Journal of Instrumentation

W-band multi-channel correlation reflectometry for core turbulence measurement on EAST

To cite this article: M.F. Wu *et al* 2020 *JINST* **15** P12009

Published by IOP Publishing for Sissa Medialab

Received: *September 11, 2020*
Accepted: *October 19, 2020*
Published: *December 7, 2020*

W-band multi-channel correlation reflectometry for core turbulence measurement on EAST

M.F. Wu,[a,b] F. Wen,[b,1] H.M. Xiang,[a,b] T. Zhang,[b] G.Z. Mao,[c] Z.X. Liu,[a] Y.M. Wang,[b] G.S. Li,[b] Y.K. Liu,[d,e] K.N. Geng,[d,e] F.B. Zhong,[a,b] K.X. Ye,[a,b] J. Huang,[a,b] Z. Zhou,[f,g,b] X. Han,[b] S.B. Zhang,[b] G. Zhuang,[a] X. Gao[a,b] and EAST team

[a] *School of Nuclear Science and Technology, University of Science and Technology of China, No. 96, Jinzhai Road, Baohe District, Hefei, Anhui 230026, People's Republic of China*

[b] *Institute of Plasma Physics, Chinese Academy of Science, 350 Shushanhu Road., Hefei, Anhui 230026, People's Republic of China*

[c] *Shaanxi Sofilter Electronic Technology Co., Ltd, 1123 Hangchuang Road, Chang'an District, Xi'an, Shaanxi 710000, People's Republic of China*

[d] *Advanced Energy Research Center, Shenzhen University, 3688 Nanhai Avenue, Nanshan District, Shenzhen 518060, People's Republic of China*

[e] *Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Optoelectronic Engineering, Shenzhen University, 3688 Nanhai Avenue, Nanshan District, Shenzhen 518060, People's Republic of China*

[f] *Department of Physics, Nanchang University, 999 Xuefu Avenue, Honggutan New District, Nanchang, Jiangxi 330031, People's Republic of China*

[g] *Jiangxi Province Key Laboratory of Fusion and Information Control, Nanchang University, 999 Xuefu Avenue, Honggutan New District, Nanchang, Jiangxi 330031, People's Republic of China*

E-mail: wenfei@ipp.ac.cn

Abstract: An X-mode polarized W-band multi-channel correlation reflectometry is installed on the Experimental Advanced Superconducting Tokamak (EAST). The reflectometry with two poloidally spaced receiving antennas works at four different probing frequencies (i.e. 79.2 GHz, 85.2 GHz, 91.8 GHz, 96 GHz), which enables measurement of density fluctuation at 4 (radial) $\times$ 2 (poloidal) spatial points. The diagnostics applied to observe density fluctuation and turbulence perpendicular velocity in plasma core on EAST. The detailed description and initial experimental results are presented in this paper.

Keywords: Nuclear instruments and methods for hot plasma diagnostics; Plasma diagnostics - interferometry, spectroscopy and imaging

[1]Corresponding author.

https://doi.org/10.1088/1748-0221/15/12/P12009

2020 JINST 15 P12009

Contents

1 Introduction

Reflectometry has been widely used in the magnetic confinement devices for many years. The reflectometry is a radar-like technique that injects a microwave into the plasma and receives the wave reflected from the cut-off layer where the refractive index is zero. The density fluctuation at the cut-off layer can be derived from the phase fluctuation of the reflected wave. Due to very low injection power of the probing microwave beam, the reflectometry is a non-perturbative diagnostic tool for measuring the electron density and fluctuation [1, 2] from edge to core of fusion plasmas, which is helpful for studying the MHD activity and the abnormal transport associated with plasma turbulence.

To save valuable spatial resources, a technique of injection of multi-frequency microwaves has been applied in microwave reflectometry to measure the density fluctuation at different radial positions simultaneously, such as the correlation reflectometry installed on CCT [3], TFTR [4], JET [5], and JT-60U [6]. In addition, the density fluctuations at different poloidal positions can be measured by a correlation reflectometry with poloidally separated antennae, such as the reflectometry on T-10 [7] and TEXTOR [8]. For the EAST, several correlation reflectometries have been developed over the years [9]–[13]. However, these reflectometries are all focused on turbulence measurement in edge pedestal region. Internal transport barrier (ITB) has been observed on EAST [14]–[16]. It is well-known that the confinement improvement in ITB is related to turbulence suppression in plasma core [17]. In order to understand formation and dynamics of ITB, an X-mode polarized W-band multichannel poloidal correlation reflectometry has been developed on EAST. Its measurement capability of density fluctuation and vertical velocity of turbulence in the core of plasma has been tested in latest campaign. In the rest of the paper, details of the diagnostics are described in section 2. The experimental results are given in section 3 followed by a summary in section 4.

