

# MAGNETIC FLUCTUATIONS AND ENERGY FLUX IN THE EDGE REGION OF RFX

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## 1. Introduction

Understanding the energy transport mechanisms in the Reversed Field Pinch (RFP) represents an outstanding issue for the reactor potential of this configuration. In recent years progress has been made in this field, especially concerning the edge of the plasma where probes can be inserted. At low plasma current and with magnetic modes locked away from the measurement region, it has been found that the energy transport is anomalous and fluctuation-driven; moreover, the contribution due to electrostatic turbulence is small in all RFP experiments where this measurement has been performed (see references in [1]). On the other hand, the anomalous transport due to the magnetic activity is now under intense investigation.

In the MST RFP the perpendicular energy flux driven by magnetic fluctuations has been obtained by correlating the parallel energy flux fluctuations, measured by a fast pyrobolometer, with the radial magnetic field fluctuations [2]. The magnetic contribution has been found to be small at the edge and large inside the reversal surface of the toroidal magnetic field, where the magnetic field is expected to be stochastic.

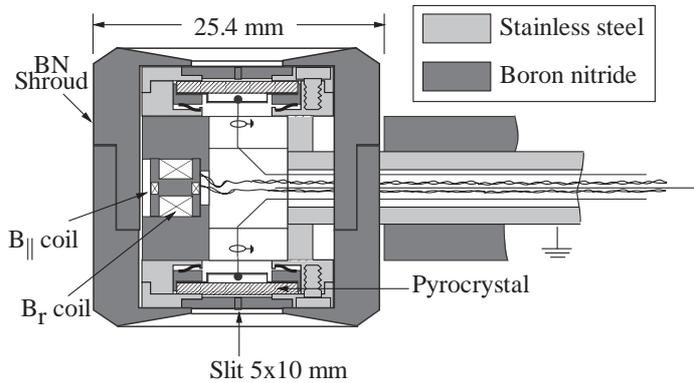
Conversely, on the RFX experiment (major radius 2 m, minor radius  $a = 0.46$  m) [3], there are indications that the magnetic activity plays an important role in the energy losses at the edge. In this experiment, the tearing modes are found to be phase-locked (and also locked at the wall) giving rise to macroscopic magnetic disturbances, resulting in enhanced local losses due to parallel transport, thus affecting the global power balance [4]. It must also be mentioned that an asymmetry in the parallel energy flux is found at the edge of RFP plasmas [5], which is associated to a non-thermal tail in the electron energy distribution function.

In order to give some insight into this subject, the radial energy flux due to the magnetic field fluctuations has been measured at the edge of RFX using the same technique as the one applied to MST.

## 2. Probe description and data analysis techniques

The equipment is similar to that used on MST [6] (Fig. 1). It consists of two LiTaO<sub>3</sub> pyroelectric crystals, with a 10.7 mm diameter and 0.5 mm thickness, facing the plasma at 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 the electrical contact and to reduce the pick-up noise [7], both sides of the crystals are covered by a 0.5 μm thick Au film laid over a 120 Å Cr layer. The bolometer sensitivity is assumed to be

$1.2 \cdot 10^{-7}$  A/W [6]; the current signal is fed to a fast current-to-voltage converter (measured bandwidth  $\approx 150$  kHz). The magnetic coil signal is numerically integrated after subtraction of the offset. For all signals, the sampling frequency is 1 MHz.



