Evaluation of fast particle transport for quasi-symmetrical magnetic fields

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1. Introduction

The success of magnetically controlled thermonuclear fusion relies on the confinement of charged particles, which, unfortunately, is not fully determined by the designed magnetic field but by a combination of external and self-generated electric and magnetic fields. However, there is a population of particles, not only essential for attaining fusion conditions but whose confinement is largely determined by the external magnetic field, namely fast particles and more specifically α-particles.

In this work we examine the dependence of fast particle confinement on different types and levels of symmetries in the magnetic field. This study will be performed by analyzing the trajectories of a large number of fast particles for three types of magnetic field symmetries and with different levels of symmetry within each family. The trajectories will allow us to obtain average properties of the configurations, including the evolution of the loss fraction of particles or mapping the confinement time of particles to their birth position. The statistical nature of the fast particles transport is estimated with the Hurst exponent, obtained through the rescaled-range [R/S] analysis [1], which is a statistical measure that quantifies the type of correlations present in a temporal series at different timescales and will allow us to determine whether the particle transport is being diffusive, super-diffusive or sub-diffusive.

2. Tracing Particle Trajectories

Since collisionless particle confinement for purely symmetric configurations is *perfect*, to study the dependence of fast particle transport we have considered two different levels of approximated magnetic field symmetries named with the prefix *almost* (A) and *quasi* (Q) for the three *natural* types of symmetries in toroidal geometries, namely toroidal (T), poloidal (P) and helical (H) symmetries (S). These magnetic configurations were constructed in Boozer magnetic flux coordinates by changing the harmonic composition of the magnetic field strength. Whereas the almost-symmetric configurations mainly contain the basic harmonics for the underlying symmetry their quasi-symmetric counterparts contain a much broader spectra and are much more similar to what can be achieved with a real coil set.

The confinement of fast particles was studied by numerically integrating the equations of motion using the parallel Monte Carlo MOCA code [2]. The results presented in this work were

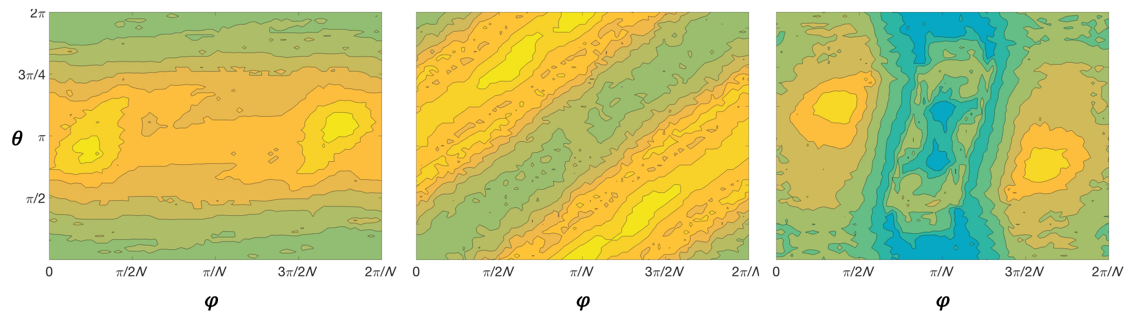

Figure 1: *Pitch averaged confinement time for QTS (left), QHS (centre) and QPS (right) configurations.*

obtained using α-particles and consequently the magnetic configurations were scaled to reactor sizes, all having the same nominal magnetic field and volume. For every configuration, a set of $64 \times 64 \times 64$ particles were uniformly distributed in poloidal, toroidal and pitch angles at a given flux surface and their trajectories were followed until they crossed the last closed flux surface (LCFS). Figure 1 shows the pitch averaged confinement time as a function of the initial position on the flux surface for the QTS, QHS and QPS configurations. The underlying type of symmetries can be clearly distinguished.

