Development progress of a Correlation ECE and nT phase angle dianostic for AUG

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Introduction

It is now widely accepted that drift-wave turbulence is responsible for anomalous transport in tokamaks. Within the last few years gyrokinetic codes have been able to match the measured turbulent heat flux within experimental errors [1]. Heat transport generated by this turbulence is intrinsically a multi-field phenomenon, being a function of the fluctuations in electrostatic potential, temperature, density and the relationships between these fluctuations. For this reason multi-field measurements are required to fully test non-linear gyrokinetic models of turbulence.

However, several quantities calculated from these simulations are sensitive to the logarithmic profile gradients, including common experimental benchmarks such as density and temperature fluctuation amplitude. Gyrokinetic simulations of an ASDEX Upgrade plasma [2] suggest that the phase angle between the temperature and density fluctuations (nT-phase) may be far less sensitive to these gradients and could thus be used as a more robust comparison to experiment. Additionally, these simulations suggest that the phase-angle of the linear modes can be approximately preserved in the non-linear regime allowing the possibility of mode identification and comparison to reduced quasi-linear transport models. Successful attempts to measure the nT-phase angle were performed on DIII-D [3] using a combination of a multi-channel narrowband ECE receiver coupled with a reflectometer. Here we report on the progress of such a diagnostic for ASDEX Upgrade along with a Correlation Electron Cyclotron Emission (CECE) radiometer

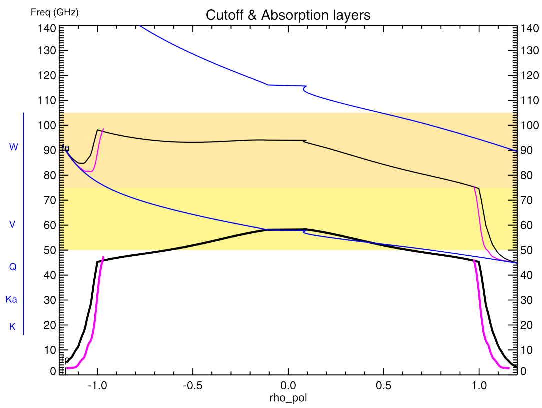

Figure 1: The cutoffs and resonances for a typical 2.5T ASDEX Upgrade discharge. One may select a frequency for either O or X mode reflectometers to be coincident in radius with a 2nd harmonic X mode CECE channel.

for the measurement of temperature fluctuation amplitudes.

Diagnostic Principles

Both $\delta T/T$ and nT-phase measurements described here rely on the principle of correlation. In the case of the CECE, a regular radiometer is insufficiently sensitive to measure the temperature fluctuations due to the fluctuation of the thermal radiation itself. This can be circumvented by employing two narrow-band radiometer channels spaced sufficiently closely in frequency so that they do not overlap, but fall within the correlation length of the turbulence [4, 5, 6]. The uncorrelated thermal noise is averaged out leaving only the correlated part. For two signals s_1 and s_2,

$$\frac{\delta T^2}{T^2} \propto \frac{\int s_1(t)s_2^*(t)dt}{\left[\int s_1(t)s_1^*(t)dt \int s_2(t)s_2^*(t)dt\right]^{1/2}}. \tag{1}$$

The principle behind the nT-phase measurement is very similar in character. In this case we have a reflectometer sample region co-located with that of a CECE channel in the plasma. This is achieved in practice by arranging that the two systems share an optical path to the plasma and choosing the frequencies so that the 2nd harmonic ECE resonance and the reflectometer cut-off are co-located within the plasma (see Figure 1). A range of time-series analysis techniques are available; of particular interest is the coherence, defined as the normalised ensemble average of a number of signals in frequency space,

$$\gamma_{\mathrm{nT,m}}(f) = \frac{\langle s_1(f)s_2^*(f)\rangle_t}{\left[\langle s_1(f)s_1^*(f)\rangle_t \langle s_2(f)s_2^*(f)\rangle_t\right]^{1/2}}, \tag{2}$$

with the measured cross-phase defined as the argument of $\gamma_{\mathrm{nT,m}}$.