2 Description of diagnostics

2.1 Principles and instruments

The W-band multi-channel correlation reflectometry system is installed at the low field side of the EAST (R=1.85 m, a=0.45 m) with an antenna array. The antenna array consisting of a transmitting antenna and two receiving antennas is located 16 cm below the midplane, directly facing the center of the plasma. Two receiving antennas with poloidal separation of 5 cm are placed on the left of the transmitting antenna, which is very similar to previously developed reflectometry [11, 12].

The schematic of the W-band multi-channel correlation reflectometry is shown in figure 1. The signals with fixed frequencies (13.2 GHz, 14.2 GHz, 15.3 GHz, 16 GHz) from four phase-locked sources are sextupled to W band (75–110 GHz) by active frequency multipliers, respectively. The power of output waves from the multipliers is about 14 to 16 dBm. Then the four probing waves are coupled together through a multiplexer. Then a 20 dB directional coupler divide the coupled microwave into two parts. One part with most of the power is probe signal, which is transmitted to the plasma by the pyramid antenna L, while the other part with low power is reference signal of the receiving channel.

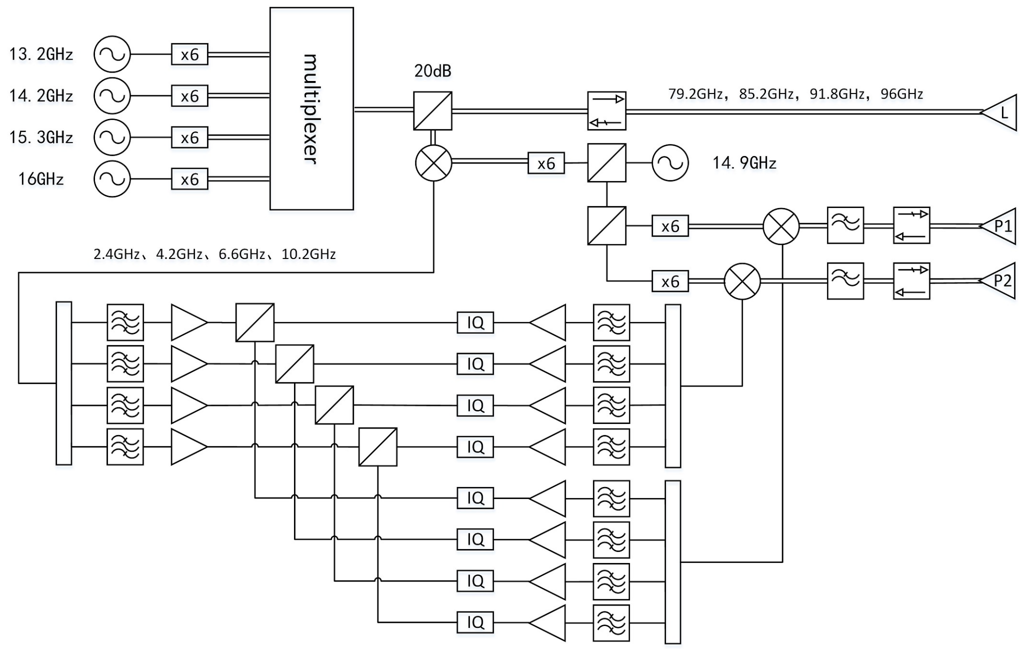

Figure 1. The schematic of the W-band multi-channel correlation reflectometry on EAST.