**Fig. 1.** Schematic view of the pyrobolometer equipment.

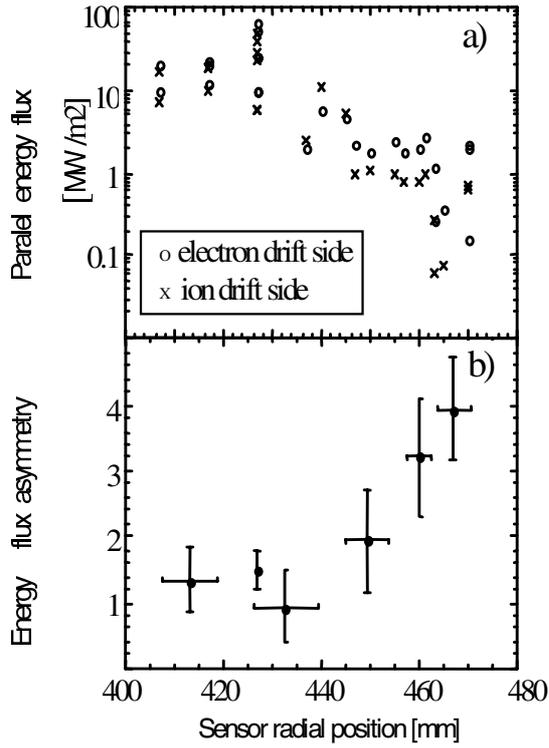
of this angle during a plasma shot. Hence, when absolute values are presented, a nominal angle ( $6^\circ$ ) is assumed for the total magnetic field direction with respect to the poloidal direction. The outer region of RFX has been explored by inserting the probe up to 60 mm into the plasma, corresponding to 11% of the minor radius; the toroidal field reversal surface is at  $50 \div 70$  mm from the first wall.

The net electron 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 one. The magnetic fluctuation contribution to the radial energy transport has been computed in the frequency domain as the covariance between the fluctuating net parallel energy flux,  $\tilde{q}_{||}$ , and the radial component of the fluctuating magnetic field normalised to the poloidal magnetic field,  $\tilde{b}_r$  [2]. 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.

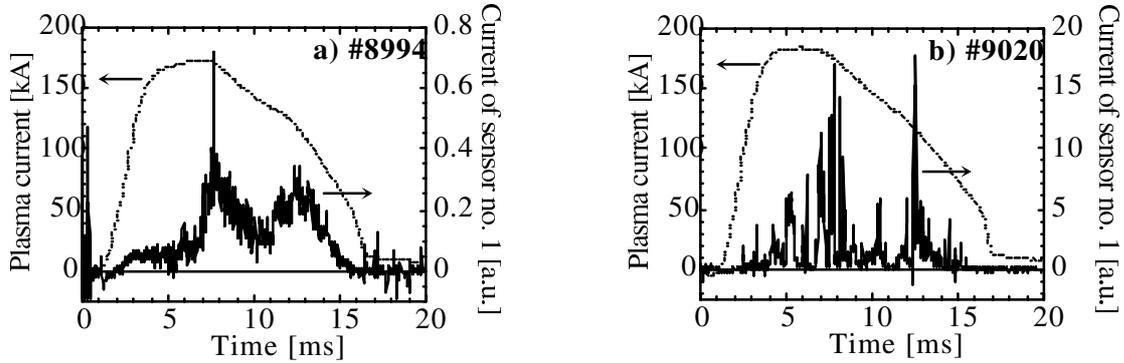
### 3. Experimental conditions and results

To reduce the parallel energy flux, the RFX experiment was operated at low plasma current ( $\sim 150$  kA) and high density ( $\sim 2 \cdot 10^{19}$  m $^{-3}$ ), so that almost 80% of the power was lost by radiation, as measured by bolometric tomography. For these discharges a global power balance indicates that the radial energy flux, obtained as the fraction of power lost by transport divided by the first wall surface, was on average 100 kW/m $^2$ . The locked mode was forced away from the pyrobolometer section to prevent local events from affecting the results.

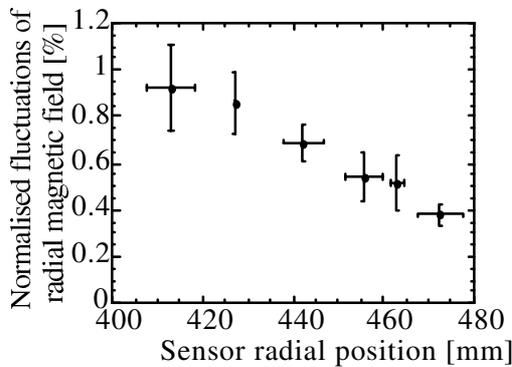
As shown in Fig. 2-a the parallel energy flux rises at the edge with a rather steep gradient. The energy flux asymmetry, defined as the ratio between the parallel energy fluxes measured on the electron and on the ion drift sides, is found to be about 3 at the extreme edge (up to  $\approx 10$  mm of insertion), decreasing towards unity deeper inside, as shown in Fig. 2-b. The values of the asymmetry factor observed at the edge are in agreement with previous energy flux measurements, averaged over the entire discharge, obtained from calorimetric probes [8]. The decrease of the asymmetry towards unity inside the plasma confirms the



