Investigation of suprathermal ion transport in TORPEX

A. Bovet, A. Fasoli, I. Furno, K. Gustafson, P. Ricci

École Polytechnique Fédérale de Lausanne (EPFL)

Centre de Recherches en Physique des Plasmas (CRPP)

Association Euratom-Confédération Suisse, CH-1015 Lausanne, Switzerland

Introduction

In burning plasmas, fast ions may be generated by ion cyclotron resonance heating, neutral beam injection and fusion reactions. Fast ions will be responsible for a significant fraction of plasma heating and, in some scenarios, non-inductive current drive. Fast ions are also present in natural plasmas, such as the solar corona or the magnetosphere, where they are presumably accelerated by wave-particle interactions. The high temperatures of tokamak plasmas and the huge spatial scale of astrophysical plasmas make measurements of the fast ion transport very challenging. Basic plasma devices offer the possibility to study the interaction between fast ions and plasma turbulence with easy access for diagnostics and well-establish plasma scenarios. Experiments in the linear plasma device LAPD have shown that fast ion transport is increased in presence of turbulent or coherent electrostatic waves and that it is generally nondiffusive [1]. Basic aspects of fast ion transport in ideal interchange-mode unstable plasmas are investigated in the simple toroidal plasma device TORPEX. The magnetic field configuration of TORPEX consists of a toroidal component ($B_t \simeq 75$ mT) and a smaller vertical component ($B_v \simeq 2$ mT), resulting in helical open field lines, with ∇B and curvature. With this magnetic geometry, the fast ion motion without plasma is a combination of the gyromotion along the field lines and the vertical ∇B and curvature drifts.

Experimental setup

The fast ion source consists of a thermionic emitter with a two-grid accelerating system installed in a boron-nitride casing and produces fast ion currents up to 10 μA through an outlet with a diameter of 8 mm. The design of the source was optimized to increase the emission in a miniaturized size [2]. The source is mounted on a motorized movable system and can be continuously moved over a toroidal distance of 50 cm.

A miniaturized gridded energy analyzer (GEA) is used to measure fast ion energy and current profiles. To improve the signal to noise ratio, a design with two identical analyzers facing opposite directions was chosen [2]. The advantage is that one detector measures the fast ion beam together with the background signal while the second detector measures only the background noise. Each fast ion detector (15 mm in diameter, 35 mm in length and in inlet diameter of 8 mm), is able to measure fast ion currents as small as 0.1μA. Both detectors are installed on a two-dimensional (2D) moving system, which can position them at almost any point of the poloidal cross-section. The 2D moving detector system is motorized and allows automatic reconstruction of the fast ion current profile with a spatial precision of $\sim$ 5 mm.

Synchronous detection is used to increase the signal-to-noise ratio [2, 3]. The emitter voltage is modulated by a reference signal at a given frequency ($\sim$ 1 kHz). This modulation results in an undesired space-dependent capacitively coupled noise in the detector. To remove this parasitic effect, an analog lock-in amplifier has been developed. Before demodulation by the lock-in, the detector signal is gated by a reference signal with a dead time window during the capacitive cusp. The final signal is then integrated to obtain a DC output proportional to the fast ion current.

Theoretical investigation of suprathermal ion transport in TORPEX

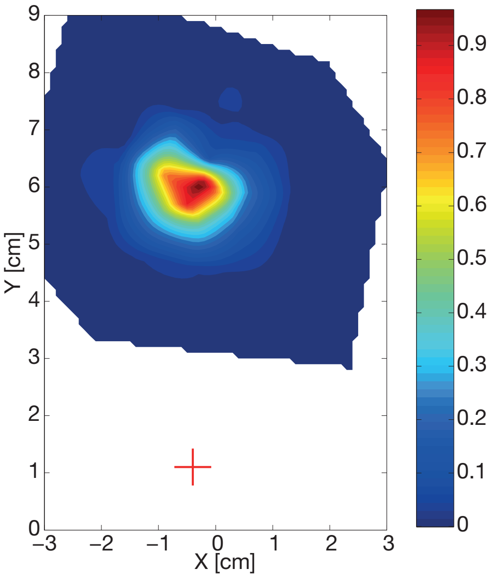

Figure 1: Poloidal profile of the fast ion current [a.u.] at a toroidal distance of 54 cm from the source. The red cross indicates the poloidal position of the injection.

