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The perpendicular electron energy flux driven by magnetic fluctuations in the edge of TEXT-U

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Abstract

A fast bolometer was used for direct measurements of parallel electron energy flux in the edge of TEXT-U. The fluctuating component of the parallel electron energy flux, combined with a measurement of magnetic fluctuations, provides an upper limit to the perpendicular electron flux. This magnetically driven energy flux cannot account for the observed energy flux.

PACS numbers	52.25.Fi	Transport properties
	52.25.Gj	Fluctuation phenomena
	52.35.Ra	Plasma turbulence
	52.55.Fa	Tokamaks

Introduction

The transport of both particles and energy across the magnetic field of tokamak edge plasmas is anomalously large[1]. Whereas particle transport in the plasma edge is now well explained by existing electrostatic turbulence data[2], it is not well established that the same electrostatic turbulence explains energy fluxes. Another possible mechanism to explain electron energy transport involves magnetic fluctuations. Here we demonstrate directly that magnetic fluctuations do not transport significant energy for the observed thermal transport in the extreme edge of TEXT [3].

A series of experiments was performed on TEXT-U in which the total particle flux and that associated with the measured electrostatic turbulence were compared[4]. The data showed agreement between the two fluxes in amplitude and in scaling with magnetic field and electron density, from which it was concluded that electrostatic turbulence could account for thermal particle transport in TEXT. Experiments on other machines have confirmed the agreement between total and electrostatic turbulence driven fluxes[2].

The situation concerning energy fluxes is less clear. The edge total energy flux, comprised of both conduction and convection, is more difficult to measure than the total particle flux because of significant losses from other mechanisms such as radiation, charge exchange, and ionization. Separating electron and ion fluxes is difficult because of uncertainties in the edge ion temperature and thus uncertainties in the power transfer between electrons and ions. Similarly the energy flux associated with electrostatic turbulence is more difficult to measure than the electrostatically driven particle flux because of the requirement for precise details of not just density and electric field fluctuations, but also temperature fluctuation information. Nevertheless attempts to compare total and electrostatic turbulence driven energy fluxes have been made, and within large error bars the electrostatic turbulence can explain electron energy flux[5]. Generally convection dominates conduction, making it difficult to separate the conducted component.

Another possible mechanism to explain the anomalous large edge conducted energy flux across the magnetic field is the destruction of magnetic surfaces by magnetic fluctuations. Direct measurements[6] of the associated flux in the Madison Symmetric Torus (MST) reversed field pinch (RFP) revealed a connection between the stochastic magnetic field structure and the radial heat transport. In tokamaks the associated conducted energy flux due to the túrbulent magnetic structure has not been measured directly; rather the turbulent magnetic fluctuation amplitude is measured and then a model used to estimate the energy flux. It is usual to assume that a quasi linear collisionless regime is applicable[7]; the measured magnetic fluctuations are then at least an order of magnitude too small to explain the observed energy flux[5]. However the choice of interpretive model can be crucial, for example invoking a strong turbulence regime has lead to the conclusion that the magnetic turbulence can explain edge energy transport[8]. In TEXT-U a series of experiments with externally controlled static magnetic stochasticity verified that the expected quasi linear collisionless formula was applicable for electron thermal transport, but failed to confirm the presence of other expected regimes[9]. The choice of decorrelation mechanism and thus decorrelation time is important.

It is assumed that runaway particles are transported[7] by magnetic fluctuations so that a measurement of runaway electron diffusion can be related to the magnetic fluctuations. Making certain assumptions concerning orbit averaging[10] allows the connection that $\chi_e / D \propto v_{\parallel \mathrm{thermal}} / v_{\parallel \mathrm{runaway}}$. Results[11] from modeling and measured diffusion of runaway electrons are that the inferred thermal conductivity resulting from magnetic fluctuations is several orders of magnitude too small to account for the observed energy transport in the edge of TEXT-U.

Because of the difficulties discussed above, it was decided to directly measure the link between magnetic fluctuations and cross magnetic field energy transport in TEXT following the techniques demonstrated on the reversed field pinch MST[6].

Experiment

TEXT-U is a medium sized tokamak with plasma major radius R = 1.05 m and minor radius a = 0.27 cm. For the results presented here, the toroidal field $B_T = 2.0$ T, the plasma current $I_p = 200$ kA and the central chord average plasma density $\bar{n}_e = 2\mathrm{x}10^{19}\ \mathrm{m}^{-3}$. The circular cross section plasma was defined by three rail limiters located at the top, bottom, and outside of the plasma at the same toroidal location. The toroidal magnetic field was in the same direction as the plasma current, and the ion grad **B** drift was upwards. The pyrobolometer was mounted on the top of the tokamak, displaced 90° toroidally from the limiters in the plasma current direction. The front edge of the pyrobolometer was located at the same radial location as the limiters (r = 0.27 m), with active area located 13 mm further out (at r = 0.283m) where the local measurements of temperature and density are $T_e \approx 30$ eV and $n_e \approx 2\mathrm{x}10^{18}\mathrm{m}^{-3}$.

