Investigation of fast ions transport in TORPEX

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Abstract

Basic aspects of fast ion transport in interchange-dominated plasmas are investigated in the simple toroidal plasma device TORPEX. Fast ions are generated by a miniaturized lithium 6+ ion source, which emits fast ions with energies up to 1KeV, and are detected using a double gridded energy analyzer mounted on a two-dimensional movable system in the poloidal cross-section. By applying to the fast ion source a modulated biasing voltage, we use a synchronous detection scheme to improve the signal-to-noise ratio. An analog lock-in amplifier has been developed, which allows removing capacitive noise associated with the voltage modulation. We characterize vertical and radial transport of the fast ions, which is associated with the interchange-generated plasma turbulence.

1. Introduction

In burning plasmas, fast ions may be generated by ICRH, NBI and fusion reactions. As fast ions will be responsible for a significant fraction of plasma heating and non-inductive current drive, understanding their transport across the magnetic field is of fundamental importance. The interaction between highly energetic ions and small-scale (drift wave-like) turbulence is an open problem in fusion plasmas, which has not been extensively investigated to date. One of the reasons is that, in the present tokamaks, fast ions do not play a crucial role, as will be the case on ITER [1]. The other, more fundamental reason is that, as fast ions usually have a gyroradius that is larger than the turbulence scale, their interaction with turbulence is expected to be weakened or almost entirely suppressed by gyro-averaging effects [2, 3]. A number of theoretical studies find that the interaction of fast ions with turbulence is reduced when the gyroradius is increased, while several other authors demonstrate that, when the gyroradius increases up to the fluctuation correlation length, the fast ion transport could remain unchanged or even increase. However, recent tokamak results [4] indicate that significant redistribution of supra-thermal ions can be induced by turbulence, at least in some ranges of fast ion energies and of the ratio between fast ion energy and background plasma temperature. Experimental indications of non-diffusive transport of fast ions in strong drift turbulence have been obtained in the linear basic plasma physics device LAPD at UCLA [5]. So far, no direct measurements of fluctuation induced fast ion transport on toroidal devices have been performed. Thus, there exists a strong need for experimental data with which to compare and validate the relevant theoretical and numerical models. In this work, we investigate the interaction of fast ions with ideal interchange instabilities and turbulence in TORPEX plasmas, in a relatively simple experimental environment with easy access for diagnostics and well-established plasma scenarios [6].

2. The TORPEX device and the interchange dominated plasma regime

The experiments are performed on the TORPEX device (major radius R = 1m, minor radius a = 0.2m). Hydrogen plasmas are produced and sustained by microwaves ($P_{EC} \approx 150$ W) in the electron cyclotron range of frequencies. A vertical magnetic field $B_z = 2.1$ mT is imposed on a toroidal field of $B_t = 76$ mT, resulting in helical magnetic field lines with a ∇B and curvature, that terminate on the lower and upper walls of the vessel. Experimental measurements [7] and numerical simulations [8] reveal that plasma turbulence in the present configuration is dominated by an ideal interchange mode with parallel, $k_{//} = 0$, and perpendicular, $k_z \approx 48m^{-1}$, wave numbers.

3. Experimental setp-up: fast ion source and detector

The relatively low energy required for the fast ions (100eV- 1keV) allowed a design of the source based on a very small cylindrical structure (24mm in diameter and 50mm in length), which can be installed directly inside the TORPEX vacuum vessel [9]. The source is based on a two grid accelerating system with a thermionic emitter and produces fast ion currents up to 10μA (fig. 1). The electronics of the source allow fast ion current modulation with a frequency up to 10 kHz.

