Study of the magnetic fluctuations scaling in the RFX Reversed Field Pinch

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I. INTRODUCTION

Confinement in Reversed Field Pinch configuration is largely determined, at least in the inner plasma region, by the amplitude of magnetic fluctuations. These fluctuations lead to a stochasticization of the magnetic field, allowing an easy radial transport and degrading the classical energy and particle confinement. At the same time, they are also necessary to sustain the RFP configuration by the dynamo action, for this reason it is a crucial issue for the RFP research to know the dependence of the magnetic fluctuations amplitude on the plasma parameters. In this way we could estimate if the dynamo requirements are compatible with a reactor relevant confinement time.

For the RFP configuration the relevant MHD parameter is the dimensionless Lundquist number, $S=\tau_R/\tau_A$, the ratio of the resistive diffusion time $\tau_R=\mu_0 a^2/\eta$, and the Alfvén time $\tau_A=a/V_A$, where a is the minor plasma radius, η is the resistivity and V_A is the Alfvén velocity. Many theoretical and numerical models with different approximations [1-4] have been developed to study the dependence of the magnetic fluctuations amplitude on S, giving in some cases different scalings. The S dependence has also been analyzed experimentally in many RFPs obtaining different results [5-7], which however were affected by the lack of a direct measurement of some necessary physical quantities. So far it still remains an open question which model and theoretical scaling law describes better the experimental results and, consequently, can give some insights into the future results to be expected by presently operating Reversed Field Pinch devices.

In this work we study the experimental dependence of magnetic fluctuations amplitude on Lundquist number in the RFX [8] device. Due to the high plasma currents (up to 1.1 MA in the set considered here) obtainable in RFX, a broad range of S is available for the scaling, while a complete set of diagnostics allows to directly measure all the quantities necessary to estimate S.

II. EXPERIMENTAL SETUP AND COMPUTATIONAL METHODS

To measure magnetic fluctuations, RFX is equipped with two toroidal arrays of 72 toroidal and poloidal field pick-up coils installed between the vacuum vessel and the shell at poloidal angles of $\theta_{ext}=20.5°$ and $\theta_{int}=200.5°$. To reduce the amount of stored data for each shot, only 72+72 pick-up coils are acquired. In this way both even and odd components of the magnetic field harmonics can be computed up to n=36 for one single field component or up to n=18 for both field components. The pick-up coils signals are electronically integrated and sampled at a frequency of 10 kHz. This sampling frequency is high enough since the presence of the vacuum vessel between the plasma and the coils dumps the frequencies over ≈ 5 kHz. Moreover all the RFX discharges are affected by wall locked modes, the stationary field component providing in this way nearly all of the magnetic field spatial perturbation.

To compute the magnetic field fluctuations we used the two toroidal field arrays, estimating the even and odd components with the zero order toroidal field correction as:

$$B_\phi^{even} = \frac{1}{2}\left[B_\phi^{ext}\sqrt{\frac{R + b\cos\theta_{ext}}{R - b\cos\theta_{ext}}} + B_\phi^{int}\sqrt{\frac{R + b\cos\theta_{int}}{R - b\cos\theta_{int}}}\right],$$

$$B_\phi^{odd} = \frac{1}{2}\left[B_\phi^{ext}\sqrt{\frac{R + b\cos\theta_{ext}}{R - b\cos\theta_{ext}}} - B_\phi^{int}\sqrt{\frac{R + b\cos\theta_{int}}{R - b\cos\theta_{int}}}\right],$$

and then by Fourier transforming the even and odd B_ϕ modes to obtain the toroidal harmonics $b_{\phi_n}^{even}$, $b_{\phi_n}^{odd}$.

To compute the poloidal field modes we used the relations $b_{\theta_n}^{even}=0$, $b_{\phi_n}^{odd}/b_{\theta_n}^{odd}$ = na/R that can be deduced from the curl-free condition, **k**×**B**=0 when the fluctuations are dominated by m=0,1. The validity of the previous relations was confirmed experimentally in a different set of shots, where the toroidal and poloidal fields components were acquired at the same time. Having done this we acquired only the toroidal field component in order to resolve the highest possible number of harmonics.

