# INVESTIGATIONS ON TEMPERATURE FLUCTUATIONS AND ENERGY TRANSPORT IN ETG DOMINATED LARGE LABORATORY PLASMA

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## Abstract

Large Volume Plasma Device (LVPD) has successfully demonstrated excitation of Electron Temperature Gradient (ETG) driven turbulence in finite beta ($\beta \sim 0.01 - 0.4$) plasma, satisfying threshold condition of ETG, $\eta_{\mathrm{ETG}} = \mathrm{L_n}/\mathrm{L_{T_e}} > 2/3$. Observed mode follows scale length and frequency ordering $k_\perp \rho_e \leq 1 << k_\perp \rho_i, \Omega_i < \omega << \Omega_e$, where $k_\perp$ is the perpendicular wave vector, $\rho_\mathrm{e}, \rho_\mathrm{i}$are Larmor radii of electron and ion, respectively, and $\Omega_\mathrm{i}, \Omega_\mathrm{e}$ $\omega$ are the ion, electron gyro frequencies and the mode frequency respectively. The paper discusses results on measurement of energy flux in LVPD due to the ETG turbulence and diagnostic development for this measurement. The experimentally observed radial heat flux found comparable to theoretically estimated values.

## 1. INTRODUCTION

Plasma confinement and control of plasma transport remains a significant challenge towards achieving fusion power. Plasma confinement is determined mainly by collective modes, arises due to the presence of gradients in density, temperature , magnetic fields, etc. These gradients works as a free source of energy and leads to the generation of different instabilities, enabling anomalous transport of plasma particles and energy. Although, it is well known that during L-mode operation, both ion and electron thermal transport remains anomalous in nature but in high confinement (H-mode) scenerio, due to the presence of internal transport barrier, ion heat transport no more has remains anamolous in nature whereas electron thermal transport still remain anomalous. Focus is thus shifted to the understanding of physics of anamalous electron heat transport across the confining magnetic field, well envisaging its implications for ITER and advanced Tokamak discharges[1]–[4].

Available literature on numerical and theoretical approaches shows significant advancement in contribution on ETG turbulence and transport but experimental investigations provides no direct evidence of its existence in tokamaks. The reason for no direct measurement of ETG may be due to the extremely small-scale length in high magnetic field environment of fusion devices ($k_\perp \rho_e \sim 1$ when $\rho_e \sim \mu m$ ). The ETG mode is a short wavelength, low frequency mode, $k_\perp \rho_e \leq 1 \ll k_\perp \rho_i$, $\Omega_i < \omega \ll \Omega_e$ where $k_\perp$ is perpendicular wave-vector, $\rho_e$ and $\rho_i$ are the larmor radii of electron and ion, respectively, $\Omega_e$ $(= eB/m_e)$, $\Omega_i (= eB/m_i)$ and $\omega$ are electron, ion gyro-frequencies and mode frequency respectively[5].

Introduction of Electron Energy Filter (EEF) divides LVPD plasma into three distinct experimental regions of Source, EEF and Target plasmas. Unambiguous, identification of ETG turbulence is successfully demonstrated in core region of target plasma ( $x \leq 45cm$ )[6], [7].

In presence of ETG turbulence, measurements of particle flux has been carried out and inward turbulent particle flux is observed which is against the law of entropy production[8], [9]. Here an attempt is made to measure radial heat flux transport. A specially designed triple Langmuir probe for real time measurement of temperature fluctuations in pulsed plasma of LVPD is used. The estimated thermal flux is compared with the numerically obtained values, by using the formulation derived for ETG turbulence in a slab geometry.

This paper is organized as follows: the details on experimental setup and diagnostics are discussed in section 2. The experimental results and discussion on ETG turbulence and measurement of conductive heat fluxes with comparison with theoretically obtained values will be given in section 3. Finally, paper will conclude with summary in section 4.

