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Anomalous impurity diffusion in an experimentally measured turbulent potential

R. Pánek[1], L.Krlín[1], J. Stöckel[1], D. Tskhakaya jr.[2]*, S. Kuhn[2], P. Pavlo[1], M. Tendler[3]

[1]*Association EURATOM-IPP.CR, Institute of Plasma Physics, Academy of Sciences of the Czech Republic, CZ-182 21 Prague 8, Czech Republic*

[2]*Association EURATOM-ÖAW, Department of Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria*

[3]*Association EURATOM-VR, Alfvén Laboratory, Fusion Plasma Physics, Royal Institute of Technology, S-1044 Stockholm, Sweden*

**Permanent address: Institute of Physics, Georgian Academy of Sciences, 380077 Tbilisi, Georgia*

1. Introduction

It is generally accepted that tokamak edge-plasma turbulence causes anomalous diffusion. Potential structures formed as a result of plasma turbulence are observed in the poloidal plane of tokamaks, with typical poloidal correlation lengths $\lambda = 10 - 20\ mm$, lifetimes $\tau \approx 10 - 20\ \mu s$, and amplitudes U < 100 V. Theoretical studies addressing the anomalous diffusion in these fields are usually based on the test-particle drift approximation and on the electrostatic field resulting from the Hasegawa-Mima model (see, e.g., [1]) or the Hasegawa-Wakatani model [2].

In our foregoing papers [3,4] we have shown in these models that considerable differences between the drift and Hamiltonian (inclusion of finite Larmor radius) approaches can appear for impurity ions. Consequently, significantly different diffusion coefficients can be obtained.

In this paper we seek to find out whether the effects obtained in those models [3,4] will also appear in more realistic potential structures measured experimentally.

2. Model description

Weare going to study the dynamics of C^+ impurity ions in a turbulent potential obtained experimentally from measurements performed with a two-dimensional array of 8x8 Langmuir probes [5] in the CASTOR tokamak. This unique probe array enables to measure the turbulent potential structure in a poloidal cross-section in the area element of 4.2 cm (poloidally) by 3.15 cm (radially) with time resolution 1 μs. The CASTOR tokamak has a major radius $R = 0.4m$ and a minor radius $r = 0.1m$. The confinement region is restricted by a poloidal limiter with radius $a = 0.085\,m$. The toroidal magnetic field is typically $B = 1\,T$ and the plasma current is in the range of $I_p = (10 \div 15)\ kA$. This yields for the safety factor at the separatrix $q(r = a) = 8 \div 10$. The line averaged density is $\bar{n} = 10^{19}\ m^{-3}$, and the central electron and ion temperatures are $T_{e0} = (150 - 200)\, eV$, and $T_{i0} = (50 - 80)\, eV$, respectively.

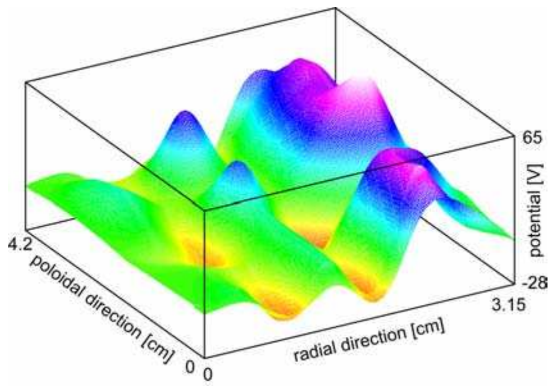

Fig. 1: Snapshot of the turbulent potential relief measured by the 2D array of Langmuir probes.

We use the 2-dimensional Particle-in-Cell (PIC) code BIT2 [6] developed at Innsbruck University on the basis of the XPDP2 code from U.C. Berkeley [7]. Approximately 10^5 particles (C^+ ions) are followed in the test-particle approach, using both the Hamiltonian and drift approaches. The particles are initially distributed uniformly over the whole sample measuring 4.2 cm (poloidally) by 3.15 cm (radially). We assume periodic boundary conditions in the poloidal and radial directions for calculating the variance and the diffusion coefficient. The regions close to the boundary are smoothed in order to suppress artificial effects and to enable periodicity. To simplify analysis of the results, the initial particle velocity is chosen as v_0 = *0* ms^{-1}. The dynamics of the test particles is determined by the time-dependent turbulent potential

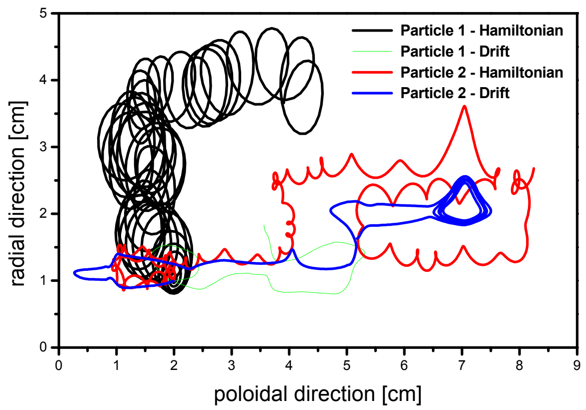

Fig. 2: C^+ impurity trajectories in the experimentally obtained turbulent potential using the Hamiltonian and drift approaches, taken over 30 μs.

obtained from the experiment. The potential values inside the probe array are determined using standard interpolation (Fig. 1).

