical blob size in plasmas generated in four different gases. (Right) Joint probability of normalized blob radial velocity versus blob size. Superimposed are the commonly used scaling laws $\tilde{v} = \sqrt{2\tilde{a}}$ and $\tilde{v} = 1/\tilde{a}^2$ (dashed and dash-dotted white), as well as the new scaling law (solid white) with corrections due to a background of plasma (thick black) and additionally a background of neutrals (thin black). The symbols indicate the peaks of the distributions for different ion masses (working gases): H (square), He (diamond), Ne (plus), and Ar (circle).

5. Effects of blobs – cross field transport and intermittent plasma flow

The influence of blobs on the generation and transport of angular momentum is investigated using toroidal velocity measurements from Mach probes, in combination with reconstructions of time and space-resolved I-V characteristics from Langmuir probes at the same location. In this way, conditionally sampled Mach numbers and ion sound speeds can be obtained [16].

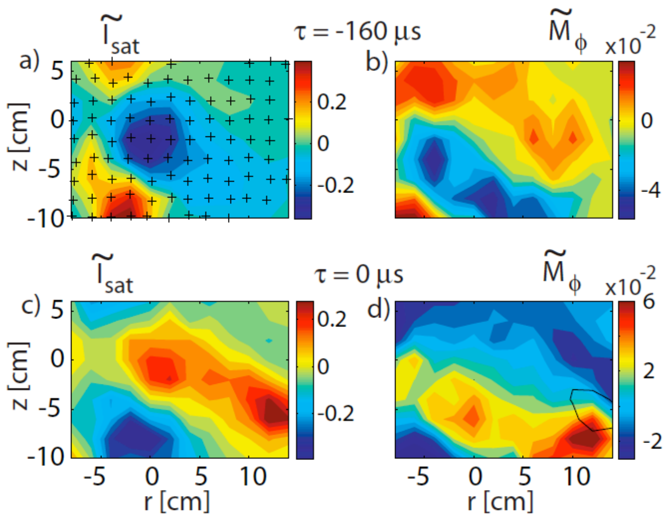

FIG. 5. 2D reconstruction from conditional sampling of perturbed ion saturation current (left) and Mach number (right), at two different times. The phase between density (Isat) and flow perturbations is about $\pi/2$, and appears to be carried along the blob trajectory. The black contour on frame d) represents the corresponding density blob.

A statistical analysis of toroidal Mach number measurements shows that the third moment of the Probability Density Function (PDF), the skewness, is almost always negative and tends to zero in the source-free region where blobs propagate. In this region, the Mach number PDF is more Gaussian than the density PDF, an observation that is in agreement with previous results from the JET tokamak [17]. The link between toroidal flows and blobs is experimentally demonstrated. The phase shift between the toroidal flow and the density perturbations observed in the interchange mode where the blob is born is conserved along the blob radial trajectory. This leads to dipolar structures of the blob-induced flow or to monopolar perturbations, so large that the toroidal flow gets transiently reversed. An example of a toroidal momentum blob with dipolar structure is shown in Fig. 5. We also observe that the larger the density blob, the larger the toroidal flow perturbation.

6. Interaction of supra-thermal ions with turbulence

Fusion plasmas are heated by suprathermal ions generated by additional heating systems or by fusion reactions (3.5MeV α's, the dominant source in burning plasma regimes). An important question is therefore how strong is the interaction between these suprathermal ions and the background turbulence, and what are its consequences on the ion (phase-space) transport. Significant theoretical developments have been undertaken to address this issue [18], but direct experimental measurements are so far available only in linear devices [19]. TORPEX is well suited to address this question, taking advantage of the relatively simple experimental environment with easy access for diagnostics and the well characterized background turbulence.

A system for experiments on the interaction between fast ions and the turbulence including the source and detector has been built and successfully exploited [20]. Using this scheme we have investigated the interaction of fast ions with ideal interchange turbulence. Fast ions with energy in the range 100eV- 1keV are injected into the plasma using a miniaturized source (24mm in diameter and 50mm in length), which can be installed directly inside the TORPEX vacuum vessel. The source is based on a two grid accelerating system with a thermionic emitter and produces fast ($Li6+$) ion currents up to 5μA, which do not produce any significant effect to the background plasma, e.g. in terms of heating. Fast ion current modulation (up to 10kHz) is used in connection with a synchronous detection scheme. The fast ion current density profile is measured using a miniaturized gridded energy analyzer (GEA) which is installed on a 2D moving system, toroidally separated for these experiments by 12.9°. By moving the detector in between discharges, one can obtain the full fast ion current density profile. To improve the signal to noise ratio, a design with two identical analyzers was adopted, one measuring the fast ion beam together with the background noise and the other measuring only the background noise. Each fast ion detector is able to measure fast ion currents as small as 0.1μA.