## 2. EXPERIMETAL SETUP AND DIAGNOSTIC DEVELOPMENT

The experiments on energy flux measurement is carried out in target region of Large Volume Plasma Device (LVPD)[10]. LVPD is a cylinderical device producing plasma in it by using a combination of radial and axial confinement schemes. The radial confinement is provided by a set of 10 garlanded coils producing axial magnetic field, $B_z \sim 6.2$ Galong its length and axial confinement by a pair of cusped ($-4$ kG, surface field) back and end plates. The plasma source contains 36 numbers of hairpin shaped tungsten filaments , distributed in a periphery of a rectangle of size $(130cm \times 90cm)$. The pulsed Argon plasma of duration, $\Delta t_{discharge} \sim 9.2\ ms$ is produced by appliying a discharge voltage of -70 V between filament assembly and the anode ( device). The EEF is a rectangular shaped solenoid made up of 155 number of turns and is divided into 19 discrete set of coils being controlled independently from outside the device.

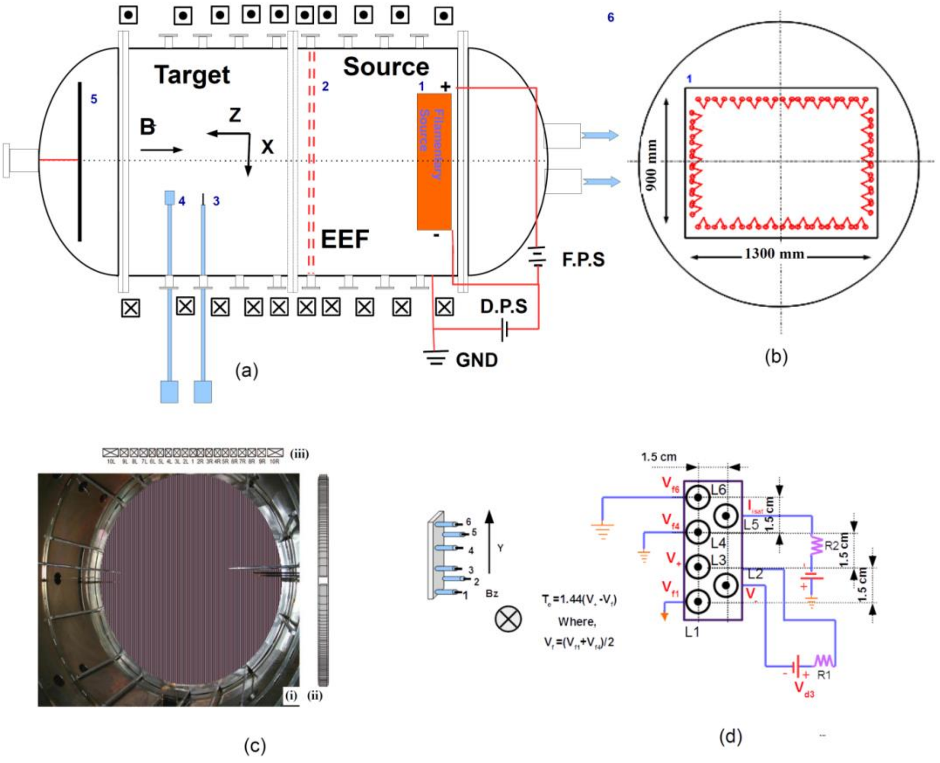

*Fig. 1: Schematic of experimental Device (Large Volume Plasma Device) (a) Top View of Large Volume Plasma Device, (b) front view of filament assembly in the source side of device, (c) the photograph of EEF mounted within the device. The Top side bar serves as coil identifier and RHS side bar defines extent of aspect ratios of each of the 19 coils and (d) Langmuir probe assembly for simultaneous measurement of potential and temperature fluctuations for heat flux measurement.*

The measurement of basic plasma parameters (electron temperature, $T_e$ , plasma density, $n_e$ , floating potential, $\phi_f$ and plasma potential, $\phi_p$) is undertaken by using conventional cylindrical Langmuir probes (W,

