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Time Series Statistical Analysis for Electron Temperature Fluctuations Measurements in Plasmas

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Introduction

Energy and particle transport processes in magnetically confined plasmas are strongly coupled to the fluctuations of plasma quantities, among which the electron temperature is quite critical. The measurement of the electron temperature fluctuations in the plasma core is particularly compelling, as they contribute to the transport driven by electrostatic mechanisms. Unfortunately, the degree of knowledge of $\tilde{T}_e$ is very much dependent on the region of plasma under study. While the plasma edge is relatively well diagnosed since a long time by means of insertable probes, little is known about $\tilde{T}_e$ in the plasma core [1,2] where no material objects can be inserted. Moreover even less information is available about the time evolution of the fluctuations level [3]. We report here the first measurements of the core electron temperature fluctuations in the Reversed Field Pinch (RFP) plasma, a self-organizing magnetic configuration for the confinement of thermonuclear plasmas. They have been obtained, with high time resolution, with a simple diagnostics and with the application of an advanced adaptive statistical technique, the Singular Spectrum Analysis (SSA) [4].

Double filter electron temperature fluctuations

The measurements of the core electron temperature, T_e have been performed in the large RFX experiment (minor radius a=0.46 m, major radius R=2 m) with the soft x-ray (SXR) double filter technique [5]: the SXR emission is measured by two Si detectors, covered by beryllium foils of different thickness, and viewing the same region of the plasma. The overall bandwidth of the present RFX diagnostics is ~ 8kHz. Nonetheless, this bandwidth is large enough to detect a significant fraction of the temperature fluctuations. From the propagation of the experimental errors in the SXR channels, it is possible to estimate a maximum random error $\Delta T_e/T_e$ ~ 6%, which includes the T_e profile uncertainty and the effect of impurities. Consequently T_e fluctuations below this value cannot be detectable on a single-time basis, unless we apply statistical tools to the overall time evolution of T_e.

The SSA decomposition

The SSA starting point is a decomposition of a time series, which we assume to be a realization of a process compound by a deterministic part (a slowly evolving term, i.e. the ``trend", plus fluctuations) and of a random noise affecting the measurement.

The original N-elements long time series x_i is "embedded" [6] in a vector space of dimension M, giving rise to a multivariate time series X_j of length M-N: SSA is based on the diagonalization of the covariance matrix of X_j, whose eigenvalues λ_k are called "singular values", and whose eigenvectors $\boldsymbol{\rho}_k$ are defined Empirical Orthogonal Functions (EOFs). Each EOF defines the impulse response function of a linear filter: the various (N-M) elements long filtered versions of the time series, called Principal Components $x_i^{PC,k}$ (PCs), are defined as $x_i^{PC,k} = \sum_{j=1}^{M} \rho_{k,j} x_{i+j}$. It can be shown that there's not a unique expansion of x_i in terms of the PCs $x_i^{PC,k}$. To overcome this difficulty Vautard et al [7] define for each PC an N-element

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long time series called Reconstructed Component (RC), $x_i^{RC,k}$, so that the original time series can be uniquely expanded as a sum over the RCs:

$$x_i = \sum_{j=1}^{M} x_i^{RC,j}$$

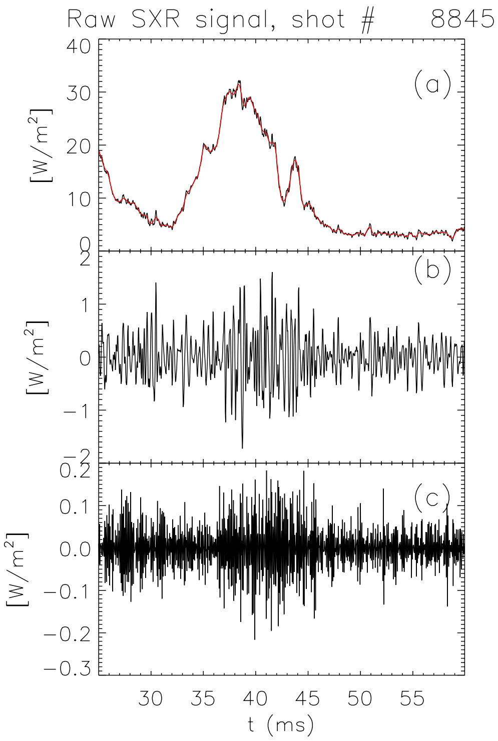

Fig. 1)

<u>*Signal/Noise enhancement; detrending*</u>

In order to discard the RCs contaminated by the noise Vautard [7] developed a rigorous but CPU-intensive Monte Carlo algorithm. By exploiting the analogy between the SSA decomposition and the multivariate time series context (see [8] and the references therein), we determined the set of RCs which contribute to the noise by adopting an information theoretic approach. In particular we consider the Akaike (AIC) and the Minimum Descriptive Length (MDL) criteria, applied to the singular spectrum. Under the reasonable assumptions that the time series is a realization of an ergodic process and that the noise is white, the noise cut-off k_n in the singular spectrum is found by minimizing the unbiased estimate of a properly defined likelihood [8]. The denoised time series is then written as the sum of the first k RCs.

