Basic investigations of turbulence and interactions with plasma and suprathermal ions in the TORPEX device with open and closed field lines

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Abstract TORPEX is a flexible device dedicated to investigating basic plasma physics phenomena of importance for fusion. It can feature a simple magnetized toroidal (SMT) configuration with a dominant toroidal magnetic field and a small vertical field component, or accommodate closed field-line configurations of increasing complexity. Among these are simple plasmas limited by the vessel on the low field side, single or double-null X-points, and even advanced divertor configurations like snowflakes. Using an extensive set of diagnostics, systematic studies of plasma instabilities, their development into turbulence and meso-scale structures, and their effects on both thermal and suprathermal plasma components are performed. The impact of the experimental results obtained on TORPEX is enlarged by their systematic application to model validation, performed using rigorous methodologies for quantitative experiment-theory comparisons. In the past two years, we conducted investigations of suprathermal ion-turbulence interaction on SMT plasmas. These investigations reveal that the transport of suprathermal ions is generally non-diffusive and can be super- or sub-diffusive depending on two parameters: the suprathermal ion energy normalized to the electric temperature and the electric potential fluctuations normalized to the electron temperature. The orbit averaging mechanism predicted to reduce the effect of turbulence on the suprathermal ions in burning plasmas has been clearly identified, both for gyro- and drift-orbits. To better mimic the SOL-edge magnetic geometry in tokamak, we have installed a current-carrying conductor suspended in the center of the chamber to produce magnetic configurations that creates closed-field line configurations. First experiments are devoted to the characterization of the background plasma and fluctuation features in the presence of quasi circular-shaped flux surfaces. Measurements of toroidal and poloidal wave numbers indicate field aligned modes. Further studies are under way to compare the experimental measurements with the simulation results and assess the main instability driving mechanism.

1. Introduction

In recent years, fusion research has been advanced not only by activities on medium-size and large tokamaks but also by combining theoretical/numerical studies of fundamental phenomena with experiments on basic plasma physics devices, which offer full diagnostic access and freedom in control parameters. On TORPEX, a basic plasma physics device at the Center for Plasma Physics Research (CRPP) in Lausanne, Switzerland [1], research focuses on advancing our understanding of plasma turbulence by bridging the gap between experiments and simulations. With a continuously improving set of diagnostics, of theoretical and modeling tools together with a detailed methodology for validating them, research on TORPEX has attained a level at which quantitative comparisons between theory and experiment can now be performed. Here, we review recent progress in understanding fundamental aspects of the interaction between turbulent structures and suprathermal ions. We also report on first measurements aiming at identifying the nature of the instabilities in closed-field line configurations, and at investigating the blob dynamics in the presence of an X-point.

2. The TORPEX device: simple magnetized torus (SMT) and closed field lines configurations

TORPEX (R = 1 m, a = 0.2 m) is a toroidal device in which a small vertical magnetic field B_z~4 mT is superposed on a toroidal magnetic field B_T~100 mT to form helical magnetic field lines whose both ends terminate on the vessel. A picture of TORPEX with the main elements and an example of helical field line are shown in Fig. 1. This configuration, usually referred to as *simple magnetized torus* (SMT), is a simplified paradigm of a tokamak scrape-off layer, since