$\Phi = 1mm$ and $L = 5mm$) and Centre Tapped Emissive Probe (CTEP)[11]. The plasma density is estimated from the ion saturation current, measured by keeping the probe at fixed bias of $\sim -80V$. Specially designed compensated Langmuir probes are used for the measurement of electron temperature by sweeping the probe between $-80V - +20V$ over a swept period of $500\mu s$. All these probes are mounted at different axial locations in the ETG region on radially movable probe shafts. The floating potential is measured in floating condition of Langmuir probe. The mean electron temperature obtained with single Langmuir probe (SLP) is compared with triple Langmuir probe (TLP) diagnostic for real time temperature fluctuations measurements.

The TLP diagnostic developed for real time, temperature fluctuation measurements in pulsed plasma of LVPD offer salient features namely, 1) bandwidth $\le 300\,kHz$, 2) galvanic isolation $\ge 250V$, 3) input impedance for voltage measurement exceeding $\sim 10M\Omega$ and current measurement with shunt resistor $\sim 300\Omega$ respectively. The probe assembly shown in figure 1(d), consists of two sets of three Langmuir probe. Each probe is having dimension $(W, \phi = 1mm, L = 8mm)$. Probes numbering, L1, L2, L3 and L4 are used for electron temperature measurement. The poloidally separated probes L1, L4 and L6 are used to measure floating potential. The potential $(V_+)$of positively biased probe L3 is also measured. The Langmuir probe L5 measures ion saturation current and is biased at high negative potential with respect to plasma potential to estimate mean and fluctuations density of plasma. By choosing suitable value of bias voltage between L2 and L3, one calculates electron temperature, $T_e$ by using expression $T_e = (V_+ - V_f)/\log 2$, where $V_f$ is the average value of $V_{f1}$ and $V_{f4}$ [12].

The fluctuating poloidal electric field, $E_\theta$ can be obtained by vertically separated probes using $\widetilde{E_\theta} = -\partial\tilde{\phi}/\partial y$ where $\delta V_r$ is derived from $\delta E_\theta \times B$ drift. The radial velocity fluctuations are responsible for conductive $(n_o < \delta T_e \delta V_r >)$ and convective heat flux $(T_e . < \delta n_e \delta V_r >)$ having correlation to temperature and density fluctuations respectively. The fluctuations in electron temperature, $\delta T_e$, density , $\delta n_e$ and potential, $\delta\phi$ are measured for the complete plasma peroid of $10\,ms$ with a smapling rate of $1MS/s$. The data is acquired with a 12bit digitizer based PXI data acquisition system. An ensemble of 100 shots from the steady state window is used for carrying out spectral analysis viz., correlation, coherency, phase, power spectra and joint wave number - frequency spectrum, S(k,w)[13].

## 3. EXPERIMENTAL RESULTS AND DISCUSSION

The measured profiles of plasma density, and elctron temeprature in the target region of LVPD satisfies the plasma background conditions for excitation of ETG turbulence. Uniform radial plasma potential profile ensures the absence of radial electric field in the core of target plasma. Radial profiles of plasma density and electron temperature are shown in figure 2(a) and 2(b). The obtained $S(k,w)$ and radial profiles of plasma density and electron temperature satisfies the condition $k_\perp \rho_e \le 1$ and $k_\perp \rho_i > 1$ , and frquency odering $\omega_{ci} < \omega \ll \omega_{ce}$.The scale length of density, $L_n = \left(\frac{1}{n}\frac{dn}{dx}\right)^{-1} \approx 300\ cm$ and electron temperature , $L_{T_e} = \left(\frac{1}{T_e}\frac{dT_e}{dx}\right)^{-1} \approx 55\ cm$ satisfies the threshold, $\eta_{ETG} = L_n / L_T > 2/3$ of ETG turbulence in the core region ( $x \le 45cm$).