Fluctuation induced transport fluxes are given by quadratic correlations of appropriate fluctuating quantities. The radial energy flux arising from electron motion parallel to the magnetic field is given by $Q_r = Q_\parallel \bullet \hat{r} = (Q \bullet \hat{b})(\hat{b} \bullet \hat{r})$ where $\hat{b}$ and $\hat{r}$ are unit vectors along the magnetic field and the radial direction respectively. Separating Q and $\hat{r}$ into equilibrium and fluctuating quantities yields the ensemble-averaged radial energy flux[12]

$$Q_r = \frac{<\tilde{Q}_\parallel \tilde{B}_r>}{B} \qquad (1)$$

where $\tilde{Q}_\parallel$ is the fluctuating electron heat flux parallel to the equilibrium magnetic field, $\tilde{Q}_\parallel = \int v_\parallel (mv^2 / 2)\tilde{f}(v)dv$, $\tilde{B}_r$ is the fluctuating radial magnetic field, and B is the equilibrium field. The ensemble average < > is realized experimentally by averaging many time records. Since the phase of the fluctuations is assumed random over a magnetic surface, the ensemble average approximates a magnetic surface average.

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. For that purpose we have developed a fast, insertable pyrobolometer[13,14]. The bolometer incorporates pyrocrystals of $LiNbO_3$ for parallel 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. Details of calibration and the design can found in references 13 and 14. The electrons enter the bolometer through two small, 1 mm in diameter, apertures on opposite sides of the bolometer's protective boron nitride shroud. When the bolometer is aligned along magnetic lines it measures the field aligned heat flux simultaneously in both directions, which yields the net parallel heat flux. The separation of the entrance apertures was 2.5 cm parallel to the field and it imposed the lower limit to the short wavelength resolution. The magnetic coil size in the radial direction was 50 mm which set the limit on the perpendicular wave vector.

The electron flux entering the bolometer can be controlled (gated) with the biased electrodes (repeller) situated between the entrance aperture and the pyrocrystal. The purpose of the gating is to decrease the total energy deposited into the bolometer. In the described experiments the length of the gating pulse was 8 ms. The measurements were taken during the constant current part of TEXT-U discharge 285 ms after the start of the discharge. The waveform of the parallel heat flux with 1 ms averaging is shown in Fig.1. Due to a high level of electrostatic pickup we were unable to resolve high frequency components of the heat flux; therefore, only low frequency components of the parallel heat flux are available for the analysis. The rms. amplitude of the low frequency parallel heat flux is $Q_{\parallel 0} = 80 \times 10^{-4}$ W/m^2.

The spectral power of the radial magnetic field fluctuation is shown in Fig. 2. The spectrum is similar to the poloidal magnetic field spectra described in reference 15. The rms. amplitude of the $\tilde{B}_r$ fluctuation with f > 10 kHz, $\tilde{B}_r^{rms}(f > 10kHz) = (\sum_{f>10kHz} |B_r(f)|)^{1/2}$ = 3.9×10^{-6} T; the total rms amplitude is $\tilde{B}_r^{rms} = 2 \times 10^{-5}$T. We mention a cutoff frequency of 10 kHz on the basis of reference 15 which demonstrated that low frequency components do not contribute to the fluctuation driven transport because the coherency between $\tilde{B}_r$ fluctuations and density fluctuations was nearly zero for low frequencies.

We estimate an upper limit on the magnetic fluctuation induced heat transport by the following procedure. Equation (1) can be spectrally decomposed as

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

where $|\tilde{Q}_{\parallel}(\omega)|$ and $|\tilde{B}_r(\omega)|$ are the spectral amplitudes of the two fluctuating quantities, $\gamma(\omega)$ is the coherence, and $\phi(\omega)$ is the phase shift between the fluctuating electron heat flux and the fluctuating radial magnetic field. First, we assume the spectral amplitudes $|\tilde{Q}_{\parallel}(\omega)|$ are less than $Q_{\parallel 0}$. Measurements on MST RFP[6] as well as the CCT tokamak[16] show this assumption to be valid. Second, we assume that $\gamma(\omega) = 1$, and a zero phase shift, $\phi(\omega) = 0$, for all modes. Third, we replace the $\tilde{B}_r$ amplitude by its rms value $\tilde{B}_r^{rms}$. After all that we have an upper limit estimate for equation 2