Finally the total RMS fluctuation amplitude (poloidal and toroidal) has been computed by summing over all the harmonics:

$$b^{even} = \sqrt{\frac{1}{2}\sum\left(b_{\phi_n}^{even}\right)^2},\ b^{odd} = \sqrt{\frac{1}{2}\sum\left[\left(b_{\theta_n}^{odd}\right)^2 + \left(b_{\phi_n}^{odd}\right)^2\right]},\ b = \sqrt{\left(b^{even}\right)^2 + \left(b^{odd}\right)^2}\ .$$

The electron density is measured by a multichords MIR interferometer, and the electron temperature is measured by three different systems: a soft X-ray pulse height analyzer, a double filter X-ray and a multipoint single time thomson scattering diagnostics.

A key quantity of the S parameter never measured before in a RFP is the Z_{eff}. In RFX Z_{eff} is obtained by absolutely calibrated bremsstrahlung measurements performed in three different spectral regions (two in the visible and one in the infrared region). To avoid possible measurements error due to spectral contamination by line radiation, the measured Z_{eff} is accepted only when there is agreement between the three systems.

In principle the Lundquist number can be computed from its definition:

$$S = \frac{\tau_R}{\tau_A} = \frac{\mu_0 a^2}{\eta}\frac{B}{a\sqrt{\mu_0 m_i n_e}}\ .$$

Since several quantities in the previous relation depend on the radial position, some characteristic values for each of them has to be chosen. Concerning the magnetics, we used the poloidal field at the wall $B_\theta(a)$ which is directly measured. For the density we used the central chord line average electron density which, due to the nearly flat RFX density profile, is very close to the section average density.

The resistivity was calculated using the Spitzer expression with approximate linearization for the Z_σ value:

$$\eta_{Spitzer} = 5.22\ 10^{-5}\frac{\ln\Lambda}{T_e(0)^{3/2}}\left(0.4 + 0.6\ Z_{eff}\right)\ ,$$

where we decided to use the central electron temperature, and we neglected any additional effect on the resistivity due to trapped particles.

II. EXPERIMENTAL RESULTS

To study the dependence of the magnetic fluctuations on the Lundquist number, we tried to see if different scaling exponents could be found under different plasma conditions. We selected the discharges according to their set-up and mode spectral distribution. In particular we analyzed the following sets of discharges: standard, quasi single helicity (QSH [9]), pulsed poloidal current drive (PPCD [10]) and rotating locking mode induced by an external rotating toroidal field modulation (RTFM [11]). In terms of S, due to the high level of plasma current (up to 1.1 MA), it has been possible to extend the analysis up to $S \approx 4\ 10^6$.

Standard discharges are presented in fig. 1 where fluctuations amplitude (even and odd) normalized to the poloidal field at the wall is drawn versus S, without any selection in current, density or pitch parameter. A quite good correlation between the two parameters was found. By a power regression analysis we computed the scaling relation between the normalized magnetic fluctuations and the Lundquist number obtaining an experimental value of α_E=–0.15±0.01 for the exponent. This result was compared with the scaling law found for the toroidal fluctuations amplitude by the numerical experiments performed with the 3D MHD SPECYL code [4]. As it is possible to see in fig. 2 the SPECYL code obtains $\alpha_{SPECYL}=0.22$, a value consistent with the experimental one. A better agreement was obtained ($\alpha_E=-0.18\pm0.02$) considering, as in the numerical study, only the toroidal field fluctuations which are directly measured.

A similar value was also previously found in the MST device, but only in high density discharges. For the standard discharges we tried to see if other combinations of the parameters that enter in the S formula correlate in a better way with the normalized fluctuations amplitude. We performed the following regression:

$$b/B_\theta(a) = A\, I_\phi(a)^a\, T_e(0)^b\, n_e^c\, \left(0.4 + 0.6\, Z_{eff}\right)^d$$

As it is possible to see in fig. 3, the correlation is only slightly better when compared to the previous S scaling, while the exponents are similar to those obtained from the S scaling. This means that the Lundquist number is a good parameter to describe the magnetic fluctuations dependence.

