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Magnetic fluctuations and energy transport in RFX

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Abstract

In thermonuclear fusion plasmas, transport losses are usually believed to be caused by turbulent fluctuations. Particularly in the outer region of tokamaks, stellarators and reversed field pinches, electrostatic turbulence accounts for particle transport. In tokamaks, electrostatic fluctuations can also be responsible for the radial energy flux; in reversed field pinches, energy transport cannot be ascribed to electrostatic turbulence only.

In the plasma edge of the reversed field experiment device, identified as the region between the toroidal field reversal and the first wall, an extensive study of magnetic fluctuations and of the related radial energy flux has been performed. It is found that magnetic fluctuations carry most of the radial flux of energy. However, close to the wall the magnetic fluctuation-driven energy flux decreases abruptly, so that another mechanism must be invoked. There are indications that the energy flux channel in this region is the macroscopic magnetic deformation due to the phase locking of magnetic modes.

1. Introduction

In the toroidal devices used for the confinement of magnetic fusion plasmas, it is experimentally found that the transport losses far exceed the predictions of collisional transport theories. Such an anomalous transport is usually attributed to turbulent fluctuations [1]: if suitable correlations exist between the fluctuations of plasma parameters, transport may result perpendicularly to the local magnetic field [2, 3].

An important part of the experimental research in this field has concentrated on the edge region of the plasma, where probes may be inserted to measure the fluctuating quantities [1, 4]. Concerning the transport properties, both in tokamak and in reversed field pinch (RFP) experiments, the main contribution to the radial particle flux is found to be associated with electrostatic fluctuations; moreover, in tokamaks, the electrostatic particle flux dominates over the flux induced by magnetic fluctuations [1, 5, 6]. As far as the transport of energy in tokamaks is concerned, electrostatic fluctuations seem to account for the total outward energy flux, as estimated from the global energy balance, whereas the contribution of magnetic fluctuations might be negligible [1]; however, the experiments are not conclusive yet [7].

In RFPs, electrostatic fluctuations do not account for the whole transport of energy [8, 9]; so the experimental investigation tackled the problem of assessing the importance of the energy flux driven by magnetic fluctuations. Indeed magnetic fluctuations are intrinsic to the RFP, as this configuration is maintained by a strong dynamo mechanism, which converts part of the energy externally supplied to the poloidal magnetic field component into energy associated with the toroidal field component. Hence, magnetic fluctuations as high as some per cent of the total magnetic field are normally present, mainly due to instabilities resonating inside the reversal surface of the toroidal magnetic field [10]. It must be remembered that, in the edge region of RFPs, the main magnetic component is the poloidal magnetic field generated by the toroidal plasma current.

In the Madison symmetric torus (MST) experiment, it is found that the magnetic fluctuation-induced energy flux is larger than in tokamaks and is comparable to the total energy flux in the 'core' ($r/a > 0.75$) of the plasma, where the magnetic field is expected to be stochastic; however, the magnetic contribution to the energy flux decreases towards the edge of the plasma [11].

In the reversed field experiment (RFX), there are indications that the magnetic field fluctuations play a significant role in the energy transport; in particular, they seem to remarkably affect the superthermal component of the electrons. Indeed, the edge region of the RFX is characterized by a non-thermal distortion of the electron energy distribution function, due to the presence of a superthermal tail, carrying most of the parallel current density and a remarkable parallel energy flux [12]. If such a parallel flux is correlated to some extent with the fluctuations of the radial magnetic field, energy can be transferred outwards. As shown later, in the RFX superthermal electrons are good candidates to explain the energy losses due to magnetic fluctuations, as expected since the fastest particles are known to be the most susceptible to being affected by this kind of fluctuation [13].

It is also worth mentioning that in the RFX the tearing modes are found to be phase-locked (and also locked to the first wall). The resulting macroscopic magnetic disturbances enhance the local losses due to parallel transport, thus affecting the global power balance [14].

The present paper is dedicated to the investigation of the transport of energy through magnetic fluctuations. The experiments were performed in the RFX device (major radius 2 m, minor radius $a = 0.46$ m) [15] using the same diagnostic system which had already been employed in the MST [11] reversed field pinch and in the CCT [16] and TEXT-U tokamaks [17].