$$Q_{r\,max} = Q_{\parallel 0}\tilde{B}_r^{rms} / B \qquad (3)$$

For B = 2.0 T, $Q_{\parallel 0} = 80\text{x}10^{-4}$ W/m^2, and $\tilde{B}_r^{rms} = 2\text{x}10^{-5}$ T, Eq. 3 yields $Q_{rmax} = 8\text{x}10^{-8}$ W/m^2. This is much less than the loss rate at the last closed flux surface, $P_{Ohm}/A_s = 1\text{x}10^{-4}$ W/m^2, estimated from the input Ohmic power reduced by radiation and charge exchange losses. However our measurements were made 13 mm behind the limiter so that the total perpendicular energy flux is reduced from the 10^{-4} W/m^2 by parallel flow to the limiters. Measurements of density and temperature scale lengths [20-30 mm] and infrared camera measurements of the limiter temperature give a scale length for power loss of 10 mm. Therefore, the total perpendicular energy flux at the location of the pyrobolometer is of the order $0.3\text{x}10^{-4}$ W/m^2. This is still about a factor of 400 larger than the maximum electron thermal flux associated with magnetic fluctuations (8 x10^{-8} W/m^2).

Conclusions

By direct measurements of parallel heat flux and magnetic fluctuations, we have demonstrated that magnetic fluctuations cannot account for the observed thermal transport in the edge of TEXT.

Acknowledgments

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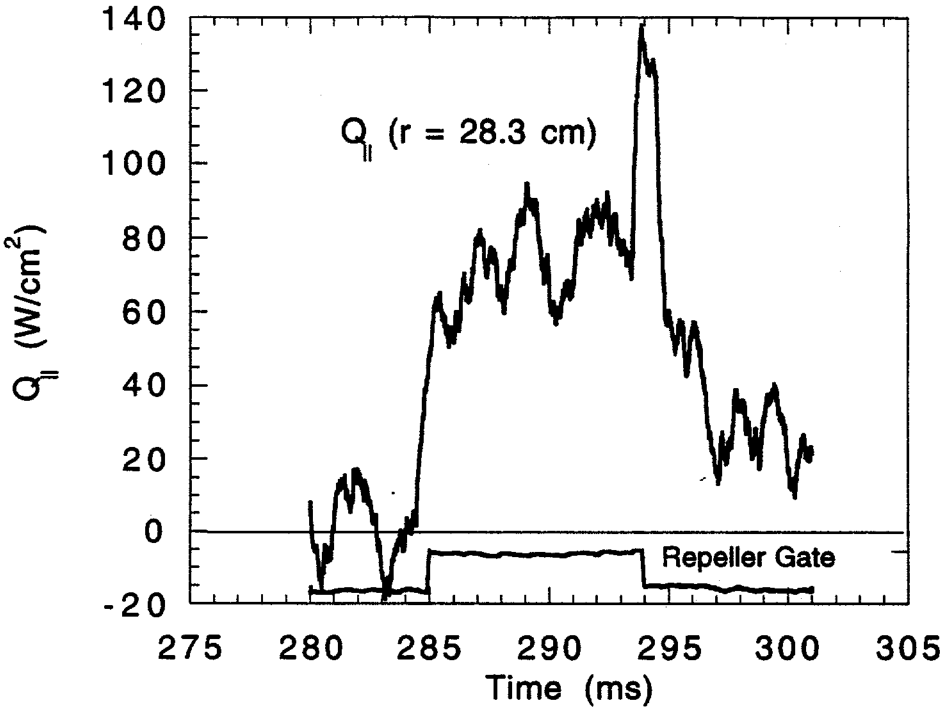
Figure captions

Fig. 1. Low frequency component (averaged over 1 ms) of the parallel heat flux. The repeller gating pulse shows the time window of the measurements. The radial position of the bolometer was r = 0.283 m.