In TORPEX, the tracer particles trajectories are integrated in a turbulent electrostatic field resulting from ideal interchange driven turbulence, provided by 2D simulations of the drift-reduced Braginskii fluid equations [4]. The fast ion simulations explicitly include the charge and mass of ^{6}Li ions, as well as the magnetic field geometry, which effectively causes curvature and ∇B drifts. They also allow one to set the amplitude of the turbulent fluctuations as an independent parameter. Particle orbits are computed by solving Newton equation with the Lorentz force, thus including gyroaveraging implicitly to a high accuracy. Comparisons between experiments and simulations are performed using a synthetic diagnostic mimicking the detector and allowing the three-dimensional profile of the fast ion current to be computed [5].

A comprehensive theoretical investigation of the behavior of the fast ions as tracer particles in TORPEX plasmas was recently completed [5, 6]. The study was performed in plasmas dominated by ideal interchange turbulence. The results show that the spreading of fast ions in the plane perpendicular to the magnetic field is generally nondiffusive, with $\sigma_R^2(t) \sim t^\gamma$, where $\gamma \neq 1$. Here, $\sigma_R^2(t) = \langle (R - \langle R \rangle)^2 \rangle$ is the variance of the ions radial position. A large number of different ensembles of fast ions was used to explore the variations of the value of γ as a function of two dimensionless quantities: the ratio of the fast ion energy to the electron temperature, $\mathscr{E} = E/T_e$, and the ratio of the amplitude of turbulent fluctuations to the electron temperature, $\xi = e\tilde{\Phi}/T_e$, here $\tilde{\Phi} = \Phi - \bar{\Phi}$. It was seen that, depending on the value of these parameters, the value of γ can vary from $\gamma > 1$ (superdiffusive) to $\gamma < 1$ (subdiffusive), due to the effects of gyroaveraging and, more significantly, curvature-drift averaging [5].

First experimental results and comparison with theory

A first set of experiments with the toroidally moving system for the source was recently conducted and preliminary results are presented here. We use a scenario with $B_t = 74$ mT and $B_v = 2$ mT, resulting in a simple magnetized torus configuration (SMT) with vertical magnetic field line return distance $\Delta \simeq 17$ cm. The plasma is dominated by an ideal interchange mode, localized around the position of maximum pressure gradient, with $k_{\parallel} \simeq 0$, and, $k_{\perp} \simeq 37\ \mathrm{m}^{-1}$. The time average electron density at the injection location is $\bar{n_e} =\sim 5 \cdot 10^{15}\ \mathrm{m}^{-3}$ and the standard deviation of the floating potential time series, indicating the level of fluctuations, is ~ 1 V. These plasmas, similar to those extensively studied in [7] using electrostatic probes, are characterized by the presence of a region on the low-field side, where blobs are observed to propagate radially outward resulting in intermittent transport of particles, heat, momentum and current [8].

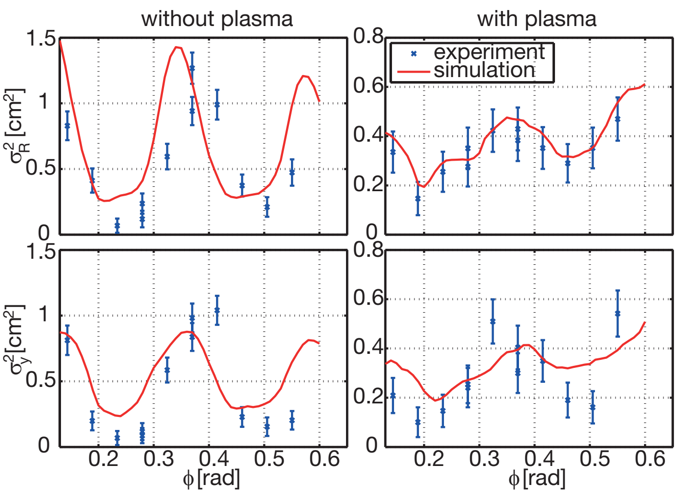

Figure 2: Radial (top) and vertical (bottom) variances of the beam profile at several toroidal positions.