The paper is organized as follows: first the experimental conditions and the diagnostic system are described (section 2) and then the experimental results are shown (section 3). A short discussion and some proposals for further measurements are finally given (section 4).

2. Probe description and data analysis techniques

In the MST device the perpendicular energy flux driven by magnetic fluctuations was obtained by correlating the parallel energy flux, measured by a fast pyrobolometer, with the radial magnetic field fluctuations [18]. The equipment used in the RFX is the same as that used in the MST device (figure 1). It consists of two $LiTaO_3$ pyroelectric crystals, having 10.7 mm diameter and 0.5 mm thickness, facing the plasma in opposite directions along the magnetic field. A slit is placed in front of each crystal to reduce the deposited energy; the slit is 7 mm long, 1 mm thick and 1 mm wide. The probe is completed by a coil measuring the radial component of the magnetic field. To ensure electrical contact and to reduce pick-up noise [19], both sides of the crystals are covered by a 0.5 μm thick Au film, laid over a 120 Å Cr layer. The current signal generated by the detector is then fed to a fast current-to-voltage converter (measured bandwidth $\sim$150 kHz). The magnetic coil signal is numerically integrated after

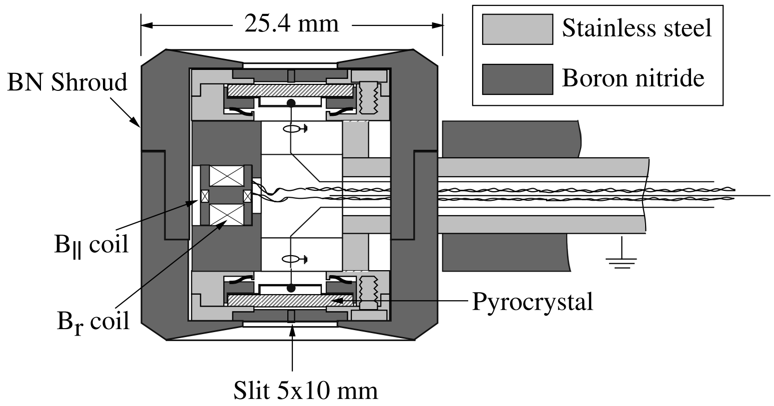

Figure 1. Schematic view of pyrobolometer equipment.

subtraction of the offset. For all signals, the sampling frequency is 1 MHz. Regarding the bolometer sensitivity, the nominal value for these pyrocrystals (0.12 μA W^{-1}) is used [18]; as a consequence of the non-negligible uncertainty associated with this choice, the systematic error on the absolute values of the energy fluxes can be estimated to be about a factor of two.

In order to minimize the energy flux, during the experiments the crystals were oriented at grazing incidence (nominal angle 15°) with respect to the local magnetic field. Because of the shallow exposure angle, the absolute calibration of the system turns out to be difficult since it is not easy to accurately monitor small variations of this angle during a plasma shot. When absolute values are presented, a nominal angle (6°) is assumed for the total magnetic field direction with respect to the poloidal direction. The effect of toroidal magnetic field fluctuations on the transmission function of the system was assessed by assuming a perturbation of the toroidal magnetic field equal to 1% of the poloidal magnetic field (the latter being the main component of the magnetic field in a RFP plasma). It results that the shallower the exposure angle, the higher the effect; particularly, at the lowest nominal exposure angle used, this perturbation might introduce a ~20% error on the relative value of the transmission function.

The outer region of the RFX was explored by inserting the probe into the plasma up to $r/a = 0.86$. The toroidal field reversal surface was located at $r/a = 0.81$–0.86, as estimated by the polynomial function model [20].

The parallel energy flux is obtained by subtraction of the fluxes measured on the electron and on the ion drift sides (the electron drift side is defined as the upstream side of the superthermal electron flow at the edge and the ion drift side is the opposite side): the uniform contributions due to radiation and to the ions that possibly cross the slit are eliminated and a net electron parallel energy flux thus results. Since the detectors were not polarized with respect to the plasma, the result is a measure of the contribution of the superthermal component of the velocity distribution function.