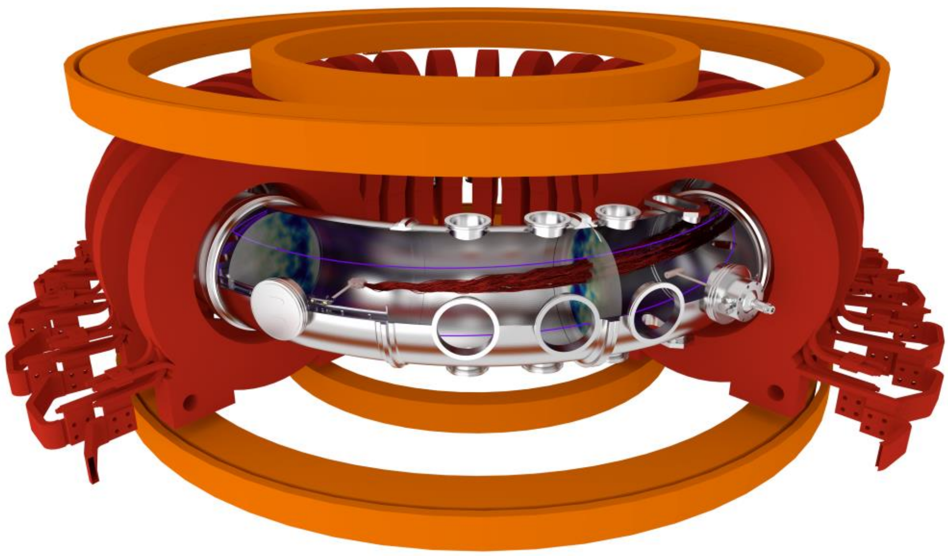

FIG. 1. View of the TORPEX device with the main elements (vacuum vessel, toroidal and poloidal coils) together with the suprathermal ion source and one gridded-energy analyzer (GEA) detector. A helical magnetic field line of a SMT configuration is shown in violet. The suprathermal ion source is mounted on the toroidal moving system. Examples of simulated suprathermal ion trajectories computed for 30 eV ions are shown in red. Simulated plasma potential profiles at two toroidal positions are shown. These are obtained from numerical simulations using the GBS code [6].

it features open field lines, ∇B and magnetic field curvature. Plasmas of different gases are produced by microwaves in the electron cyclotron frequency range (2.45 GHz) injected either from the low-field side or the bottom of the device. Here, we focus on hydrogen plasmas, which are characterized by electron temperatures T_e~5-15 eV and densities $n_e \sim 1\text{-}5\times10^{16}$ m^{-3}.

Extensive sets of Langmuir probes (LP) are used to characterize electrostatic fluctuations in terms of linear dispersion relation, statistical properties, and non-linear wave-wave interactions. An example of a 2D array of LPs, dubbed 2DSSLP, is shown in Fig. 2. In particular, full spatio-temporal imaging of electrostatic fluctuations is performed using HEXTIP, an array of 85 LPs, providing a complete coverage of the poloidal cross section.

To better mimic the SOL-edge magnetic geometry in tokamak, we have installed a new system [2] that creates twisted field line configurations, consisting of a 1 cm radius toroidal copper conductor suspended inside the vacuum vessel by an electrical coaxial feed-through and by three vertical stainless steel wires. Four further horizontal supports stabilize the conductor and allow placing it at different vertical positions so that SMT configurations can be recovered by pulling it up to the top of the vacuum vessel. A picture of the system with the main elements is shown in Fig. 2. Different configurations can be obtained in conjunction with a set of toroidal coils for the vertical magnetic field. Among these are simple plasmas limited by the vessel on the low field side, single or double-null X-points, and even advanced divertor configurations like snowflakes. A current up to 1kA flows in the conductor. The maximum slew rate of the power supply is 1400A/sec, which allows reaching the maximum current in 700ms. We currently use a power supply capable of driving 1.1 kA. The power supply is floating and is remotely controlled using an electronic module with its ground decoupled from the ground of the toroidal conductor circuit. For simplicity, water-cooling is used only for the portions of the conductors embedded in the coaxial feed-through. The flat top current duration (~1 s) is limited by the Ohmic heating of the wire with almost pure radiative cooling in vacuum.

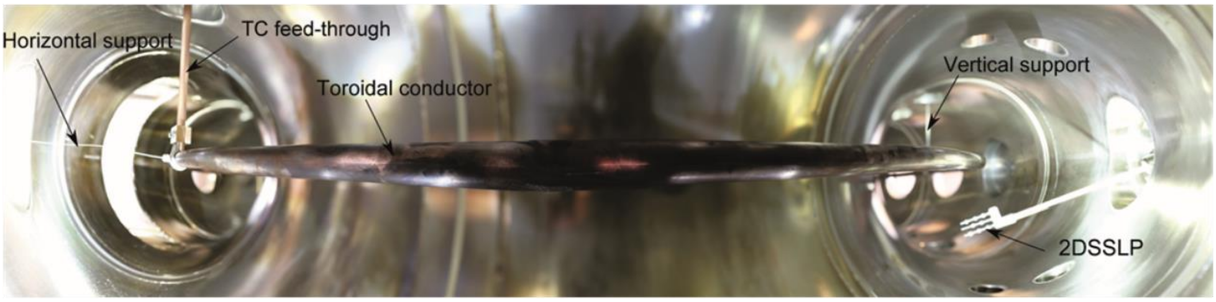

FIG. 2. Wide-angle view of the toroidal conductor installed inside TORPEX. Visible are the feed-through together with the vertical and horizontal supports.