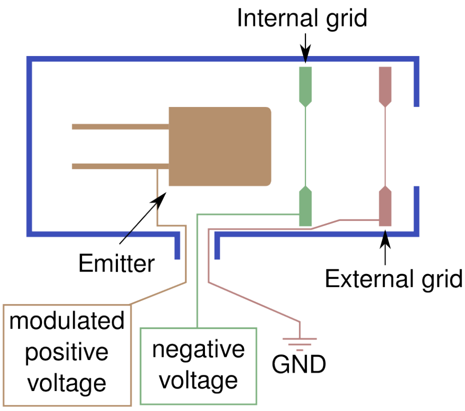


Fig. 1 : Scheme of the fast ion source

A miniaturized gridded energy is used to measure fast ion energy and current density profiles. To improve the signal to noise ratio, a design with two identical gridded energy analyzers facing opposite directions was chosen. The advantage of this configuration is that one GEA measures the fast ion beam together with the background signal and the other measures only the background noise. Each fast ion detector has small dimensions (15mm in diameter and 70mm in length), and is able to measure fast ion currents as small as 0.1µA. The fast ion source and the double gridded energy analyzer are installed on 2D moving systems. The 2D moving systems can position the source and the detector almost at any point of the poloidal cross-section. The 2D moving detector system is motorized allowing the automatic reconstruction of the fast ion current density profile within a single discharge.

4. Data treatment and analysis method

A synchronous detection scheme is used to improve the signal-to-noise ratio [9]. An analog lock-in amplifier, with the capacity to remove capacitive noise associated with the voltage modulation, has been developed. Before demodulation by the lock-in, the signal coming from the detector is multiplied by a signal with a dead time (fig. 2). The dead time is set to remove the position-dependent capacitive effects and the final signal is then integrated to give a DC output proportional to the fast ion current.

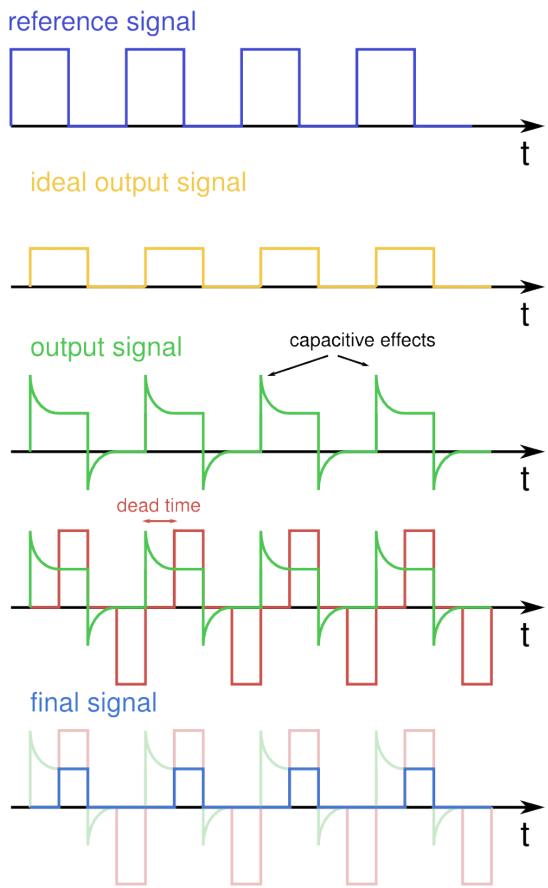


Fig. 2 : Principle of the lock-in detection with a dead time

5. Theoretical interpretation framework

On the theoretical level, we follow fast ion tracer trajectories using the full Lorentz force, with E and B-fields specified by a numerical model of drift-reduced Braginskii equations (GBS) in two dimensions [10]. This model was previously validated to describe interchange turbulence on TORPEX. We explore the properties of fast ion transport on timescales and energies accessible to experimental measurements, and at asymptotic limits. Using a synthetic diagnostic, we observe that the measured ion dispersion agrees with predictions extracted by the GBS and tracer simulations. The rate of dispersion is strongly dependent on the ratio of ion energy to electron temperature. Radial dispersion tends to be super-diffusive for low energies and sub-diffusive for higher energies, mainly due to the vertical drift-averaging effect. An example of the reconstruction of the ion response to turbulence (here for a fast ion energy of 300eV) is given in Fig. 3. For low energies, a Lévy walk model, based on a flight length diagnostic, is used to describe the random walk process of fast ions in the turbulence.

