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First measurement on electron heat transport by heatwaves in the core plasma of Wendelstein 7-X

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In the first operation phase of Wendelstein 7-X, OP 1.1, modulated electron cyclotron resonance (ECR) heating was used for heatwave studies with a 32 channel heterodyne radiometer measuring electron cyclotron emission (ECE) [1, 2]. Square wave ECR heating modulation with a duty cycle of $2/3$ was chosen to extract information about heatwaves at the second and, where possible, fourth and fifth harmonics of the modulation frequency. Due to the chosen duty cycle the third harmonic was suppressed.Typical modulation depths were around 33 %. Both on- and off-axis modulated ECR heating scenarios were investigated. Examples are shown in figure 1.

Thomson density and electron temperature half-profiles were used as basis for a fit whose fitting parameters served as input for the `TRAVIS` code modeling radiation transport [3]. The results of `TRAVIS` provide the radial location of the layer emitting electron cyclotron resonance radiation. Note that channels that contain a large fraction of downshifted radiation are neglected in this paper due to their poor spatial resolution. Furthermore, the nominal magnetic field at the plasma axis used as input for `TRAVIS` was corrected by 12.5 mT resulting from phase profile symmetrization of an off-axis discharge with higher modulation frequency.

An example of the Fourier analysis is shown in figure 2. To increase the precision of the heat pulse phase and amplitude, an integration over the frequency range that shows a flat phase and a high coherence is performed (indicated by grey bars).

The phase and amplitude profiles of the propagating heatwaves derived from this analysis are shown in figure 3. In figure 3a and figure 3b one can clearly identify the regions in which the ECR heating takes place (cyan hatching). The peaks at roughly $r_{\text{eff}} \approx \pm 0.18\,\text{m}$ in figure 3b are attributed to the power deposition region. However, the profiles are not steep enough to confidently narrow down the absorption regions below approximately 10 cm and the modulation frequencies are too low to derive the power deposition profile directly. An evaluation of discharges

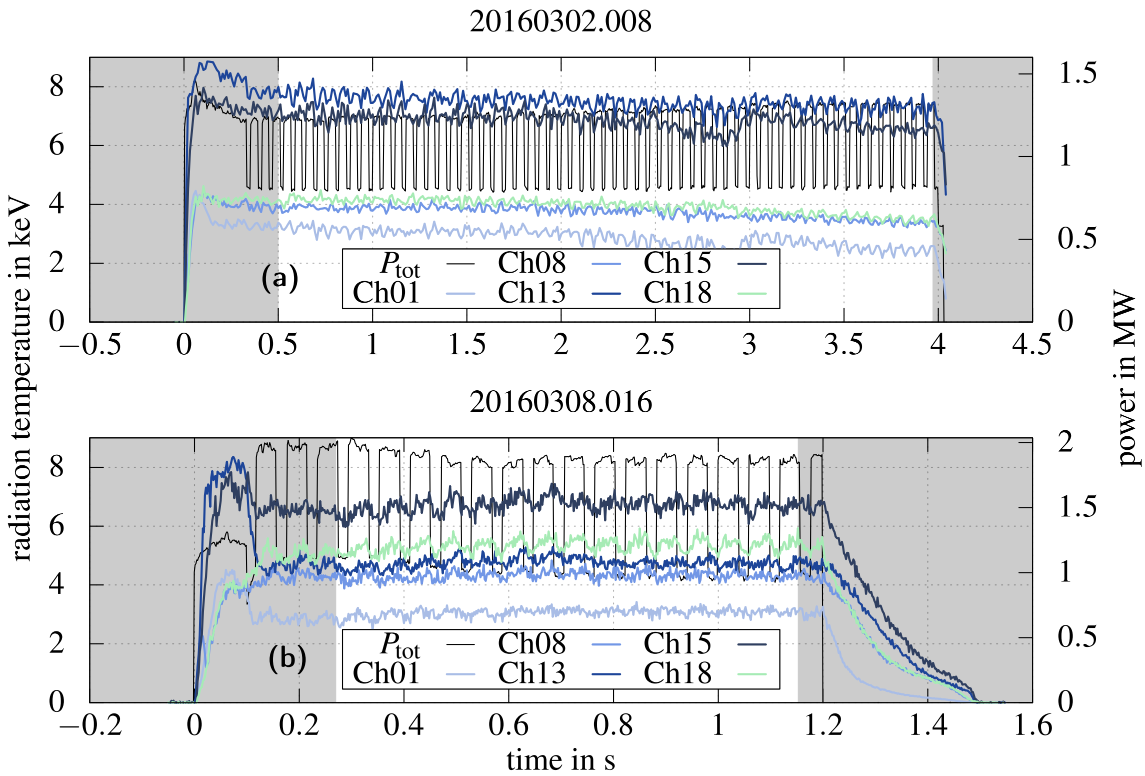

Figure 1: ECRH power and selected ECE channels for example discharges with modulated electron cyclotron resonance heating: **(a)** on-axis discharge modulated with 17 Hz and a modulation depth of approximately 35 %, **(b)** off-axis discharge with a modulation of 17 Hz and a modulation depth of circa 42 %. In both cases the average electron temperature remains relatively stable in the interval considered for further evaluation (white area). The white area neglects the first 150 ms of the modulation as the heatwave needs time to reach the edge channels. Channel 1 corresponds to a frequency at the low field side (LFS) near the last closed flux surface, channel 8 is near the gradient region at the LFS, while channels 13, 15 and 18 are near the plasma core.

with higher ECR heating modulation frequency is currently underway. The increase in the amplitude for $r_{\mathrm{eff}} \gtrsim 0.15\,\mathrm{m}$ in figures 3c and 3d is not yet clearly understood [1, 2]. The higher harmonics show only a small amplitude and are less accurate.