3. Investigations of suprathermal ions transport in SMTs

In the past two years, we conducted investigations of suprathermal ion-turbulence interaction, a basic issue for burning plasmas. A miniaturized source is used, which produces $Li6^{+}$ ions with energies in the range 25eV-1keV, which is much larger than the background plasma energy (T_e~2-10 eV). A motorized system moves toroidally the ion source continuously over a distance of ~50 cm. The suprathermal ion detection is performed by double-gridded energy analyzers (GEAs) that utilize differential measurements between two collectors to cancel thermal plasma contributions to the signal. Each detector has small dimensions relative to the plasma size (inlet diameter of 8mm), and is able to measure ion currents as small as 0.1μA. Synchronous detection is used to increase the signal-to-noise ratio by modulating the emitter bias voltage at a given frequency (~1 kHz). Two GEAs are available and are mounted on 2D motorized positioning systems that can move them at almost any point of the poloidal cross-section. A CAD drawing of the source together with one GEA is shown in Fig. 1. This system allows reconstructing the three-dimensional profile of the suprathermal ion beam, which can then be compared with numerical simulations [3-5].

For the present experiments, the suprathermal ions are injected at two energies (30 eV and 70 eV) in a SMT plasma dominated by ideal-interchange turbulence, which is characterized by the presence of radially propagating blobs. Two examples of 3D measurements of the current profiles are shown in Fig. 2 for suprathermal ions of 70 eV (top) and 30 eV (bottom).

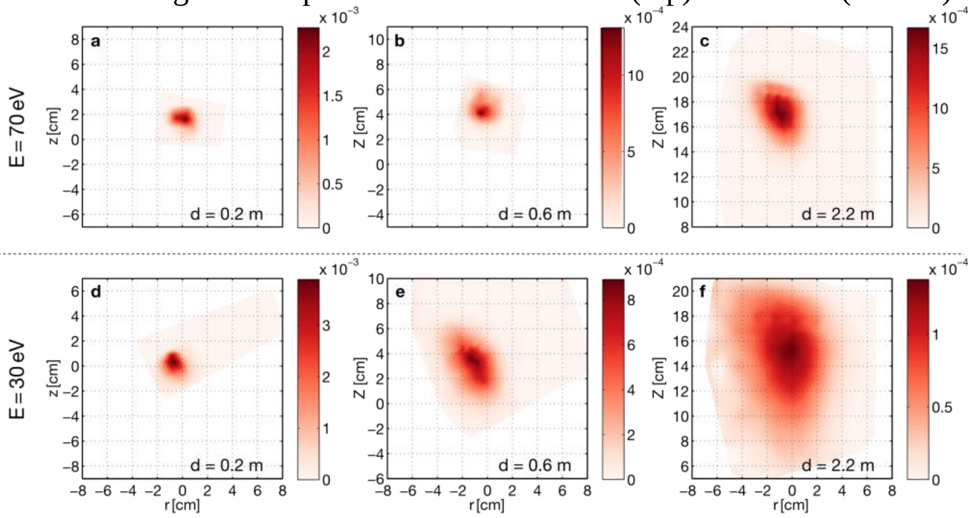

FIG. 3. Poloidal suprathermal ion current profiles at different toroidal distances for two injection energies.

To gain insight into the experimental data, trajectories of tracer $Li6^+$ ions are obtained by numerically integrating the suprathermal ion equation of motion in the SMT turbulent fields. These are computed using a 2D version of the Global Braginskii Solver (GBS) code, which implements a model based on the drift-reduced Braginskii fluid equations, previously validated against TORPEX data [6]. To compute the ion tracer trajectories, the source parameters are based on measurements done without magnetic fields; $1.5x10^5$ particles are launched with initial parameters modeled with Gaussian distributions. Examples of suprathermal ion trajectories are shown in Fig. 1. Using a synthetic diagnostic on the simulated data, which takes into account the phase-space acceptance of the detector, 3D profiles of the fast ion current beam are reconstructed and their radial width is computed. The corresponding comparison between experiments and simulations is shown in Fig. 4.