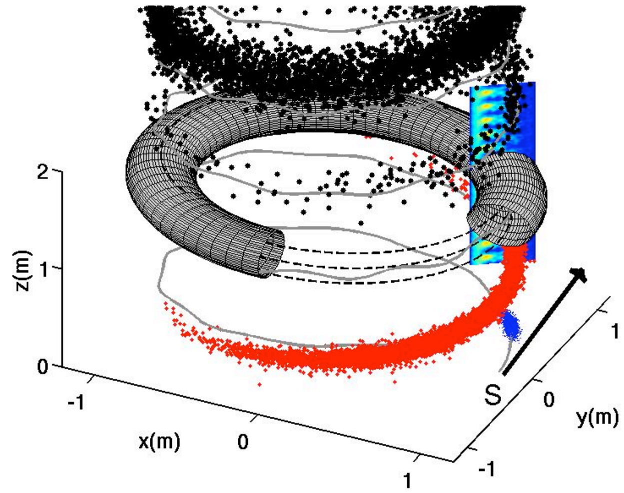


Fig. 3 : Trajectories of Li6+ ions at 300eV) in TORPEX turbulent fields. A single trajectory (gray line) is shown along with a population of ions at an early time (blue points), and two later times (red and black points).

6. Experimental results and comparisons with theory

A first set of experiments has been conducted with energies of the fast ions ranging from 88eV to 290eV. The source is positioned at X=-2.5cm and Y=0cm, with a slight angle downward. Source and detector are separated toroidally by 25°, corresponding to 42cm. The density fluctuations at the injection position are of the order of $\delta n/n \sim 50\%$. Profiles of the fast ion current density with and without plasma were reconstructed for energies of 88eV, 142eV, 190eV and 290eV (fig 4). The vertical shift of the center of the fast ion distribution is due to a combination of the ion Larmor motion and the drifts induced by curvature and gradient of the magnetic field.

The profiles are all broadened by the plasma, meaning that the interaction of the fast ions with the plasma is significant. This plasma effect is largest for ions of 88eV. The radial and vertical full width at half maximum (FWHM) for different energies is represented on figures 6 and 7.

Comparison with the simulation is possible using a synthetic diagnostic allowing the poloidal cross section of the fast ion current density to be represented (fig. 5). Comparison of the profiles and FWHM for each case shows relatively good agreement. However, as shown on figure 10 for 300eV, the spread of the beam is extremely sensitive to the distance traveled by the fast ions. Indeed, the effect of the gyromotion of the fast particles is reflected by an oscillation of the beam width visible on fig. 9. As the energy increases the Larmor radius increases and this effect becomes predominant. Both the experiment and the simulations show that the plasma, i.e. turbulence, effect is the largest for low ion energies. The trend is then similar until the 143eV case. At 300eV the oscillations associated with the gyromotion are more important and it becomes more difficult to find a close agreement with 2D measurement.

