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To cite this article: Wandong Liu *et al* 2019 *Nucl. Fusion* **59** 112013

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An overview of diagnostic upgrade and experimental progress in the KTX

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Received 29 December 2018, revised 15 March 2019

Accepted for publication 5 April 2019

Published 22 July 2019



Abstract

The Keda Torus eXperiment (KTX) is still operated in the commissioning phase, and preparation for the operation capability of the KTX phase II upgrade is underway. The diagnostics in the KTX have been greatly developed: (1) the terahertz interferometer has been upgraded to seven chords for electron density profile inversion; (2) a Thomson scattering system with a 5 Joule laser has been installed and commissioning is in progress; (3) a 3D movable probe system has been developed for the electromagnetic turbulence measurement; (4) double-foil soft x-ray imaging diagnostics have been set up and a bench test has been completed; (5) an edge capacitive probe has been installed for the radial electrical field measurement; (6) a multi-channel spectrograph system has been built for detecting impurities of carbon and oxygen. In addition, the design of a new compact torus injection system has been completed for feeding and momentum driving. Pilot research, such as the 3D reversed field pinch physics and electromagnetic turbulence, etc, have been conducted in the discharge status of the KTX. The 3D spectra characters of electromagnetic turbulence are firstly measured using a classical two-point technique by Langmuir probe arrays set on the 3D movable probe system and edge magnetic sensors. The forward scattering is collected by the interferometer system, which shows the potential for turbulence research. The electromagnetic turbulence is tentatively investigated in the KTX. The formation of a quasi-single-helicity state in the KTX regime is also preliminarily explored in simulation.

Keywords: reversed field pinch, diagnostic, turbulence, upgrade

(Some figures may appear in colour only in the online journal)

1. Introduction

The middle-sized Keda Torus eXperiment (KTX) is the only reversed field pinch (RFP) machine in China, which is located

at the University of Science and Technology of China [1]. One of the missions of the KTX is complementary to the existing international RFP facilities. As one of the magnetic confinement fusion reactor candidates, the advantages of RFP make it possible to be developed into a type of compact and economic fusion reactor. The research priorities of KTX would be physics and technologies related to RFP confinement improvement and self-organization, for example, the quasi-single-helicity (QSH) state, ‘Dynamo’ mechanism and an

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edge active feedback control scheme. The KTX group also aims for cooperation with tokamak and stellarator groups for common characteristics of physics issues among those three types of configurations [2–4]. For example, the beta value in the RFP configuration can be much higher than that in the other two configurations [5], which is an advantage in future fusion reactors, and the external kink mode could be a problem if approaching the beta limit in tokamak configurations [6]. Therefore, RFP could be an appropriate platform for advanced research on high beta physics and resistive wall mode (RWM) control. Also, density limit disruption will be a devastating problem for plasma with high parameters in the tokamak configuration, while there is usually only thermal crash in the RFP [2, 3]. There is a similar phenomenon during the discharge terminal process in both configurations, therefore, the density limit study in RFP may help us to understand the mechanicals and to inspire people with new control methods to avoid or mitigate disruptions in large tokamak devices. As a middle-sized magnetic fusion machine in a university, one of the important missions of the KTX is to serve as a training platform for students, both at graduate and undergraduate levels, and they will be the future human resources of machine operation, diagnostic development, physics research and subsystem maintenance of fusion devices.

The KTX is a middle-sized RFP device with a major radius of $R = 1.4$ m and minor radius of $a = 0.4$ m. Three types of discharges can be run in the KTX, as mentioned in a previous paper [7]. One type of discharge is called ultra-low- q plasma, with a fixed toroidal magnetic field about 0.17 T and fast plasma current rising. The maximum plasma current can reach about 200 kA, and the time duration is usually less than 10 ms, which corresponds to the preceding capacitor bank discharge waveform. Another type of discharge is called low-current tokamak discharge with lower plasma current rising and a fixed toroidal magnetic field about 0.17 T. The maximum plasma current is only about 30 kA, and the discharge duration can reach 25 ms, which is approaching the shell penetration time, 20 ms. The KTX can also be run in RFP mode of course, with about 2 ms edge toroidal field reversed duration state. Over the last two years, a few methods have been tried to carry out wall conditioning, including wall baking, glow discharge cleaning and repeated low plasma current discharge cleaning, and it has been found that improvement in the maximum plasma current and realization of a longer RFP state are probably limited by the power supply, but not impurities from the wall. The maximum loop voltage at the present stage is about 150 V, which is not quite low compared with other RFP machines, however, the high loop voltage is not long enough to sustain plasma current rising to get through the RFP plasma start-up phase with high resistance [8]; thus what needs to be upgraded is the capacitance of the main ohmic capacitor bank. In addition, the results from the RFX and MST suggest that the QSH state tends to occur in large plasma current parameters [9–13]. The KTX will augment its capabilities (large plasma current, longer discharge time, edge and core measurement) with sufficient ohmic heating power, edge feedback control [14, 15], independent equilibrium control power and profile and fluctuation diagnostics in a national