Effect of spatial filtering and channel displacement

The non-zero spatial response of both the reflectometer and ECE radiometer act to smooth out plasma fluctuations much smaller than their respective beam sizes. Such effects can be quantitatively modeled following a similar procedure to that used by Bravenec et al [7]. Here we follow a similar approach to model the nT-phase system, explicitly keeping the phase terms in order to calculate the effect of non-ideal behavior, such as imperfectly aligned beams, on the measured nT cross-phase. For clarity, the main thrust of Bravenec's argument is reproduced

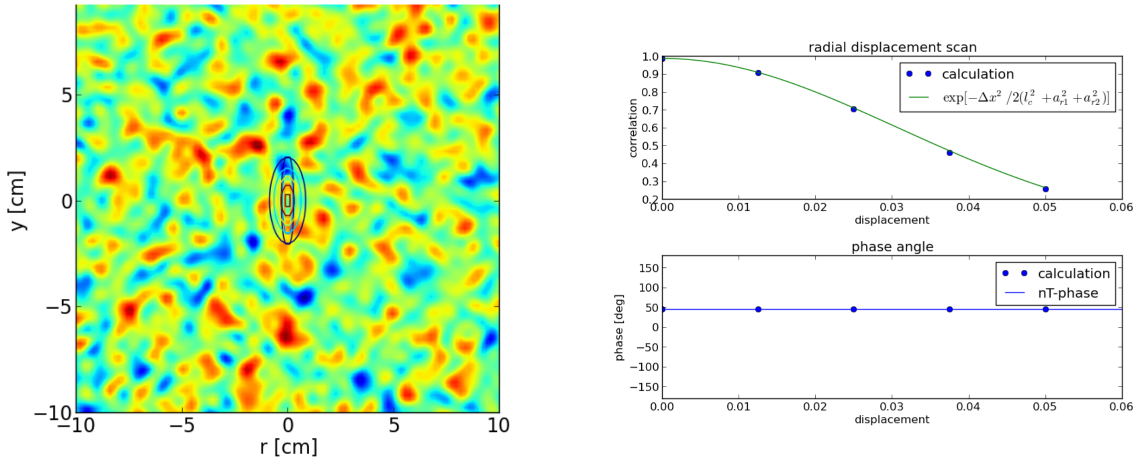

Figure 2: (a) An example of the spatial point spread functions taken for the reflectometer and CECE. The CECE radial width is taken to be that of the relativistic broadening at 1keV. (b) Maximum coherence and phase angle as a function of radial displacement. Notice that while the measured coherence is reduced, the phase angle is unaffected in this case.

here. The convolution theorem states that the convolution of two functions can be expressed as their product like so,

$$f * g = \mathcal{F}^{-1}\{\mathcal{F}\{f\} \cdot \mathcal{F}\{g\}\} \tag{3}$$

Assuming for now that we may approximate the response of both diagnostics with bi-variate Gaussians, coherence before and after convolution are related like so,

$$\begin{aligned} \gamma_{nT,m}(\omega, \mathbf{k}) = \exp\left\{-(a_1 + a_2)k_r^2 - 2(b_1 + b_2)k_r k_y - (c_1 + c_2)k_y^2\right\} \\ \exp\left\{i[k_r(r_2 - r_1) + k_y(y_2 - y_1)]\right\} \gamma_{nT}(\omega, \mathbf{k}) \end{aligned} \tag{4}$$

$$\begin{aligned} a_i &= \frac{1}{2}\left[(w_{r,i}\cos\alpha_i)^2 + (w_{y,i}\sin\alpha_i)^2\right] \\ b_i &= \frac{1}{4}\left[w_{r,i}^2 \sin(2\alpha_i) - w_{y,i}^2 \sin(2\alpha_i)\right] \\ c_i &= \frac{1}{2}\left[(w_{r,i}\sin\alpha_i)^2 + (w_{y,i}\cos\alpha_i)^2\right] \end{aligned} \tag{5}$$

where, k_r and k_y are the radial and perpendicular wavenumbers, r_i and y_i are the displacements of the two beam centres from the origin, $w_{r,i}$ and $w_{y,i}$ are the radial and perpendicular Gaussian beam waists and α_i is the tilt of the beam allowing approximate modeling of non-parallel cut-offs and resonances.

