

ON THE INTERPRETATION OF LASER ABLATION DATA IN FUSION PLASMAS

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1. Introduction

Impurity injection by laser ablation of thin films of non recycling metal impurities has become a standard method to probe particle confinement in fusion plasmas. The standard data analysis method was established in Refs. [1]. The results of the analysis can be either global confinement time, from the decay of line emissions of highly ionized species, or the diffusion coefficient and convective velocity from a more elaborated analysis using full impurity transport codes. In most cases, this is merely a convenient phenomenological description of data difficult to understand from first principles, and examples can be found where serious limitations are evident when explicit comparison of data and simulations are fully displayed [2].

In recent years significant effort has been made to elucidate whether magnetic turbulence is the mechanism responsible for anomalous electron energy transport [3]. However, less endeavour has been dedicated to determine if this mechanism plays a role in particle transport. This is due to the incorrect perception that anomalous signifies transport rates that are an order of magnitude higher than neoclassical ones. However, strange relaxation kinetics and unexpected dependencies of transport rates on plasma parameter scans are a hallmark of anomaly too. For this reason, we try to determine if any hallmark of dispersive transport can be found in laser ablation data, since in a chaotic system, such as this would exist in a plasma with islands and stochastic regions, strange kinetics should be expected [4]. This paper is organized as follows; First we discuss, at a qualitative level, why we should expect strange kinetic behaviour in a plasma with islands. Second, we describe the type of analysis we have performed to justify new ways to look at these data. Finally, we present the analysis of selected data of the literature from this point of view.

2. Theoretical background

Although only indirect estimates of the Chirikov parameter exist for tokamaks [5], either mixed magnetic topologies or situations close to stochastic threshold are probable states of the braided magnetic field. Accumulated evidence for magnetic islands producing different signatures in diagnostics can be found, see Ref. [6] and references therein. However, a more difficult task is to establish a causal-effect relationship between such signatures and the resulting anomalous transport.

Simple nonlinearities in the hamiltonian can induce fractal motions with non-standard statistical properties [4]. This behaviour has been termed “strange kinetics”. They fall outside

the domain of brownian motion, and their statistical nature is reflected by values of γ (the time exponent relating distance with time) between unity (brownian motion) and two (ballistic motion). Turbulent diffusion, in an open system where energy is pumped in through mixing, is characterized by $\gamma=3$. When a particle is sufficiently far from the boundary layers in the stochastic sea, or inside a stochastic web it performs random motion until a boundary layer is reached where the particle orbit becomes entangled. In that case, trapping of a particle in the boundary layer signifies that it propagates along the surface of an invariant torus for a long time before escaping from the boundary layer. Thus trappings and flights represent complementary orbital characteristics. Extremely long flights are called stochastic jets, caused by the domains of very small values of the real part of the Lyapunov exponents. The distribution of stochastic jet lengths has a power-like tail contrary to the Gaussian case of the normal diffusion. The particle is trapped between the island border and the nearest cantorus and this explains why one can observe a higher density of dots in the stochastic sea of a Poincaré map. This could also be the cause of radiation enhancement at these locations in plasma radiation profiles [6]. We cannot see cantori directly but they disclose themselves as boundaries of dark strips inside the stochastic sea domain; cantori are invariant Cantor sets that may be viewed as remnants of KAM curves that have been destroyed as a nonlinearity parameter is increased. The density is inhomogeneous and the most visited parts are narrow strips close to island boundaries. Transport near stochastic threshold, see White [4], can be understood in terms of two basic functions: the waiting time distribution about magnetic islands and the size distribution of these islands. Near threshold, the islands have two effects on transport. First, a geometrical effect; the volume occupied by the islands does not contribute to transport. Second, a dynamical effect: an orbit spends a long time wandering around each island before crossing the stochastic sea and striking the next island. A basic consequence of such stickiness has been demonstrated in computer experiments on two-dimensional area-preserving maps. Initializing a large number N_0 of randomly chosen initial conditions in the chaotic region, the survival probability appears to have a long-time algebraic (as opposed to exponential) decay; $F(t) \approx t^{-z}$ with $z \approx 1.5$. This is a brief summary of theoretical findings after detailed numerical simulations performed in recent years and they have been the driving force for looking for strange kinetics in impurity relaxation in fusion plasmas.