magnetic confinement fusion energy program, which has just acquired support from the ministry of Science and Technology of China. The 3D physics in the QSH state [16], density limit [2, 17], disruption and electromagnetic turbulence [18–20] with improved confinement will be the main physics research priorities during and after the phase II upgrade of the KTX machine. Before this, some diagnostics have been added, and advanced research starts in the current state of discharge.

This paper reports results primarily from the year 2017 to 2018. Some diagnostic system upgrades and new data processing methods are described in section 2. Section 3 discusses a facility added for more flexible operation of the KTX, which is a compact torus injection system. The initial experimental results of electromagnetic turbulence are discussed in section 4, and some simulation results on QSH are reported in section 5, followed by an overview of future planned upgrades and a summary in section 6.

2. Diagnostic upgrade

In terms of the measurement position of plasma, the newly developed diagnostic systems can be divided into core diagnostics and edge diagnostics. Figure 1 shows the occupancy of windows in the KTX by diagnostics, pumping and feeding. One of the upgraded edge diagnostics is movable electro probes at different positions compared to the previous ultra-fast reciprocating probe system in the poloidal and toroidal direction. The data acquisition channels for edge magnetic probes [21], including Mirnov array and eddy current probes [22], have been upgraded to their full capacity. Capacitive probe arrays [23] for edge electric field measurements have been applied. For core measurement, the previous terahertz interferometer system [24] has been upgraded to seven channels, and a new Thomson scattering system with one observation point in the center of the plasma has been developed in the KTX. A new spectrometer has been introduced for impurity diagnostic and flow speed measurement. A double-foil tangential soft x-ray (SXR) fluorescence system has been set up for fast imaging of 2D electron temperature.

2.1. Multi-channel interferometer system

A one-chord interferometer system based on 650 GHz solid-state sources has already been applied in the KTX [25]. The output power of the source is about 2 mW. The whole system with very compact size is set on a light non-metal platform, which is less than 200 kg, and the phase shift caused by the vibration effect is optimized under the phase noise of intermediate frequency, which is about 0.0186π , corresponding to a minimum detectable chord-integrated density of $4.5 \times 10^{16} \text{ m}^{-2}$. After the successful application of the solid-state sources, the one-chord system has been upgraded to seven chords.

To minimize the size of the whole system and to minimize the loss of beam energy, the whole system is designed to be set just beside the vacuum vessel, as shown in figure 2(a). The whole system is supported by two SUS304 pillars, which are