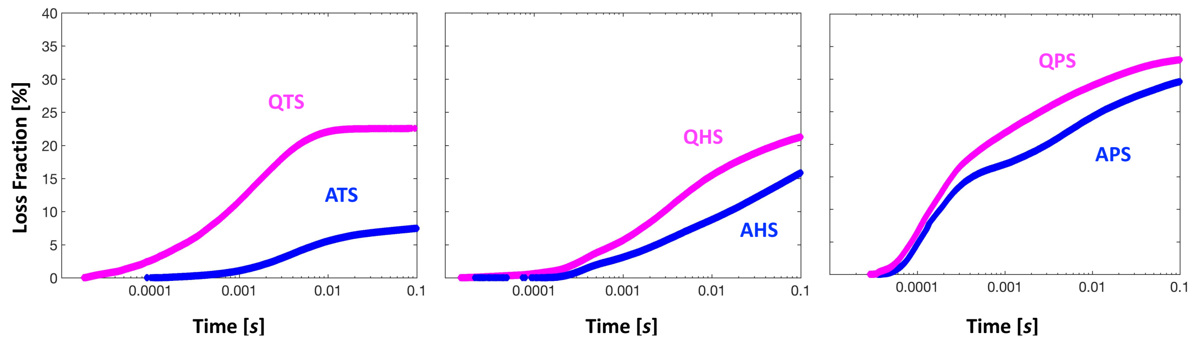

Figure 2: *Loss fraction over time for Toroidal (left), Helical (centre) and Poloidal (right) configurations.*

Analyzing particle trajectories, it is also possible to calculate the evolution of the loss fraction for the different configurations, see Figure 2. As a first conclusion, one can see that almost-symmetric configurations show a smaller loss fraction than their quasi-symmetric counterparts. As expected, increasing the level of symmetry decreases the loss fraction. Independently of the type or level of symmetry, one can identify three regimes. First, there is a very short one, in which there are no losses. This can be explained by the fact that those particles whose fate is to be lost require some time to reach the LCFS. This is followed by a rise in the loss fraction associated to quickly lost particles which is usually referred as to *prompt losses*. In the final part, there is a *saturation* related with a reduced amount of losses. These phases are connected to the structure of the magnetic field and a different particle population. The long term saturation implies that there are particles which are never being lost; these are the *passing* particles whose averaged radial drifts are zero. The *prompt losses* are due to deeply trapped particles and have significant radial drifts. Losses in the intermediate regime are due to a shallowly trapped particles that frequently bounce but whose average radial drifts are small but non negligible and are usually called *transition particles*. This last population is the most relevant to establish the detailed relation between the type and level of the symmetry of the magnetic field and the radial transport of collisionless particles since even small magnetic field changes can give rise to large modifications of their average drifts.

3. Transport Dynamics

To characterize the dynamics of these transition particles we have used a tool coming from the fractional transport theory and estimated the transport dynamics through the Hurst exponent, evaluated from the rescaled-range $[R/S]$ analysis of all tracked particles radial speed. The $[R/S]$ analysis provides the $[R/S]$ function, which scales with the time increment by a power law value that equals the Hurst exponent H: $[R/S] \sim \tau^H$, for the self-similar signals. The rescaled range function was estimated for every particle and then averaged over all particles.