3. Impurity relaxation

Two different types of functions have been used for strange relaxation fitting in disordered media: the stretched-exponential and dispersive transport hopping distribution. The latter shows up in a log-log plot of I as a function of t when the sum of the slopes at times $t/t_r < 1$ and at times $t/t_r \gg 1$ would be $-[(1+\alpha)+(1-\alpha)] = -2$. The stretched - exponential decay, often termed Kohlrausch relaxation, is described by the time dependence $\exp[-(t/\tau)^\beta]$, where $0 < \beta < 1$, and is observed in a wide class of disordered systems. Stretched relaxation has been simulated by assuming that the diffusion is a continuous-time random walk, which is defined to be an alternation of steps and pauses with the step distribution given by $p(r)$ and the pausing-time

distribution, by $\psi(t)$. The normal (Gaussian) transport and diffusion result from a $\psi(t)$ with finite first and second moments. However, in disordered systems the diffusion law becomes anomalous $\langle R^2(t) \rangle \approx t^\beta$. The Kohlrausch coefficient β has been in this way related to the statistic of the random walk Shlesinger [4].

We have performed this type of analysis on published raw data from ≈ 40 impurity injection experiments. Here, for illustration purposes we have selected one configuration scan from the TEXT tokamak [8], performed by the ORNL group injecting Scandium, and several systematic studies of the W-7 AS stellarator where Aluminum was injected [9]. In Fig. 1, we show the trend of the TEXT data when fitted by a stretched exponential, where not only the τ increases but also the Kohlrausch parameter β exhibits a systematic behaviour as the operational limit is approached. Close to this limit, 15 kG case, the relaxation exhibit a strange kinetics quite similar to that found in TEXTOR [10] and other tokamaks.

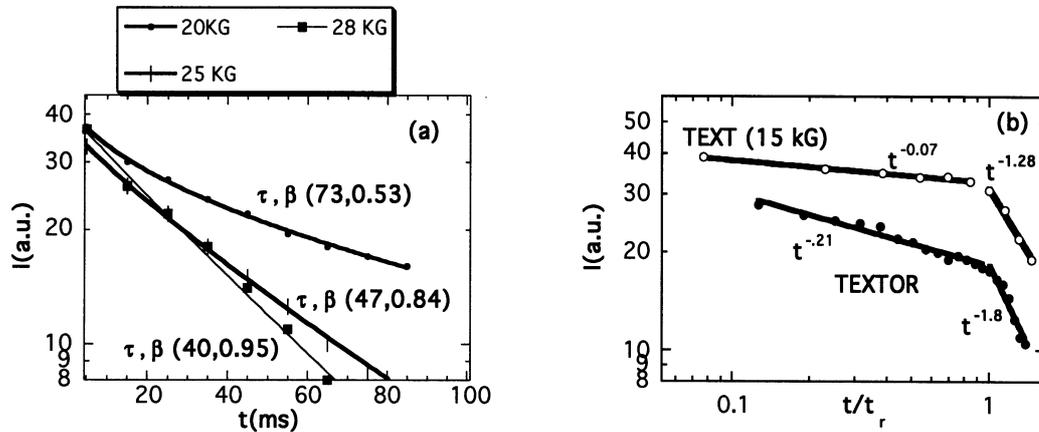


Fig. 1. The impurity relaxation behaviour as the tokamak operational limit is approached: a) Relaxation was fitted by a stretched-exponential, the decay parameter increases and the β decreases as the limit is approached; b) double-log plot of impurity relaxation, very close to the density or MHD limit in two tokamaks.