To determine the RCs that contribute to the trend of the denoised time series, we use the standard non parametric statistical test based on the Kendall's rank correlation coefficient. This ``de-trending" procedure is somewhat subtle, because it depends on the time scale over which the test is performed. Since we are interested in fluctuations faster than the characteristic resistive MHD time scale, (i.e. in the 10^{-3}s range in RFX), we test each RC over a time scale of 3 ms, which is the typical average period of coherent MHD oscillations like sawteeth (Dynamo Reconnection Events [9]), and we determine the trend cut-off k_t so that the fluctuations are written as $x_i = \sum_{j=k_t}^{k_n} x_i^{RC,j}$. In Fig. 1 we show an example of application to a raw signal of the double filter diagnostic: trend, fluctuations and noise are shown in panels a,b,c respectively. In order to extract $\tilde{T}_e$ we apply SSA twice: at first to denoise the raw SXR and secondly to separate the slow trend from the fluctuations.

<u>*Correlation with magnetic fluctuations*</u>

To illustrate the behavior of $\tilde{T}_e$ in the RFP we present the results of a systematic analysis done on a dataset of discharges where Pulsed Poloidal Current Drive (PPCD) experiments [10] have been performed. We have chosen these experiments, which are transient in nature, since they are characterized by the strongest controlled variation of magnetic fluctuations during individual shots. They represent an excellent test bench to study whether electron temperature fluctuations are coupled to magnetic fluctuations. In Fig. 2 are summarized several time traces taken during the RFX discharge # 8845. Fig 2-A,B show respectively the time evolution of the core electron temperature T_e and of the edge toroidal magnetic field fluctuations level normalized to the edge total field $\tilde{b}_\varphi / B(a)$ for m=1 modes, which are the most important in the RFP due to its safety factor profile. These modes are mainly generated by global resistive instabilities and are resonant in the plasma core. Fig. 2-C show the normalized fluctuations level (averaged over 1 ms) for the core electron temperature, $\tilde{T}_e / T_e$: the PPCD phase is characterized by a lower level of temperature fluctuations, decreases from ~2.5% to ~1.2%. The same technique has been applied to a central interferometer chord [11]:the time evolution of the chord integrated density fluctuations, $\tilde{n}_e$ is reported in Figure 2-D. The same behavior is observed in Fig. 3 which shows the ensemble averages of the results of SSA analysis on individual discharges for a dataset made by 18 reproducible 0.85 MA PPCD discharges. To perform this averaging the time scale for each shot has been normalized, with $t^*=0$ corresponding to a time of 2 ms before the start of the PPCD experiment and $t^*=1$ to a time 4 ms after the instant when the inductively driven poloidal electric field has gone back to zero. Eight average points have been considered inside this lag. Figure Fig. 3-A displays the time evolution of the temperature trend $<T_{e0}>$, which increase from ~180 eV before the PPCD to ~260 eV at the peak. Figure Fig. 3-B,C,D show the ensemble averages of the normalized temperature $< \tilde{T}_e / T_e >$, edge toroidal magnetic field $\tilde{b}_\varphi / B(a)$ and density fluctuation levels.

Discussion

These measurements indicate that there is a significant difference between electron temperature fluctuations in the core and in the edge of the RFP. In fact measurements of $\tilde{T}_e / T_e$ in the plasma edge (0.86 <r/a< 1), performed in 0.3 MA plasmas [12], show that their relative amplitude is ~ 40%. Moreover core T_e fluctuations appear to be of the same order of magnitude as those measured in tokamak and stellarator [1,2]. The behavior of $\tilde{T}_e / T_e$ both in individual shots (Fig. 2) and in the ensemble average (Fig. 3) indicates a good correlation between magnetic and electron temperature fluctuations in the RFP plasma core. This correlation hints that the latter could be originated by the processes which produce the former, i.e. mostly global tearing modes in the RFP. This explanation is qualitatively consistent with the results of an advanced 3D MHD numerical simulation [13] which shows that the RFP dynamical evolution is governed by current sheet reconnection. Due to these current sheets, originated by magnetic instabilities, a fluctuating component of the ohmic dissipation power is observed, which is very likely driving temperature fluctuations.