The contribution of the magnetic fluctuations to the radial transport of energy was computed in the frequency domain as the covariance (product of Fourier transforms) between $\tilde{q}_{\parallel}$, the fluctuating net parallel energy flux, and $\tilde{b}_{\mathrm{r}}$, the radial component of the fluctuating magnetic field normalized to the poloidal magnetic field [21]:

$$\int \tilde{q}_{\parallel}\tilde{b}_{\mathrm{r}}\gamma_{\mathrm{qb}}(\nu)\cos(\varphi_{\mathrm{qb}}(\nu))\,\mathrm{d}\nu \qquad (1)$$

where $\gamma_{\mathrm{qb}}(\nu)$ is the cross coherence and $\varphi_{\mathrm{qb}}(\nu)$ the cross-phase between $\tilde{q}_{\parallel}$ and $\tilde{b}_{\mathrm{r}}$.

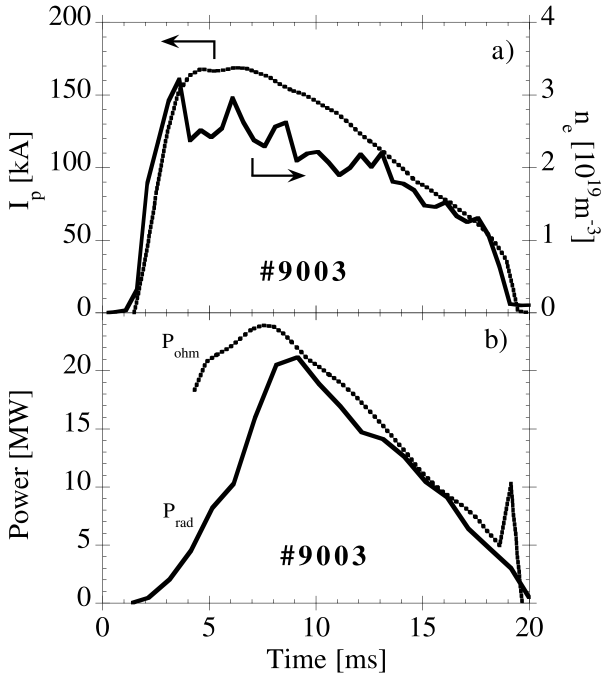

Figure 2. Main plasma parameters: (a) toroidal current and electron density; (b) ohmic and radiated power.

As a cross-check, the computation was also performed in the time domain as $q_r = \langle \tilde{q}_{\|} \tilde{b}_r \rangle$, giving comparable results.

The rms value of magnetic fluctuations has been evaluated as the auto-covariance of the magnetic field signal.

3. Experimental conditions and results

To reduce the parallel energy flux, the RFX experiment was operated at low plasma current ($\sim$150 kA) and high density ($\sim 2 \times 10^{19}$ m^{-3}), so that almost 80% of the power was lost by radiation on average. This is confirmed by the total radiation data obtained from bolometric tomography.

For these discharges a global power balance indicates that the radial energy flux, obtained as the fraction of input power lost by transport divided by the first wall surface, was on average 100 kW m^{-2}. The locked mode position was forced away from the pyrobolometer section to prevent local events from affecting the results. Thus only cross-field energy transport due to magnetic fluctuations was measured; the contribution of locked modes to the energy transport is not considered in the present paper, since these perturbations are stationary in the laboratory frame of reference and their contribution cannot be determined with a simple local measurement. An example of discharge current, plasma density, input ohmic power and radiated power is shown in figure 2. Ohmic power data before 4 ms are not displayed as they were affected by large disturbances during the setting-up phase. During the measurements the plasma was in the multiple helicity state, in which several toroidal magnetic modes are simultaneously present [22].