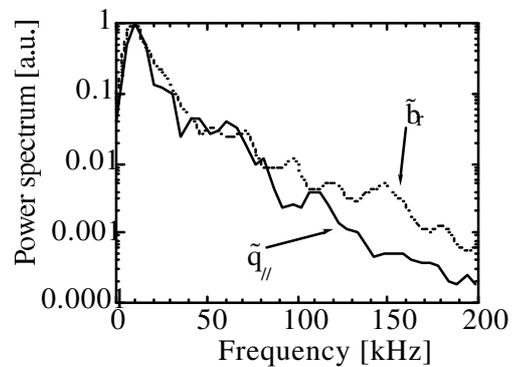
**Fig. 2.** Parallel energy fluxes (a) and energy flux asymmetry (b) as a function of the probe radial position.



**Fig. 3.** Main plasma current and typical waveforms of pyrosensor current: a) slit located 13 mm outside the plasma; b) slit inserted 40 mm inside the plasma.



**Fig. 4.**  $\langle \tilde{b}_r^2 \rangle^{1/2}$  as a function of the radial position; the bars indicate the standard deviation.



**Fig. 5.** Power spectra of the parallel energy flux,  $\tilde{q}_{||}$ , and of the radial magnetic field,  $\tilde{b}_r$ .

results of a Fokker-Planck code developed to study the superthermal electron population at the edge of RFP's [9]. The typical waveforms for two different radial positions are presented in Fig. 3; in the same figures, the plasma current waveforms are also shown. It is worth noting that, deep inside the plasma, the energy flux shows bursts (see Fig. 3b).

By means of the coil located on the pyroblometric system, a radial scan of  $\langle \tilde{b}_r^2 \rangle^{1/2}$ , the total amplitude of the normalised fluctuating radial magnetic field, has been performed up to  $\approx 50$  mm inside the plasma (Fig. 4). The value of  $\langle \tilde{b}_r^2 \rangle^{1/2}$  is obtained by integrating the power spectrum of  $\tilde{b}_r$  over the frequencies greater than 5 kHz. It is found that  $\langle \tilde{b}_r^2 \rangle^{1/2}$  decreases almost linearly from 1% to 0.4% as the magnetic coil is taken out of the plasma.

The power spectra of  $\tilde{b}_r$  and  $\tilde{q}_{||}$  are shown in Fig. 5. They are essentially concentrated in the frequency range below 20 kHz, as in MST [10]; the  $\tilde{q}_{||}$  power spectrum decays slightly faster than that of the magnetic fluctuations. As observed in the MST experiment [2], the coherence between energy flux and magnetic fluctuations is low (typically 0.2); the same is also observed in RFX when bursts appear in the  $q_{||}$  waveform; moreover no clear dependence of the coherence on the probe position has been found.

The data analysis in the frequency domain indicates that also the major contribution to the radial energy flux lies in the range below 20 kHz, as in the MST case [10].

It must be noted that at the outermost insertions the radial energy flux derived from the magnetic fluctuations and from the nominal calibration of the pyrobolometer is one hundred times lower than expected from the global energy balance: as in MST, the magnetic fluctuations are not responsible for the energy transport at the extreme edge of the plasma. Conversely, their relevance increases while entering the plasma; indeed, despite the uncertainties in the probe calibration, the radial energy flux in the innermost positions seems to be of the same order of magnitude as the energy flux obtained from the global balance.

Thus the energy losses at the plasma edge must be traced back to another cause. It was already shown that a substantial fraction of the energy may reach the first wall parallel to the magnetic field by the wall-locked modes [4]. Moreover, the contribution of superthermal electrons to the energy loss due to electrostatic fluctuations has not been assessed as yet.

To summarise, the measurements show the decrease of the radial magnetic field fluctuations as a function of the radial co-ordinate of the coil. The previously obtained energy flux asymmetry data are confirmed and extended to inner positions, where the asymmetry is found to decrease. As in the MST case, also in RFX, far from the wall-locking location, the magnetic fluctuations do not account for the energy loss at the edge of the plasma; suggested energy loss channels include the phase-locking of magnetic modes and the superthermal electron contribution to the electrostatic fluctuations.

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