Measurement of turbulent electron temperature fluctuations on the ASDEX Upgrade tokamak using correlated Electron Cyclotron Emission[a)]

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Turbulent temperature fluctuations are measured on the ASDEX Upgrade tokamak using pairs of closely spaced, narrow-band heterodyne radiometer channels and a standard correlation technique. The pre-detection spacing and bandwidth of the radiometer channel pairs is chosen such that they are physically separated less than a turbulent correlation length, but do not overlap. The radiometer has 4 fixed filter frequency channels and two tunable filter channels for added flexibility in the measurement position. Relative temperature fluctuation amplitudes are observed in a Helium plasma to be $\delta T/T = (0.76 \pm 0.02)\,\%$, $(0.67 \pm 0.02)\,\%$ and $(0.59 \pm 0.03)\,\%$ at normalised toroidal flux radius of $\rho_{\text{tor}} = 0.82$, 0.75 and 0.47 respectively.

I. INTRODUCTION

For the design of future fusion reactors, a physics based understanding of the heat loss channels is an essential element. It is now accepted that the anomalously high heat transport observed in tokamaks is due to turbulent fluctuations driven by drift-wave like instabilities in the plasma[1]. Much progress has been made over the past few decades in understanding and modelling the underlying turbulent mechanisms and large gyro-kinetic modelling codes are now often able to reproduce experimental heat fluxes within error bars (see for example[2,3]). Validation of their predictions against measurements of the underlying turbulent micro-structure, such as fluctuation amplitude, correlation length, fluctuation phase relations and spectral index, can serve to help refine and reduce these models further.

Under regular tokamak conditions, core turbulent electron temperature fluctuations are sufficiently broadband (∼0.5 MHz) and low-amplitude (∼1 %) that a conventional radiometer is fundamentally unable to detect them and thus correlation techniques are required to further extract the signals[4–8]. This situation arises, as can be seen from Equation 1, from the fact that to increase the sensitivity of a radiometer one must either decrease the video bandwidth, B_{vid}, or increase the pre-detection bandwidth, B_{IF}. Limits are set on B_{vid} by the fluctuation bandwidth and on B_{IF} by the spatial scale of the turbulence and the linewidth of the ECE emission.

$$\frac{\delta T_{\text{e}}}{T_{\text{e}}} > \sqrt{\frac{B_{\text{vid}}}{B_{\text{IF}}}} \tag{1}$$

The first use of cross-correlation to measure temperature fluctuations utilised two radiometer channels with differing lines of sight to the same volume of plasma[5]. The two lines of sight ensured that the thermal noise fluctuations were uncorrelated, while the common temperature fluctuations remained correlated[4]. Later, the same line of sight was used and closely-spaced, non-overlapping frequency channels served to separate thermal noise from temperature fluctuations[6]. Here we describe a CECE radiometer of the latter type which has allowed, for the first time, measurements of turbulent temperature fluctuations on ASDEX Upgrade (AUG) and the first turbulent temperature fluctuations in Helium plasmas.

II. CORRELATION ECE DIAGNOSTIC

A Correlation Electron Cyclotron Emission (CECE) diagnostic utilises cross-correlation in order to be able to measure small, broadband temperature fluctuations. Defining a pair of series of fluctuating ECE power (i.e. with zero mean) as $\{x(t), y(t)\}$ and their corresponding one-sided cross-spectral density functions $\{G_x(f), G_y(f)\}$, then we can define the coherence function $\gamma(f)$ as,[9]

$$\gamma(f) = \frac{|G_{xy}(f)|}{\sqrt{G_x(f)G_y(f)}} \tag{2}$$

$G_x(f)$ is estimated from an ensemble average of N independent time records. The temperature fluctuation level up to the limit f' can then be calculated by the integral of the coherence over the video bandwidth,

$$\left(\frac{\delta T_{\text{e}}}{T_{\text{e}}}\right)^2 = \frac{1}{B_{\text{IF}}} \int_0^{f'} \gamma(f)\, df \tag{3}$$

The cross-correlation allows further averaging to be performed without reducing the video bandwidth of either signal. The sensitivity of such a radiometer is then given by:

$$\frac{\delta T_{\text{e}}}{T_{\text{e}}} > \left(\frac{B_{\text{vid}}}{2\Delta t}\right)^{1/4} \left(\frac{2}{B_{\text{IF}}}\right)^{1/2} \tag{4}$$