Within an infinite slab geometry with uniform plasma [5] one can calculate in a simplified model

$$\chi \approx \frac{3\omega}{4(\partial_r \varphi)^2}. \tag{1}$$

With the phase delay derived from the figures one obtains $\chi_{\mathrm{e}} \approx 0.3\,\mathrm{m}^2\,\mathrm{s}^{-1}$. This value is around neoclassical energy transport level [6] being of the right order of magnitude. Evaluation of the higher harmonics results in diffusivity values of the same order of magnitude.

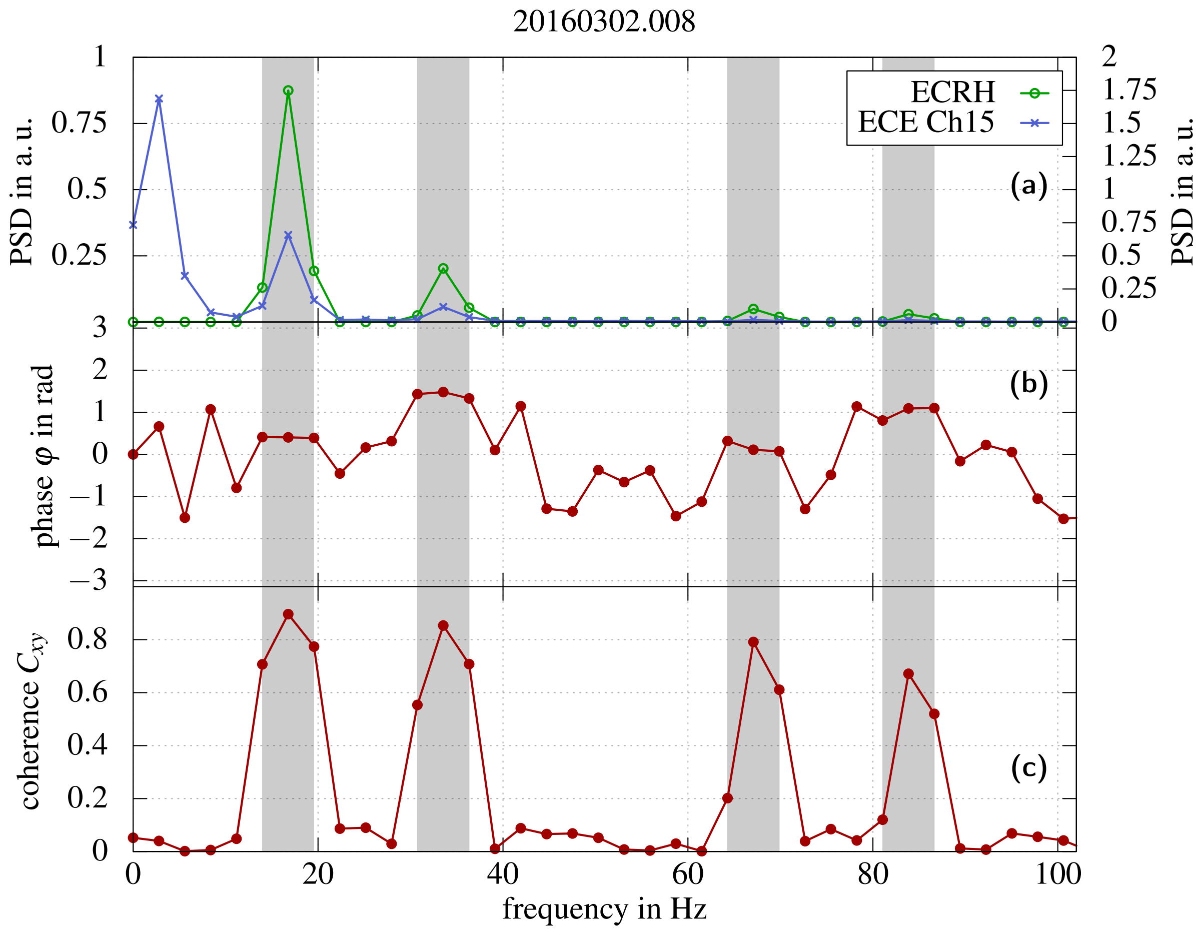

Figure 2: FFT evaluation of an ECE signal (channel 15, corresponding to the central part of the plasma) using Welchs average periodogram method [4]. **(a)** power spectral densities of the ECRH reference signal and the 15th channel of the ECE. The modulation frequency, and its second, fourth and fifth harmonics are clearly seen. **(b)** phase, and **(c)** coherence, as calculated from the cross spectral density.

