# Measurement of Magnetic Fluctuation Induced Energy Transport in a Tokamak

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(Received 24 July 1995)

Magnetic fluctuation induced electron energy transport is measured in the Continuous Current Tokamak [R. J. Taylor *et al.*, Phys. Rev. Lett. **63**, 2365 (1989)] at $0.75 < r/a < 1$ for fluctuations with $0 < f < 150$ kHz. The flux, produced by electrons traveling parallel to a fluctuating magnetic field, is obtained from the correlation between the fluctuations in the parallel heat flux and the radial magnetic field. It was found that the magnetic fluctuations do not contribute to the total energy transport except in the vicinity of the $q = 2$ magnetic surface in the presence of large amplitude Mirnov oscillation.

PACS numbers: 52.55.Fa, 52.25.Fi, 52.25.Gj, 52.55.Pi

The role of magnetic fluctuations in the transport of energy in a tokamak has been an unresolved question for decades. Lacking direct measurements of the energy flux driven by magnetic fluctuations, inferences have been made from measurements of the magnetic fluctuation amplitude. For example, a simple quasilinear estimate [1,2] $\chi_e = v_e L \tilde{b}_r^2$ of the electron thermal conductivity is often applied to experiment ($v_e$ is the electron thermal velocity, $L$ is the parallel correlation length for the magnetic fluctuations, and $\tilde{b}_r = \tilde{B}_r/B$ is their relative amplitude). This estimate usually implies that magnetic fluctuation induced transport is small at the plasma edge, as concluded in TEXT-U [3]. On the other hand, the level of fluctuations may become significant deeper in the plasma core [3,4]; experiments with a variable safety factor $q$ in the TOKAPOLE tokamak [5] indicate significance of magnetic fluctuations at low $q$. Experiments in the ISX-B tokamak [6] at high beta (plasma pressure), Doublet III [7], and JET [8] show a correlation between confinement time and magnetic fluctuations. As the confinement time decreases, the fluctuations increase; however, causality between them was not established.

To determine decisively the role of the magnetic fluctuations in energy transport requires measurement of the energy flux specifically generated by the fluctuations. The radial energy flux arising from electron motion parallel to the magnetic field is given by $Q_r = Q_\parallel \cdot \hat{r} = (Q \cdot \hat{b})(\hat{b} \cdot \hat{r})$, where $\hat{b}$ and $\hat{r}$ are unit vectors along the magnetic field and the radial direction, respectively. Separating $Q$ and $\hat{b}$ into equilibrium and fluctuating quantities yields the ensemble-averaged radial energy flux [9]

$$Q_r = \frac{\langle \tilde{Q}_\parallel \tilde{B}_r \rangle}{B}, \tag{1}$$

where $\tilde{Q}_\parallel$ is the fluctuating electron heat flux parallel to the equilibrium magnetic field [i.e., $\tilde{Q}_\parallel = \int v_\parallel (mv^2/2) \tilde{f}(v) dv$], $\tilde{B}_r$ is the fluctuating radial magnetic field, $B$ is the equilibrium field, and the brackets $\langle\ \rangle$ represent the flux surface averaged product of fluctuating quantities. The key to measuring the energy flux from fluctuating magnetic field is to obtain $\tilde{Q}_\parallel$ and $\tilde{B}_r$ locally within the plasma.

In this Letter we present direct *measurement* of magnetic fluctuation induced electron heat transport in the Continuous Current Tokamak (CCT) [10] device. This work differs from all past work in which transport is *calculated* using the Rechester-Rosenbluth transport model [2] with the measured $\tilde{B}_r$ as input. We use the fast bolometer technique that was utilized in a reversed-field pinch (RFP) [11] and a tokamak scrape-off plasma [12]. The fluctuating electron heat flux parallel to the equilibrium magnetic field was measured with a fast insertable pyroelectric bolometer [13,14]. The magnetic field fluctuations were measured with a small pickup coil located inside the bolometer; the radial heat transport was calculated by correlating these two quantities. The magnetic heat transport was measured within $0.75 < r/a < 1$. We establish that the magnetic fluctuations cannot account for the total energy transport. An exception occurs in the vicinity of the $q = 2$ rational surface in the presence of a large amplitude coherent low-frequency (Mirnov) oscillation. At this location where a magnetic island presumably resides, the energy flux from magnetic fluctuations can be as large as the total energy flux; elsewhere it only contributes about 5% of the total energy flux.

