Digital Correlation ECE Measurement Technique with a Gigahertz Sampling Digitizer*)

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The concept of digital correlation electron cyclotron emission (ECE) measurement is proposed for studying of the mesoscale phenomena. The recent progress in fast sampling and computing enables the acquisition of waveforms of intermediate frequency (IF) in the range of several gigahertz. Correlation analysis using an IF digitizing technique can be helpful for analyzing mesoscale phenomena. This paper discusses the concept and characteristics of the IF digitizing technique for correlation analysis, and presents an example of IF waveform acquisition of ECE.

Keywords: ECE, correlation, gigahertz sampling, intermediate frequency, mesoscale turbulence, LHD

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1. Introduction

In magnetized plasmas, it is widely recognized that turbulence phenomena as well as MHD instabilities impact confinement characteristics, so the understanding of turbulence structures is important to establish a discharge scenario with better confinement. To gain a better understanding of the physical mechanism of the relationship between turbulence and transport, it is essential to simultaneously observe spatiotemporal structures of micro- to macro-scale turbulence. Here, the macro scale is assumed to be comparable to the device size a_i, while the micro-scale is comparable to the ion Larmor radius ρ_i. Typical values of these parameters are given in Table 1.

Some studies of macroscale phenomena in large plasma devices have been reported. In the Large Helical Device (LHD) at the National Institute for Fusion Science (NIFS), long-range correlated fluctuations in electron temperature have been discovered, and their typical size is found to be half of the plasma minor radius [1]. However, it is fundamentally difficult to observe meso- or micro scale phenomena with enough spatial and temporal resolution. Because of the lack of measuring devices for small scale phenomena, there are few experimental reports that address relationships between meso- and macroscale phenomena. Consequently, there is a strong need for development of measuring devices for studying mesoscale phenomena. In this paper, we propose an advanced ECE measurement called digital correlation electron cyclotron emission (DCECE) for measuring mesoscale phenomena. To illustrate the method, preliminary data are presented here.

2. Concept of Digital Correlation ECE

2.1 Hardware set-up

The electron temperature T_e is the basic parameter, and its fluctuations $\tilde{T}_\mathrm{e}$ provide important information about microscale turbulence. The quantity $\tilde{T}_\mathrm{e}$ is generally measured as fluctuations in the intensity of ECE. In Tesla machines the second harmonic frequency range in ECE of plasma is 30–300 GHz, which is called “RF”. To detect RF, a coherent local oscillator (LO) with the proper frequency downconverts a RF signal to an intermediate frequency (IF), whose value is up to several dozen gigahertz. Because the power of the IF frequency is proportional to the power of the RF frequency, we can determine T_e as the power spectrum of IF $P_\mathrm{IF}(f_\mathrm{IF})$. If we let r be the radial position in plasma device, then the resulting T_e is a function of r by conversion from f_IF to r. Typically, after the heterodyne downconversion, IF is detected by spectrometers, filter banks, and demodulators [2].

Such heterodyne detection is also used in the LHD [3, 4]. A schematic diagram of the heterodyne radiometer used in LHD is shown as in Fig. 1. The RF whose frequency is 100–150 GHz is divided into a lower sideband (LSB, 100–132 GHz) and upper sideband (USB, 132–150 GHz) by using a low-pass filter and a high-pass filter whose cutoff frequency is 132 GHz. Only the USB pass is shown in Fig. 1. In the ECE measurement system in LHD, the IF (0–18 GHz), which is downconverted from USB or LSB with the output of the 132 GHz Gunn oscillator, is de-

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Table 1 Typical values of parameters at each scale of turbulence. L_c is the correlation length, a is the device size, ρ_i is the ion Larmor radius.

	size	(LHD case)	frequency	Te diagnostic
macro-	$L_\mathrm{c} = a$	~ 50 cm	~ 10 kHz	conventional ECE
mezo-	$L_\mathrm{c} = \sqrt{a\rho_\mathrm{i}}$	~ 3 cm	~ 100 kHz	DCECE (proposed)
micro-	$L_\mathrm{c} = \rho_\mathrm{i}$	~ 2 mm	~ 1 MHz	DCECE? (as its envelop fluctuation)

tected by a 32-channel filter bank. The IF digitizing technique has been applied for plasma diagnostics, instead of the conventional fileter bank [5].

Recently, a digitizer sampling at several dozen gigahertz has been developed commercially, so it becomes possible to obtain the IF waveform digitally over a sufficient frequency band. If the sampling frequency is over several giga-hertz, it is also possible to obtain the waveform continuously [6]. We propose using this sampling digitizer for the correlation ECE, by exploiting the merits of fast speed sampling and continuity. As a test for obtaining an IF waveform, LabMaster 10-36Zi (Teledyne Lecroy Co.) was applied. The sampling frequency is 80 GHz. The effective band frequency is up to 36 GHz. The maximum data length is 512 Mbyte which corresponds to 6.4 ms.

