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Fluctuation measurements with the 2-D ECE Imaging system on TEXTOR

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Introduction

The experimentally determined transport levels in tokamak plasmas are one to two orders of magnitude higher than predicted by neoclassical transport theory [1]. This extra transport is thought to be due to plasma turbulence. Fluctuations of the plasma electron temperature T_e, electron density n_e, electric field E and magnetic field B can result in additional radial transport of heat and particles. A wide variety of candidate turbulent modes has been discussed in the literature [2-5].

The turbulent electron temperature fluctuations can in principle be measured by ECE. But the expected fluctuation levels (a few tenths of a percent in the centre, up to a few percent at the edge) are small compared to the (unavoidable) thermal noise in ECE measurements. Consequently, a direct observation of temperature fluctuations by ECE is not possible. Correlation techniques are necessary to suppress the thermal noise to levels significantly below the expected level of temperature fluctuations.

The 2-D ECE Imaging (ECEI) diagnostic [6] on TEXTOR (B_T=1.9-2.6T, R=1.75m, a=0.46m, circular cross-section, limiter) is designed for measuring small-scale, high frequency temperature fluctuations. This paper explores the feasibility of fluctuation measurements using ECEI. The characteristics of the ECEI system, relevant for fluctuation measurements, are discussed. As proof of principle and illustration of the analysis techniques, fluctuation measurements of the so-called quasi-coherent mode [7] near the plasma edge are presented, demonstrating the capabilities of ECEI.

2-D ECE Imaging system

The newly installed ECEI diagnostic at TEXTOR yields real time 2-D measurements of the electron temperature in an 8 by 16 array of sampling volumes, corresponding to an approximately 8 by 16 cm area of the poloidal cross section of the TEXTOR plasma (see Fig. 1).

ECEI differs from a conventional ECE radiometer in that the ECE radiation from the plasma is imaged onto an array of 16 detectors. This setup enables simultaneous measurement of 16 horizontal sightlines. Each sightline is subsequently treated as a normal ECE radiometer with 8 channels. This gives a 2-D array of 8 (radially) by 16 (vertically) sampling volumes in the poloidal plane. The inter-channel spacing in the radial direction is 0.5 GHz,

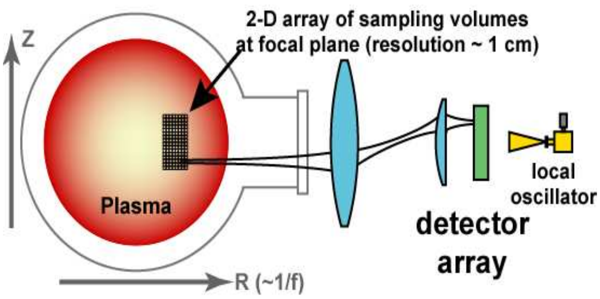

Fig. 1: Schematic overview of ECEI. (In reality reflective optics are used).

corresponding to typically 1 cm in the plasma. Also the inter-channel spacing in vertical direction is about 1 cm (determined by the optics).

The system is designed to observe the second harmonic X-mode ECE radiation in a 4 GHz wide frequency band, tunable over the frequency range of about 100 to 130 GHz. Under normal TEXTOR operation (B_T=2.25 T) this provides access to the center and the low field side of the plasma.

The spatial resolution in the direction perpendicular to the line of sight is typically 12 mm vertically and 9 mm toroidally (FWHM) in the focal plane of the optics. The focus can be shifted to ensure that the observation volume is always in focus.

The spatial resolution in the radial direction is determined by the bandwidth of the ECE radiation selected by each channel (B_{IF}) and by the plasma parameters, the same as with a conventional ECE radiometer. The IF bandwidth B_{IF} of 300 MHz, along with broadening effects in the plasma, leads to a radial resolution below 1 cm.

The time resolution is determined by the video bandwidth B_V of the system. The maximum B_V, and hence the maximum detectable fluctuation frequency, is currently set to 200 kHz. The sampling frequency is normally set to twice the video bandwidth.

The accuracy of the temperature measurements is determined by the thermal noise level, which forms a fundamental limitation of ECE measurements. Increasing B_V (better time resolution) or decreasing B_{IF} (better spatial resolution) increases the relative thermal noise level according to [8]:

$$\frac{\sqrt{\langle \Delta T_R^2 \rangle}}{\langle T_R \rangle} = \sqrt{\frac{2B_V}{B_{IF}}} \qquad \text{Eq. 1}$$

Taking B_{IF}=300 MHz and B_V=200 kHz gives a thermal noise level of about 4%. This value is close to the experimentally observed noise levels of the ECEI.

