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Scaling of energy confinement time in RFX with magnetic fluctuations: comparison of experimental data with turbulent transport models.

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Confinement in the Reversed Field Pinch (RFP) configuration is largely determined, at least in the inner plasma region, by magnetic perturbations whose origin is well described by visco-resistive MHD [1]. These fluctuations are recognized to be responsible for the RFP sustainment through dynamo action but, at the same time, they lead to stochastization of the magnetic field, allowing for an enhanced radial transport, thus degrading energy and particle confinement. This is due to the combined effect of a relatively high amplitude of magnetic perturbations (of order one hundredth of the confining magnetic field, to be compared with typical values two orders of magnitude smaller in tokamaks), coupled with a large number of internal resonances, that hence overlap over most of the radius, effectively "shortcircuiting" plasma centre and perifery. Investigating the transport due to magnetic fluctuations, hence, is one of the main experimental and theoretical tasks in RFP research. Fully numerical MHD approaches can provide substantial quantitative informations but simplified methods are preferred as long as they are able to provide an intuitive picture of the problem at hand with quantitative (although possibly less precise) predictions. The standard reference is ref. [2], where explicit formulas for field line, heat and particle diffusivity are given. Provided that the total magnetic field may be written as $\mathbf{B} = \mathbf{B}_0 + \mathbf{b}$, where $\mathbf{B}_0$ is the unperturbed magnetic field, such that good magnetic surfaces do exist, while $\mathbf{b}$ is a small perturbation that breaks these surfaces, the Rechester-Rosembluth (RR) field line diffusivity is

$$D_{fl} = \tilde{b}^2 \Lambda \qquad (1)$$

where $\tilde{b} = b/B$ and Λ is the autocorrelation length of the field lines. Particle (heat) diffusivity is related to (1) through ion (electron) thermal velocity u_{th} :

$$D_{st} \approx D_{fl}\, u_{th} \qquad (2)$$

This formula is to be corrected for highly collisional regimes:

$$D_{st,coll} = D_{fl} u_{th} \frac{\lambda_{coll}}{\lambda_k} \quad , \quad \frac{\lambda_{coll}}{\lambda_k} < 1 \qquad (3)$$

where $\varsigma = \lambda_{coll}/\lambda_k$ = (mean free path between collisions)/(Kolmogorov length).

The issue is whether experimental transport data from RFPs can be compared with and interpreted in terms of RR's formula. In actual RFPs no direct local measurements of transport coefficients are routinely available, hence one must resort to comparisons with global quantities. In literature [3,4] comparisons have been made against theoretical and experimental scaling of energy confinement time τ_E, on the basis of the qualitative scaling

$$\tau_E \approx \frac{a^2}{D} \qquad (4)$$

with *a* typical length of the device (minor radius). Since the relevant parameter in RR diffusivity is the normalized magnetic perturbation amplitude $\tilde{b}$, Eq. (4) translates operatively into a scaling of τ_E versus the amplitude of the magnetic fluctuations (together, possibly, with other relevant plasma parameters). Admittedly, such comparison, in a RFP, is dubious since it is known that a relevant fraction of confinement (hence, of τ_E), in these machines is due to edge mechanisms, not of purely magnetic origin, rather electrostatic one. Therefore, the scaling (4) will be followed by empirical data only approximately, at best. Earlier studies gave, to this regard, conflicting results: Hattori *et al* [3] claimed verification of RR scaling from measurements taken on TPE-1RM15 machine, while Terranova *et al* [4] denied it on the basis of RFX data. Fairly recently, thoretical work is appearing where the validity of diffusive paradigm itself, in realistic RFP magnetic fields, is being questioned [5,6].

In this work we will make a re-examination of the same data used in the study [4], and show that, indeed, they may still be consistent with a modified RR scaling, according to some corrections provided in earlier papers by D'Angelo and Paccagnella [7].

Taking into account the temperature dependence into u_{th}, Eq. (4) may be written as a scaling relation involving the measurable quantities $\tilde{b}$ and temperature *T*. The exact form of the scaling depends upon the regime one supposes to work in. We can divide the possible regimes into:

I) Standard RR regime, characterized by a small (ideally vanishing) Kolmogorov length (equivalently, diverging Lyapunov exponent for field line divergence) all across the plasma volume. This regime is, obviously collisionless.

