

Non-diffusive supra-thermal ion transport associated with blobs in TORPEX plasmas

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Introduction

In burning plasmas, supra-thermal ions, generated by ion cyclotron resonance heating, neutral beam injection and fusion reactions, will be responsible for most of the plasma heating and, in some scenarios, non-inductive current drive. Understanding their transport across the magnetic field is of fundamental importance. In some regions of the plasma, this transport can be affected by the interaction between the supra-thermal ions and small-scale turbulence, such as intermittent blobs, generated by plasma instabilities. In TORPEX simple magnetized toroidal (SMT) plasmas ($R=1$ m, $a=0.2$ m), we investigate the supra-thermal ion physics in a basic experimental environment with easy access for diagnostics and well-established plasma scenarios [1]. We report on recent advances in the understanding of non-diffusive transport of supra-thermal-ions, obtained by using extensive sets of three-dimensional (3D) data, together with numerical simulations of ion tracers in turbulent fields, and theory development.

Experimental setup

A miniaturized Li^+ ion source emits supra-thermal ions with energies up to 1 KeV. The source consists of a thermionic emitter with a two-grid accelerating system in a boron-nitride casing (inlet diameter 8 mm). Li^+ ion currents up to 10 μA are obtained. The source is mounted on a motorized rail system and can be continuously moved over a toroidal distance of about 50 cm (see Fig. 1).

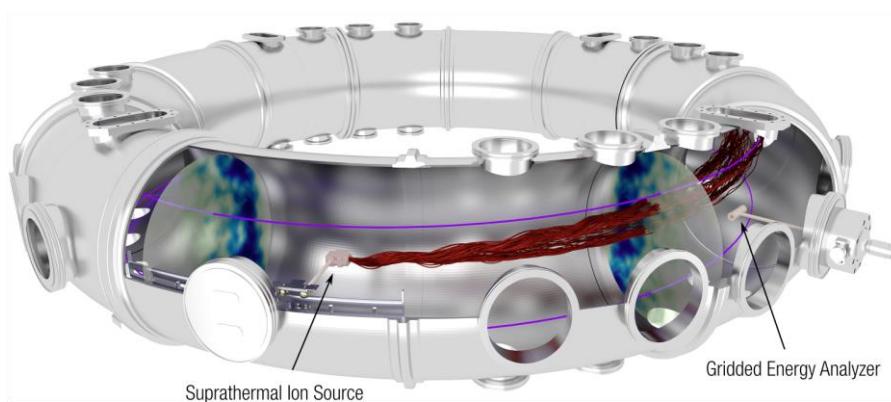


Figure 1. View of the TORPEX vessel with a helical magnetic field line shown in violet. The supra-thermal ion source mounted on the toroidal moving system and one detector on a 2D moving system are also shown. Examples of supra-thermal ion trajectories computed in the case of an initial energy of 30 eV are shown in red.

Ion energy and current density profiles are measured using two identical gridded energy analyzers (GEAs) installed on two-dimensional poloidal moving systems. Each GEA has two detectors facing opposite directions for noise subtraction and has small dimensions relative to the plasma size. Ion currents as small as $0.1 \mu\text{A}$ can be measured. Synchronous detection is used to increase the signal-to-noise ratio by modulating the emitter bias voltage at a given frequency ($\sim 1 \text{ kHz}$). The fast ion source and detectors allow measurements of the time-averaged 3D ion beam as it interacts with the plasma and its turbulence [2].

Experimental results

The supra-thermal ions are injected in a plasma dominated by ideal-interchange turbulence, which is characterized by the presence of radially propagating blobs [3]. Two examples of 3D measurements of the current profiles are shown in Fig. 2 for supra-thermal ions with an energy of 30 eV (top) and 70 eV (bottom). A broadening due to the interaction with the plasma is revealed, which is more significant for ions with an energy of 30 eV than for those with an energy of 70 eV. To gain insight into the experimental data, trajectories of tracer Li^{6+} ions are obtained by numerically integrating the supra-thermal ion equation of motion in the SMT turbulent fields, which is simulated using a 2D model based on the drift-reduced Braginskii fluid equations [4]. The source parameters are based on measurements done without magnetic fields; 1.5×10^5 particles are launched with initial parameters modeled with Gaussian distributions. Examples of supra-thermal ion trajectories are shown in Fig. 1. A synthetic diagnostic, representing the phase space acceptance of the detector, computes the 3D profiles of the fast ion current density. The comparison between experiment and simulations of the evolution of the beam width as a function of the toroidal distance is shown in Fig. 2-right for ions with 30 eV and 70 eV.

