Experimental studies of runaway electron beam instabilities in J-TEXT Tokamak

Z. Y. Chen[1], W. Yan[1, *], G. N. Zou[1], Y. W. Sun[1] and J-TEXT Team[1,2]

[1]*International Joint Research Laboratory of Magnetic Confinement Fusion and Plasma Physics, Huazhong University of Science and Technology, Wuhan, 430074, China*

**E-mail: yanwei1090@hust.edu.cn*

Abstract

Major disruptions in tokamak plasmas can generate high-energy runaway electron (RE) beam, posing a significant threat to device safety. In recent years, wave-runaway electron interactions, which can enhance the pitch-angle scattering of runaway electrons, have been considered a potential alternative approach for RE mitigation. A newly developed Ion Cyclotron Emission (ICE) diagnostic on the J-TEXT tokamak enables measurements of high-frequency instabilities driven by fast or runaway electrons. Utilizing this ICE diagnostic, the studies of high-frequency instabilities excited by runaway electrons have been carried on J-TEXT. During the plasma current ramp-down phase, high-frequency waves in the range of MHz excited by runaway electrons have been successfully detected. These results provide valuable references for runaway electron mitigation in large-scale tokamak devices.

I. Introduction

Runaway electrons (REs) result from the plasma disruptions in large scale tokamak carry very high energy, and an uncontrolled runaway electron beam can bombard and melt the first wall, causing irreversible damage to the device [1]. Kinetic instability has been suggested as a possible way to cause controlled loss of REs [2].

The ion cyclotron emission (ICE) diagnostic was initially used to study high-frequency plasma instabilities induced by fast ions, but experimental studies in recent years have found that this diagnostic can also be used to study fast and runaway electron driven kinetic instabilities [3, 4]. This is achieved by measuring magnetically confined plasma emissions within the ion cyclotron frequency range, commonly focusing on cyclotron harmonics up to $n = 10$ [5]. Ion Cyclotron Resonance Heating (ICRH) antennas and magnetic probes are commonly used as ICE probes.

In order to study the kinetic instabilities driven by runaway electrons and fast electrons, an ICE diagnostic has been developed on the J-TEXT tokamak. Using this diagnostic, high-frequency waves driven by fast electrons and runaway electrons have been measured on the J-TEXT tokamak. The content of this article is organized as follows. Sec. II describes the construction of the ICE diagnostic. The experimental results on the J-TEXT are shown and

[2]See the author list of "*Y. Ding et al 2024 Overview of the Recent Experimental Research on the J-TEXT Tokamak, Nucl. Fusion 64 112005*, https://doi.org/10.1088/1741-4326/ad336e"

discussed in Sec. III. Conclusion is presented in Sec. IV.

II. ICE diagnostic on J-TEXT

The ICE radio-frequency (RF) probe is located on the mid-plane of J-TEXT [6]. This ICE diagnostic system comprises a magnetic probe, a high vacuum coaxial cable with high-temperature resistance, a vacuum feedthrough, RG58 RF transmission lines, a DC break, power splitters, a low-pass filter, band-pass filters, power detectors, an oscilloscope, an analog-to-digital converter (ADC) digitizer. The overall structure of this system is illustrated in Figure 1. The ICE diagnostic is divided into two systems. System 1 monitors the power signals of high-frequency magnetic fluctuations in the frequency range 10 MHz-150 MHz. System 2 uses an oscilloscope to analyze the spectrum of a signal spanning from 7 kHz to 200 MHz.

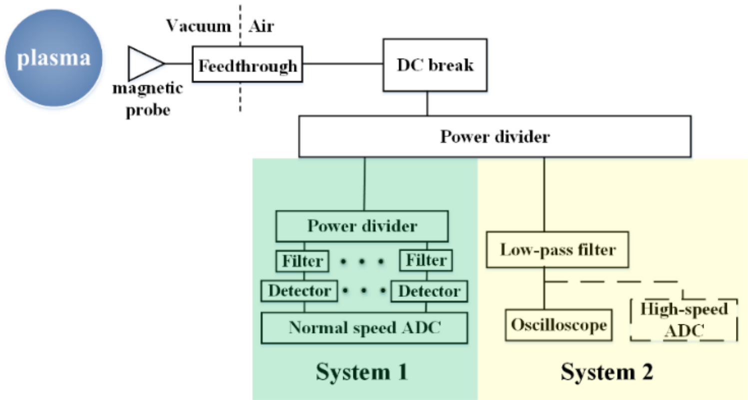

Figure 1: The ICE diagnostic system structure diagram on J-TEXT.

III. High-frequency instabilities excited by REs

High-frequency waves driven by REs have been observed on the J-TEXT tokamak using ICE diagnostic. Figure 2 presents a typical waveform at the end stage of a low-density discharge. During the plasma current decreased phase, the line-averaged electron density dipped below $0.146*10^{19}$ m^{-3}. During this temporal juncture, high-frequency signals manifested across all channels of ICE system 1. The appearance of the ICE signal represents the onset of the energetic particle-driven kinetic instabilities. The core FEB exhibited a rapid increase and the ECE signal at 118.5 GHz has an abrupt elevation at this point in time. The coherent behavior of these diagnostic signals lends support to the inference that the observed plasma waves are indeed triggered by runaway electrons. In addition, the significant increase in the ECE signal here is may be induced by fast pitch angle scattering of runaway electrons. The signal activity across the five channels of ICE system 1 spanned approximately from 0.753 s to 0.8916 s, while B_t remaining constant at 1.6 T throughout this duration. The core FEB signal disappears at 0.8576 s, much earlier than the disappearance of the ICE signal, which may be due to the radial drift of the runaway electrons motion trajectory, which eventually exceeds the detection range of the core FEB detector.

