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# Multi-channel poloidal correlation reflectometry on experimental advanced superconducting tokamak

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A new multi-channel poloidal correlation reflectometry is developed at Experimental Advanced Superconducting Tokamak. Eight dielectric resonator oscillators with frequencies of 12.5 GHz, 13.5 GHz, 14.5 GHz, 15 GHz, 15.5 GHz, 16 GHz, 17 GHz, and 18 GHz are used as sources. Signals from the sources are up-converted to V band using active quadruplers and then coupled together. The output waves are launched by one single antenna after passing through a 20 dB directional coupler which can provide the reference signal. Two poloidally separated antennae are installed to receive the reflected waves from plasma. The reference and reflected signals are down-converted by mixing with a quadrupled signal from a phase-locked source with a frequency of 14.2 GHz and the IF signals pass through the filter bank. The resulting signals from the mixers are detected by I/Q demodulators. The setup enables the measurement of density fluctuation at 8 (radial) × 2 (poloidal) spatial points. A coherent mode with an increasing velocity from 50 kHz to 100 kHz is observed by using the system. The mode is located in the steep gradient region of the pedestal. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4960162]

## I. INTRODUCTION

In recent years, the correlation reflectometry is proved to be an effective tool to measure the turbulence and to calculate the perpendicular rotation of the turbulence. Reflectometry has been installed on many fusion machines nowadays and works as diagnostics for electron density profile and fluctuation.[1,2] Reflectometry is a radar-like technology based on injecting a low power microwave into the plasma. The injected wave is reflected at the cutoff layer and the density fluctuation can be derived from the phase fluctuation of the reflected wave. A technique of injection of multi-frequency microwaves has been developed in order to measure the density fluctuation at different radial positions simultaneously. This technique was applied on many machines such as CCT,[3] TFTR,[4] JET,[5,6] and JT-60U[7] years ago. A poloidal correlation reflectometry with poloidally separated antennae was installed at T-10[8] and TEXTOR.[9] Most recently, a novel multi-channel system which enables measurement at distinct spatial locations is developed, such as Doppler backscatter system at DIII-D[10] and multi-channel reflectometry at NSTX.[11]

A radial and poloidal correlation reflectometry[12] was installed on Experimental Advanced Superconducting Tokamak (EAST). This system is proved to be a good tool to measure the pedestal turbulence and provide the vertical turbulence velocity ($v_{perp}$). The system can measure four spatial positions in plasma simultaneously, each two of which are poloidally spaced but in the same radial position. It is difficult for the system, however, to provide density fluctuation measurements at different radial locations simultaneously. In order to expand the capacity of the system, the new multi-channel reflectometry operating at eight different probing frequencies (50 GHz, 54 GHz, 58 GHz, 60 GHz, 62 GHz, 64 GHz, 68 GHz, and 72 GHz) is installed at EAST. This setup enables the measurement of the electron density fluctuations at eight different spatial positions simultaneously.

## II. SYSTEM DESIGN

The overview of the correlation reflectometry system at the EAST including system location is illustrated in Fig. 1. The antenna system is installed outside of the machine with a distance of 1.9 m relative to the separatrix. The probing wave is launched into the plasma after passing through a pyramidal antenna, since the port is 16 cm below the mid plane. In order to guarantee that the wave is perpendicularly launched to the corresponding cutoff layers, there is a launching angle of 7° relative to the mid plane. The schematic of the millimeter-wave system is illustrated in Fig. 3. Eight dielectric resonator oscillators (DROs) with fixed output frequencies of 12.5 GHz, 13.5 GHz, 14.5 GHz, 15 GHz, 15.5 GHz, 16 GHz, 17 GHz, and 18 GHz are sources. The output power of each source is 10 dBm. The output signal of the source is quadrupled to V

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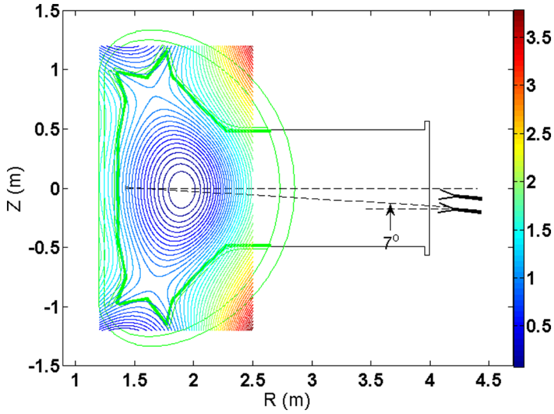


FIG. 1. System location of the reflectometry relative to plasma and vacuum vessel. Colored curves are magnetic surfaces. Bold green lines indicate the vacuum vessel of EAST. Receiving antennae are illustrated. Normalized magnetic flux is indicated by the color bar.