2.2 Analysis procedure

In principle, electron temperature fluctuations can be obtained as fluctuation of IF spectra. A block diagram of the analysis is shown in Fig. 2. Discretized IF data $x(t)$ are converted to complex components of the spectra $fx^{\mathrm{IF}}(t_\mathrm{w}, f_\mathrm{IF})$, where t_w is the typical width of the time window, and f_IF are the IF frequency components. To reduce the error caused by discretization, fx is usually smoothed by averaging in the time domain. We can arbitrarily choose the width of the time window and the number of averaging samples; these choices determine the time resolution of T_e fluctuations. Then power spectra $pow^{\mathrm{IF}}(t_\mathrm{w}, f_\mathrm{IF})$ calculated from fx are averaged in the frequency domain. The result is the electron temperature $T_\mathrm{e}(t_\mathrm{w}, r)$, where r is the radial position in the torus plasma and is the solution of $f_\mathrm{IF} = 2f_\mathrm{ce} = 2eB(r)/2\pi m_\mathrm{e}$. This averaging in the frequency domain corresponds to the use of a frequency filter in conventional radiometer with a filter bank. This is one merit to DCECE because the observed T_e is not influenced by filter characteristics and a narrow-band filter can easily be applied. In principle, a very narrow band could be used, but because of discretization errors, it makes no physical sense for the filter band to be narrower than the band corresponding to a few multiples of the electron Larmor radius. We

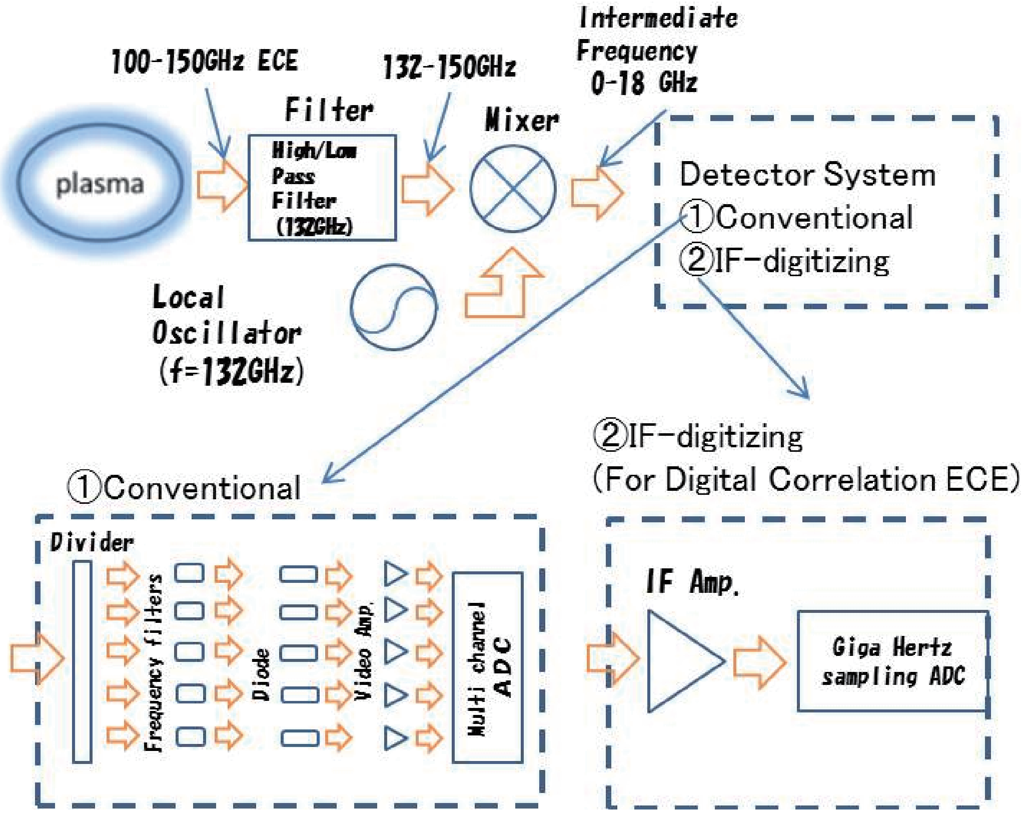

Fig. 1 Schematic of the heterodyne system. (1.lower left) Detector is radiometer with conventional filter bank. (2.lower right) IF digitizing method for DCECE.