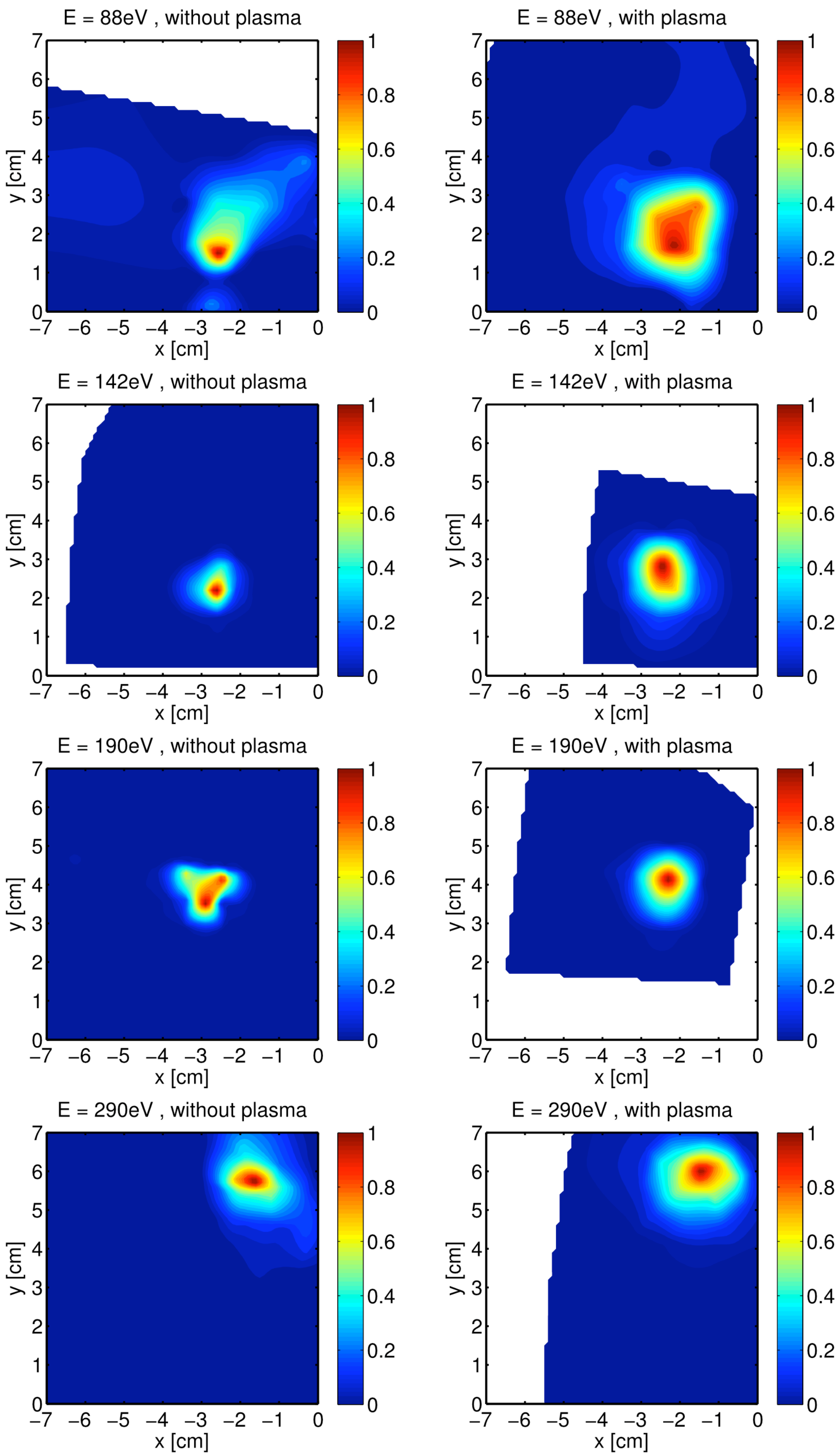


Fig. 4 : Experimental fast ion current density profiles for different energies, with and without plasma.