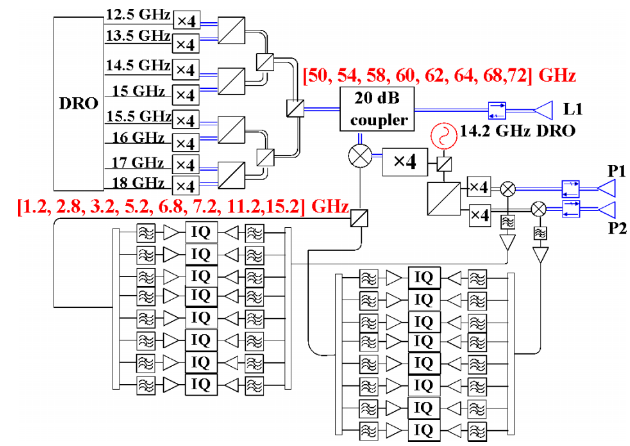


FIG. 3. The schematic of the millimeter-wave system of multi-channel poloidal correlation reflectometry on EAST.

band (50 GHz–75 GHz). In order to realize the simultaneous launching of the eight probing waves through one antenna, each two of the quadrupled signals are coupled with a 3 dB coupler, and then coupled together for launching. Launching power of each frequency is about 3 dBm due to the losses when passing through the 3 dB couplers. The V-band multi-frequency output of the directional couplers passes through a 20 dB directional coupler to provide a signal to the RF input of balanced mixers in both of the two receiving channels. The small amount of power from 20 dB coupler is the so-called "reference" signal of receiving channels.

The reflected wave from plasma is received by two poloidally spaced antennae shown in Fig. 2. The antenna arrangement is the same as the system in Ref. 15. There is a distance of 5 cm between two receiving antennae. The received signal is down converted with a mixer. Down conversion is achieved by a quadrupled DRO with a frequency of 14.2 GHz. This DRO source also provides the local oscillation signal to the reference and receiving channels. By using balanced mixers with the phase locked source as local oscillation, the reference signals are also down-converted to intermediate frequencies.

Down-converted signals from both the reference channels and the receiving channels are pre-amplified and then pass through an eight-way power splitter and a narrow band filter bank. The center frequencies of the filter bank are especially designed to be the same as the corresponding intermediate frequencies shown in Fig. 3, so that the specific launching frequency of each channel is selected from the single reference and receiving channel. The output signals of the filter bank are amplified again to provide optimum power to the I/Q detectors. Each I/Q detector is built in with a 1.5 MHz low-pass filter in both I and Q output. The thirty two in-phase signals (I

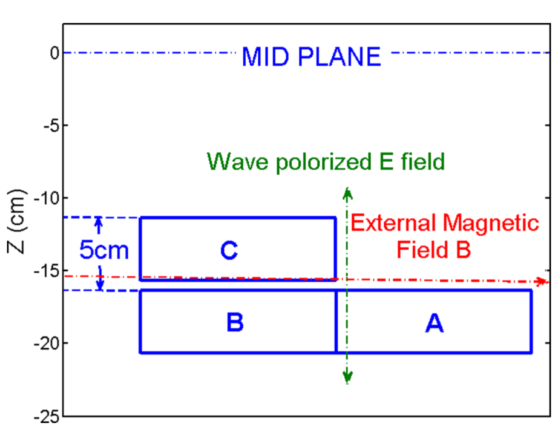


FIG. 2. Antenna arrangement of correlation reflectometry. A is the antenna. B and C are receiving antennae.

