Higher Harmonics in the Perturbative Transport Study in TJ-II ECH Plasma

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We analyzed the higher harmonics of temperature perturbation in the modulated electron cyclotron heating experiment on TJ-II plasma. The higher harmonics (e.g., 5th harmonic) exhibited significantly weaker decay in amplitude as they propagated in radius as compared with the prediction by diffusive model. The change in the time derivative of temperature at the onset (and turning-off) of the heating power propagates in radius with very little temporal smoothening.

Keywords: heat pulse propagation, higher harmonics, nondiffusive transport

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Recently, a new method for analyzing anomalous transport in magnetically confined plasmas was developed. This new method directly measures the gradient–flux relation by studying the temperature response with respect to modulations of the electron cyclotron heating (ECH) power. Using this method, hysteresis in the gradient–flux relation was observed in LHD plasmas [1, 2]. Because heat flux is a multivalued function of gradient, the temperature perturbation dynamics are far from a simple diffusive response with constant diffusion coefficient. Therefore, higher harmonics can exhibit smaller or larger spatial damping rates in comparison with the diffusive response. To observe the violation of the simple diffusive relation $q = -n\chi\nabla T$ with homogeneous χ, measuring the higher harmonics of temperature perturbation in the heating modulation experiment was proposed [3]. In this rapid communication, we report the application of the abovementioned method to the modulated electron cyclotron heating (MECH) experiment on the TJ-II [4].

The power modulation experiment with line-averaged values around $0.5 \times 10^{19}\,\mathrm{m}^{-3}$ was performed on a low-density plasma using continuous on-axis heating with 250 kW and modulated 50 kW (square waveform, 50% duty cycle) microwave beams. The modulation frequency of ECH (f_{mod}) is 180 Hz, mostly absorbed in the central core $r/a \leq 0.3$ (plasma radius $a = 0.2$ m), as determined in previous heat wave propagation experiments [5]. The electron temperature profile was measured at ten points in the high-field side region of $0.0 < r/a < 0.9$ using an ECE heterodyne radiometer with a time resolution of 10 µs [6]. The comparison with the T_e measured using a He beam indicates that ECE can measure T_e even at the edge [7].

We applied the conditional averaging technique [1]. In this procedure, the ECH turn-on time (t_{on}) is detected in each period and temporal evolutions of the electron temperature for time intervals of $-3\,\mathrm{ms} < t - t_{\mathrm{on}} < 3\,\mathrm{ms}$ were extracted; the extracted signals were averaged over 25 modulations. Post averaging, the noise level significantly decreased. Figure 1 illustrates the power spectrum of the conditionally averaged temperature perturbation and

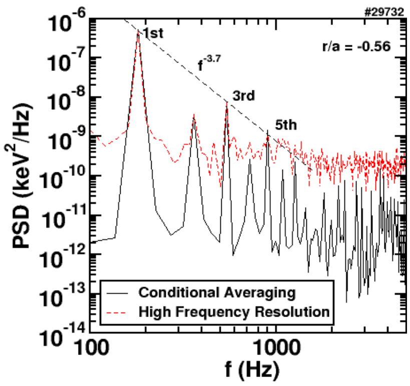

Fig. 1 Power spectrum of the conditionally averaged temperature perturbation (black solid line) and that calculated from the raw signal (red dashed line). Higher harmonics up to the 5th are presented. The black dashed line is for visual aid.

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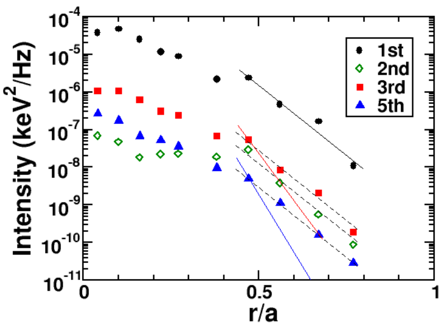

Fig. 2 Radial profile of the intensity of the fundamental 2nd, 3rd, and 5th harmonics.

the power spectrum of the raw signal with higher frequency resolution. Harmonics are unambiguously observed up till the 5th harmonic. By observing the amplitude of higher harmonics at various radii, propagation of the temperature perturbation associated with the power modulation can be studied.