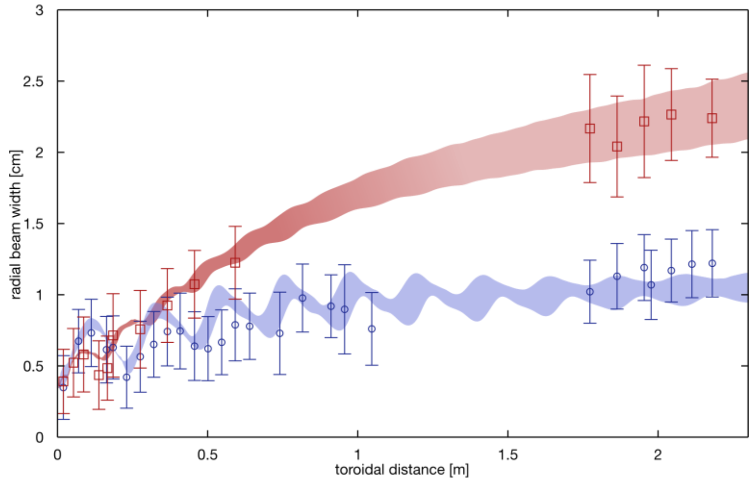

FIG. 4. Radial width of the beam, computed as the standard deviation of the suprathermal ion current profiles, as a function of the toroidal distance traveled by the ions. Red squares and blue circles represents experimental measurements for ions having an energy of 30 eV and 70 eV respectively. The continuous bands represents the results of numerical simulations done with ions of 30 eV (red) and 70 eV (blue) and are obtained with the synthetic diagnostic.

The experimental measurements are shown on top of the results obtained from the synthetic diagnostic, revealing a good agreement. Close to the source, the profiles have a similar size for the two energies. As the distance is increased, the radial width of the 30 eV ion beam grows much faster than that of the 70 eV ions. This indicates, as already suggested by Fig. 2, that the interaction with the plasma turbulence results in a larger spreading for ions with lower energy.

To quantify the ion dispersion, we model the time evolution of the radial variance of particle displacements by a power law $\sigma^2(t) \sim t^\gamma$. In order to compute the value of the radial transport exponent, γ_R, the evolution of $\sigma^2(t)$ is computed from the numerical simulations matching the experimental measurements. The results are shown in Fig. 5. Different transport regimes are observed, depending on the ion energy. After a brief ballistic phase, in which the fast ions do not interact significantly with the turbulence, a turbulence interaction phase follows, which shows the entire spectrum of fast ion spreading: super-diffusive ($\gamma_R>1$), diffusive ($\gamma_R=1$), or sub-diffusive ($\gamma_R<1$), depending on particle energy and turbulence amplitude. In the interaction phase, an exponent of $\gamma_R=0.51\pm0.01$ is found for ions of 70 eV and $\gamma_R= 1.20\pm0.04$ for ions of 30 eV, indicating that the transport varies from a sub-diffusive to a super-diffusive regime as the energy of the ions is decreased. For 30 eV ions, after the super-diffusive phase, a third phase is visible in which the transport is close to diffusive ($\gamma_R=0.92\pm0.04$). These results are consistent with numerical studies showing different transport regimes in the interaction phase depending on the suprathermal ion energies and turbulence fluctuation levels, which determine the relative sizes of the ion orbits and the turbulent structures. These results are also interpreted by using a generalization of the classical model of diffusion, the so-called fractional Lévy motion, which encompasses power-law statistics for the displacements and correlated temporal increments [4].