PPCD discharges show a much smaller magnetic fluctuations amplitude compared to standard discharges, but a very similar scaling exponent (fig. 4). Since during PPCD the dynamic regime might be altered by the external action, the fluctuations amplitude could in principle follow a different scaling law than the one associated with the usual dynamo providing all the current necessary for sustainment. The result obtained for the S exponent, with only a moderately lower correlation, seems to indicate that during PPCD the fraction of poloidal current driven by the plasma is nearly constant for the various plasma conditions.

When plasma rotation is induced by an external toroidally rotating m=0 n=1 or n=2 B_ϕ error field, the odd magnetic fluctuations amplitude and scaling does not change compared to standard discharges (fig. 5), while the even part is affected only on the externally produced harmonics.

A small number of quasi single helicity discharges has been obtained up to now with all the measurements needed to compute S. This small set does not allow us to evaluate an S scaling exponent. Nonetheless we can see that the fluctuations amplitude is slightly higher than in standard discharges (fig.5). It is interesting to note that quasi single helicity discharges are seen only in the lower region of the S values obtained in RFX. This is in agreement with numerical simulations [4] which showed that the quasi single helicity state is more easily obtainable at low S.

The dependence of the energy confinement time of the standard discharges on the Lundquist number has also been analyzed. It has been found that at

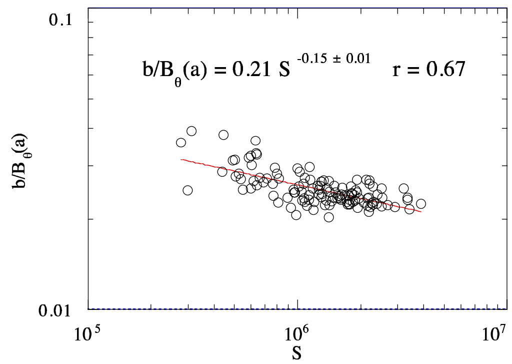

Fig. 1. Normalized toroidal and poloidal field fluctuations versus S for standard discharges.

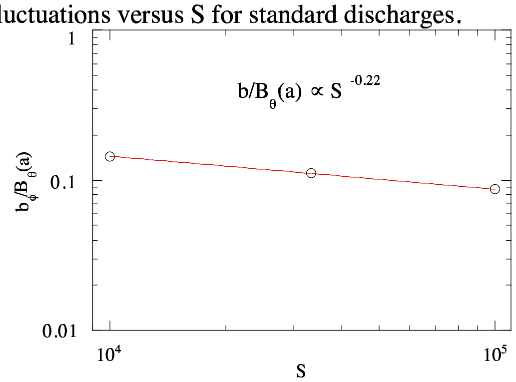

Fig. 2. Normalized toriodal field fluctuations versus S from SPECYL numerical simulation.

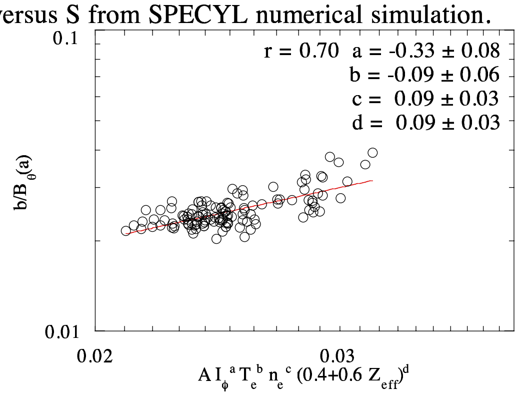

Fig. 3. Multivariable regression for normalized toroidal and poloidal field fluctuations.