The signals received by the pyramid antennas P1 and P2 are filtered by a low pass filter (<114 GHz), and then mixed with the local oscillation (LO) signal by a balanced mixer to achieve frequency down-conversion. The LO signal is 89.4 GHz microwave, which is sextupled from output signal of a 14.9 GHz phase-locked source. The LO signal is also mixed with the reference signal by a mixer to down-convert the reference signal. The intermediate frequencies (IFs) from reference branch are 2.4 GHz, 4.2 GHz, 6.6 GHz, and 10.2 GHz, respectively. All the down-converted signals pass through a four-way power divider and a filter bank with four narrow passband filters to acquire signals with the desired frequency. The output signals of the filter banks are amplified to provide optimum power for the in-phase and quadrature (I/Q) demodulators. Lastly, I/Q signals are low-pass filtered at 1 MHz and are digitized by a data acquisition system with a sampling rate of 2 M/s.

2.2 Key components

2.2.1 Multiplexer

The multiplexer in the signal transmission part of the system is a waveguide output multiplexer that is used to couple the four input microwave signals together. In order to increase power capacity and reduce insertion loss, a branched waveguide structure is utilized. The circuit simulation model of multiplexer is shown in figure 2. The branched waveguide structure consists of waveguide T-junctions (E-T1 to E-T4), waveguide sections (L1 to L13) of different lengths connecting the waveguide T-junctions, channel filters (Filter 1 to Filter 4) and ends of multiplexer (Short and Port 5). One end of the branched waveguide is short-circuited, while the other open-circuited end is the output end of the multiplexer. Each channel filter is a band-pass filter adapted to the channel frequency (Port 1 to port 4).

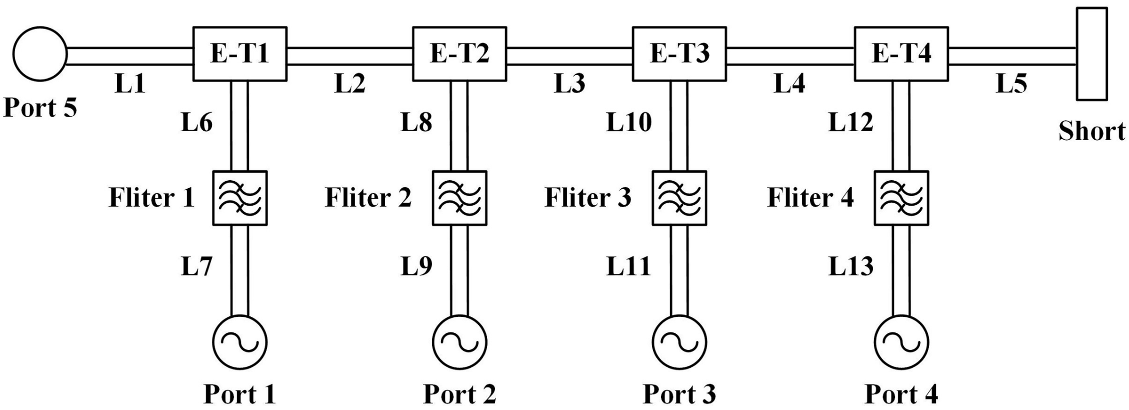

Figure 2. The circuit simulation model of multiplexer.

Since there is no isolation device between each channel filter of the multiplexer, mutual influence among these channels may destroy the original passband characteristics of the filter and even cause the impedance mismatch at the common end, which will deteriorate the transmission characteristics in the passband of each channel. To eliminate the interaction between each channel, it is necessary to optimize the phase distance of waveguide sections. In addition, the coupling coefficient related to the channel filter and even the resonant frequency of some resonators also has to be optimized. A set of optimal values can be obtained only through computer optimization design technology.

To realize the technical requirements of the multiplexer, the TE10 mode 3th-order Chebyshev function band-pass filter is used as the channel filter. The waveguide T-junction of the multiplexer is an E-T junction. Figure 3 shows the circuit simulation results of the multiplexer respectively. As shown in the figure, there is no passband overlap and no mutual influence between the filters.