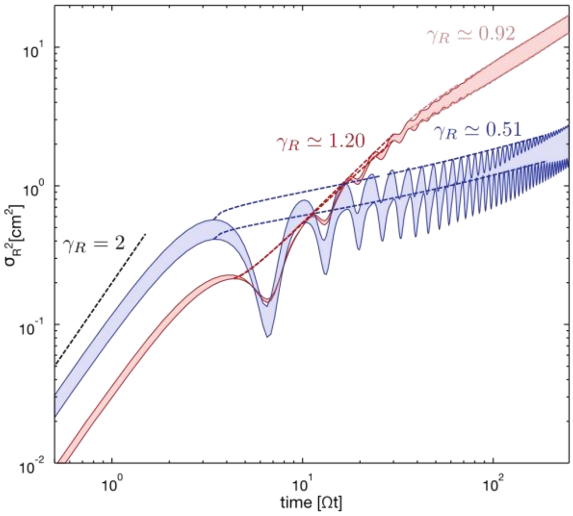

FIG. 5. Variance of the ion radial positions as a function of time (normalized to the ions gyroperiod) obtained from the numerical simulations matching the experimental data, for ions having an energy of 30 eV (red) and 70 eV (blue). Fits of the different phases, shown in dashed lines, provide the transport exponent γ_R.

The existence of different non-diffusive transport regimes should naturally be accompanied by different signatures in the time traces of the detected suprathermal ions, which could be the sole method to reveal different transport regime less easily diagnosed in fusion-grade plasmas. Initial results on TORPEX indicate a clear transition in the intermittency properties from the case corresponding to sub-diffusion to that characterized by super-diffusion [7]. For the 30 eV case, Fig. 6 displays the time-evolution of the GEA signals with the GEA detector located at the position of maximum time-averaged ion current, indicated in Fig. 7 by the cross. Due to the low signal-to-noise level, the suprathermal ion source was modulated at 30 Hz to detect differences in the statistical features of the signals. During the on-phase, the signal is clearly intermittent, Fig. 6-(a), and is characterized by a positively skewed probability distribution function, Fig. 6-(b), which is suggestive of a process associated with intermittent blobs.

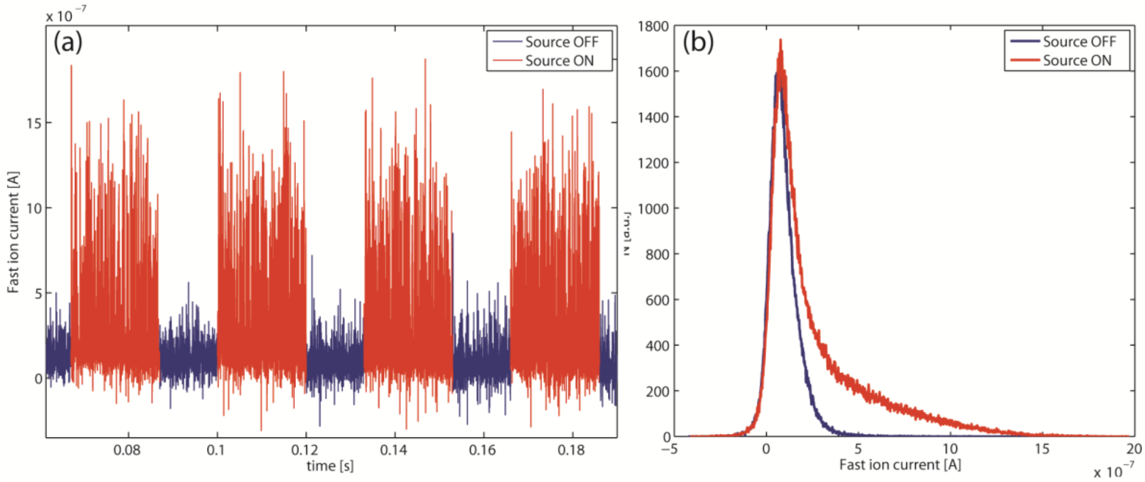

FIG. 6. (a) Time evolution of the GEA signal and (b) its probability distribution function during periods in which the suprathermal ion source is switched on and off.

Figure 7 shows the poloidal profile of the skewness for the two energies. While the skewness profile for the 70 eV ion beam is flat, Fig. 7-(b), the profile for the 30 eV ions reveals a region of high skewness around the peak of the time-average current. This indicates that the broadening of the 30 eV suprathermal ion beam is due to intermittent bursts perturbing the gyromotion of the ions. This pattern is not visible on the skewness profile for 70 eV ions. This implies that, in the surrounding of the profile, where the time traces have a low time-averaged current compared to the center of the profile, the intermittency is more important. Using conditionally-averaged measurements, we show that the observed intermittency is caused by the interaction of the suprathermal ions with blobs [7]. Conditionally-averaged measurements prove that the intermittency in the superdiffusive ions is due to their higher sensitivity to intermittent blobs, which move the ions through their electrical field both inwards and outwards, depending on the their relative location.