A series of experiments were performed with and without plasma production, in the presence of the neutral gas and the full magnetic field configuration. These allow to isolate the effect of the plasma and its fluctuations on the fast ion distribution. The results for an injection of 300eV ions in the blob region are shown in Fig. 6, where profiles with and without plasma are displayed. We note that in the presence of plasma (produced in this case by 400W of microwave power), the profile is broader than in the case without plasma. Although this difference is small, it exceeds what can be estimated as the error bar (about 0.15cm), and is observed systematically [4].

To interpret this data, we integrated the single particle equations of motion in the background magnetic field with or without the turbulent electric field obtained by the 2D simulation ($k_{//}=0$) based on drift-reduced Braginskii equations [21]. To match the measured values, the amplitude of the electric field fluctuations is amplified ad hoc by a factor of two. The source and detector experimental set-up is taken into account to predict the fast ion current profile that should be measured in the experiment. The theoretical predictions confirm that in the presence of turbulence there should be a modest but measurable radial broadening of the radial profile with respect to the case without plasma.

Although a number of details remain to be addressed in the comparison, including the motion of the fast ion profile centroid with plasma and the beam profile vertical width and spreading, the radial broadening of the fast ion current profile observed in the experiment agrees qualitatively with broadening in simulated turbulent electric fields of realistic structure and intensity. We conclude that turbulence and the related structures do have an effect on the fast ion distribution.

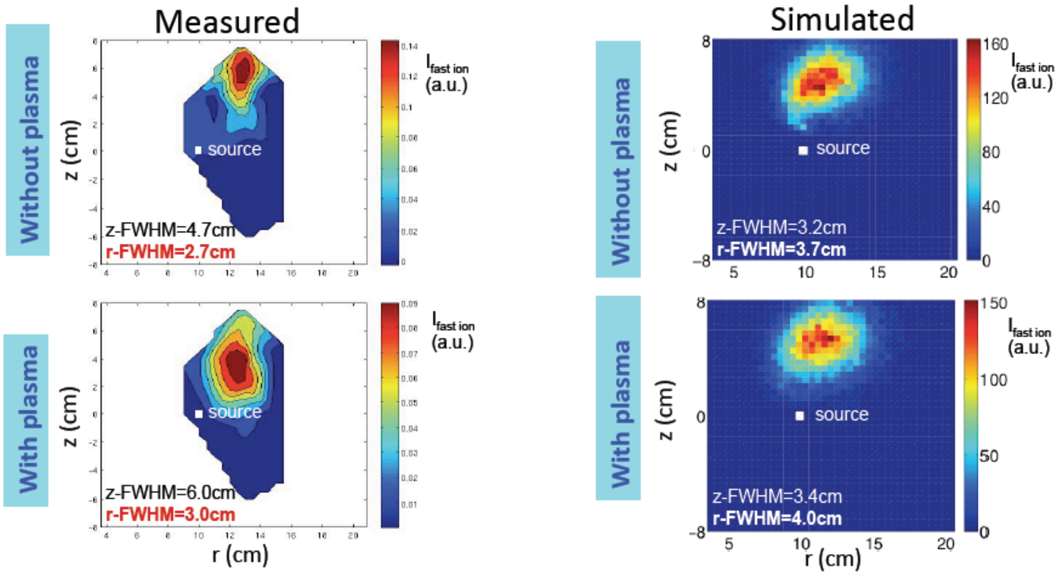

FIG. 6 Left: fast ion current density profiles measured without (top left) and with (bottom left) plasma, for a fast ion energy of 300eV, and injection in the blob region. The data corresponds to a total of 98 discharges. Right: fast ion current density profiles simulated in the absence (top right) and in the presence (bottom right) of turbulent electric field. The white square indicates in each plot the position of the fast ion injector (about 12.9°, or 25cm, apart from the detector, toroidally).

7. Conclusions and outlook

Progress in understanding turbulence and related cross-field transport of fusion relevance is achieved in the simple magnetized plasmas of the TORPEX toroidal device. Several research avenues have been opened and will further be developed to provide a test bed for code benchmarking and theory validation in the field of plasma turbulence interactions. Following significant improvements in the basic understanding of blob dynamics, methods to control blobs will be addressed, such as the introduction of conducting limiters of various geometries and the inclusion of a set of biased plates. Local currents related to the compensation of the curvature driven charge separation, the mechanism damping blob motion, will be directly measured using ad hoc miniaturized magnetic coils, and compared with the theory and scaling law developed on TORPEX. Other plasma production schemes (such as helicon sources) and magnetic topologies (such as tokamak-like configurations) will be developed to further enlarge the range of plasma conditions over which turbulence and related effects may be explored, and to address the effects of a transition in field line topology mimicing the core-SOL interface in magnetic fusion devices. The investigation of the fast ion interaction with turbulence will continue with enhanced injection and diagnostic capabilities, including fast optical imaging methods [22], to elucidate the nature of the induced fast ion transport and its dependence upon the ion energy and its ratio to the background plasma temperature, the key quantity for determining the orbit averaging effects.

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