Correlation measurements

The thermal noise can be suppressed by cross correlating two signals with independent noise. The correlated fluctuations that are present in both signals will survive the cross correlation and will be revealed in the cross correlation function. The cross correlation function $C_{12}(l)$ of two signals $S_1(t)$ and $S_2(t)$, as a function of the time lag l can be written as

$$C_{12}(l) = \lim_{T_M \to \infty} \frac{1}{T_M} \int_0^{T_M} S_1(t) S_2(t+l)\,dt \qquad \text{Eq. 2}$$

where T_M is the time over which S_1 and S_2 are measured. $C_{12}(l)$ can be seen as the dot product between S_1 and S_2 shifted by a time lag l. If S_1=S_2 one speaks of the auto correlation function. Figure 2 gives some examples of correlation functions for some idealised synthetic signals. The amplitude of the (correlated part of the) fluctuations is found by taking the square root of the amplitude in C_{12}.

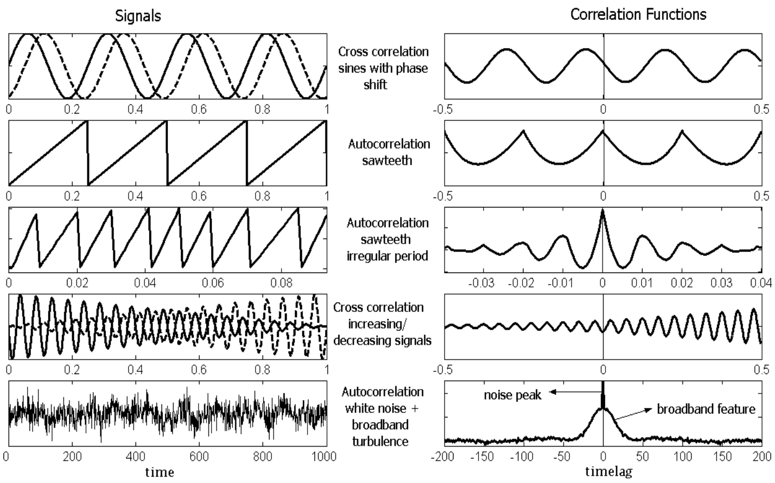

Fig. 2: Examples of correlation functions for typical signals.

Correlating (discrete) signals of length N reduces the noise by a factor of $N^{1/2}$. Because fluctuations are contained quadratically in C_{12}, this leads to a minimal detectable fluctuation level of

$$\frac{\sqrt{dT_R^2(t)}}{\langle T_R(t)\rangle} = N^{-1/4}\sqrt{\frac{B_V}{B_{IF}}}\,. \qquad \text{Eq. 3}$$

For ECEI data at maximal sampling rate, taking 2s of data (10^6 data points), this theoretically leads to a minimal detectable fluctuation level of about 0.1 %.

Correlated broadband phenomena with bandwidth B cause a peak in C_{12} that falls off with a decay time

$$\tau_{1/2} = \sqrt{\frac{\ln 2}{\pi}}\cdot\frac{1}{B} \qquad \text{Eq. 4}$$

Optical thickness

The optical thickness is a very important plasma parameter for the interpretation of fluctuation measurements (especially near the plasma edge). For 2nd harmonic X-mode radiation well below the cut-off frequency the optical thickness τ_0^{2X} is [9]:

$$\tau_0^{2X} = \frac{\pi k_B e}{\varepsilon_0 m_e c^3}\cdot n_e T_e \cdot \frac{R^2}{B_0 R_0} \qquad \text{Eq. 5}$$

Only in optically thick plasmas ($\tau>>1$) does the measured radiation intensity reach the Rayleigh-Jeans intensity, and is consequently only a function of electron temperature. In optically thin plasmas (neglecting the possible influences of suprathermal radiation and wall reflections) the measured radiation temperature T_R can be expressed as:

$$T_R = T_e\left(1-e^{-\tau}\right) \qquad \text{Eq. 6}$$

Since the optical thickness τ is a function of both n_e and T_e, not only temperature fluctuations, but also density fluctuations will result in fluctuations of T_R. Assuming dT_e and dn_e have the same phase, a first order approximation gives [10]:

$$\frac{dT_R}{\langle T_R\rangle} = (1+a)\frac{dT_e}{\langle T_e\rangle} + a\frac{dn_e}{\langle n_e\rangle} \quad with \quad a = \frac{\tau\cdot\exp(-\tau)}{1-\exp(-\tau)} \qquad \text{Eq. 7}$$

For example, for $\tau=2$ about 30% of the density fluctuation level is seen in T_R. For $\tau>6$ density fluctuations hardly influence T_R.

First fluctuation measurements near the plasma edge

Previously reported measurements with the TEXTOR O-mode reflectometer [7] have shown the existence of certain density fluctuations near the plasma edge, the so-called quasi-coherent mode, with a typical frequency of 50-100 kHz, amplitudes of up to a few percent and high poloidal mode number (around m=50). This quasi-coherent mode provides a test bed for the ECEI system.