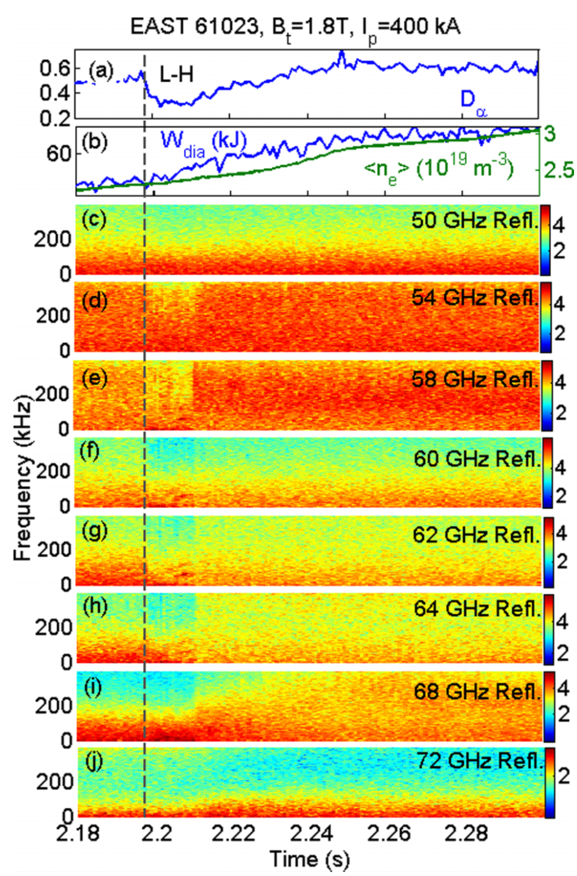


FIG. 4. (a) Dα signal and (b) averaged density and store energy of EAST discharge 61 023. (c)–(j) Frequency spectrum of the reflected signal measure by the eight probing channels. The dashed line is the time of L–H transition determined from the Dα signal. Power of the signal is indicated by the color bar.

signals) and quadrature signals (Q signals) are digitized with a sampling rate of 2 MHz which provides a video bandwidth of 1 MHz.

## III. MEASUREMENT OF DENSITY FLUCTUATION

The key objective of the system is the measurement of density fluctuation at eight different radial positions simultaneously. Fig. 4 illustrates the basic plasma parameters and frequency spectrum of I/Q complex signals of eight channel measurement during the period of L–H transition of EAST discharge 61 023. The spectrum is calculated by fast Fourier transformation (FFT) which can be used to analyze the density fluctuation. The plasma is heated by a lower hybrid wave and enters into H-mode operation at 2.2 s. High frequency fluctuation is suppressed immediately after L–H transition. A coherent mode is observed in 58 GHz, 60 GHz, 62 GHz, and 64 GHz channels of the multi-channel system during the ELM (edge localized mode)-free phase. The coherent mode is born at a frequency of 40–50 kHz and then gradually increases to 100 kHz in the fluctuation spectrum measured by reflectometry in the pedestal region. The coherent mode can persist for several milliseconds and is finally replaced by broad band fluctuation in the later ELM-free phase.

In order to calculate the radial probing positions of corresponding launching frequencies and further determine the location of the coherent mode, the X-mode cutoff position[1] is reconstructed with the electron density profile measured by the reflectometry[13–15](Q, V, and W bands) at EAST as illustrated in Fig. 5. Unfortunately, we do not have the density profile measurement of this discharge. We choose a discharge with the same plasma parameters as EAST discharge 61 023 to calculate the density profile.

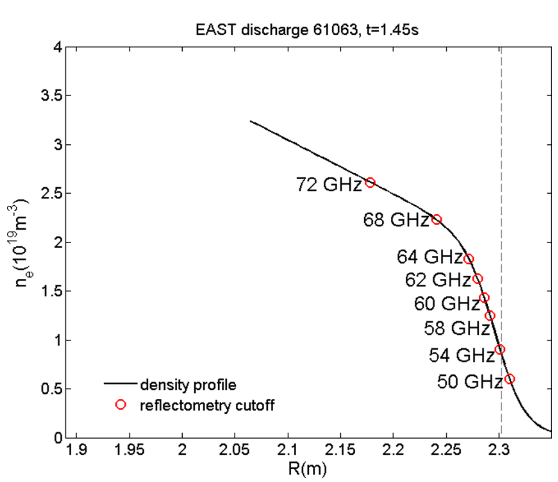


FIG. 5. Black curve is the electron density profile measured by reflectometry. Red circles are cutoff points of corresponding launching frequencies. The dashed line is the location of the separatrix.

The radial positions of cutoff points corresponding to each launching frequencies indicate that the probing positions of 50 GHz and 54 GHz are located near the separatrix, while the probing positions of 58 GHz, 60 GHz, 62 GHz, and 68 GHz are in the steep gradient pedestal region where the coherent mode appears. Higher frequency channels, namely, 68 GHz and 72 GHz, are located in the pedestal top and core regions of plasma.

## IV. SUMMARY AND DISCUSSION

A newly developed multi-channel poloidal correlation reflectometry is designed and installed. The system works in eight frequencies and measures electron density fluctuation at eight different radial positions simultaneously. An example of measurement of fluctuations in H-mode plasma heated by a lower hybrid wave is illustrated. A coherent mode with increasing frequency is observed in the steep gradient region of pedestal.

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