The (CCT) plasma has a major radius $R = 1.5$ m and minor radius $a = 0.36$ m. In the described experiments the plasma current $I_p = 40$ kA, the toroidal magnetic field $B_T = 0.25$ T, the safety factor at the edge $q(a) = 2.6$–$3$, and the line averaged density $n_e = 2.5 \times 10^{12}$ cm$^{-3}$.

The parallel electron heat flux was measured with a fast, insertable pyrobolometer. Details of the design and calibration can be found in Refs. [13,14], and only pertinent features are reported here. The bolometer incorporates pyrocrystals of $LiNbO_3$ for the heat flux measurements and a small magnetic coil for radial magnetic field measurements. Both measurements were absolutely calibrated and their frequency bandwidth was measured to be 150 kHz. The electrons enter the bolometer through small, thin, 1 mm in diameter, apertures in the protective boron nitride

 0031-9007/95/75(21)/3866(4)$06.00 

shroud. There are two apertures located on the opposite sides of the shroud. When the bolometer is aligned along the magnetic field it measures the field aligned heat flux simultaneously in two opposite directions. These heat fluxes are subtracted from each other in order to yield the net parallel heat flux. This approach allows one, in addition, to subtract the plasma noise signals (found to be small) and the radiation power (also found to be small in comparison to the direct electron power flux). The ions enter the bolometer as well and are not explicitly separated, but their heat flux is small by a factor of $(m_e/M_i)^{1/2}(T_i/T_e)^{3/2}$ in comparison to the electron flux. The bolometer collects all electrons with energy up to $\sim$2 keV when the electron gyroradius becomes comparable to the entrance aperture radius, which results in an estimated 20% reduction in the total electron heat flux.

The separation of the entrance apertures in the parallel direction was 2.5 cm, which determines the parallel wavelength resolution. The magnetic coil diameter was 0.5 cm and the length (perpendicular to the magnetic field) 0.3 cm. The perpendicular correlation length for these fluctuations is 4–8 cm, measured previously in CCT using magnetic probes. The parallel wavelength for the frequency range of interest is much larger than the 2.5 cm separation of the apertures.

The comparatively low-temperature and low-density CCT plasma tolerates probe insertion quite well without any adverse effect, as it was established by numerous probe experiments in this machine. After a proper conditioning at the plasma edge we could insert the probe as deep as $r/a = 0.75$ without change in discharge parameters such as loop voltage, plasma current, plasma density, visible and UV radiation, magnetic activity, and plasma position. The extent of the insertion was limited by the probe damage rather than plasma perturbation. The measurements were recorded during 8 ms at the CCT discharge flattop period.

Typical frequency spectra of the parallel heat flux and the radial magnetic field are shown in Fig. 1. The magnetic spectrum features a high amplitude low-frequency coherent peak (Mirnov oscillation) centered at $\approx$5 kHz and low amplitude broadband high frequency fluctuations. In order to differentiate between them, we draw a separation line at 20 kHz. The radial profile of the fluctuation amplitudes is shown in Fig. 2. In addition, the equilibrium (dc) value of the parallel heat flux is shown.