A more careful analysis is ongoing and requires amongst other things a more accurate mapping of the effective radius, which would then also allow for the determination of the power deposition zone and a more precise knowledge of the on-axis magnetic field which may deviate from its nominal value.

Acknowledgements

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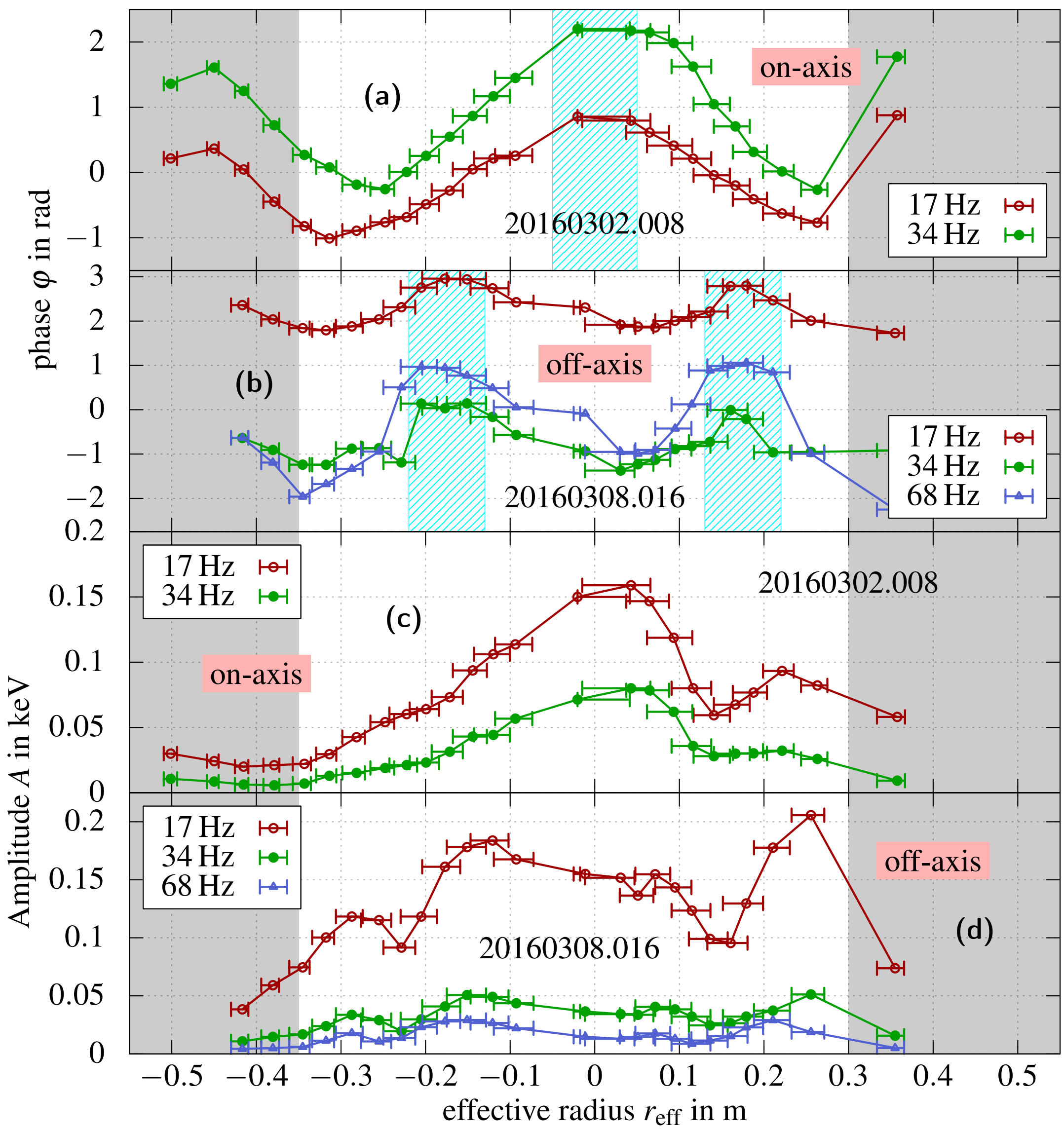

Figure 3: Phase delay profiles ((**a**), (**b**)) and amplitude profiles ((**c**), (**d**)) for on- and off-axis heating, respectively. The phase profiles are symmetrized by correcting for the small magnetic discrepancy from the nominal value that has been indicated by high frequency off-axis discharges. The residual asymmetry for the on-axis discharge could be a result of a local finite beta in the plasma center which is currently under investigation. The amplitude profiles show less clear on-/off-axis heating signatures, which might be caused by the systematic absolute calibration uncertainties. Due to effects mentioned above, regions shaded in grey should not be directly related to heatwave propagation.

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