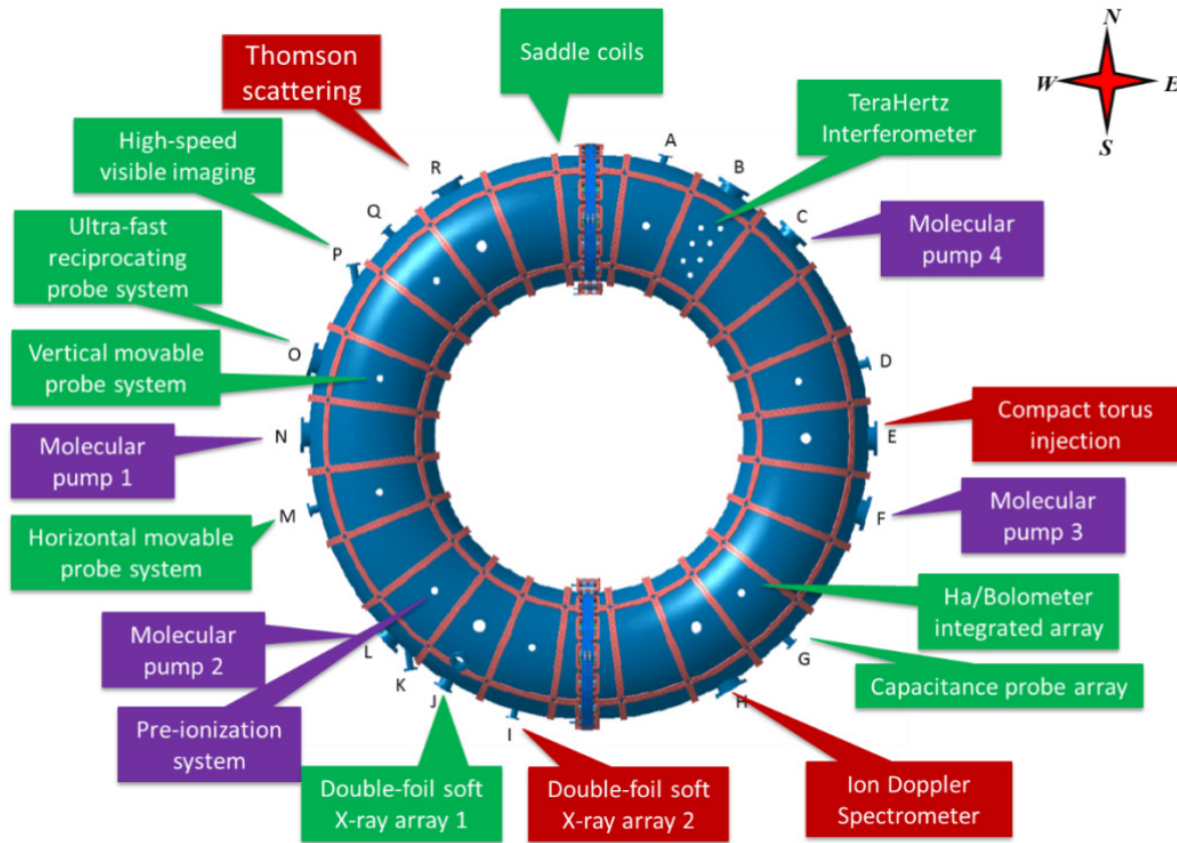
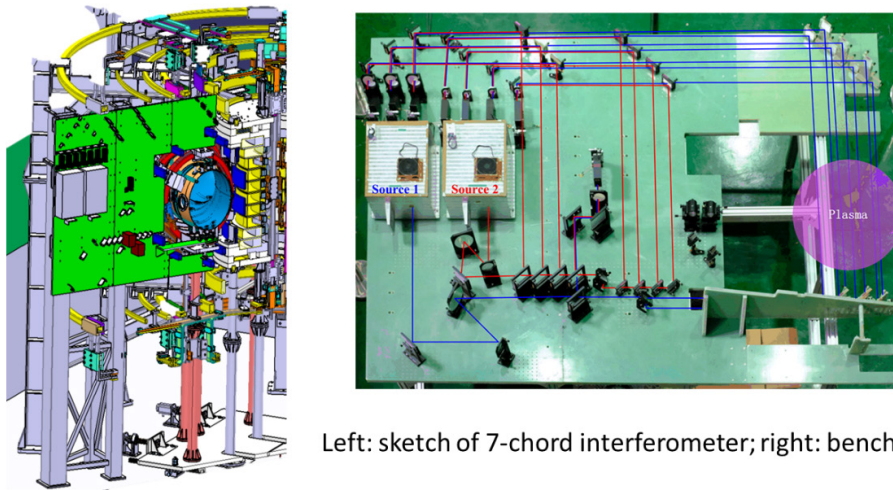


Figure 1. The diagnostic distribution in the KTX. The diagnostics in the red block are being developed. The magnetic coils on the inner surface of the vacuum vessel and interlayer of the composite shell are not shown in this figure.



Left: sketch of 7-chord interferometer; right: bench test.

Figure 2. A diagram of the seven-chord interferometer system (a) and the bench experiment (b).

independent from the other part of the KTX machine and are filled with silica sand to damp acoustic waves. The sources, the optical elements and the mixers are all fixed on the vertical platform, which is shown in green in figure 2(a). The platform has two arms distributed like a tuning fork, and the vacuum vessel ring traverses the gap, which is made from epoxy resin to avoid vibration caused by the induced eddy current, as are the mounts of the optical elements. It has been proved that this method can decrease the phase vibration level

close to the noise from a solid-state electronic system. The platform is composed of five pieces of smaller board, and this design makes it convenient for assembling and disassembling, which is important for the ‘double C’ structure [1] operation in the future. There are seven sets of vertical windows, allowing for seven channels of beam light going through. These sets of windows are arranged in two rows at different toroidal locations. On one hand, this type of distribution can avoid overlapping between beams going through two adjacent