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The correlation ECE radiometer at AUG is installed on an optical front end which was made for the AUG steerable Doppler reflectometer[10]. Plasma radiation is focussed by a steerable elliptical mirror into a smooth-bore broad-band Gaussian-beam antenna, as shown in Fig. 1. The internal bore of the antenna is 25 mm long and varies in radius from 19 mm to 28 mm at the mouth[10]. The antenna is then coupled to a 38 mm oversized waveguide, which is in turn coupled to a 3 dB splitter in order that the reflectometer and CECE can operate simultaneously. After the splitter, the oversized waveguide is tapered down in stages to fundamental F-band waveguide and passed through a sideband filter between 105-113 GHz or 117-125 GHz. This forms a hybrid waveguide-quasioptical system with the potential of later performing correlation analysis between reflectometer and CECE channels. Fig. 2 shows the electronic schematic for the receiver. After the sideband filter, the signal is passed through a Millitech MSH-08 x2 subharmonic mixer which is powered by a Millitech GDV-15 Gunn-varactor tuned local oscillator (LO) which may be tuned in the range 57.5 GHz ± 900 MHz. This tuning allows flexibility in the measurement positions.

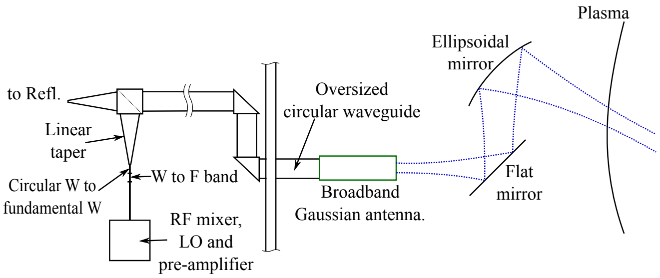

FIG. 1. Schematic showing the optical setup for the correlation ECE. The optical path is shared by the ASDEX-Upgrade steerable Doppler reflectometers.

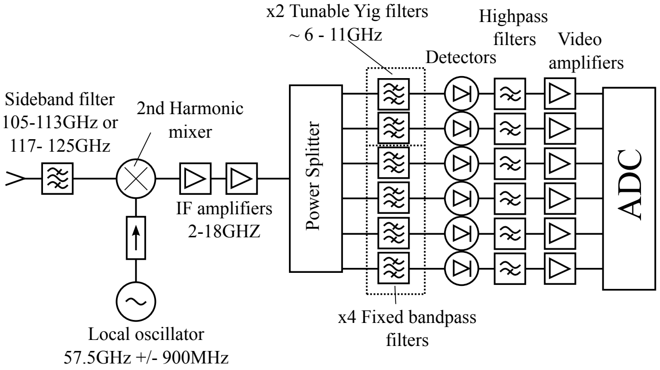

FIG. 2. A schematic of the CECE electronics. A filter bank includes 4 fixed and 2 tunable narrow-band filters.

A combination of power splitters and filters make up the CECE filter bank and the diagnostic has four fixed frequency pre-detection filters which can be easily modified, but typically consist of filters centred around 4.000, 4.250, 8.000 and 8.250 GHz and of 100 or 200 MHz bandwidth. The other two channels may consist of either 100 or 200 MHz bandwidth YiG filters whose centre frequencies are tunable in the range 6 - 12 GHz and allow important flexibility in the measurement position. The filters are controllable remotely over ethernet via a 'Control By Web' X-312-I analogue output module.

CECE is sensitive to comparatively long wavelength fluctuations relevant for studying Ion Temperature Gradient (ITG) and Trapped Electron Mode (TEM) turbulence. The calculation of the sensitivity of the diagnostic as a function of wavelength is described by Bravenec[11] and is completely defined by the spatial volume of the measurement in the plasma. For CECE the radial resolution is set by a combination of the broadening mechanisms for the ECE line radiation (predominantly the relativistic mass change as a function of electron energy and the re-absorption of the ECE radiation by the plasma[12]) and the filter bandwidth and spacing. The perpendicular wavelength limit is set by the Gaussian beam width at the measurement position. For the current set-up the $1/e$ electric field radius of the Gaussian beam w_{meas}, between ρ_{tor} of 0.7 to 0.9 is approximately 3.7 cm, giving a perpendicular wavevector limit $k_{\perp,\mathrm{lim}} = 2\sqrt{2}/w_{\mathrm{meas}}$ of 0.76 cm^{-1}. w_{meas} will be reduced to 2.0 cm in the next experimental campaign with the installation of a new focussing mirror, giving an increased $k_{\perp,\mathrm{lim}}$ limit of 1.4 cm^{-1}. In units of the ion Larmor radius ρ_i, these translate to a $k_\perp \rho_i$ value of 0.15 and 0.28 respectively. Radially, pairs of frequency channels are spaced 2-4 ρ_i, within the expected radial correlation length for the turbulence of between 5-10ρ_i[13].