The former TEXTOR and TEXT data are shown in Fig. 1(b) and in this limit the dispersive transport hopping distribution seems appropriated to account for this strange relaxation. We must highlight that, numerically, both functions are difficult to distinguish in practice as $\beta > 1$. The stretched-exponential is a better fit than the standard one, which signifies that the decay parameter, τ , is varying along the whole relaxation. The alternative fitting, with two power-like fittings, permits the tail decay to be separated from the beginning and contrast how this behaviour compares with former model predictions. We believe that the improvement of confinement, as evidenced in the type of fitting to the dispersive transport signature, could be a manifestation of strange kinetics and particle trapping predicted by the referenced theoretical studies. It is obvious that the role played by magnetic islands increases as the density or the MHD limit is approached.

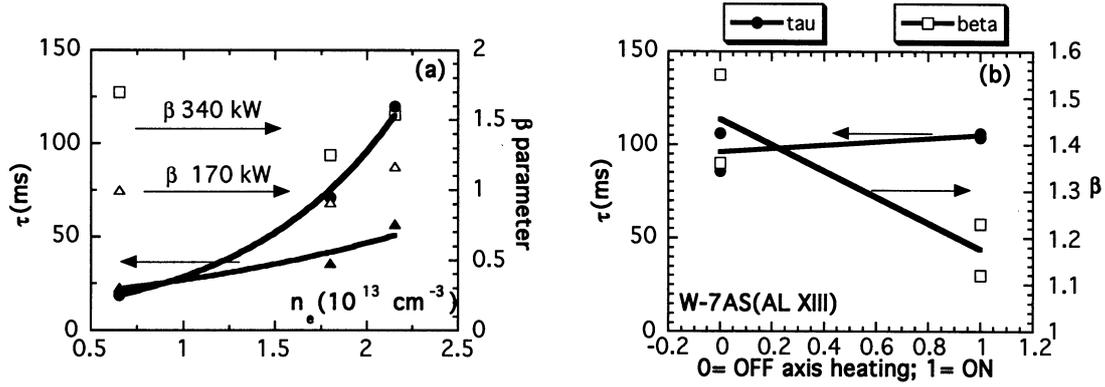


Fig. 2. Analysis of W-7AS data using a stretched-exponential; (a) two density scans for two different values of ECRH injected power; (b) two similar discharges with on/off axis heating.

The analysis of W-7 AS stellarator data is shown in Figs. 2(a) and (b). The first figure highlights the higher β parameter value exhibited in the density scan with the highest injected ECRH power. In fig. 2(b), we show the influence of on and off axis heating on the Al XIII relaxation analysis. Although no significant differences are found for τ , the β parameter is smaller for on axis heating; note: similar behaviour was found for this data set when analysing the Al XII relaxation. In conclusion, the lack of available raw data of systematic scans have limited the scope of this work. However, our analysis is more extensive than pure exponential relaxation, so when performed over a wider range of data it should shed more light on anomalous transport mechanisms and reveal the conditions where dispersive transport signatures, exist with β different than 1 or with long-time algebraic decays.

Acknowledgements

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References

- [1] Seguin F.H. and Petrasso R.: Phys. Rev. Lett. **51**,455 (1983); Fussmann G.: Report IPP III/105 (1985); Leung, W.K. et al.: Plasma Phys. Control. Fusion **28**, 1753 (1986).
- [2] Horton L.D. et al.: Nucl. Fusion **32**,481 (1992).
- [3] Bikerton R.J.: Plasma Phys. Control. Fusion **39**, 339 (1997).
- [4] Shlesinger M.F. et al.: Nature **363**, 31 (1993); Zaslavsky G.M., White R.B. et al.: Transport, Chaos and Plasma Physics. World Scientific (1994).
- [5] Castle G.G. and Wootton A.J.: IEEE Trans. Plasma Sci. **22**,371 (1994).
- [6] Zurro B. et al.: Europhys. Lett. **40**, 269 (1997).
- [8] Isler R. et al.: Phys. Rev. Lett. **55**, 2413 (1985).
- [9] Kuhner G. et al.: in Plasma Physics and Controlled Nuclear Fusion Research (*Proc. 15th Int. Conf.*, 1996) vol. 145.
- [10] Castracane J. et al.: Nucl. Fusion **27**, 1921 (1987).