Fast ions are injected in the blob region with an energy of ~ 70 eV and an horizontal orientation. The source is moved toroidally between each discharge over a total distance of ~ 50 cm, in steps of ~ 5 cm. Ploidal profiles of the fast ion current are reconstructed at each toroidal position. Fig. 1 shows an example of a fast ion current profile at a toroidal distance of ~ 54 cm from the source. The red cross indicates the position of the injection, showing the displacement of the beam spot due to the vertical drift. Measurements are made with and without plasma, in the presence of magnetic fields. The radial and vertical spatial variances of the fast ion current profiles are shown as a function of the toroidal angle ϕ in Fig. 2.

Simulations are performed with source parameters based on measurements done without mag-

netic field. 10000 particles are launched with initial parameters modeled with Gaussian distributions. The energy is 70 eV with a standard deviation of 10 %. The initial position is $X_0 = -0.4$ cm and $Y_0 = 1.1$ cm with standard deviation of 1.2 mm. The initial value of the vertical and horizontal angles are $\alpha_0 = -0.04$ rad and $\beta_0 = 0.04$ rad, respectively, with standard deviation of 0.19 rad and 0.13 rad, respectively. Simulations of the turbulence are performed with different values of the particle and heat sources to match the experimental time average n_e and T_e profiles. At the injection point, the fluctuations level of the floating potential is larger in the simulation than in the experiment. To match the potential fluctuations, the simulated plasma potential fluctuations are multiplied by a factor $\Xi = 0.3$. Figure 2 displays along the toroidal direction the variance of the beam profiles obtained with the synthetic diagnostic, from the simulations, and from experimental measurements. A remarkable agreement is obtained. For the case without plasma (Fig. 2-right), this also provides a benchmark for the particle tracer solver. The oscillations of the variance of the beam due to the Larmor motion of the particles are clearly evident, although a small mismatch in the phase of the oscillations between experiment and simulation is observed. This is not observed in the presence of plasma, although the absolute value of the variance is decreased. Indeed, the spreading on the initial angle, in the simulations, had to be decreased by a half to match the experiment. Those differences could be explained by the fact that the functioning of the source is affected by the surrounding plasma. In Fig. 2, the turbulent broadening of the beam is clearly revealed by the radial variance of the beam, which increases as a function of the distance from the source. Numerical simulations at later times indicate that, in these conditions, fast ions undergo a subdiffusive transport with $\gamma \simeq 0.78$.
The experimental setup is ready to explore the different fast ion transport regimes that are predicted by theory. The fast ion energy can easily be changed and the turbulent fluctuations amplitude can be varied by injecting at different locations, in the mode or in the blob region.

This work is partly supported by the Fonds National Suisse de la Recherche Scientifique.

References

[1] Zhou, S. et al. *Phys. Plamas* **19**, 055904 (2012).

[2] Plyushchev, G. et al. *Rev. Sci. Instrum.* **77**(10), 10F503 (2006).

[3] Bovet, A. et al. *Nucl. Fusion, in press* (2012).

[4] Ricci, P. et al. *Phys. Rev. Lett.* **100**, 225002 Jun (2008).

[5] Gustafson, K. et al. *Phys. Plamas* **19**(6), 062306 (2012).

[6] Gustafson, K. et al. *Phys. Rev. Lett.* **108**, 035006 Jan (2012).

[7] Furno, I. et al. *Phys. Rev. Lett.* **100**, 055004 Feb (2008).

[8] Labit, B. et al. *Phys. Plamas* **18**(3), 032308 (2011).