The radial energy flux driven by magnetic fluctuations is obtained from the fluctuation measurements by forming the correlated product of Eq. (1). The flux surface average $\langle\ \rangle$ is realized experimentally by averaging many time records. Since the phase of the fluctuations is random over a magnetic surface, the ensemble average approximates a magnetic surface average. The product can be decomposed into spectral components

$$Q_r = B^{-1} \sum_f |\tilde{Q}_{\parallel}(f)|\,|\tilde{B}_r(f)|\gamma(f)\cos[\phi(f)], \qquad (2)$$

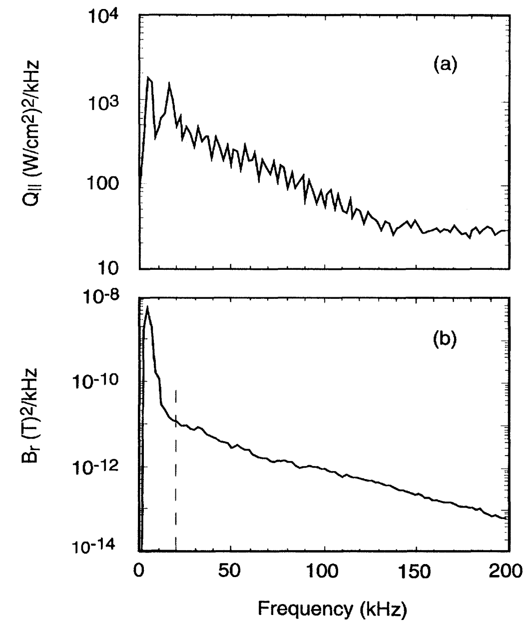


FIG. 1. Frequency spectra of the fluctuations of the parallel electron heat flux (a) and radial magnetic field (b). The vertical dashed line at 20 kHz separates the high-frequency and low-frequency regions.

where $|\tilde{Q}_{\parallel}(f)|$ and $|\tilde{B}_r(f)|$ are the average spectral amplitudes of the two fluctuating quantities, $\gamma(f)$ is the cross coherence, and $\phi(f)$ is the phase shift between

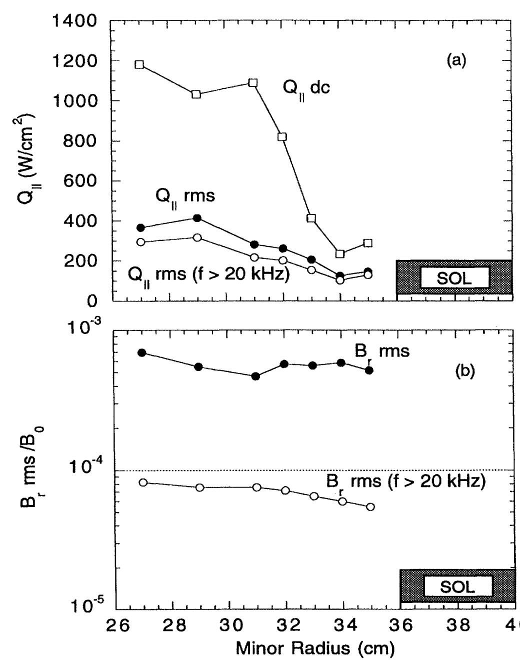


FIG. 2. Radial profile of fluctuation amplitudes of the parallel electron heat flux (a) and radial magnetic field (b). The equilibrium (dc) value of the parallel heat flux is shown for comparison.

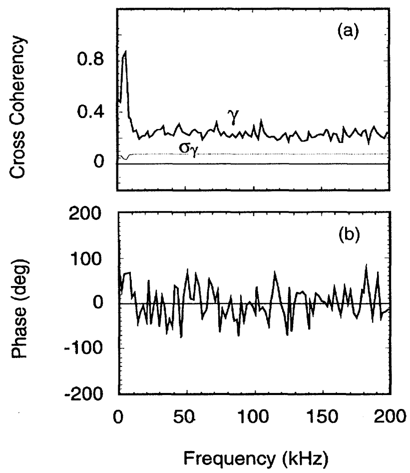


FIG. 3. Cross coherence (a) and phase shift (b) between the fluctuations of the radial magnetic field and parallel electron heat flux at the probe radial position of 29 cm. The statistical noise level of the cross coherence is shown by the thin solid line.

the fluctuating electron heat flux and the fluctuating radial magnetic field. The spectral amplitudes, cross coherence, and the phase shift were calculated using the fast Fourier transform (FFT) technique. To cross check the calculations, the transport was also calculated using direct time averaging. The statistical analyses of our data showed a very good agreement between the direct time averaging and the spectral analyses.