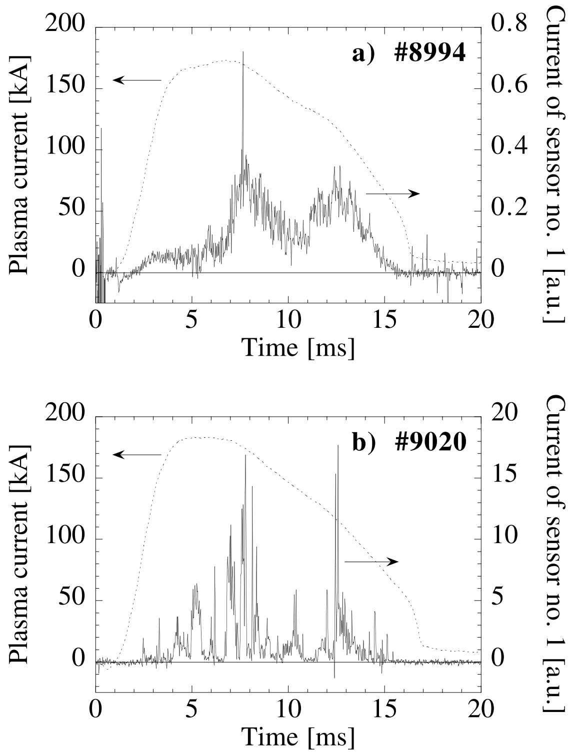

Figure 3. Main plasma current and typical waveforms of pyrosensor current: (a) slit located at $r/a = 1$; (b) slit inserted at $r/a = 0.88$.

Typical waveforms of the signals, for two different radial positions, are presented in figure 3; in the same figures, the plasma current waveforms are shown to ensure that the discharges were very similar as far as the global parameters were concerned. It is worth noting that, deep inside the plasma, the energy flux shows bursts (see figure 3(b)). Indeed, by varying the insertion from $r/a > 0.97$ to $r/a < 0.95$ a qualitative change in the power spectra of $q = q_1 - q_2$ is observed; correspondingly, no qualitative change is found in the power spectrum of $\tilde{b}_{\rm r}$.

Figure 4(a) shows that the parallel energy fluxes decrease at the edge on both the ion and electron drift sides; likewise, the net parallel energy flux diminishes in the edge region (figure 4(b)). The energy flux asymmetry, defined as the ratio between the parallel energy fluxes measured on the electron and on the ion drift sides, is found to be about three at the extreme edge of the plasma (for $r/a > 0.95$), decreasing towards unity deeper inside, as reported in figure 4(c). The values of the asymmetry factor observed at the edge are in agreement with previous energy flux measurements, averaged over the entire discharge duration, obtained from calorimetric probes [23]. The decrease in the asymmetry towards unity inside the plasma is in agreement with the results of a Fokker–Planck code developed to study the superthermal electron population at the edge of RFPs [24].

By means of the coil located in the pyrobolometric system, a radial scan of $\langle \tilde{b}_{\rm r}^2 \rangle^{1/2}$, the total amplitude of the normalized fluctuating radial magnetic field, has been performed up to $r/a = 0.86$ (figure 5). The value of $\langle \tilde{b}_{\rm r}^2 \rangle^{1/2}$ is obtained by integrating the power spectrum of $\tilde{b}_{\rm r}$ over frequencies greater than 500 Hz. It is found that $\langle \tilde{b}_{\rm r}^2 \rangle^{1/2}$ is 1% in the outer region of the plasma, increasing to 2.5% deeper inside.

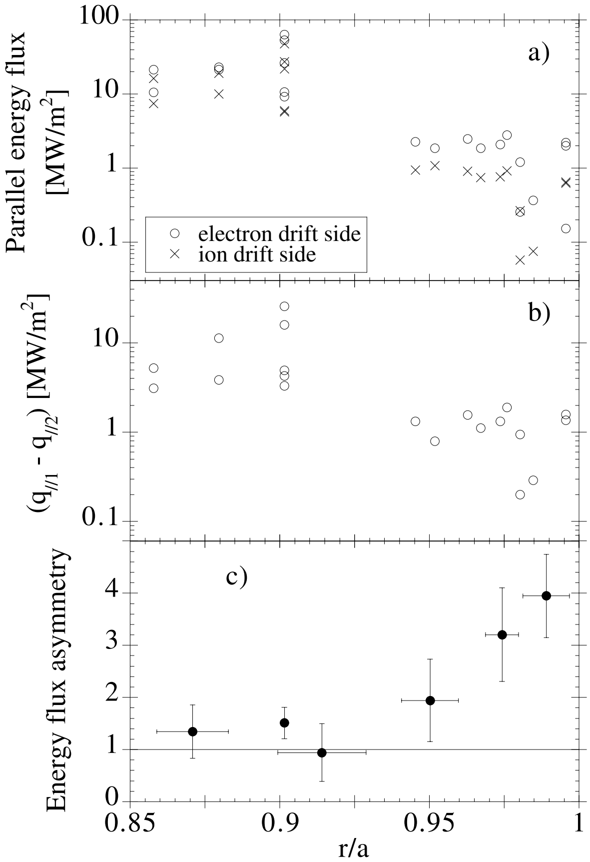

Figure 4. Parallel energy fluxes (a), net parallel energy flux (b) and energy flux asymmetry (c) as a function of the probe radial position.