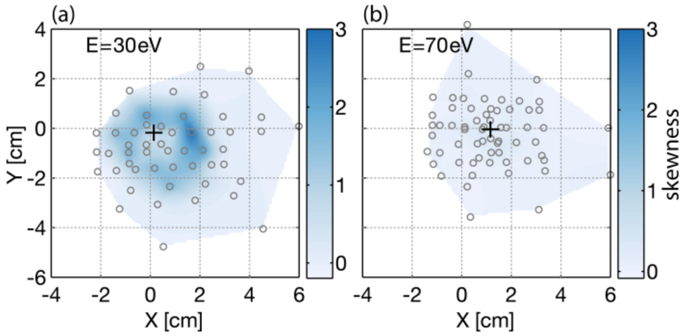

FIG. 7. The skewness profile for the 30 eV ions (a) reveals an annular region of high skewness around the peak of the time-averaged profile. This suggests that the broadening of beam is due to intermittent blobs perturbing the ion gyromotion. This pattern is not visible for 70 eV ions (b). Gray circles show the positions of measurements and the black the positions corresponding to the time traces.

4. Turbulence investigations in configurations with closed-field lines

First measurements of the plasma properties in the presence of a current in the toroidal conductor of the order of 600 A are shown in Fig. 8. This figure displays the profiles across the plasma cross section of the time-averaged density (a) and its fluctuations (c) (standard deviation of the signal up to the system Nyquist frequency, i.e. in the range 0-125kHz) during the current flat-top. The measurements clearly indicate the creation of circular symmetric profiles centered on the magnetic axis.

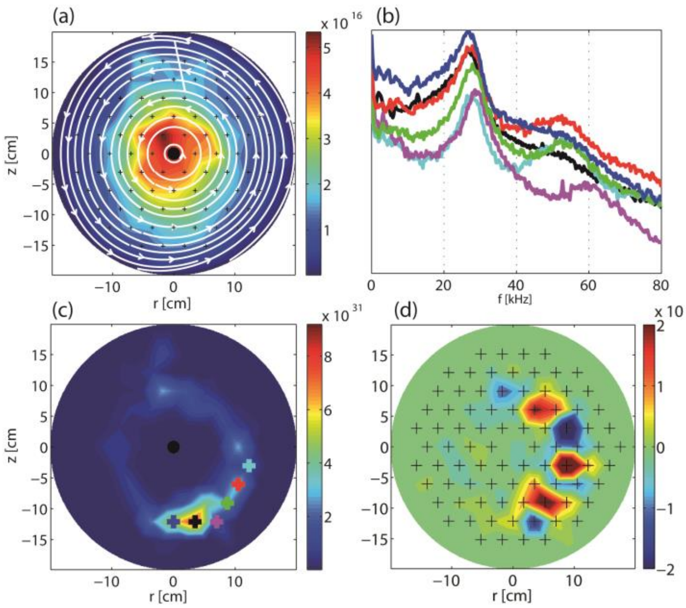

FIG. 8 HEXTIP data in closed-field line configuration. (a) Electron density time-averaged profile; (b) spectra of ion saturation signals from probes located around the region of strong mode activity; (c) profile of the standard deviation of the probe filtered signals in the frequency band between 16.1 and 22.7 kHz; (d) mode structure from conditionally sampled ion saturation data.

Plasma fluctuations feature a clear ballooning character with the presence of quasi-coherent modes between 15-30 kHz, Fig. 8-(b). The conditional sampling data in Fig. 8-(d) reveal the spatial structure and localization of the coherent mode. The first characterization of the mode spectral properties was performed in terms of toroidal and poloidal wave numbers. A dominant toroidal mode number n~1 is found together with a poloidal mode numbers m that are related to safety factor by the relation q=m/n. This indicates that the modes are field-aligned as expected for interchange-driven instabilities. Further studies are foreseen to compare the measurements with the simulations of the CRPP theory group to assess the main driving mechanism of the observed modes [8].