Fig. 2. Spectral power of the radial magnetic field fluctuations. The radial position of the bolometer was r = 0.283 m.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$Q_{\parallel}$ (W/cm^2)
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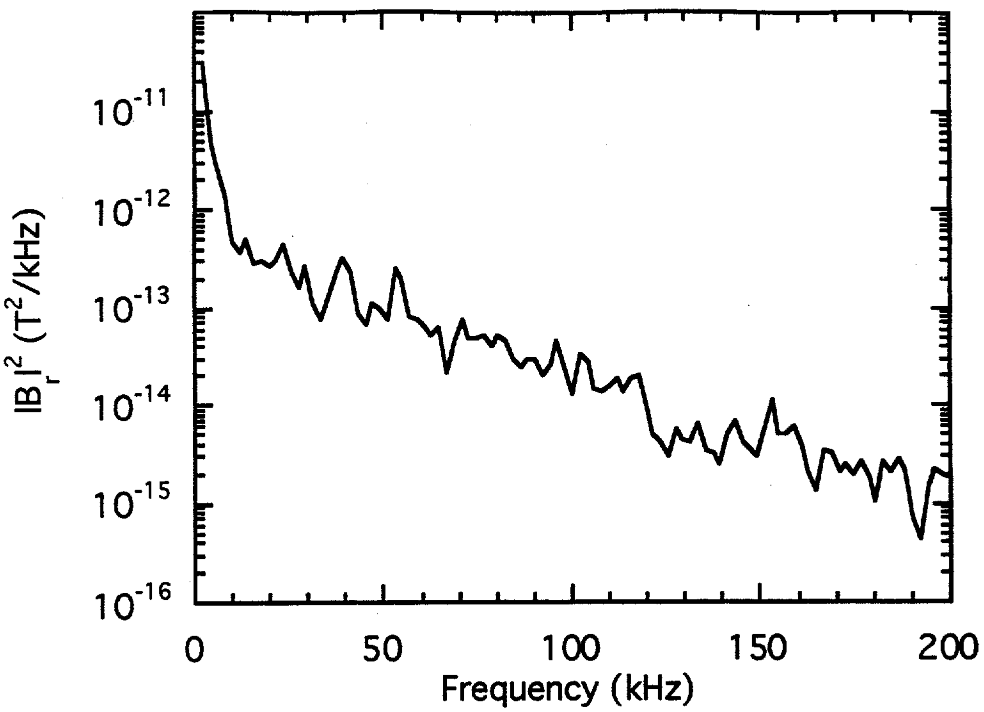
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10^{-14}
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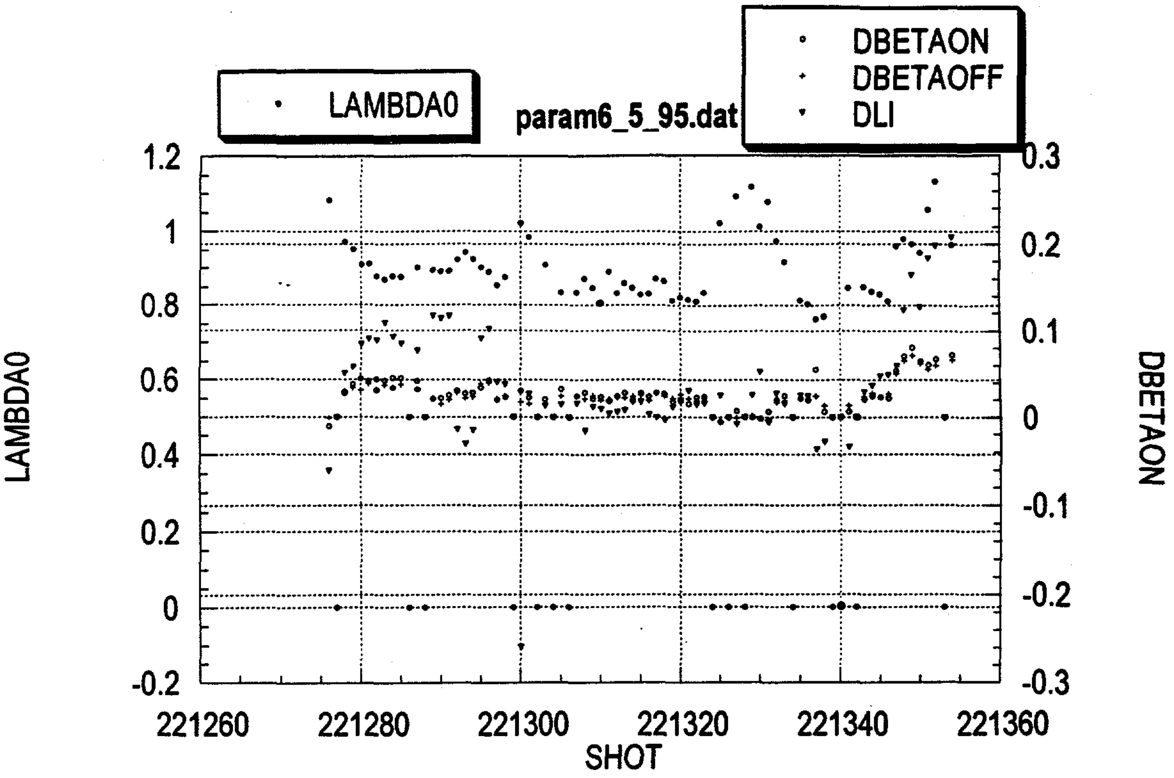
200
Frequency (kHz)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