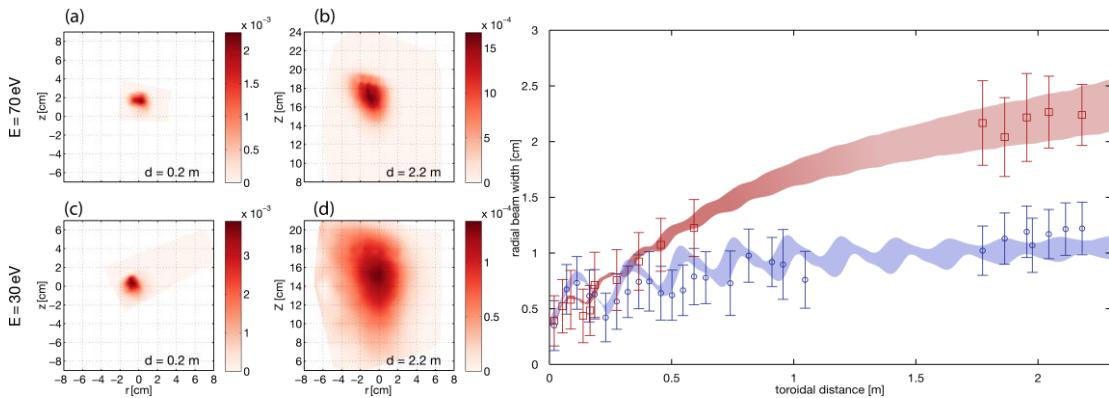


Figure 2. Left: supra-thermal ion current profiles for two injection energies at different toroidal distances (a, c = 0.2 m, b, d = 2.2 m). Top: E=70 eV, bottom: E=30 eV Right: Radial width of the beam, computed as the radial standard deviation of the ion current profiles, as a function of the toroidal distance. Experimental measurements for ions of 30 eV (red squares) and 70 eV (blue circles) respectively. The continuous bands represent the results of numerical simulations for 30 eV (red) and 70 eV (blue) ions and are obtained using synthetic diagnostic.

The standard deviation of the radial profiles is used to characterize the radial width of the beam as a function of the toroidal direction. The experimental measurements are shown on top of the results obtained from simulations with the synthetic diagnostic, revealing a good agreement. Close to the source (Fig. 2 a, c) 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.

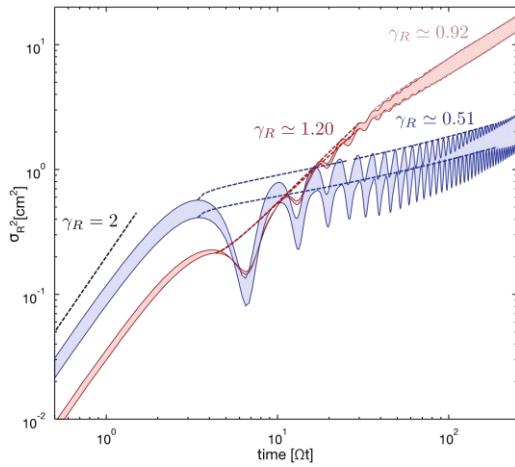


Figure 3. Variance of the ion radial positions as a function of time (normalized to the ions gyroperiod) obtained from the numerical simulations matching the experimental data, for ions having an energy of 30 eV (red) and 70 eV (blue). Fits of the different phases, shown in dashed lines, provide the transport exponent γ_R .

diffusive ($\gamma_R < 1$), depending on particle energy and turbulence amplitude. In the interaction phase, an exponent of $\gamma_R = 0.51 \pm 0.01$ is found for ions of 70 eV and $\gamma_R = 1.20 \pm 0.04$ 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 after approximately 1 m in which the transport is close to diffusive ($\gamma_R = 0.92 \pm 0.04$). These results are consistent with numerical studies showing different transport regimes in the interaction phase depending on the supra-thermal 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 Levy motion, which encompasses power-law statistics for the displacements and correlated temporal increments. This leads to non-diffusive dynamics described by fractional diffusion equations [5, 6].

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. 3. Different transport regimes are observed, depending on the energy of the ions.

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-

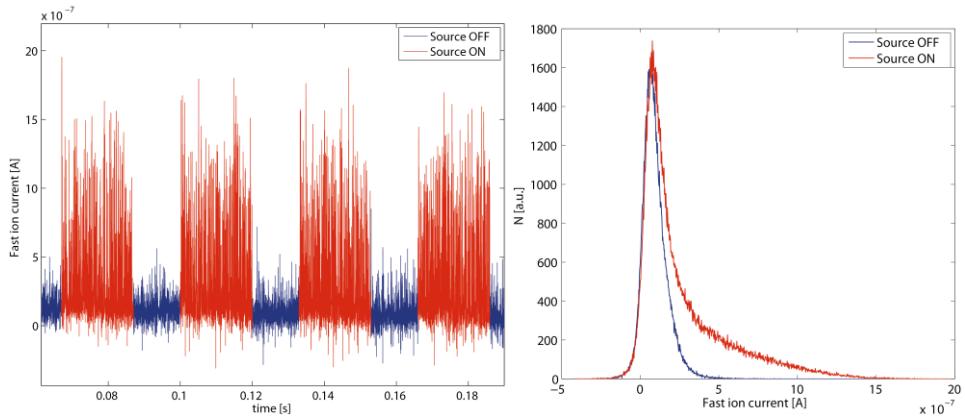


Figure 4. Time evolution of the GEA signal (left) and its probability distribution function (right) during periods in which the supra-thermal ion source is switched on and off.

The existence of different non-diffusive transport regimes for supra-thermal ions should naturally be accompanied by different signatures in the time traces, which could be the sole method to reveal different transport regimes 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. For the 30 eV case, Fig. 4 displays the time-evolution of the GEA signals with the GEA detector located at the position of maximum time-averaged ion current. Due to the low signal-to-noise level, the supra-thermal 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 and characterized by a positively skewed probability distribution function, which is associated with the presence of blobs.

Future experiments will include the injection of supra-thermal ions in TORPEX plasmas characterized by more complex magnetic geometries, including closed field lines and the presence of X-points [7].

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