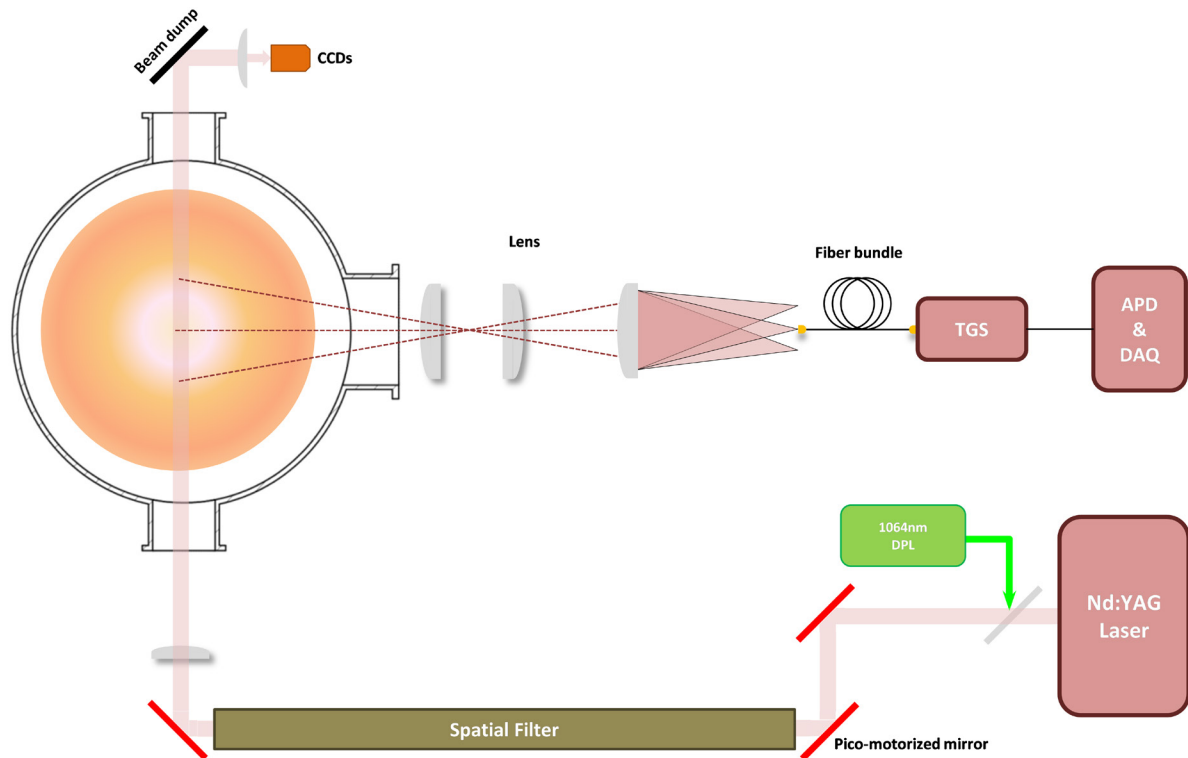


Figure 3. A schematic layout of the KTX TS system.

windows, and on the other hand, this makes the cross-correlation analysis of density fluctuation signals between two different toroidal locations possible. The total weight of the platform, including the microwave and optical components, is less than 400 kg, and no requirement for a clean room and long wave guide makes the whole system a very compact and light-weighted one. The optical design was simulated using Code V software [26] based on the theory of Gaussian optics. The simulation results can be tracked at each critical position to show beam spot size and energy. Two terahertz solid-state sources are used for the heterodyne interferometer. The fixed frequency of one source is 650 GHz, and the frequency of the other can be adjusted between 630 GHz and 655 GHz. Both sources have a maximum output power about 2 mW. In brief, the power of the beam is required to be uniformly distributed into eight. Since the light path is longer compared with the one-chord interferometer system, beam divergence is another effect that should be taken into consideration. After upgrading to a multi-channel system, the cross-talk has to be avoided for phase measurement. The maximum space constraint condition is from the diameter of the vacuum vessel and the distance between two adjacent windows, therefore, a large-sized mirror is not allowed. The optimization target is to increase the Rayleigh length of the beam across the vacuum vessel area and to minimize the beam size at the same time. A telescope unit consisting of a convex mirror and a concave mirror is used to lengthen and focus the beams going through the cross section of the vacuum vessel. Aluminum concave mirrors above the vacuum vessel windows are applied to focus the beam for the second time. To focus the beam energy into the horn mouth of the mixer in a very short distance (<2 cm),