Figure 4(a) and 4(b) show the picture of the finished multiplexer and its insertion loss measured in laboratory, respectively. Due to the machining accuracy error, the pass-band of the multiplexer has a little bit deviation from the design values, which causes the four frequency points approaching

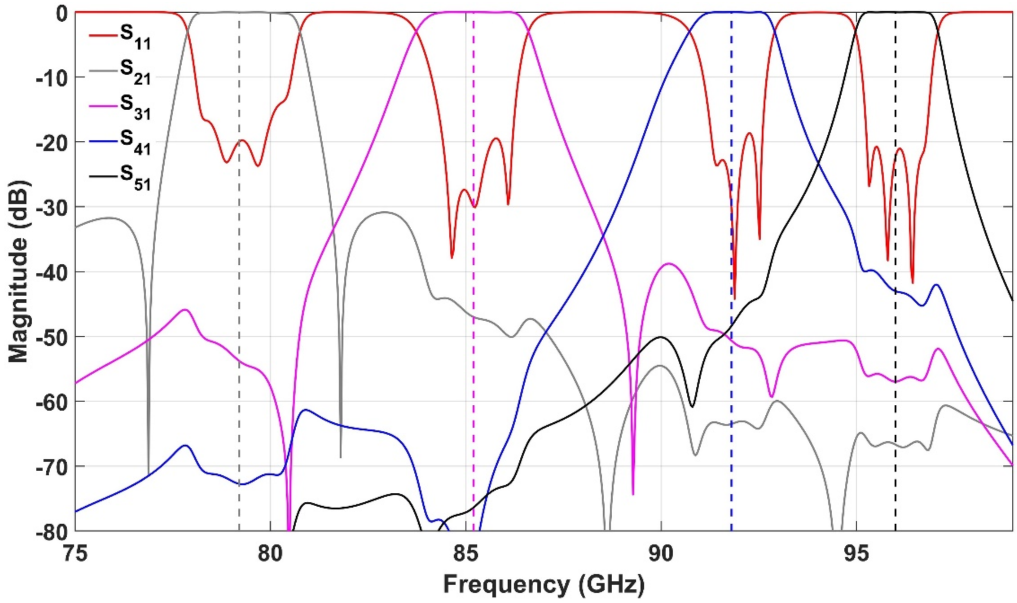

Figure 3. The circuit simulation results of the multiplexer. The dashed line indicates the frequency of the probing microwave beam.

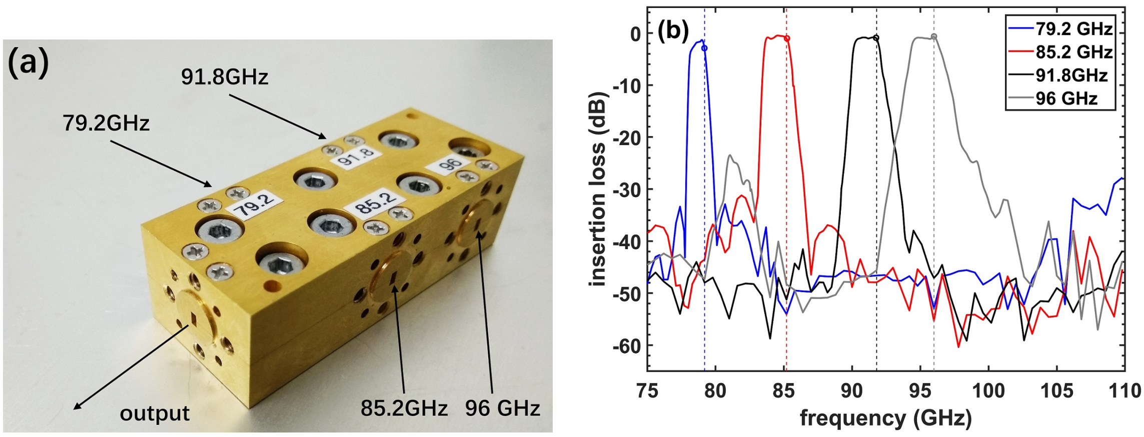

Figure 4. (a) Finished multiplexer and (b) its insertion loss measured in laboratory. The different colors indicate the four channels of the multiplexer, respectively. The dashed line indicates the frequency of the probing microwave beam.

the falling edge of the corresponding pass-band, as shown in figure 4(b). Nevertheless, the insertion loss for each channel is still less than 3 dB, which is acceptable for this system. In the future, the multiplexer will be redesigned and processed to locate the four frequency points in the center of the passband, thereby reducing these factors that may disrupt the stable operation of the system.