II) Collisional RR regime, in which the ratio $\varsigma = \lambda_{coll}/\lambda_k < 1$ but both λ_{coll} and λ_k are very small with respect to all the other lengths involved. This regime, however, won't be further considered; actually, it shares some features (the field line diffusivity) with regime (I), while, for some others (the explicit expression for ς) must rely upon calculations done for next point. Hence, it is a hybrid between regimes (I) and (III).

III) Collisional regime in presence of finite Kolmogorov length. This regime was studied numerically in two papers by D'Angelo and Paccagnella [7] for a realistic model of RFP magnetic field. Basically, since Kolmogorov length may theoretically be related to the amplitude of fluctuations through a power law, $\lambda_k \propto \tilde{b}^{-a}\ (a > 0)$, regimes (I) and (II) are defined by a huge level of magnetic fluctuations ($\tilde{b} \approx O(1)$); this regime is instead defined by $\tilde{b} << 1$. A related consequence is that the level of magnetic fluctuations is likely to be not completely homogeneous across the plasma. Due to the finiteness of λ_k , it is quite natural invoking a finite value also for the ratio ς, for this reason we label this regime as "collisional".

Without entering into details, for which we refer to the original literature, the three main findings from [7] are: A) the field line diffusivity is more weakly dependent from $\tilde{b}$ than suggested by (1): $D_{fl}^{DP} \propto \tilde{b}^{1.5}$. The basic reason being the decrease of Λ with $\tilde{b}$. B) The Kolmogorov length scales with magnetic fluctuations as $\lambda_k \propto (\tilde{b})^{-0.4}$. C) the ratio ς, for a realistic RFP, is of order unity. In order to deal in an unified fashion with the whole range of ς values, it will be convenient to use a unique parametrization. The simplest interpolating formula for diffusivity is

$$D = D_{no-coll}\,\gamma \quad , \quad \gamma = \frac{1}{1 + 1/\varsigma} \qquad (5)$$

The function $\gamma(\varsigma)$ interpolates between 1 (collisionless limit, $\varsigma \to \infty$) and ς (collisional limit, $\varsigma < 1$). Eqns. (4,5) coupled with the above scaling provide formally a bivariate scaling for τ_E: $\tau_E = \tau_E(\tilde{b}, T)$. However, empirically, the temperature is found to be a decreasing function of magnetic disorder (see Fig. 1):

$$T \propto \tilde{b}^{-0.7} \tag{6}$$

Such a negative correlation could be expected: if magnetic fluctuations degradate the quality of energy confinement, the temperature-that is a measure of the energy content of the plasma-can hardly remain unaffected.

Using scaling (6) with Eqns. (4,5), we may at last write $\tau_E(\tilde{b})$ for the two regimes:

$$\tau_E \approx \begin{cases} \left[D_{fl} \times u_{th}\right]^{-1} \propto \left[\tilde{b}^2 \times T^{1/2}\right]^{-1} \approx \tilde{b}^{-2} \times \tilde{b}^{0.7/2} \approx \tilde{b}^{-1.65} & (7-I) \\ \left[D_{fl}^{DP} \times u_{th} \times \dfrac{1}{1+\dfrac{\lambda_k}{\lambda_{coll}}}\right]^{-1} \approx \dfrac{1 + c \cdot \tilde{b}^{-0.4} \cdot \tilde{b}^{1.4}}{\tilde{b}^{1.5} \times \tilde{b}^{-0.35}} \approx \dfrac{1 + c \cdot (\tilde{b})^{1.0}}{\tilde{b}^{1.1}} & (7-III) \end{cases}$$

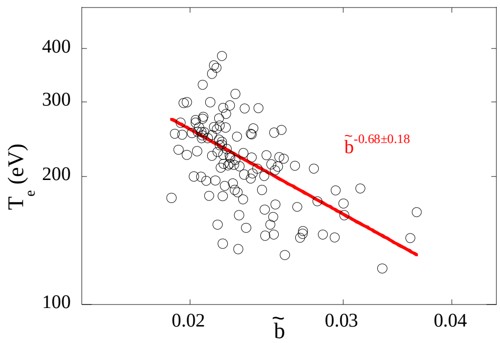

Fig. 1. *T versus* $\tilde{b}$. Red line, best fit using scaling $\tilde{b}^{-\alpha}$.