3. Simulation results

Significant differences between the drift approximation and the Hamilton approach for C^+ ions in the experimentally obtained potential become visible in Fig. 2, where the trajectories of particles with the same initial conditions are plotted for the two approaches. Within several microseconds, the trajectories diverge considerably.

In contrast to the case of the spatially periodic and time-independent potential [4], where the diffusion does not depend on the direction, the present case of the experimentally obtained potential requires the radial (x-coordinate) and poloidal (y-coordinate) diffusion to be calculated separately. We calculate the variance X^2 and the running diffusion coefficient $D_{x,y}(t)$ defined (e.g., for the x direction) as

$$X_x^{\ 2}(t) = \langle (x_j(t) - x_j(t=0))^2 \rangle = \frac{1}{N}\sum_{j=1}^{N}\left(x_j(t) - x_j(t=0)\right)^2, \qquad D_x(t) = \frac{X^2}{2t}.$$

The diffusion coefficients derived from these formulae are shown in Fig. 3. In the radial direction, the running diffusion coefficients exhibit an initial increase corresponding to the ballistic motion, and then drop to constant values $D_{xdrift} = 0.25\ m^2s^{-1}$ and $D_{xHam} = 1.0\ m^2s^{-1}$. This means that the Hamiltonian approach provides a diffusion coefficient four times higher than for the drift one. In the poloidal direction, on the other hand, the running

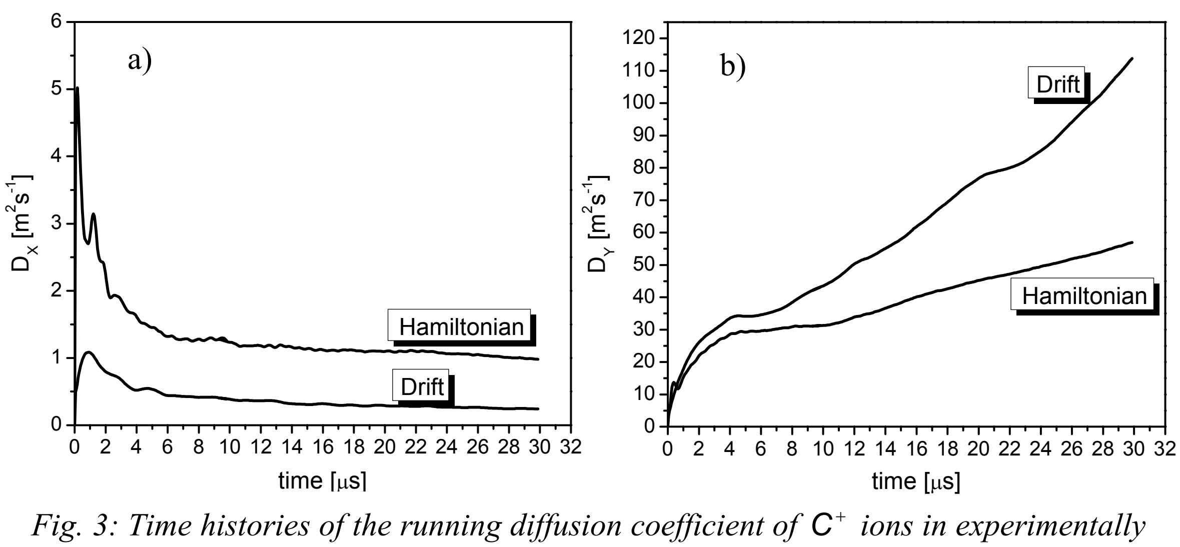

Fig. 3: Time histories of the running diffusion coefficient of C^+ ions in experimentally obtained potential form the 2D array of Langmuir probes in the radial (a) and poloidal (b) directions.

diffusion coefficient is higher in the drift approximation, reaching the value D_{ydrift} = 110 m^2s^{-1} after 30 μs, while the Hamiltonian approach yields only D_{yHam} = 50 m^2s^{-1}. This difference is caused by the fact that the turbulent structures are more elongated in the poloidal direction: since, in the drift approximation, the ions have to follow exactly the equipotentials, they move mainly in the poloidal direction. Moreover, the turbulent structures also move in the poloidal direction and the ions, which in the drift approximation are trapped in the valleys and hills, have to move along with them. In the Hamiltonian approach, on the other hand, particles can jump between equipotentials and get trapped again. Consequently, this effect enhances radial diffusion at the expense of poloidal diffusion.

4. Conclusion

We have discussed a new type of anomalous ion diffusion in a turbulent potential obtained experimentally. We have also demonstrated that the considerable differences between the drift and Hamiltonian approaches persist in such realistic turbulent structures. Consequently, the C^+ anomalous diffusion can also lead to a deficit of positive space charge. On the other hand, the non-vanishing anomalous diffusion of the electrons (for which the drift approximation is sufficient due to the very small Larmor radius), partially compensates for this effect. However, also in this case a radial electric field is generated. A quantitative estimate of the radial-electric-field amplitude requires a self-consistent solution, which will be the subject of our future work.

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