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Investigation of High Frequency Magnetic Turbulence Statistical Properties in Standard and Improved Confinement Plasmas in the MST RFP

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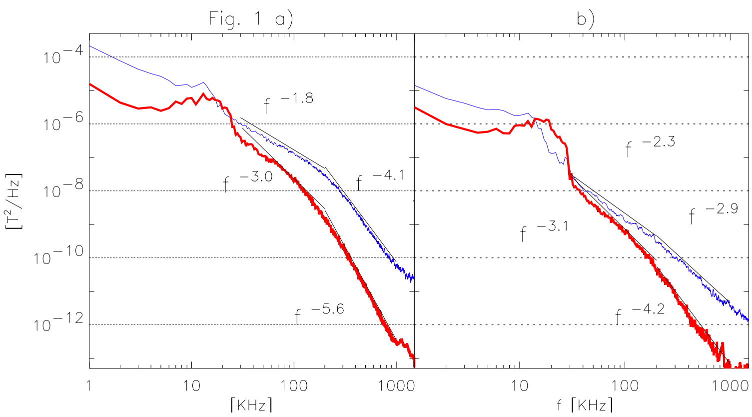
We describe the results of the measurement of magnetic fluctuations at the edge of the plasma produced in the Madison Symmetric Torus (MST) device. MST is an experiment for the confinement of plasmas in the reversed field pinch (RFP) configuration [1]. Magnetic turbulence drives energy and particle transport in the core of the RFP [2]; magnetic fluctuations due to tearing instabilities cause the equilibrium magnetic field to become stochastic, and this is a source of very high losses. Increased RFP performance relies on magnetic fluctuations reduction: to this extent positive results have been obtained with the Pulsed Poloidal Current Drive (PPCD) technique. PPCD is an inductive current profile control technique used to decrease magnetic fluctuations and improve confinement [3,4]. Previous results hint that the plasma is undergoing major changes during PPCD application.

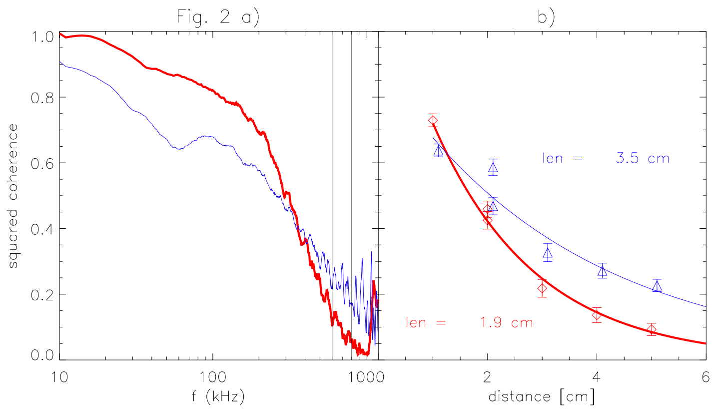
High frequency (1 MHz bandwidth, 3 MHz sampling rate) magnetic fluctuations have been measured using an array of closely spaced B_ϕ and B_θ pick-up coils [5] at the surface of MST vacuum vessel. The plasma current for the ensembles considered here is ~ 0.4 MA (but similar results hold for 0.5 MA discharges), and electron density is ~ 1 10^{19} m^{-3}. We present here a characterization of magnetic turbulence in two different experimental conditions: standard RFP plasmas and enhanced confinement plasmas, during which Pulsed Poloidal Current Drive is applied.



Typical power spectra during standard (blue thin lines) and PPCD (red thick lines) 0.4 MA discharges are shown in Fig. 1: a) refers to the toroidal component and b) to the poloidal one. They represent an ensemble average over 1 ms intervals taken between t=9 ms and t=18 ms, i.e. in the period where plasma current remains stationary.

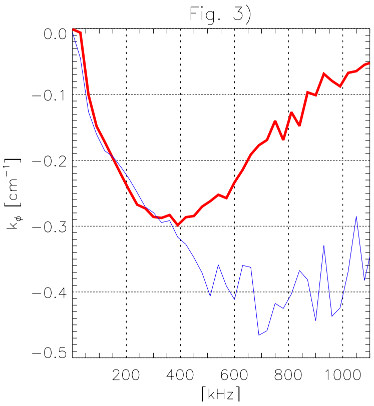
The fluctuation of the poloidal component is lower than the toroidal one as previously observed 200 kA discharges [6]. The B_θ and B_ϕ spectra have three distinctive features. First of all we note a peak in the 10-30 kHz range: this corresponds to the rotation frequency of the global MHD tearing modes, which typically falls in this range. The peak is broad as a result of the ensemble averaging. Two distinct power law slopes are observed at higher frequencies: a slower falloff (α_1~-1.8) in the range 50 kHz<f<300 kHz and faster falloff (α_2~-4.1) in the range f>300 kHz.

When PPCD is applied a significant decrease of the magnetic fluctuation level is observed. This decrease is accompanied with a change in the shape of the Fourier spectrum. While the low frequency peak and the knee are still present, the exponents of the power laws are significantly changed: α_1~-3 and α_2~-5.6 (for the B_ϕ component).