If the diffusion equation $q = -n\chi\nabla T$ holds with a homogeneous transport coefficient, the energy balance equation for the perturbation takes the form $\partial\delta T/\partial t = \chi\nabla^2\delta T$ in the region where the heating power is absent and predicts that the perturbation $\delta T \sim \exp(-\mathrm{i}\omega t + \mathrm{i}kx)$ follows the dispersion relation $k_r = k_i = k_0 = \sqrt{\omega/2\chi}$ for

$$k = k_r + \mathrm{i}k_i,$$

where x is the distance from the reference radius. The sign of the wave number is selected to allow the heat wave propagation in the x-direction. The amplitude of the mth harmonic decays exponentially with respect to radius

$$\delta T_m(x) \sim \exp(-\sqrt{m\omega_1/2\chi}x). \quad (1)$$

For the mth harmonic, $\omega_m = m\omega_1$, where ω_1 is the fundamental angular frequency of MECH; i.e., the e-folding length of the mth harmonic is shorter by a factor of $1/\sqrt{m}$ than that of the fundamental mode.

Figure 2 illustrates the radial dependence of the intensity for the fundamental, 2nd, 3rd, and 5th harmonics. In the region $r/a > 0.5$, far from the domain of power absorption, the intensity of $|\delta T_1(x)|^2$ is fitted as $|\delta T_1(x)|^2 \propto \exp(-76x)$ where $x = r - 0.5a$. Comparing the envelope profile for the fundamental component with Eq. (1), the diffusion coefficient is fitted as $\chi \sim 0.4\,\mathrm{m^2/s}$ if the diffusion relation $q = -n\chi\nabla T$ holds for a homogeneous χ. From the diffusion model, the 2nd, 3rd, and 5th harmonics are predicted with Eq. (1), which are depicted in Fig. 2 by the green, red, and blue lines, respectively. Clearly, the decay of the amplitude of higher harmonics is much slower than that predicted by the diffusion model; i.e., the diffusion model $q = -n\chi\nabla T$ does not hold in the present experiment. In contrast, the radial dependence of the higher harmonics is close to that of the fundamental component, as indicated by the black dashed lines in Fig. 2. The temporal response of the temperature perturbation in LHD is confirmed in the TJ-II plasma.

Note that the conclusions are not affected by the convective (pinch) and damping term in the transport equation. When one writes $\partial\delta T/\partial t = \chi\nabla^2\delta T - V\nabla\delta T - \delta T/\tau$, by keeping the convective heat flux, one obtains results of $k_i \neq k_r$ and $k_i = k_0 - V/2\chi$ under the conditions $|V| < \chi/a$ and $\omega > \chi/a^2 \sim 1/\tau$, which is relevant to the experimental conditions. Moreover, this result indicates that for any combination of the fitting parameters χ and V, the relation k_i (fundamental) < k_i (3rd) < k_i (5th) holds, but contradicts the observations in Fig. 2.

Errors in evaluating the deposition profile can induce weak decay of higher harmonics; however, this is not the case. Although the square wave-like ECH power modulation does not have even numbers of harmonics, the 2nd harmonic of the heat pulse is observed; it has a radial decay rate very close to that of the fundamental 3rd and 5th harmonics in the region $r/a > 0.4$.

The higher harmonics in TJ-II exhibited much weaker decay in amplitude when propagating in radius as compared with the predictions by the simple diffusive model. The similarity between the response of the higher harmonics in TJ-II and LHD plasmas suggests that hysteresis in the heat flux, in terms of the local temperature gradient, also exists in the TJ-II plasma. Further application of the method in [1] to TJ-II plasmas is encouraged. In addition, this analysis can be routinely performed in several experimental devices to study heating modulation experiments.

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