2.2.2 Filter banks

Each filter bank is composed of four narrow passband filters. The performance of the filters is shown in figure 5. The LO filter bank filters the LO signal, while the P1 and P2 filter banks are used for the received signals corresponding to the pyramid antennas P1 and P2, respectively. The

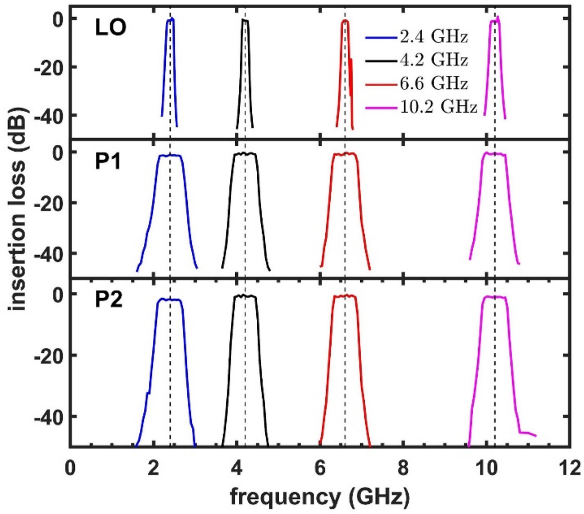

Figure 5. The performance of the bandpass filter. The dashed line indicates the center frequency of the filter, which are the same as the corresponding IF.

center frequency of the filter bank is the same as the corresponding IF, and the passbands of the filters do not overlap.

3 Experimental results

The W-band multi-channel correlation reflectometry has been applied in measurement of plasma core turbulence in EAST 2018 campaign. Figure 6 shows an example of the measurement. The plasma is heated by a tangential Neutral Beam Injection (NBI) and Electron Cyclotron Resonance Heating (ECRH). Viewed from the top, the plasma current for this discharge is 450 kA in the anti-clockwise direction, while the toroidal magnetic field is about 2.37 T in the clockwise direction. This results in that the NBI injection is in the co-Ip direction. The basic plasma parameters of this discharge (#80745) are shown in figure 6(a)–6(c). It enters into H-mode at 3.24 s. The frequency spectrums of signals measured by the four probing channels are shown in figure 6(d)–6(g). In order to determine the radial probing positions corresponding to each probing frequency, the cutoffs are calculated by using the electron density profiles (figure 7(a)) measured by the density profile reflectometry [9]–[11]. The spectrum of 79.2 GHz in figure 6(d) shows perturbation related to edge localized modes (ELMs) during H-mode, while this perturbation is not observed in other channels. This is attributed to that the cut-off position of 79.2 GHz is located just at the top of the edge transport barrier during H-mode, while the other channels are more inside the barrier. In addition, figure 6(e)–6(g) shows that high-frequency density fluctuations appear in the plasma core after the L–H transition. Figure 7(b) shows the profiles of the vertical velocity of the turbulence ($v_{\perp,\mathrm{turb}}$) at 2.45 s and 4.75 s, which are obtained by a poloidal correlation analysis [11, 18] on the reflectometry signals received by the two poloidally separated receiving antennae. The ($v_{\perp,\mathrm{turb}}$) in the ohmic plasma (t=2.35 s) core is from −0.8 km/s to −3.7 km/s, while the ($v_{\perp,\mathrm{turb}}$) in the H-mode plasma (t=4.75 s) core is from 3.4 km/s to 7.5 km/s. The negative ($v_{\perp,\mathrm{turb}}$) indicates that the turbulence structure rotates in the electron diamagnetic drift (EDD) direction.