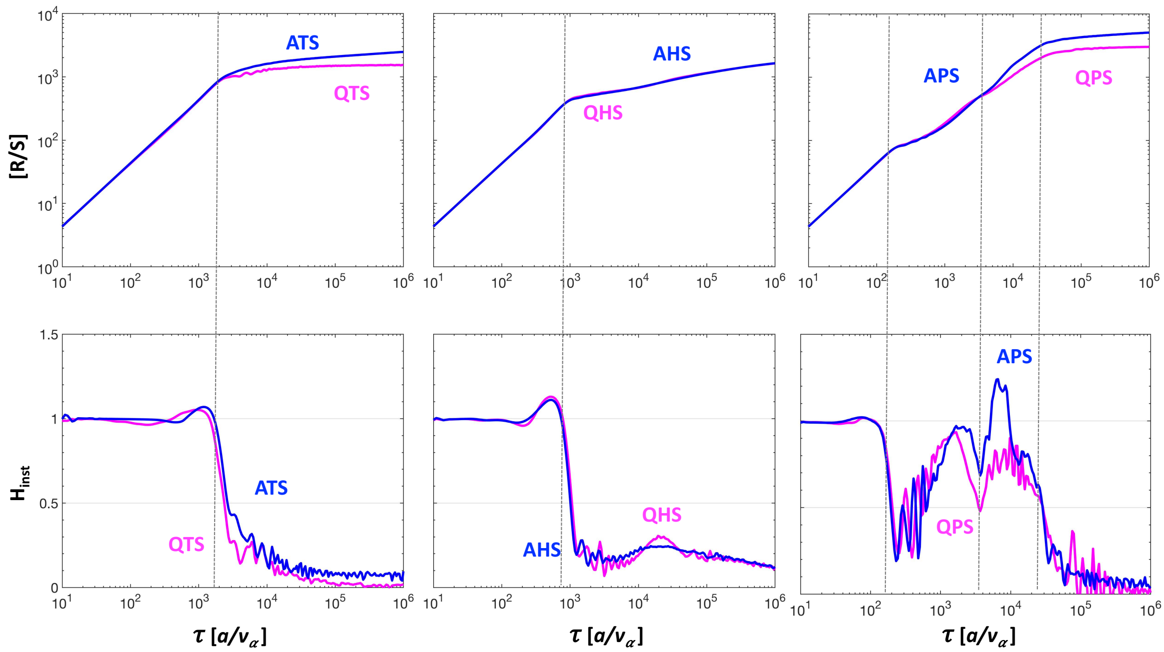

Figure 3: *Rescaled range $[R/S]$ (top) and instantaneous Hurst exponent, H (bottom) for the Toroidal (left), Helical (centre) and Poloidal (right) configurations as a function of the time lag, τ, where a is the configuration minor radius and v_α the speed of α-particles ($\sim 10^7$ m/s).*

The results of $[R/S]$ analysis are presented in the Figure 3: the $[R/S]$ function top and the Hurst exponent bottom. The basic shape of the $[R/S]$ function is very similar for all symmetries; for the lowest time lags $[R/S] \sim \tau$, thus giving a rough estimate of the period of time over which transport can be considered ballistic. The first drop in H corresponds to the most probable time spend between two reflection points, i.e. the bouncing time, see Figure 4. For the Toroidal and Helical symmetries H reduces to the perfect intermittency $H \sim 0$. In the case of the Poloidal symmetry from the pdf we can see that there is another bouncing frequency, corresponding to the changes in the slope of the $[R/S]$ and the H: pointing to a more complex dynamics and finishes with a decrease to the $H \sim 0$ level.

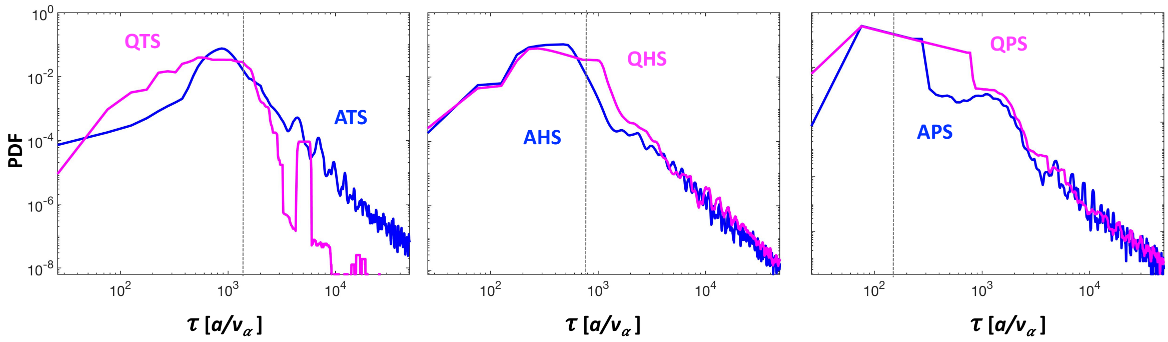

Figure 4: *Distribution function of the bouncing times for the Toroidal (left), Helical (centre) and Poloidal (right) configurations as a function of the time lag.*

We are working in improving our numerical tools and developing other statistical techniques to analyze particle trajectories with the aim of finding independent methods to identify dominant physical processes of transition particles and their relationship with the type and level of the magnetic field symmetries.

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