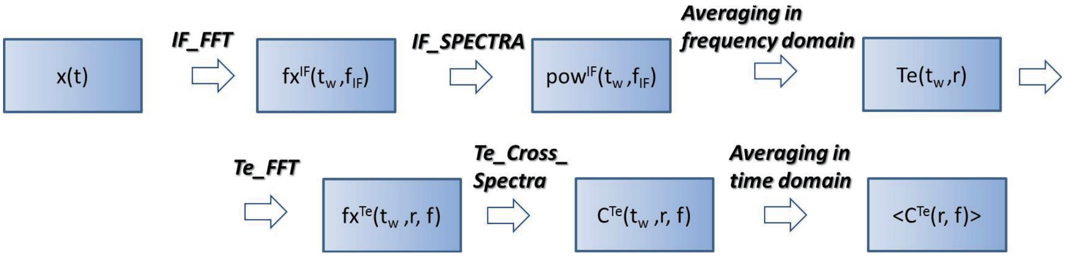

Fig. 2 Block diagram of DCECE analysis.

can obtain the fluctuations in T_e by calculating the correlation $< C^{T_e}(r,t) >$ using spatial decorrelation analysis [7]. Details of the correlation analysis are omitted from this paper.

2.3 Sensitivity limit

Because ECE is an emission from a blackbody, we can not ignore the effects of thermal noise. In practice, we are interested in the noise level (i.e. the sensitivity limit) of the detected radiation signal with finite bandwidth. The noise level is given by

$$\frac{\tilde{T}_e}{T_e^{ave}} \leq \sqrt{\frac{2B_{vid}}{B_{IF}}}, \quad (1)$$

where B_{vid} is the signal bandwidth and B_{IF} is the IF bandwidth. We can reduce the noise level using independent samples of fluctuation data. Then, if N is the number of samples, the noise level is given by

$$\frac{\tilde{T}_e}{T_e^{ave}} \leq \sqrt{\frac{1}{\sqrt{N}}\frac{2B_{vid}}{B_{IF}}}. \quad (2)$$

For a conventional ECE radiometer in LHD, $B_{IF} = 1$ GHz, the sensitivity limit of $B_{vid} = 10$ kHz is 0.4%. This is no problem for measuring MHD fluctuations. However, for measuring meso-scale phenomena with small amplitudes, the increasing of the sensitivity limit poses problem in DCECE. So data should be obtained over a time.

Results from are summarized in Table 2. The variable N_w is the width of the time window used to calculate the IF spectra. If we increase N_w, the number of IF spectra $N_{spectra}^{IF}$ decreases; that is, the sampling rate for T_e, $1/dt_{T_e}$ becomes worse and the number of data points for T_e decreases. Then, the sensitivity limit of cECE becomes worse because the number of T_e spectra, $N_{spectra}^{T_e}$ decreases, assuming the window width of the Te FFT calculation $N_w^{T_e}$ is fixed. Instead of degrading the sensitivity limit, we can obtain the T_e spectra with good frequency resolution df_{T_e} by choosing suitable values for the parameters to target the required phenomena.

2.4 Characteristics of DCECE

Characteristics of the proposed DCECE are as follows.

1. Advantages
    (a) Easy to determine location
    (b) No disturbance to target plasma
    (c) Able to chose the spatial and temporal resolutions during analysis
    (d) Simple hardware
2. Disadvantages
    (a) Difficulty in handling an enormous volume of data
    (b) Difficulty in calibrating absolute electron temperature

The most distinguishing point is the ability to change the spatial and temporal resolutions during analysis of the data (i.e. after the experiment). Saving large amounts

Table 2 Parameter survey for selected widths of the time window N_w^{IF}. $N_{spectra}^{IF}$ is the number of IF spectra. dt_{T_e} is the time resolution of T_e. $N_{spectra}^{T_e}$ is the number of T_e spectra. df_{T_e} is the frequency resolution of T_e. S.L. and cECE S.L. are sensitivity limits calculated from Eq. 2 and 3, respectively. Data length N_d, sampling rate f_s, window width of Te FFT $N_w^{T_e}$, B_{if} and B_{vid} are fixed parameter. $N_d = 512000526$, $f_s = 80$ GHz, $N_w^{T_e} = 1024$, $B_{if} = 100$ MHz, $B_{vid} = 100$ kHz. Relation among parameters are as follows. $N_{spectra}^{IF} = N_d/N_w$, $1/dt_{T_e} = f_s/N_w$, $N_{spectra}^{T_e} = N_{spectra}^{IF}/N_w^{T_e}$, $df_{T_e} = 1/N_w^{T_e}/dt_{T_e}$ The data length and sampling rate were taken from LabMaster 10-36Zi [6].