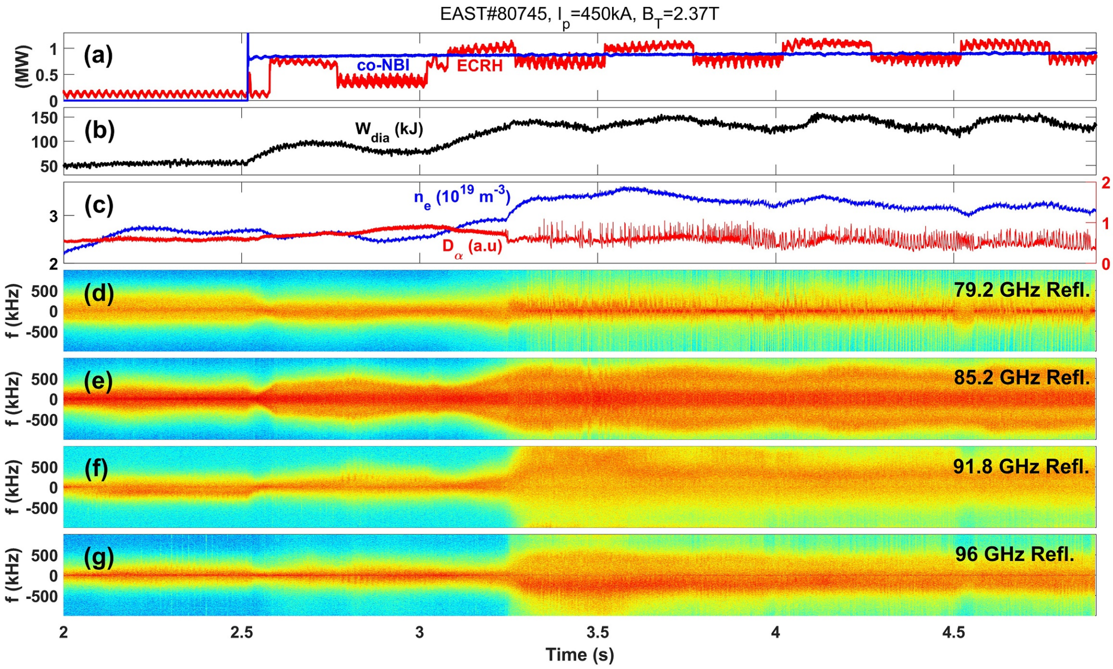

Figure 6. (a) External heating powers, (b) plasma stored energy, (c) line averaged density and Dα signal of EAST discharge #80745. (d)–(g) Frequency spectrums of the reflected signals measured by the four probing channels.

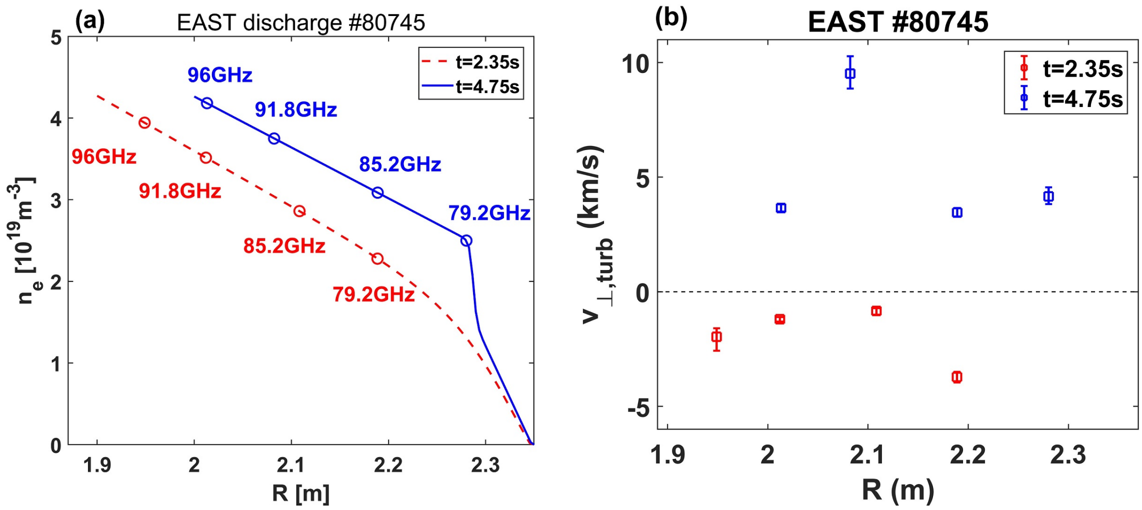

Figure 7. (a) The red dashed curves and blue solid curves are the electron density profiles measured by reflectometry at t = 2.35 s and t = 4.55 s, respectively. Red and blue circles are cutoff points of corresponding launching frequencies. (b) The vertical velocity of turbulence at t=2.35 s (for no auxiliary heating) and 4.75 s (for auxiliary heating with co-NBI and ECRH).