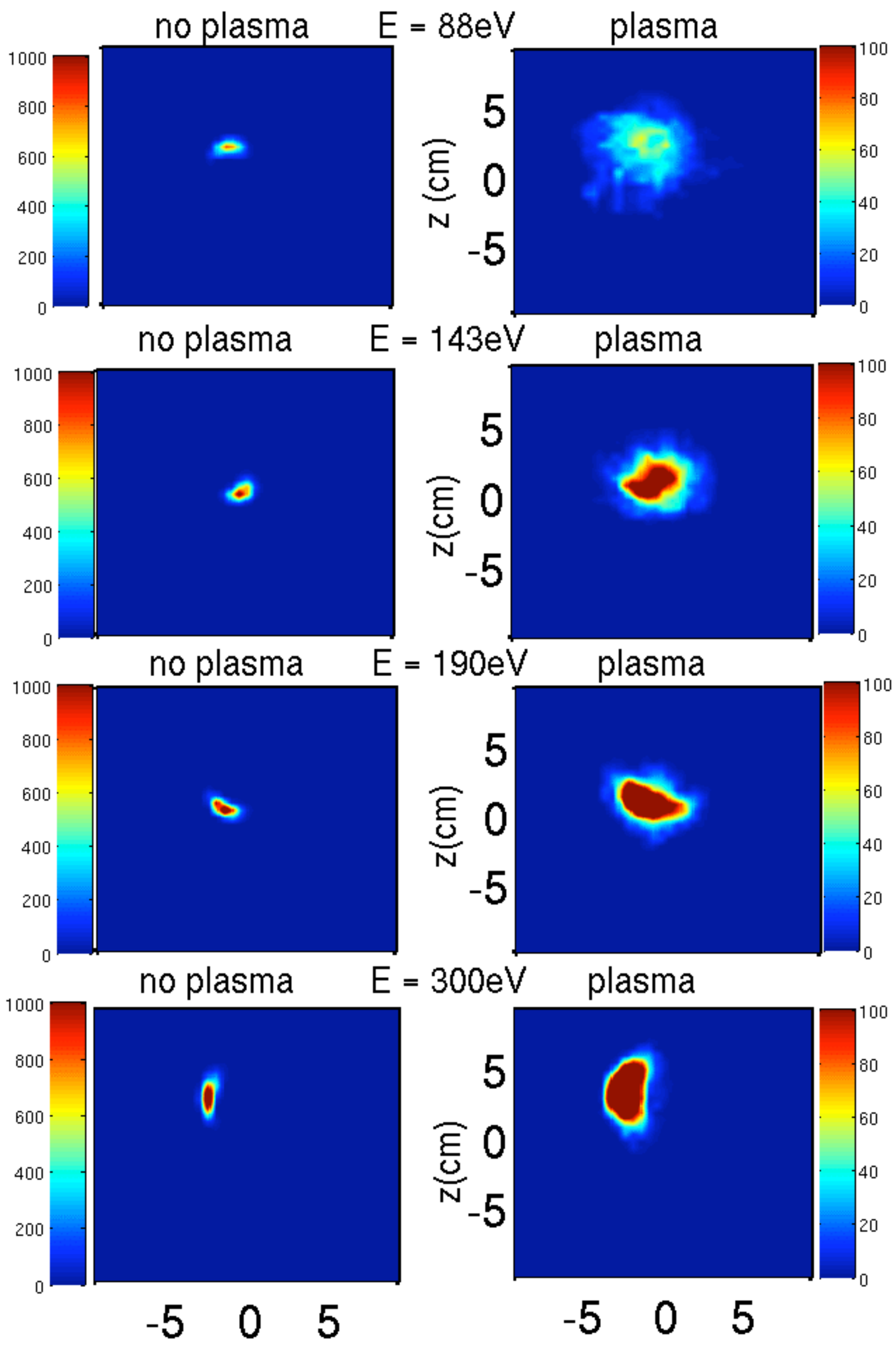
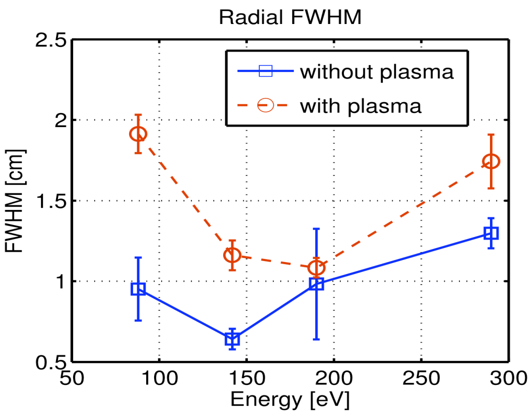


Fig. 5 : Fast ion current profile from the simulations



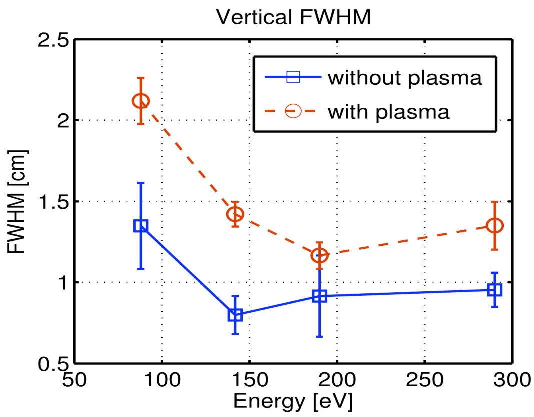
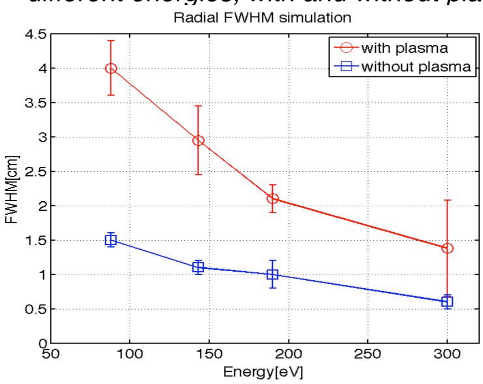


Fig. 6 : Experimental radial FWHM for different energies, with and without plasma.

Fig. 7 : Experimental vertical FWHM for different energies, with and without plasma.