Typically, ten shots were taken at each radial location. The signals were recorded during the 8 ms duration at 1 $\mu$s sampling rate. The 8 ms pulse was separated into 16 realizations at 0.5 ms each. Therefore, we had 160 experimental realizations per radial location for statistical analyses. Figure 3 shows the cross coherence $\gamma(f)$ and the phase shift $\phi(f)$ at the probe radial position of 29 cm. The statistical noise level of the cross coherence is shown by the thin solid line.

The energy flux produced by high frequency ($f > 20$ kHz) magnetic turbulence is very small. The transport evaluated from Eq. (2) for these frequencies is shown in Fig. 4. We compare this flux with the total energy flux, approximated by the ratio of the total Ohmic input power to the plasma surface area, which is about 0.2 W/cm$^2$. The high-frequency fluctuation induced flux is about 2% of the total flux. The small contribution is mostly a result of the relatively small fluctuation amplitude; even if $\tilde{Q}_\parallel$ and $\tilde{B}_r$ were perfectly coherent ($\gamma = 1$) and in phase ($\cos\phi = 1$), the fluctuation induced flux would still contribute only 10% of the total energy flux.

The low-frequency Mirnov oscillations have a high amplitude and can cause substantial radial transport. The amplitude of the oscillations varies significantly from shot to shot as well as within the 8 ms gate time. Since the magnetic transport is expected to depend on the magnetic

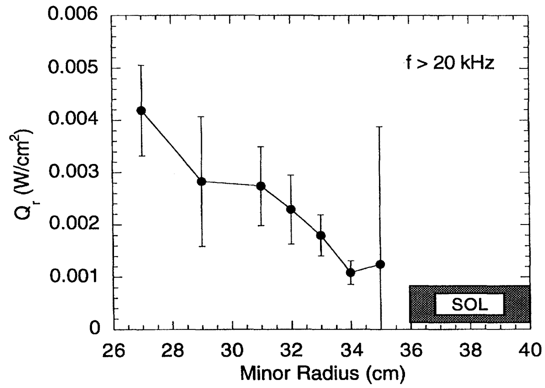


FIG. 4. Radial profile of high frequency ($f > 20$ kHz) magnetic heat transport $Q_r = \langle \tilde{Q}_\parallel \tilde{B}_r \rangle / B$. The total energy flux $P_{\mathrm{Ohmic}}/A_p = 0.2$ W/cm$^2$.

fluctuation amplitude, the 160 realizations at each radial location were grouped according to the corresponding fluctuation amplitude. Accordingly, the corresponding radial energy transport was calculated. The radial profile of the energy transport as a function of the magnetic fluctuation amplitude is shown in Fig. 5.

The radial transport is strongly peaked at $r = 29$ cm ($r/a = 0.8$). Analyses of the oscillations using magnetic pickup coil arrays located at the wall indicate the dominant mode of the Mirnov oscillation for the conditions of the experiment is $m/n = 2/1$. No mode analysis at the probe location has been made. The location of the peak coincides with the estimated position of the $q = 2$ rational surface. Estimate of the width of the $m = 2$ island (using the measured $\tilde{b}_r$) $w = 4(\tilde{b}_r R q^2/mq')^{1/2} = 6–7$ cm, agrees well with the width of the measured energy flux profile. An interesting feature is that transport is low (~5% of