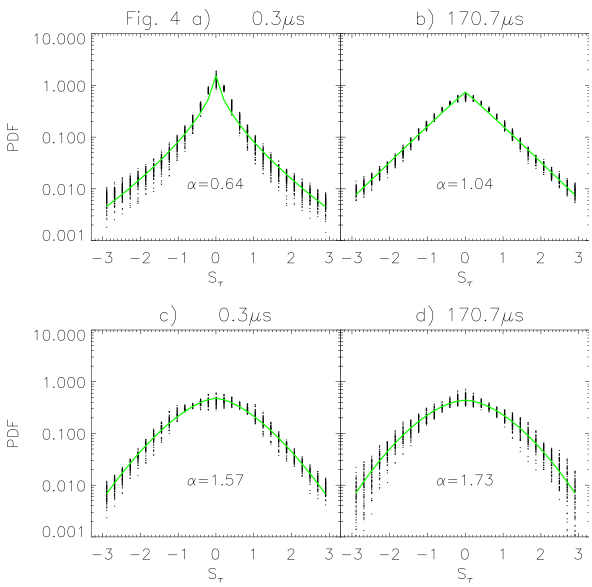


Spatial properties of magnetic turbulence also change during PPCD. The coherence function between pairs of B_ϕ coils decrease at high frequency (Fig. 2a shows the coherence as a function of frequency between B_ϕ probes separated by 5 cm). By averaging the coherence in a narrow frequency band (600-800 kHz for the example shown in Fig 2b) and fitting the dependence on the toroidal separation of the probes, we estimate the toroidal correlation length in that frequency range. While in standard discharges its value is 3.5 cm, during PPCD discharges it drops to 1.9 cm. The high frequency poloidal correlation length (which is much longer, as the edge field is mainly poloidal) shows a similar behaviour. Therefore, during PPCD, the high frequency, lower amplitude magnetic fluctuations are decorrelated when the dominant long wavelength tearing mode fluctuations are reduced.

A more complete description of the turbulence would require the knowledge of the wavenumber-frequency spectrum $S(k,\omega)$, but the insufficient spatial sampling of the magnetic fluctuation field do not allow a straightforward application of Fourier techniques. Under the assumptions that the magnetic fluctuation field is stationary, homogeneous and that it can be modelled as a superposition of waves, we can estimate S(k,ω) by means of the 2-point correlation technique [7]. We used a couple of B_ϕ coils at a distance of 2 cm (below the toroidal correlation length). A particularly interesting quantity is the first moment of S(k,ω), i.e. the statistical dispersion relation $\bar{k}_\varphi(\omega) = \int dk \frac{k}{2\pi}(S(k,\omega)/S(\omega))$ of the magnetic turbulence. Results for standard (blue) and PPCD (thick red) 0.4 MA ensembles are shown in Fig. 3 (similar results hold for 0.5 MA): we observe a marked difference for frequencies in excess of 300-400 kHz where the average k_ϕ is lower compared to standard discharges.



To get a deeper insight into the properties of magnetic turbulence, we have analyzed its statistical features by means of techniques often applied to study fluctuating time series in astrophysical and geophysical settings [8], and recently exported with success to magnetized laboratory plasmas [9]. This analysis is based on the study of the statistical distribution of the laminar times, defined as those times elapsed between two bursts in the fluctuating signal, and of the probability distribution function (PDF) of the signals. Either in standard and in PPCD shots, the distributions of laminar times $P(\tau_L)$, calculated as [8], are not exponential, but are more similar to power laws.



The second part of the analysis concerns the study of the PDF of the signal differences at various scales, defined as $S_\tau = b_\phi(t) - b_\phi(t+\tau)$, where $b_\phi(t)$ is the standardized time series of magnetic fluctuations data B_ϕ. Departures from self-similarity are typically highlighted by differences in the PDFs at various scales τ. For each shot in the ensemble, the B_ϕ time series are normalized to the variance. Fig. 4-a and -b shows the PDFs at two time scales averaged over standard shots. We note that the two PDFs have different shapes. As usually done, they can be fitted with stretched exponential functions $\exp(-b\,|x|^{\alpha})$, where the case

α=2 corresponds to the Gaussian distribution. In the case shown in Fig. 4a) and b) α=0.64 and α=1.04. We note that α is less than one at short time scales, and increases for longer time scales up to a value ~ 1. This result is consistent with similar analysis performed on fluctuations data from the RFX device [9] and indicates that PDFs are not self-similar in standard conditions. The presence of tails in the PDFs at short time scales shows in fact that larger differences are more frequent than at larger scales. This is a feature that has been interpreted as a signature of intermittency and a deviation from SOC behaviour [9]. This picture do not hold for PPCD discharges: fig.s 4 c) and d) show that PDFs do not change significantly as the scale increase, and tails are less important: PDFs during PPCD are therefore closer to those that would be expected in a self-similar regime.

All of these results suggest that the PPCD action strongly influence the structure of magnetic turbulence in the RFP. A reason for this could be found in the basic physics mechanisms involved in the PPCD action. PPCD is applied to reduce the resort of the plasma to spontaneous dynamo, driven by magnetic and velocity fluctuation. Very often in MST, and in particular for all the cases analysed here, the PPCD action is followed by a period of spontaneous fluctuations (and dynamo) reduction [3]. During these very quiescent periods, no macroscopic relaxation events, called sawteeth and associated to discrete dynamo events, are observed. As discussed in [9], measurements of electrostatic fluctuations suggest the existence of a non-linear relationship between low-frequency magnetic relaxation and the generation of high-frequency intermittent structures. When, as during PPCD, the low frequency drive associated to the dynamo events is drastically reduced (and to this extent the efficiency of PPCD in fluctuations reduction is particularly strong), we argue that a significant source for intermittency is no more present. Further analysis is required, but RFP plasma without sawteeth may be compatible with self-organized criticality (SOC) in the magnetic turbulence.

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