a hyperboloid lens is applied before the mixers. After the optimization of the optical system, the beam width between the sources and the mixers is decreased to less than 20 mm. The detected signal amplitudes from the output of the mixers are all over 0.4 V, which is much larger than the noise level. The root mean square (rms) of the intermediate frequency's phase is around 0.0674π . If we take the refractive index of O mode propagation for calculation of chord-averaged electron density, the amplitude of the phase noise level corresponds to a minimum detectable chord-integrated density of $2 \times 10^{17} \text{ m}^{-2}$. Usually the chord-integrated density is about $2 \times 10^{19} \text{ m}^{-2}$, and this phase noise leads to an error of 1%. The frequency of the intermediate signal can be set up to 5 MHz, corresponding to a time resolution of $0.2 \mu\text{s}$. The bench test of the multi-channel interferometer system based on terahertz solid-state sources has been completed, and the system will be set up on the KTX machine in the near future.

2.2. Thomson scattering (TS) system

An incoherent TS system has been designed at the KTX facility based on a high repetition rate (200 Hz), high pulse energy (5 J/6.6 ns) Nd-YAG laser. The TS system is designed to measure the plasma temperature and density along the central vertical chord. The designed plasma scattering size at the focal plane is $3.0 \times 6.8 \text{ mm}^2$, as shown in figure 3. The polychromator is operated with a 1064 nm laser, and the designed spectral range is from 1000 nm to 1100 nm. The TS light is coupled to the volume phase holographic (VPH) grating spectrometer via a collection fiber bundle. At the spectrometer focal plane, the TS spectrum is split into five

wavelength channels by a focal plane fiber bundle. A pair of aspheric lenses are used for the coupling between the focal plane fiber bundle and avalanche photodiodes (APD), and an oscilloscope, which has eight input channels, 12-bit resolution and 350 MHz bandwidth, is chosen with the aim of acquiring detailed waveforms of the TS signals. Measurements of electron temperature and density at one local position in plasma with a time-resolved profile during the entire plasma discharge can be realized by this polychromator, and the spatial profile is obtained by moving one end of the collection fiber bundle placed at the image surface of a collection lens during different plasma discharges. The focal lengths of the collimating lens and focusing lens are 116.8 mm and 87.6 mm, respectively, giving a magnification equal to 0.75. The diameter of both lenses is 65 mm. The rms radius at the focal plane for 1064 nm is better than $14\ \mu\text{m}$. Spatial frequency of the VPH grating is $900\ \text{lp mm}^{-1}$, and the width of the grating is 60 mm. The fibers are low OH silica fibers with a numerical aperture of 0.22. The core and cladding diameters of the fiber are $400\ \mu\text{m}$ and $440\ \mu\text{m}$, respectively. Both ends of the fiber bundle are coated with antireflection film ranging from 950 nm to 1100 nm, with the reflection smaller than 0.5%. The length of the collection fiber bundle is 15 m with a spectral resolution of 6 nm. The spectrum of scattered light becomes broader and is shifted to the blue side of the probing laser as the electron temperature increases; an adequate design of the wavelength channels to cover and split the TS spectrum has been considered and optimized by the error formula [27, 28]. The optimized fitting error of σ_{T_e}/T_e is minimized around 100 eV, and this minimum value is smaller than 4% by using the five spectral channels.

At present, all components of the TS have been well manufactured, and the final assembly is in progress.

2.3. SXR fluorescence system

A tangential SXR fluorescence system has been developed in the KTX for fast imaging of magnetic shear and 3D structure detection. The 2D high-speed SXR imaging diagnostics using the two-foils technique can provide an electron temperature profile with high time and space resolution. As shown in figure 4(a), the new system is based on the double filter technique SXR imaging. It consists of two holes with different thin-foil absorbers ($25\ \mu\text{m}$ and $50\ \mu\text{m}$ thick Be foil) in front of a microchannel plate (MCP). The MCP part is capable of amplifying and detecting SXRs. Finally, the SXR hits the phosphor behind the MCP and causes emission with visible light. Two imaging spot lights from the two pin-holes with almost the same view angle can be captured by a high-speed camera. The ratio between the two visible lights can be converted into electron temperature for each pixel of phosphor images [29]. Compared with traditional SXR imaging, since there are no prior assumptions of plasma profiles, magnetic field reconstruction constraints, high-density limitations and no need for shot-to-shot reproducibility, the data acquisition speed depends on the CCD camera, which is up to 150 kfps at 128×128 pixel resolution. The spatial resolution is less