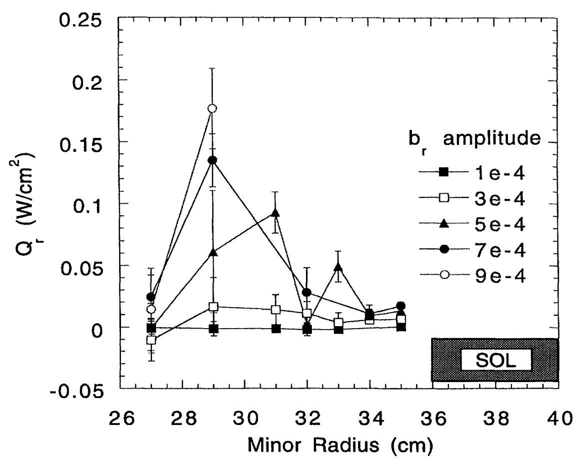


FIG. 5. Radial profile of the total magnetic heat transport profile $Q_r = \langle \tilde{Q}_\parallel \tilde{B}_r \rangle / B$. The transport is grouped according to the amplitude of the radial magnetic field fluctuation. The fluctuation amplitude is shown in the figure. The total energy flux $P_{\mathrm{Ohmic}}/A_p = 0.2$ W/cm$^2$.

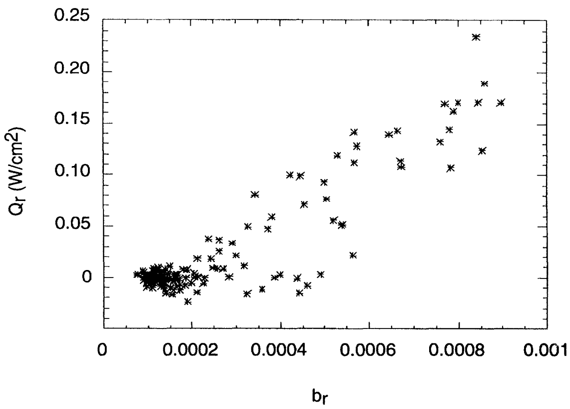


FIG. 6. Amplitude of the magnetic fluctuation induced heat flux measured at the radius of the maximum heat transport vs magnetic field fluctuation amplitude $\tilde{b}_r$. The total energy flux $P_{\mathrm{Ohmic}}/A_p = 0.2\ \mathrm{W/cm^2}$.

the total energy flux) away from the $q = 2$ surface even though the $m = 2$ amplitude stays large (see Fig. 2). The reduction in transport occurs mainly from the change in the phase shift between $\tilde{Q}_{\|}$ and $\tilde{B}_r$, from $\approx 60°$ at the peak to $\approx 90°$ (out of phase) outside of the peak.

The dependence of the energy flux, measured at the radius of the maximum of energy transport, on the fluctuation amplitude is shown in Fig. 6. The flux increases monotonically with fluctuation amplitude. At the lowest amplitude the flux is zero within the error bars, which are represented by the points scatter. At the largest amplitude, the flux (at the maximum) is comparable to the total energy flux.

In summary, we have directly measured the electron energy transport induced by magnetic fluctuations in a tokamak. We find that transport is small over the measured radial range $0.75 < r/a < 1$. Hence, magnetic fluctuations are not the cause of anomalous transport in a tokamak such as CCT. It was concluded in Ref. [3] that electrostatic energy transport dominates at the tokamak plasma edge. There is, of course, always a possibility that very short wavelength fluctuations outside the measurement range could play a role, or that under other conditions, such as high beta, magnetic fluctuations become significant.

For the discharges in which $m = 2$ Mirnov oscillations are large, we observe that the energy flux from magnetic fluctuations can become as large as the total energy flux in the vicinity of $q = 2$ surface, and over a radial range about equal to the calculated island width. This provides a strong indication of magnetic island induced transport. It is also in agreement with experiments with externally controlled static magnetic stochasticity [15] in TEXT-U tokamak. Given the overlapping of magnetic islands, this mechanism can be responsible for the total energy transport as it was implied in Refs. [7,8].

This work has been supported by the U.S. Department of Energy.

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