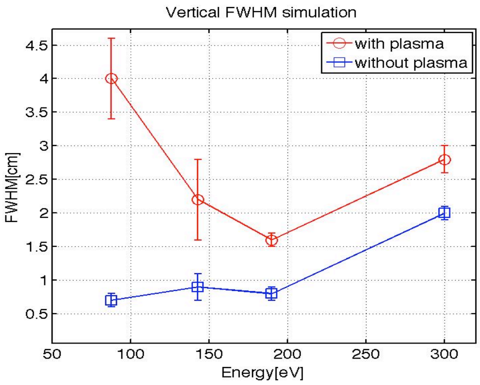


Fig. 8 : Radial FWHM from simulated profiles for different energies, with and without

Fig. 9 : Vertical FWHM from simulated profiles for different energies, with and without

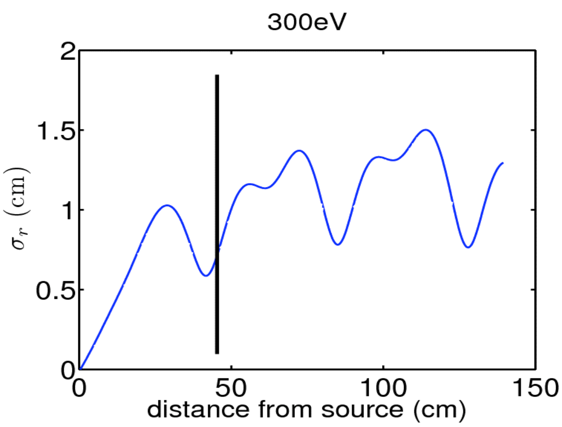


Fig. 10 : Standard deviation of the fast ions position in function of time.

7. Conclusions and outlook

First experimental results on the spatial distribution of supra-thermal ions in simple magnetized plasmas show a significant effect of ideal interchange waves and turbulence. This effect is in qualitative agreement with simulations, showing the importance of the size of the gyroradius. In order to resolve the oscillations of the beam due to gyromotion of the fast ions, and discriminate between different kinds of fast ion transport, a toroidally moving system for the source has recently been developed (fig. 11). This system will allow continuous variation of the distance between the source and the detector between each discharge to reconstruct the 3D profiles of the fast ions beam. Transport of fast ions in the presence of well diagnosed waves and turbulence will be investigated in different magnetic configurations, from the SMP described here to one with rotational transform induced by an internal wire, varying for example the fast ion energy to temperature ratio, the fast ion pitch angle, and the turbulence characteristics.

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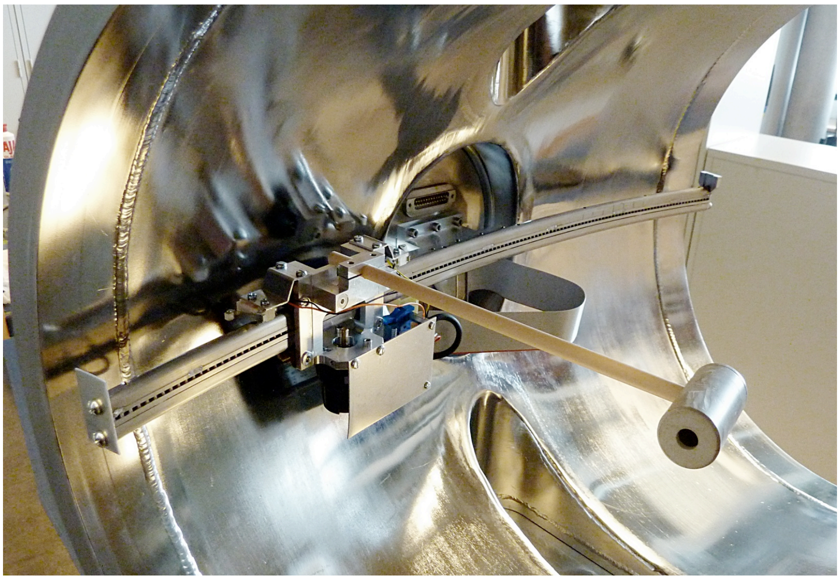

Fig. 11: Picture of the recently developed toroidally moving system allowing for a continuous variation of the source/detector distance, installed in one of the TORPEX mobile sectors.

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