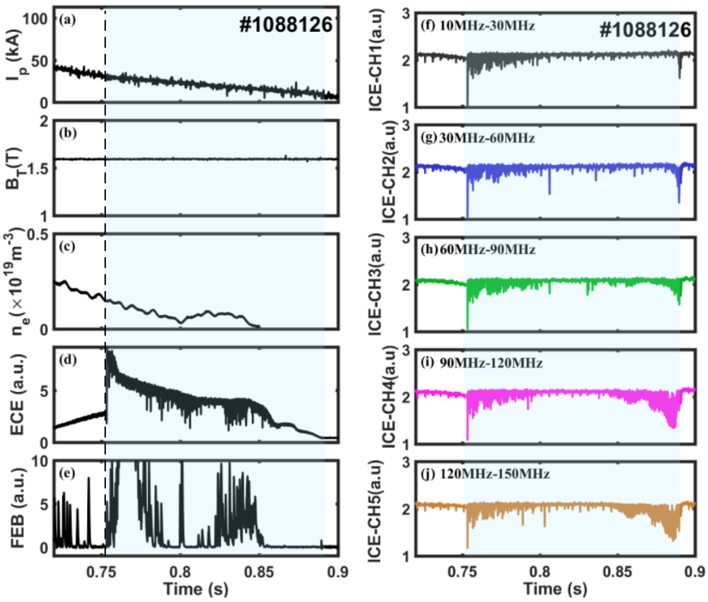

Figure 2: a typical waveform at the end stage of a low-density discharge

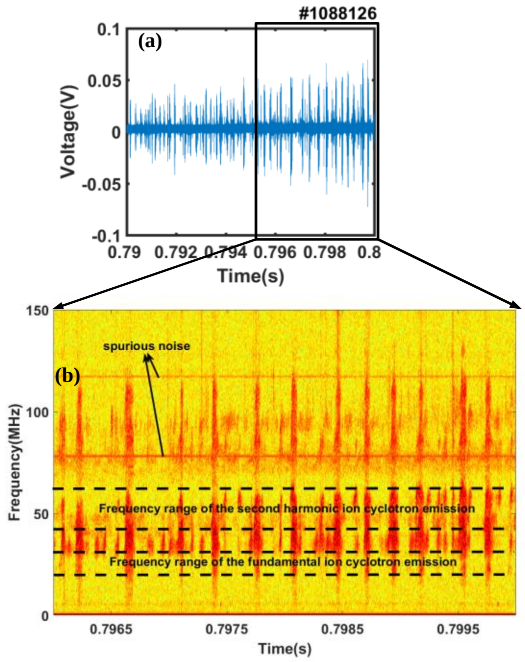

Figure 3: The high-frequency magnetic fluctuations measured by System 2 of the ICE diagnostic. (a) Original oscilloscope signal. (b) Time-frequency chart of magnetic fluctuations.

In order to further determine whether the measured waves were driven by energetic electrons or energetic ions, a spectral analysis of the waves was performed using the data collected by the oscilloscope of the ICE diagnostic system 2. The time-frequency diagram conspicuously exhibits the fundamental and second harmonic components of high-frequency waves. Figure 3 provides a visual representation of the original data and spectrum obtained from high-frequency magnetic diagnostic through oscilloscope measurements in shot #1088126 within the ICE diagnostic context, with the frequency ranges of the fundamental and second harmonic of ion cyclotron emission on J-TEXT are marked in the figure. The spectral characteristics in Figure 3 (b) can be broadly categorized into two groups, one with a very wide band and the other with a relatively narrow band. From the figure, it can be observed that only a portion of the spectrum of the measured waves falls within the frequency range of the fundamental or second harmonic of ion cyclotron radiation, indicating that these waves are not driven by fast ions. The two spectral lines at ~78 MHz and ~117 MHz in the spectrum of Figure 3 (b) are spurious noise. This noise can be caused by the circuit characteristics of the device itself, electromagnetic interference in the environment, and other external factors.

IV. Conclusion

An ion cyclotron emission (ICE) diagnostic based on a magnetic probe has been designed and installed on the J-TEXT tokamak. This ICE diagnostic is used to study the high-frequency magnetic fluctuations driven by energetic particles. The signals detected by the ICE probe are divided into two equal power signals, which enter the two systems respectively. The first system converts high-frequency signals into power signals in different frequency bands using bandpass filters and power detectors. This reduces the amount of data to be processed and allows the data to be uploaded in time after a discharge. Thus, the approximate time resolution, frequency range (10 MHz-150 MHz), and power of the high-frequency signals can be quickly judged. The second system uses low-pass filters and an oscilloscope to collect data by Nyquist sampling law, so that the frequency spectrum of signals with frequencies from 7 kHz to 200 MHz can be analyzed. Therefore, if significant signals are detected in the first system on the data server, corresponding stored data can be extracted from the second system for large-scale data processing. This structure enhances the efficiency of data storage and analysis. The high-frequency magnetic fluctuations driven by fast electrons or runaway electrons under ohmic heating have been measured on J-TEXT, which verified the feasibility of the system.

References

[1] G.F. Matthews, et al., JET Contributors7, Phys. Scr. T167, 014070 (2016)
[2] C. Liu, et al., Phys. Rev. Lett. 120, 265001(2018)
[3] L. Liu, et al., Nucl. Fusion 60, 044002 (2020)
[4] D.A. Spong, et al., Phys. Rev. Lett. 120, 155002 (2018)
[5] K.G. McClements, et al., Nucl. Fusion 55, 043013 (2015)
[6] G.N. Zou, et al., Fusion Eng. Des. 203, 114457 (2024)