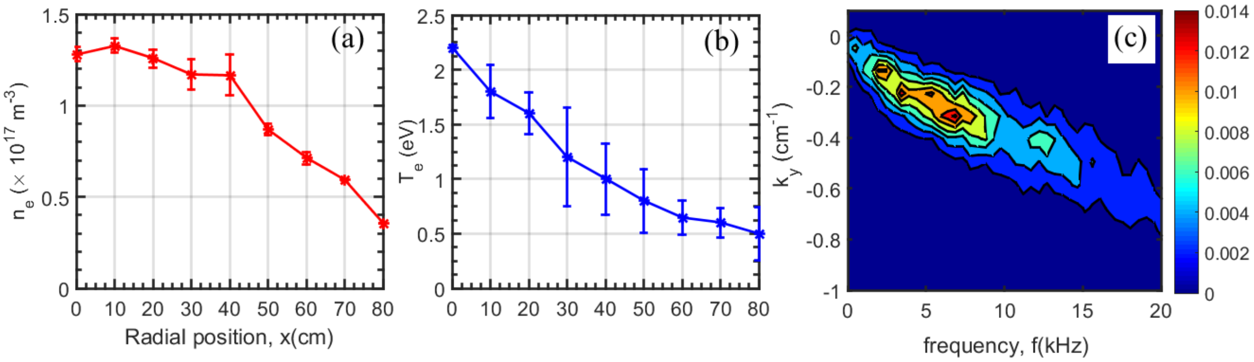

*Fig. 2: Radial profiles of (a) plasma density,* $n_e$ *, (b) electron temperature,* $T_e$ *, and (c) the joint wave number –frequency, S(*$k_y$ *,* $f$*) , where,* $k_y$ *is the poloidal wave vector.*

The collective oscillations due to ETG turbuelnce is responsible for the heat transport. The typical heat flux due to broad band fluctuations can be estimated by simulatneous measurement of temperature and potential fluctuations. A theoretical expression is formulated for the radial heat flux due to ETG scale fluctuation to verify our experimental measurement of radial heat flux. The theoretical expression for heat flux due to ETG fluctuations is obtained by use of ETG model equations since density and temperature fluctuations are related with potential equations as follows[6]

$$\tilde{n} = -\tau_e^* \tilde{\phi} \qquad (1)$$

And

$$\tilde{T} = \left[\left(\eta_e - \frac{2}{3}\right)\frac{\hat{k}}{\hat{\omega}} - \frac{2}{3}\,\tau_e^*\right]\tilde{\phi} \qquad (2)$$

Where $\tilde{n} = \frac{\delta n_e}{n_e}$ , $\tilde{\phi} = \frac{e\delta\phi}{T_e}$, $\tau_e^* = T_e/T_i(1 + i\delta_k)$, $\widetilde{T_e} = \frac{\delta T_e}{T_e}$, $\eta_e = \frac{L_n}{L_{T_e}}$ , $\hat{k} = k_y\rho_e$and $\hat{\omega} = Z\omega/c_e$, $T_e(T_i)$ is electron(ion) temperature, $L_n(L_{T_e})$ is density (temperature ) scale length , $k_y$ is poloidal wave number, $\rho_e$ is electron larmor radius, Z is axial length of device , $\omega$ is turbulence frequency and $c_e$ is electron thermal velocity. Here $\delta_k$ is taking care of ion non -adiabatic response[14] which is $\delta_k = \sqrt{\pi}\frac{\omega}{k_\perp V_{thi}}\exp(-\frac{\omega^2}{k_\perp^2 V_{thi}^2})$.

$$q = \frac{3}{2} n_0 c_e T_{e0} \Re \sum_k [(\eta_e - \frac{2}{3}) \frac{c_e \gamma_k (k_y \rho_e)^2}{L_n |\omega_k|^2} \left|\frac{e\delta\varphi_k}{T_{e0}}\right|^2 + \frac{2}{3}\frac{\delta n_{ek}}{n_0} i k_y \rho_e \frac{e\delta\varphi}{T_{e0}}] \qquad (3)$$

Figure 3(a) represents the phase angle between temperature and potential fluctuations corresponding to frequency and wave number at maximum power. This measurement is in good agreement of phase angle obtained by ETG model equations (1)-(2). Also, a confirmation of its validity can be envisaged from the fact that in the non ETG region, it deviates significantly in experiments.