The cross correlation function shown in figure 3a, measured with ECEI at R=2.17m (about 8 cm from the edge at the low field side), shows a clear 90 kHz oscillation around zero time lag. From the decay of the fluctuation amplitude with increasing time lag, a bandwidth of around 50 kHz can be derived (eq. 4), in good agreement with simultaneous reflectometer measurements at the same radius. The broad peak in the correlation function (on which the quasi-coherent mode is superposed) is the footprint of a low frequency broadband fluctuation with bandwidth around 10 kHz. The plasma ($B_{T,0}$=2.25T, I_p=400kA, $n_{e,l.a.}$=2.7e19 m^{-3}) was ECRH heated (800 kW).

The contour plot in figure 3b shows the cross correlation function as a function of poloidal channel separation Δs (relative to a reference channel 3 cm above the equatorial plane). From the phase shift as a function of Δs, a poloidal velocity of about 6 km/s can be deduced. From the Δs needed to get a phase shift of 2π, the poloidal wavelength can be estimated to be around 6.7 cm (alternatively $\lambda_{pol}=v_{pol}/f$), from which a poloidal mode number around m=40 is found. Since the analogous contour plot for radial separations doesn't show any phase shift, it can be concluded that the radial velocity is zero (or too large to resolve).

The measured radial dependence of the fluctuation amplitude is given in figure 3c (red curve). Due to the low optical thickness (about 1.5 at the outboard side of the observation volume, rapidly increasing towards the plasma centre) a mixture of electron density and electron temperature fluctuations is measured. From the electron temperature and density profiles, the optical thickness τ (eq.5) and the parameter a of eq. 7 can be calculated. The general radial dependence of the density fluctuation amplitude (dashed line in fig 3c) is known from reflectometer measurements [7], so the density fluctuation contribution to the measured radiation temperature fluctuations can be estimated (a*dn/n) and is given by the blue line in figure 3c. The shaded area in figure 3c indicates (1+a times) the electron temperature fluctuation amplitude.

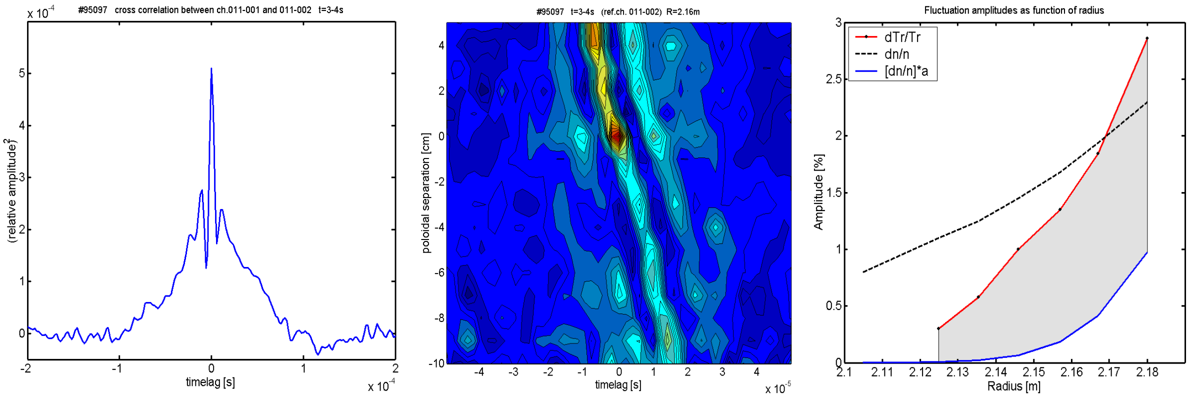

Fig. 3: ECEI fluctuation measurements of the quasi coherent mode; a) Typical cross correlation function C_{12}; b) Poloidal evolution of C_{12}; c) Radial dependence of fluctuation amplitudes.

Conclusions and outlook

The specifications of the new TEXTOR ECEI system enable measurements of electron temperature fluctuations up to 200 kHz and with a spatial resolution of 1 cm. The sensitivity of the system is limited by the unavoidable thermal noise, but this noise can be suppressed by using correlation techniques. This leads to a sensitivity as good as 0.1 %.

Measurements of the quasi-coherent (QC) mode near the plasma edge, show the capability of the ECEI system to measure high frequency, small-scale fluctuations. These measurements also show that the QC mode is not only visible as a density fluctuation, but also as a temperature fluctuation.

In the near future, measurements of the (smaller) core temperature fluctuations will be attempted in order to give new insights into the mechanisms of anomalous, turbulent transport.

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