III. RESULTS

In order to demonstrate the capability of this diagnostic, we present here measurements of broadband temperature fluctuations that were made in a Helium plasma with magnetic field of 2.5 T, plasma current of 800 kA, core line-averaged density of 2.1×10^{19} m^{-3}, 0.52 MW of Ohmic heating and 0.67 MW of Electron Cyclotron Resonance Heating.

Fig. 3 shows the magnitude of $\gamma(f)$ for three channel pairings. The integrated fluctuation levels are $\delta T/T = (0.76 \pm 0.02)\,\%$, $(0.67 \pm 0.02)\,\%$ and $(0.59 \pm 0.03)\,\%$ up to 100 kHz and at normalised toroidal flux radius of $\rho_{\mathrm{tor}} =$ 0.82, 0.75 and 0.47 respectively. This data has been averaged over 2 seconds of the plasma stationary phase resulting in a relatively low statistical noise level for this type of measurement, the statistical noise limit, $1/\sqrt{N}$, being shown as a horizontal red dashed line. No measurable coherence is found between channels which are not in a pair, implying turbulence-like radial scales. The spectral shape for each pair is broadband and is not made up of many smaller coherent structures, as can be tested by altering the frequency resolution of the coherence. The upper limit in frequency is given by $(v_{E\times B} + v_{\mathrm{ph}})k_{\perp,\mathrm{lim}}/2\pi$

For CECE measurements to be representative of temperature fluctuations the plasma must be sufficiently optically thick such that fluctuations in density do not lead to significant fluctuations in the measured radiation temperature. A discussion on the effect of optical depth on the measurement of temperature fluctuations can be

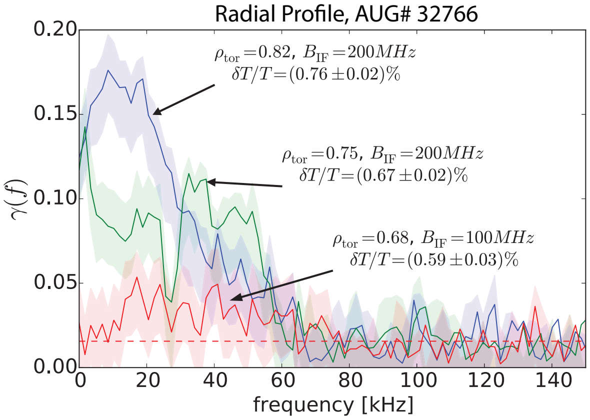

FIG. 3. The coherence between neighbouring frequency channel pairs for a Helium L-mode discharge. The red dashed line indicates the statistical noise limit, $1/\sqrt{N}$, and the shaded regions indicate the uncertainties. There is no measurable coherence between non-neighbouring channels, implying a local measurement.

found in Peters[14]. For our three measurement pairs at $\rho_{\rm tor}$ = 0.82, 0.75, and 0.68 the optical depths are 3.0, 4.1 and 5.4 respectively. Density fluctuations in this region are estimated to be $\delta n_{\rm e}/n_{\rm e} \simeq 0.5\,\%$. If we make the conservative assumption of $\delta n/n = 2$ %, then the maximum apparent fluctuation in radiative brightness due to the modulation of the optical depth is 0.16 %, 0.07 % and 0.02 % respectively. This is assuming no wall reflections, which may act to reduce these values further. These values are at least a factor of 4.8 lower than the measured fluctuation amplitudes reported. Contributions to the measured fluctuation levels from refractive effects may also be ignored since, at these densities a 2 % fluctuation in density leads to a 0.1 % change in refractive index.

IV. CONCLUSIONS

Correlation techniques can be used on radiometers with closely-spaced, narrow-band filter pairs to measure low level (<1 %) broadband (<0.5 MHz) electron temperature fluctuations associated with plasma turbulence in the core of a tokamak fusion experiment. An application of this frequency decorrelation method had been designed and built for the ASDEX Upgrade tokamak. This diagnostic shares an optical path with a reflectometer, via a novel hybrid waveguide-quasioptical transmission line, and is sensitive to wavenumbers $k_\perp$ up to 0.76 cm^{-1}. An upgrade to the focussing mirror will improve this by nearly a factor of 2, to $k_\perp$ up to 1.4 cm^{-1}. The coupled optics provides the potential of later performing correlation analysis between reflectometer and CECE channels.

Measurements in Helium plasmas have been made at three radial locations simultaneously, providing a profile of the temperature fluctuation amplitude in the outer core of an ECRH heated L-mode plasma. These measurements were determined to be local, un-influenced by effects of refraction and optically thick, meaning that the contribution to the radiative temperature fluctuations from density fluctuations is small. Further, the measurements show a broadband structure which is not the effect of many smaller coherent structures from, for example, MHD modes. Currently, work is under way to compare the fluctuation spectra to experimental predictions using gyro-kinetic codes.

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