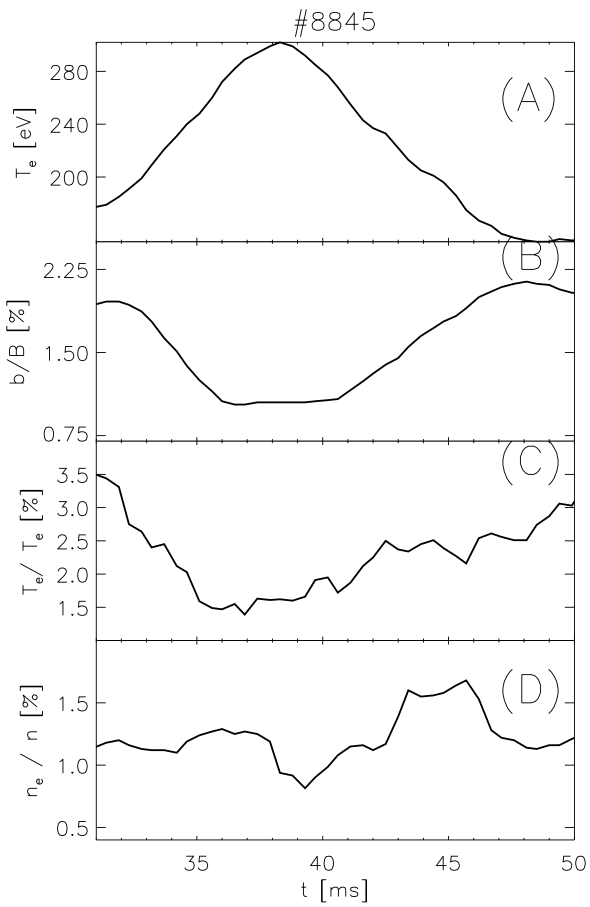

Fig. 2)

From a quantitative point of view the measured density, magnetic field and temperature fluctuation levels are compatible with the prediction of a simple model which estimates the pressure fluctuations originated by magnetic fluctuations [14]. This model, assuming an infinite parallel electron thermal conductivity, predicts that

$$\tilde{n}/n + \tilde{T}_e/T_e = \left(1/k_{//} L_p\right)\left(\tilde{b}_r/B\right)$$ where

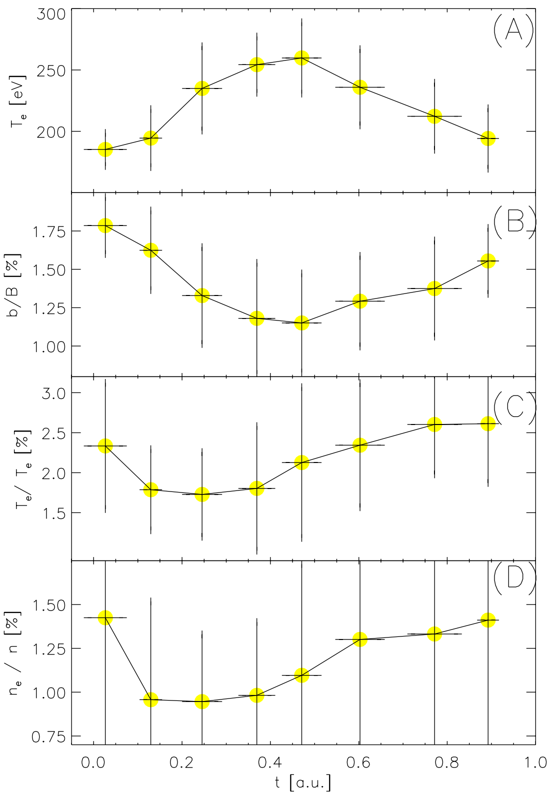

Fig. 3)

$k_{\parallel}$ is the parallel wave vector of the magnetic perturbation and L_p is the pressure gradient scale length. In RFX $k_{\parallel}^{-1} = 2\pi\ qR \approx 2\pi$ R m/n = 2π R/8, since in the core the innermost resonant (and the strongest) magnetic mode is typically (m=1,n=8) (or n=7). Assuming as an order of magnitude $L_p \approx a$, which is consistent with Thomson scattering measurements, we have $\tilde{n}/n + \tilde{T}_e/T_e = \pi\left(\tilde{b}_r/B\right)$, a relation consistent with experimental data.

Our measurement of temperature fluctuations allows the estimate of their influence on energy transport, provided that some reasonable assumptions are made. The electron energy fluxes generated by electrostatic fluctuations is [15]:

$$q_e^E = \left\{ \frac{\left\langle \tilde{p}\ \tilde{E}_\perp \right\rangle}{B_\phi} \right\} = \tfrac{3}{2} \frac{k_b}{B_\phi} \left\{ n_e \left\langle \tilde{T}_e \tilde{E}_\perp \right\rangle + T_e \left\langle \tilde{n}_e \tilde{E}_\perp \right\rangle \right\}$$

where $\tilde{E}_\perp$ is the fluctuating electric field, ϕ the plasma potential and k_b the Boltzmann constant. The ensemble averages, <…> are substituted for fluctuations levels: this assumes perfect coherence between $\tilde{E}_\perp$ and $\tilde{T}_e$ and between $\tilde{E}_\perp$, and $\tilde{n}_e$ and gives an upper estimate of q_e^E. Relying on the linear, adiabatic electron approximation of the Boltzmann relation, we assume $e\phi/T_e = \tilde{n}/n$.Since the width of k spectrum is unknown, we approximate k_θ with the poloidal diameter of the SXR detector cone view, $k_\theta = 2\pi$ / d ~ 30 m^{-1}. For a series of discharges spanning a range of plasma currents up to 1 MA we obtain q_e^E values approximately in the range 0.2 10^4 – 2 10^4 Wm^{-2}, which correspond to a fraction of the total input power influx ranging between 0.5% and 5%. These low values fit the paradigm, based on measurements and theoretical work, that core RFP energy transport is mainly magnetic fluctuations driven [16].

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