4 Summary

An X-mode polarized W-band (75 GHz–110 GHz) multi-channel correlation reflectometry has been applied to measure plasma core fluctuation on the EAST. The system operates in four frequencies and

2020 JINST 15 P12009

can measures electron density fluctuation at 4 (radial) $\times$ 2 (poloidal) spatial points simultaneously. An example of measurement of the density fluctuation and vertical velocity of the turbulence in an H-mode discharge is illustrated. With the reflectometry, the turbulence behavior in ITB plasma will be studied in future.

Acknowledgments

This work has been supported by the National Key R&D Program of China (No. 2017YFE0301205 and No. 2017YFE0300501) and National Natural Science Foundation of China (Nos. 11875289, 11675211, 11805136).

References

[1] E. Mazzucato, *Microwave reflectometry for magnetically confined plasmas*, *Rev. Sci. Instrum.* **69** (1998) 2201.

[2] R. Nazikian, G.J. Kramer and E. Valeo, *A tutorial on the basic principles of microwave reflectometry applied to fluctuation measurements in fusion plasmas*, *Phys. Plasmas* **8** (2001) 1840.

[3] T.L. Rhodes, R.J. Taylor and W.A. Peebles, *Correlation reflectometry: An experimental investigation of measurement capability*, *Rev. Sci. Instrum.* **66** (1995) 824.

[4] E. Mazzucato and R. Nazikian, *Radial scale length of turbulent fluctuations in the main core of TFTR plasmas*, *Phys. Rev. Lett.* **71** (1993) 1840.

[5] S. Hacquin et al., *Upgrade of the X-mode reflectometry diagnostic for radial correlation measurements in the Joint European Torus*, *Rev. Sci. Instrum.* **75** (2004) 3834.

[6] K. Shinohara, R. Nazikian, T. Fujita and R. Yoshino, *Core correlation reflectometer at the JT-60U tokamak*, *Rev. Sci. Instrum.* **70** (1999) 4246.

[7] V.A. Vershkov, V.V. Dreval and S.V. Soldatov, *A three-wave heterodyne correlation reflectometer developed in the T-*10 *tokamak*, *Rev. Sci. Instrum.* **70** (1999) 1700.

[8] A. Krämer-Flecken, S. Soldatov, B. Vowinkel and P. Müller, *Correlation reflectometry at TEXTOR*, *Rev. Sci. Instrum.* **81** (2010) 113502.

[9] Y.M. Wang et al., *Development of the W-band density profile and fluctuation reflectometer on EAST*, *Fusion Eng. Des.* **88** (2013) 2950.

[10] S.B. Zhang et al., *Density profile and fluctuation measurements by microwave reflectometry on EAST*, *Plasma Sci. Technol.* **16** (2014) 311.

[11] H. Qu et al., *Radial and poloidal correlation reflectometry on Experimental Advanced Superconducting Tokamak*, *Rev. Sci. Instrum.* **86** (2015) 083503.

[12] H. Qu et al., *Multi-channel poloidal correlation reflectometry on experimental advanced superconducting tokamak*, *Rev. Sci. Instrum.* **87** (2016) 11E707.

[13] H.M. Xiang et al., *Development of an ordinary mode multi-channel correlation reflectometer on EAST tokamak*, *Rev. Sci. Instrum.* **89** (2018) 10H103.

[14] X. Gao et al., *Key issues for long-pulse high-*β_N *operation with the Experimental Advanced Superconducting Tokamak (EAST)*, *Nucl. Fusion* **57** (2017) 056021.

[15] Y. Yang et al., *Observation of internal transport barrier in ELMy H-mode plasmas on the EAST tokamak*, *Plasma Phys. Controlled Fusion* **59** (2017) 085003.

[16] X. Gao, *Sustained high β_N plasmas on EAST tokamak*, *Phys. Lett. A* **382** (2018) 1242.

[17] K. Ida and T. Fujita, *Internal transport barrier in tokamak and helical plasmas*, *Plasma Phys. Controlled Fusion* **60** (2018) 033001.

[18] A. Krämer-Flecken, V. Dreval, S. Soldatov, A. Rogister, V. Vershkov and the TEXTOR Team, *Turbulence studies with means of reflectometry at TEXTOR*, *Nucl. Fusion* **44** (2004) 1143.