5. Conclusion and Outlook

In TORPEX, several advances have been achieved in the basic comprehension of turbulence in simple magnetized toroidal configurations. The recently developed internal toroidal conductor system opens new avenues for research of direct relevance for magnetically confined plasmas for fusion, allowing the production of magnetic geometries with single and double magnetic null-lines, as well as snowflake divertor configurations. These more complex magnetic configurations will be the starting point of our future investigations. We intend to identify the instabilities from which turbulence is generated, to study their nonlinear development (wave-wave and wave-particle interactions) and saturation mechanisms, and the generation of macroscopic structures. Different external control parameters will be sought to affect the fluctuation behavior, including the vertical magnetic field, the microwave power, and the neutral gas pressure.

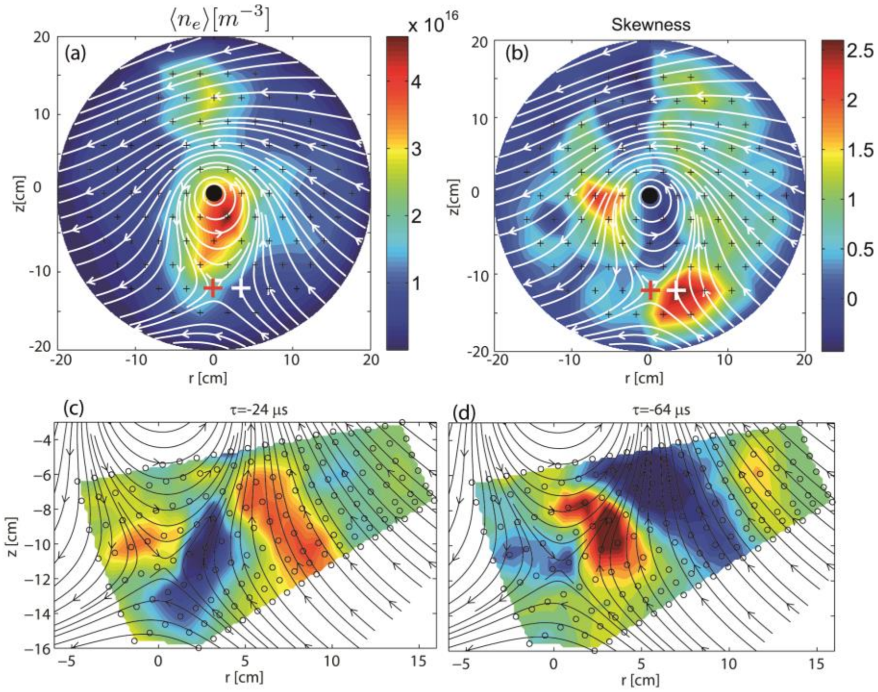

FIG. 9 X-point geometry: (a) time-averaged electron density and (b) skewness profiles. (c, d) Conditionally sampled data showing the blob generation and propagation around the X-point.

An example of a single-null X-point configuration is shown in Fig. 9. The presence of fluctuations around the X-point is revealed, Fig. 9(b), as well as the generation of intermittent blobs, Fig. 9(c, d), which propagate towards the LFS. More complex geometries with multiple fully 3D X-points and/or magnetic ergodic/chaotic surfaces could also be generated by additional ad-hoc coils installed inside the TORPEX vessel.

On the theory side, starting from the simulations of the TORPEX device, the GBS code has been recently upgraded and the physics of the tokamak SOL in the limited configuration has been the subject of a number of detailed investigations. Future development include the implementation of a flexible numerical algorithm to describe more complex geometries, in particular the presence of an X-point, and of a kinetic solver for the neutral atoms. TORPEX will continue to provide an ideal validation testbed for the future developments of GBS. Applying the same techniques on numerical and experimental data allows testing the accuracy of these techniques, and provides a basis for a benchmark of the numerical simulation, which is necessary to determine the complexity of the numerical model needed for a realistic description not only of TORPEX data but especially for fusion devices.

This work was partly supported by the Fonds National Suisse pour la Recherche Scientifique.

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