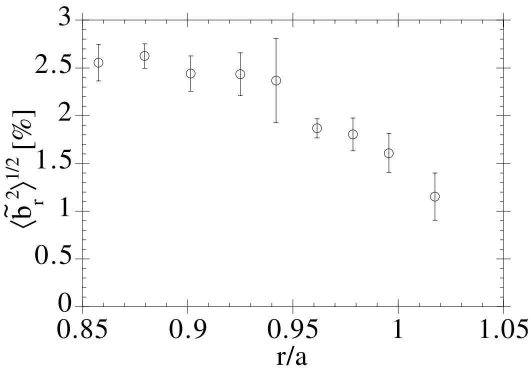

Figure 5. Radial behaviour of $\langle \tilde{b}_r^2 \rangle^{1/2}$; the bars indicate the standard deviation.

The power spectra of $\tilde{b}_r$ and $\tilde{q}_\parallel$ are shown in figure 6. They are essentially concentrated in the frequency range below 20 kHz, as in the MST experiment [11]; the power spectrum of $\tilde{q}_\parallel$ decays slightly faster than that of magnetic fluctuations. As observed in the MST

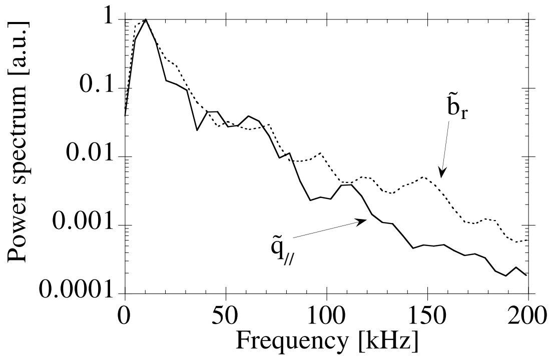

Figure 6. Power spectra of parallel energy flux, $\tilde{q}_{\|}$, and of radial magnetic field, $\tilde{b}_{\rm r}$.

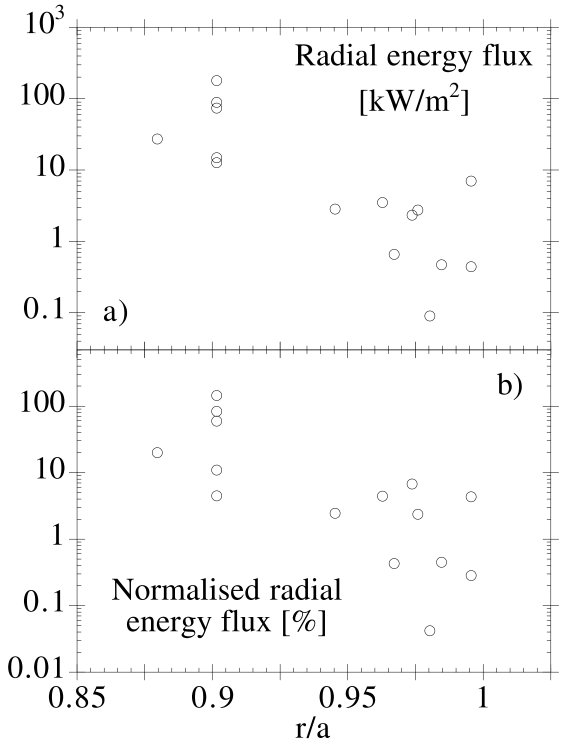

Figure 7. Radial energy flux (upper frame) and radial energy flux normalized to global energy flux (lower frame) as a function of the radial position of the detector.

experiment [21], the coherence between energy flux and magnetic fluctuations is low (typically 0.2), though well within the statistical significance; the same is observed in the RFX, even when bursts appear in the $q_{\|}$ waveform; moreover, no clear dependence of the coherence on the probe position can be found.