The labels (I) and (III) refer to collisionless RR model, and DP model, respectively.

The latter curve, (7-III) has two asymptotic trends: $\tau_E \propto \tilde{b}^{-1.1}$, $\tilde{b} \to 0$, or $\tau_E \propto \tilde{b}^{-0.1}$, $\tilde{b} \to \infty$ (this latter limit is only virtual; by definition, $\tilde{b} < 1$).

The experimental data were taken as follows: magnetic fluctuations were measured by two toroidal arrays of 72 toroidal and poloidal field pick-up coils. Since these are edge measurements, we must make the ansatz that the overall profile of magnetic fluctuations is proportional to its edge value, which is a reasonable assumption, supported also by theoretical models. The electron temperature is measured by a 20-points, single-pulse Thomson scattering diagnostic, and by a double-filter x-ray diagnostic, hence T is representative of core temperature. Finally, the energy confinement time is estimated as $\tau_E^{\exp} = nT / P_\Omega$, where n is plasma density, and P_Ω the Ohmic input power, which is a known quantity, too.

The scalings (7) are hence compared against experimental data in Fig. (2): it is evident how, for each fit, the correlation with data is rather poor. This may be a consequence of the fact that the true confinement is determined only partially by core transport. Notice, however, that not taking explicitly into account edge losses does not automatically invalidates our analysis. Edge losses, actually, are likely to depend indirectly on magnetic perturbations (since these latter deform the plasma column and make it to strike the wall) and it is just natural that their scaling be qualitatively similar to the central one (i.e., higher perturbations mean faster losses). It is easy to show that, unless the two scaling are quantitatively very different (say, two widely differing power-laws), over limited $\tilde{b}$ intervals adding edge losses is tantamount to multiply the core energy confinement by an almost constant factor. A qualitative estimate shows that this is the likely case. Also, theoretical studies showing that the mere existence of locked modes does not affect core diffusivity scaling have already been performed [6,8]. Another salient feature of Figs. (1,2) is the short range spanned by the independent variable $\tilde{b}$. This, still, is a consequence of the fact that the basin of attraction for an RFP stationary state is relatively small.

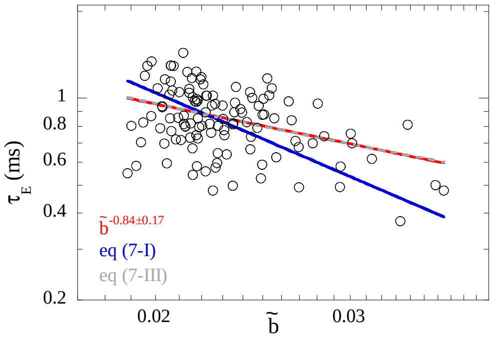

Fig. 2. τ_E *versus* $\tilde{b}$. Red line, best fit using a single power-law scaling $\tilde{b}^{-\alpha}$; grey curve, fit using τ_E from Eq. (7 - III). The two curves overlap almost exactly, and have a correlation coefficient, $R \approx 0.4$. The exponent 0.84 represents a sort of average between the high-$\tilde{b}$ and small-$\tilde{b}$ trend of (7-III). Blue line, RR estimate from Eq. (7 - I). It has the smallest correlation coefficient, $R \approx 0.1$.

Within the scarce accuracy imposed by experimental data, the naïve collisionless RR scaling has a fairly small correlation with data, thus confirming findings [4] that rejected it. On the other hand, that the more refined version (III) of magnetic field line diffusion, taking into account a variety of supplementary effects (finiteness of Kolmogorov length and its scaling with magnetic fluctuations, intermediate regime between the collisionless and the highly collisional one, scaling of temperature with magnetic fluctuations) provided a more satisfactory picture.

We remark again that ours was simply intended to be a re-examination of a set of old RFX data taken in standard confinement conditions. There is no justification in attempting to extrapolating the present results (subject, furthermore, to large uncertainties) to different improved confinement regimes (e.g., Quasi-Single-Helicity, where good magnetic surfaces are partially recovered), or to perturbation amplitudes very different from those included in the data set: in particular, at very small perturbations, good magnetic surfaces must exist again, and RR scaling must break down. Of course, nothing can still be told-due to lack of sufficient data-for the renewed RFX-mod, however, the possibility now of making the modes rotate suggests a beneficial effects on wall losses.

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