N_w	$N_{spectra}^{IF}$	$1/dt_{T_e}$	$N_{spectra}^{T_e}$	df_{T_e}	S.L.	cECE S.L.
2^{11}	250000	39.1 MHz	244	38.1 kHz	3.16%	0.80%
2^{12}	125000	19.5 MHz	122	19.1 kHz	3.16%	0.95%
2^{13}	62500	9.8 MHz	61	9.5 kHz	3.16%	1.13%
2^{14}	31250	4.9 MHz	30	4.8 kHz	3.16%	1.35%
2^{15}	15625	2.4 MHz	15	2.4 kHz	3.16%	1.61%
2^{16}	7812	1.2 MHz	7	1.2 kHz	3.16%	1.94%
2^{17}	3906	0.6 MHz	3	0.6 kHz	3.16%	2.40%

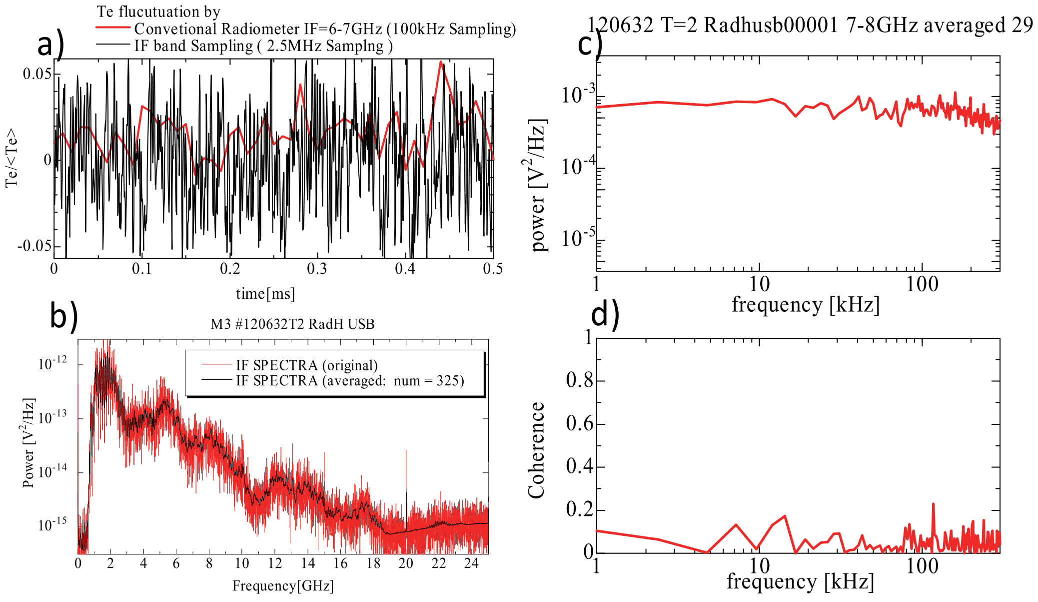

Fig. 3 Sample results form analysis of test data in LHD.

of data makes it possible to reconfigure diagnostic states. This advantage must be useful for studies of mesoscale phenomena.

3. Initial Data in LHD

The initial IF digitizing radiometer system for DCECE was constructed and tested on plasma in LHD. Fig. 3 (a) compare a raw signal from the conventional filter bank radiometer with the reconstructed fluctuation signal from the IF digitizing radiometer. The analysis parameters were $N_\mathrm{w} = 2^{16}$ and $B_\mathrm{if} = 1\,\mathrm{GHz}$. The band width B_if was the same as the band width of the filter bank. The target plasma was sustained by neutral beam (NB) heating and electron cyclotron heating; the electron temperature was approximately 4 keV. The optical thick is enough large in observed whole area. In Fig. 3 (a), both waveforms are roughly consistent. The power spectra calculated from Fig. 3 (a) are shown in Fig. 3 (b). The frequency characteristic of the mixer was up to 18 GHz, and the spectra clearly verify the upper limit of the characteristic. We can obtain the radial electron profile from the power spectra in the range 1–18 GHz using a proper calibration factor, which takes into account the various frequency characteristics of mixer, amplifier, waveguide, etc. For DCECE, it is not necessary to define the exact factor because the fluctuation analysis uses the normalized value $\tilde{T}_\mathrm{e}/\langle T_\mathrm{e}\rangle$. Fig. 3 (c) and 3(d) show the power spectra and coherence of T_e fluctuations. In those figures, the spectra and coherence are both averaged, and the number of sample spectra is 29. Even though no distinguishing power peaks can be seen, there is a weak coherence peak at $f = 116\,\mathrm{GHz}$.

4. Summary

The concept of measuring DCECE measurement is proposed for mesoscale phenomena in which the frequency is 100 kHz. DCECE is based on digitizing the IF band and analyzing spatial correlations in ECE analysis. The greatest merit in this method is that we can choose temporal and spatial resolutions after the data have been acquired. Initial IF data of ECE for DCECE were obtained in LHD, and a preliminary analysis was reported. Since there are so many analysis parameters, there are opportunities for further trials. This DCECE method would be helpful in studying phenomena having unknown scales, frequencies and amplitudes.

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