We take the radial resolution of the CECE to be set by the relativistic broadening (temperature taken to be 1keV) and a nominal value of 2mm for the reflectometer. Figure 2 (a) shows the two beams upon some synthetic turbulence. We model the coherence of density and temperature

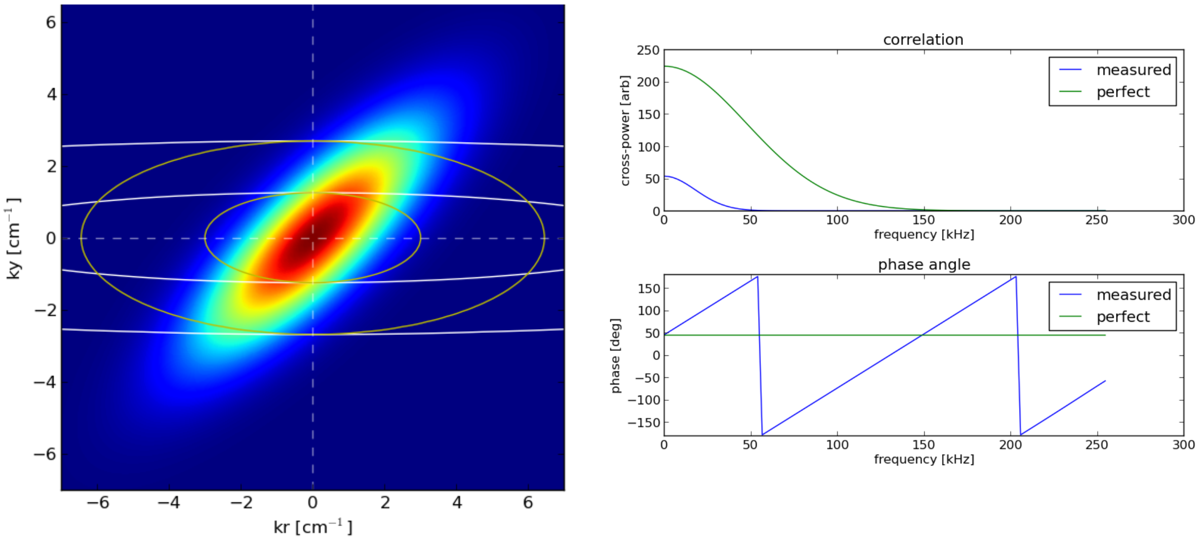

Figure 3: (a) The k-space distribution showing an exaggerated tilt. (b) The correlation analysis for the tilted k-space distribution, for a single displacement. One can see that the asymmetry around $k_r = 0$ results in an effective time delay, leading to a phase dispersion in the measurement.

with another bivariate Gaussian and we assume that it is propagating with linear phase velocity $\omega = v k_y$ along y.

We reproduce the well-known result that the non-zero width of the beams renders the diagnostic less sensitive to higher wavenumbers as the fluctuations average out over the beam size, as well as the decrease in correlation as the two beams are separated radially from each other. We wish to use this tool to investigate the effect of the effect of non-ideal behaviour of the nT-phase diagnostic which might reasonably arise, such as radial displacements due to non-matched frequencies.

Figure 2 (b) shows a numerical evaluation of Equation 3 along with a comparison to the analytic form for a symmetric Gaussian turbulence distribution. The first and most obvious effect of a radial displacement is that the measured correlation amplitude is reduced. Secondly, and perhaps not so intuitive is that for the case chosen here, the nT-phase measurement remains unaffected. This model contains no experimental noise and so, even at large displacements the phase is still measurable. The fact that the nT-phase is so robust is a direct consequence of the symmetry of the turbulence distribution around $k_r = 0$.

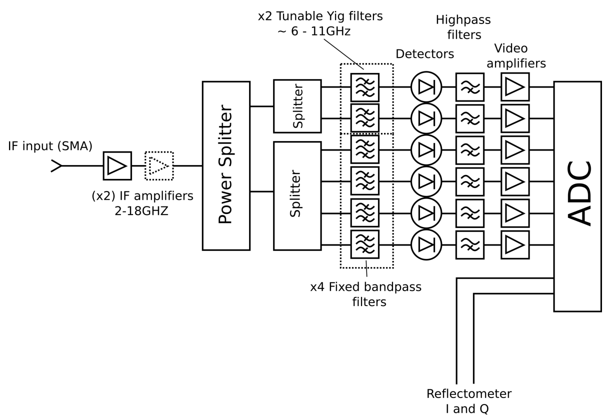

Figure 4: The IF section contains six parallel filter channels, two of which are tunable YIG filters of 200MHz bandwidth. The tunable filters provide flexibility in radial coverage and may extend the region of the plasma where a match to the reflectometer position may be found.