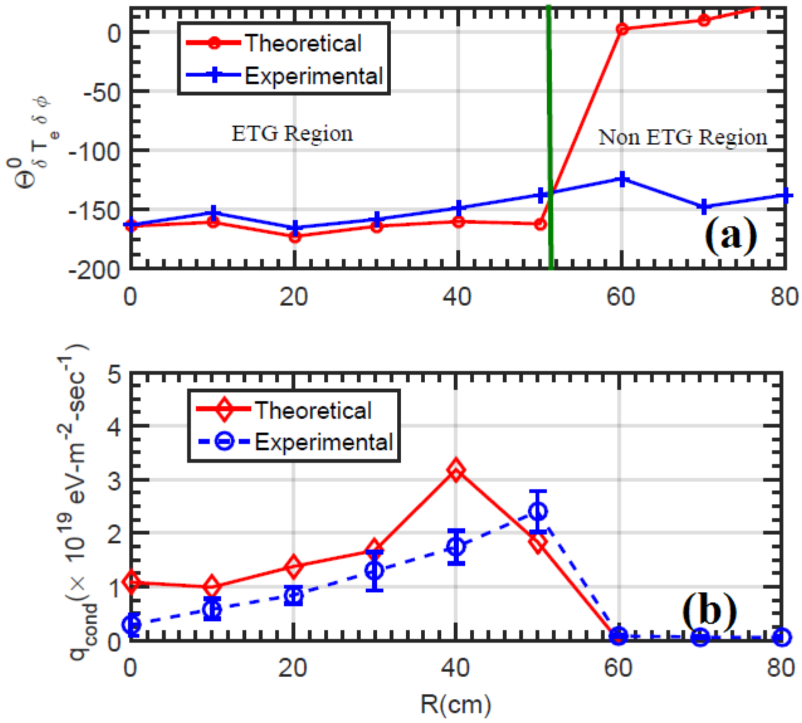

*Fig. 3: Phase angle plot between temperature and potential fluctuations for ETG turbulence in comparison with theoretical estimations (a) and the conductive heat flux measured due to correlated temperature and potential fluctuations in ETG turbulence (b).*

We measured heat flux ($q$) at different radial locations by using the Langmuir probe assembly [Fig 3(b)]. Temperature fluctuations are measured using TLP and density fluctuations is estimated from ion staturation current fluctuation measurement. The estimated conductive heat flux is shown figure 3(b). The measurement of radial heat flux is also in good match of heat flux estimated with ETG heat flux given in equation (3) ensures the validity of experimental observations.

## 4. SUMMARY AND CONCLUSION

The paper discusses the heat flux generated due to finite temperature and potential fluctuations in ETG turbulence dominated plasma. The role of temperature fluctuations in the measurement of conductive heat flux is envisaged. The phase angle between temperature and potential fluctuations shows good match with theoretical prediction obtained from ETG model equations.

The observed conductive heat flux ($n_o < \tilde{T}_e \tilde{v}_r >$) is positive in comparison to the observed particle flux reported by Prabhakar et. al. [8] in ETG turbulence condition of Large Volume Plasma Device. This observation is in good support of thermodynamically predication of positive change of entropy, as it ensures entropy production positive definite. Further understanding of thermal conductivity obtained due to temperature fluctuations can support to understand the heat/energy loss in fusion devices due small scale fluctuations. This qualitative and quantitative measurement can use to scale the heat flux losses in most of Tokomak and study on control for such losses can helps to better confinement of energy in H-mode.

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