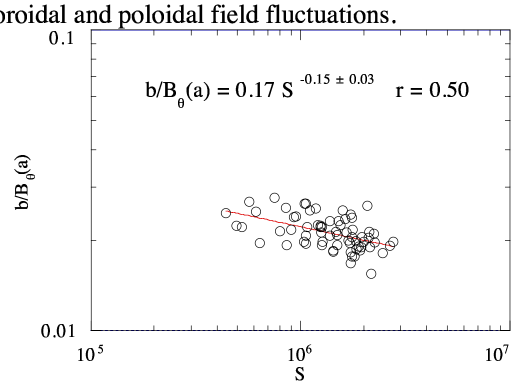

Fig. 4. Normalized toroidal and poloidal field fluctuations versus S during PPCD.

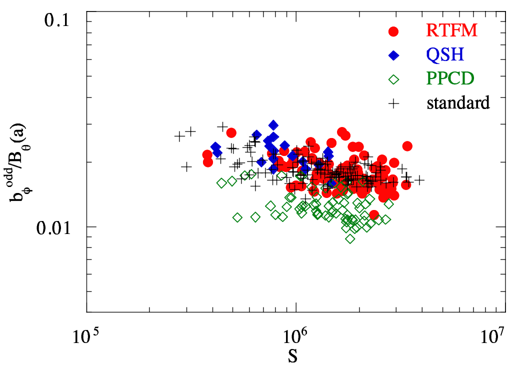

Fig. 5. Normalized odd toroidal and poloidal field fluctuations versus S for: standard, PPCD, rotating locking mode and quasi single helicity discharges.

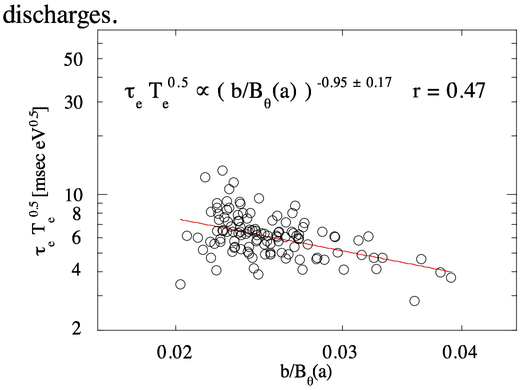

Fig. 6. $\tau_E T_e^{0.5}$ versus normalized toroidal and poloidal field fluctuations.

nearly fixed I/N value a power relation holds between the two parameters. For example for $I/N \approx 3\cdot10^{14}$ Am an expondent α=0.18±0.02 has been found. It is not surprising to see that at increased values of S a large energy confinement time has been obtained. Since magnetic fluctuations are smaller at higher S, if the energy transport is stochastic due to magnetic fluctuations, τ_E is larger at higher S. More quantitatively it is possible to see if the energy transport is well described by the stochastic model, comparing directly the energy confinement time with the fluctuations amplitude. From the quasi-linear Rechester-Rosenbluth model [12] for a collisionless plasma with heat conductivity due only to the stochastic magnetic field the energy confinement can be expressed in the following way: $\tau_E \propto (b/B)^{-2} \cdot T^{-1/2}$. To check this relation we performed the regression $\tau_E T^{1/2} \propto (b/B)^{\alpha}$ (fig. 6), and we found α=-0.95. This result confirms, within the limits of our present experimental measurements, that the heat conductivity can not be completely described by the Rechester-Rosenbluth model. Indeed, it has already been recognized that the edge transport is mainly driven by electrostatic fluctuations, and for stochastic transport the effect of collisions has also to be considered [13].

III. CONCLUSIONS

The magnetic fluctuations S-scaling has been studied in RFX under different plasma conditions. For all situations the Lundquist number correlates quite well with the fluctuations amplitude. The experimental scaling is in good agreement with the scaling obtained by numerical MHD simulations. While the fluctuations amplitude or the spectrum can be externally controlled the scaling of the fluctuations amplitude versus S is nearly constant for all the plasma configurations. The energy confinement seems to scale favorably with S although the energy transport is not completely due to stochastic magnetic field.

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