We modelled a distribution which breaks this symmetry, shown in Figure 3 (a) and the result shown in Figure 3 (b) for a displacement of 1cm. The tilt in the distribution gives rise to a phase dispersion in the measurement. The gradient in the phase in this case is directly proportional to the physical displacement of the two diagnostics in the plasma. This leads us to the conclusion that in order to detect an effect such as this we must step the position of one of the diagnostics in time. In practice this is most easily achieved by stepping the frequency of the reflectometer. This will also allow us to estimate the zero displacement phase in the presence of this effect.

Hardware

The correlation ECE radiometer is made up of two main sections: an RF down-converting stage and an IF filter-bank and detection stage. The RF stage consists of two swappable sideband filters from 105-113GHz and 117-125GHz. This allows a radial coverage of R/a from 0.4 to 0.66 and then from 0.8 to the plasma edge for a 2.5T reference discharge. This is followed by a Millitech MSH-08 sub-harmonic mixer which mixes the filtered RF signal with a tunable Gunn-diode local oscillator. The effective tuning range using the local oscillator is from 113.25 to 116.75GHz. The signal is then amplified by a Millitech, FIB-08 series amplifier and passed to the input of the IF section.

The IF section, shown in Figure 4, amplifies the signal a second time with a Millitech, FIB-08 series amplifier and splits the power six ways. Four of these signal lines are filtered using fixed bandpass filters, the exact values of which are chosen to suit the experiment, but are typically 200MHz in bandwidth. The remaining two signal lines are filtered using Micro Lambda Wireless, Inc. tunable YiG filters, the centre frequencies of which can tuned in the range 6-11GHz. These filters can, if necessary, be used to effectively increase the radial coverage of a single radiometer channel by tuning them such that they lie either side of a fixed frequency channel. This procedure increases the chance of matching the radial position of the reflectometer with one of the radiometer channels.

The radiometer will share the existing quasi-optical steerable antenna, and therefore a line of sight to the plasma, with the X and O mode Doppler reflectometers. These optics are designed so that the beam diameter is 7λ at 90GHz at $\rho_{pol} = 0.9$ for a standard ASDEX Upgrade discharge [8]. The beam size at this location is given by $\sqrt{90/f[GHz]}$, leading to a physical beam radius between 1.08cm and 0.99cm for the frequency range of the radiometer.

The signals from the steerable antenna leave the machine via an oversized circular waveguide. After this, there is either a polarising or 3dB splitter to allow coupling the radiometer to either the O or X mode reflectometers.

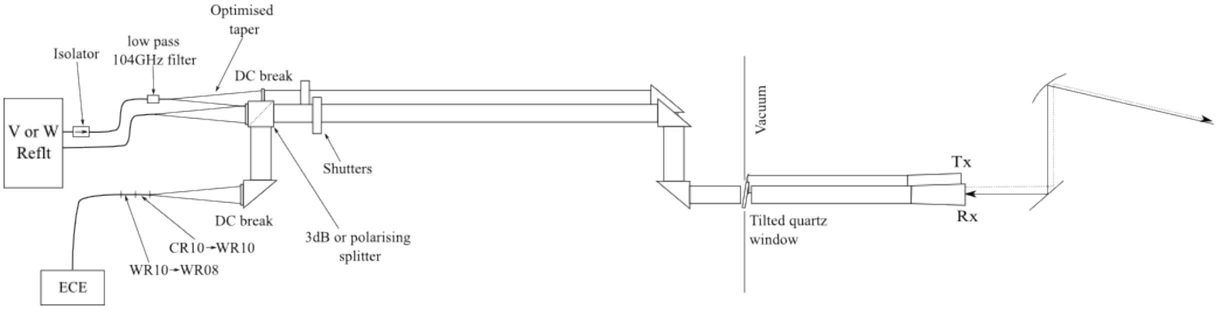

Figure 5: The waveguide transmission line for the CECE radiometer/reflectometer pair. Either a 3dB or polarising splitter can be interchanged to allow coupling to either X or O mode reflectometers.

Summary

Two correlation ECE radiometers are currently being installed on ASDEX Upgrade. One of these radiometers will share a line of sight to the plasma with a Doppler reflectometer, and measure the coherence and cross-phase angle between turbulent temperature and density fluctuations for the experimental validation of non-linear gyrokinetic models. We have shown that the phase angle is a robust quantity to radial channel displacements, provided that the the turbulent distribution function is symmetric about $k_r = 0$. If this is not the case, the resulting phase dispersion is a function of the displacement of the channels and therefore stepping the reflectometer frequency within a small range may be an effective way to measure this effect. The diagnostic will be installed the summer of 2015, with first data in the following autumn.

Acknowledgements

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