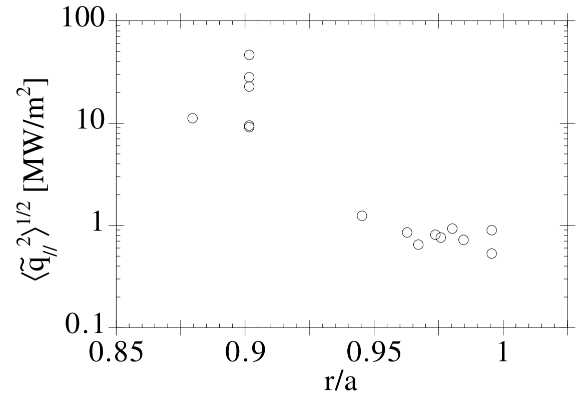

Figure 8. Radial behaviour of $\langle \tilde{q}_{\parallel}^2 \rangle^{1/2}$.

The upper frame of figure 7 displays the radial dependence of the radial energy flux as obtained according to the procedure described in section 2; the lower frame shows the percentage of the radial energy flux (as can be deduced from the global energy balance) which is due to magnetic fluctuations. It is clear that in the innermost positions the magnetic fluctuation induced energy flux reaches values comparable to the total flux lost by transport ($\sim$100 kW m^{-2}). According to these findings, superthermal electron losses due to magnetic fluctuations seem to account for the radial transport of energy in the core of the plasma. In outer regions ($r/a > 0.95$) the magnetic fluctuation induced energy flux decreases and is less than 10% of the flux derived from the global energy balance. In any case, it is important to mention that the energy flux due to the magnetic fluctuations is mainly associated with the electron drift component, indicating that the superthermal electrons could account for the main part of these losses. Indeed superthermal electrons are known to flow collimated along the electron drift side [12].

At lower densities than those which were chosen for these discharges in order to preserve the probes, the superthermal electronic tail is known to be even a factor of five higher and therefore its contribution to the global power losses might be more relevant. Nevertheless, the experiments in the MST device performed in normal density discharges with a relatively large amount of superthermal electrons gave analogous results [11]. Moreover, by comparing discharges with different density and radiation losses, it was suggested that the transport mechanism in the RFX is unaffected by radiation [25].

A detailed analysis of the various terms appearing in equation (1) shows that the power spectrum of the magnetic fluctuations cannot be the sole cause of the radial energy flux reduction towards the wall (see figure 5). Moreover, both cross coherence and cross phase do not show clear radial dependences. In contrast, at the very edge of the plasma a strong decrease in the fluctuations of the parallel energy flux is observed (figure 8), which might be responsible for most of the reduction of the radial energy flux.

4. Discussion and conclusions

In proximity of the RFX first wall, in agreement with the evidence collected in the MST experiment, the energy transport due to magnetic fluctuations seems to be orders of magnitude lower than what would be required to justify the global power balance. Since electrostatic fluctuations account only for 30% of the whole energy transport [9], the energy losses at the very edge of the plasma must be attributed to some other cause. These results are essentially the same for a wide range of parameters: they have been obtained both in the RFX at high density and in the MST experiment at normal density. As reported elsewhere [14], local measurements cannot assess the effect of the magnetic field modes locked to the wall. In the RFX the losses caused by this static deformation of the field topology are good candidates to explain the missing part of the power escaping from the plasma at the edge. To clarify this issue, some hints could be obtained from measurements performed in the position where magnetic modes are locked and in discharges where the locked modes rotate in the laboratory frame.

To summarize, the measurements show the increase in the radial magnetic field fluctuations inside the plasma. The previously obtained data of energy flux asymmetry are confirmed and extended to inner positions, where the asymmetry is found to decrease. As in the MST case, in the RFX the magnetic fluctuations do not account for the energy transport at the very edge of the plasma. As no significant differences are found between normal-density and high-density cases, it is argued that in the RFX the most probable additional energy loss channel is that due to the stationary deformation of the magnetic field, associated with locked magnetic modes.

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