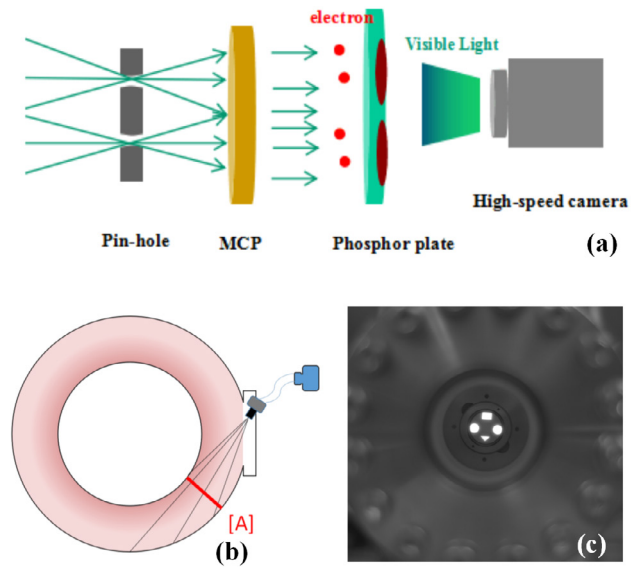


Figure 4. (a) A diagram of the SXR imaging system, (b) the installation position and visual angle of the system on the KTX, (c) a bench test of the system using an x-ray tube as the source.

than 1 cm. An initial bench test has been carried out with an x-ray tube (50 kV and 2 mA). A pierced stainless-steel plate with four holes of distinguishable shape was installed in front of the tube, and the imaging is shown in figure 4(c), which mainly proves the correctness of the optical path and the feasibility of the SXR fluorescence system. The next step is to set the system up on the KTX machine for further tests.

2.4. Impurity and ion Doppler spectrometer

A new spectrometer system is developed in the KTX, shown in figure 5. One use is for an impurity type monitor using an MSDD1004i monochromator, which is a doubly dispersed spectrum detector with an effective focal distance of 1 m. Four optical gratings inside the spectrograph allow for wavelength measurement in the range from 270 nm to 1000 nm. An electron-multiplying charge-coupled device is applied as the detector with pixel resolution 1600×200 and fps 1515. The results from initial scanning reveal that the KTX plasma may contain C, N, O, Fe, Mo and W impurities during the wall conditioning.

An ion Doppler spectrometer (IDS) is under construction and is being tested in the KTX, which is also based on the MSDD1004i monochromator. As shown in figure 5, the system includes a light collection system, spectrometer, cylindrical lens, photodiode and preamplifier. The emission light chosen for impurity ion temperature and flow velocity is CIII with a wavelength of 464.74 nm. The focal length of the lens for light collection is 25 mm, and the length of the optical fiber from the vacuum vessel window to the diagnostic room is 30 m. The diameter of the cylindrical mirror is 2 mm, and is used to refract the light in parallel to the detector, which is a multi-element photodiode array in the system. The output signal from the photodiode is amplified by the coefficient of $10^6\ \text{V A}^{-1}$ before data acquisition, and the bandwidth is 100 kHz.

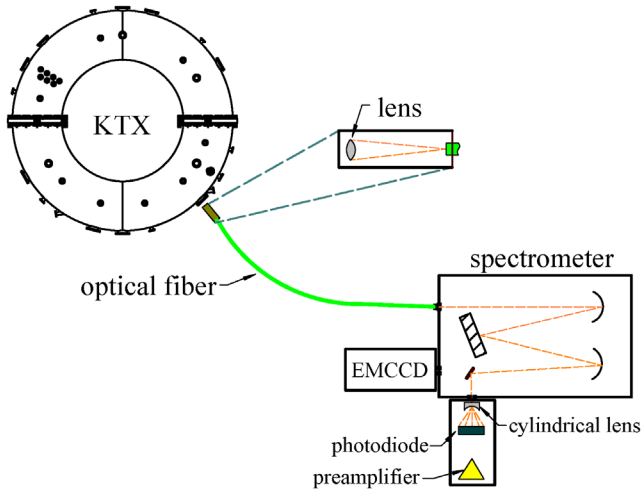


Figure 5. A schematic of the spectrometer diagnostic in the KTX.

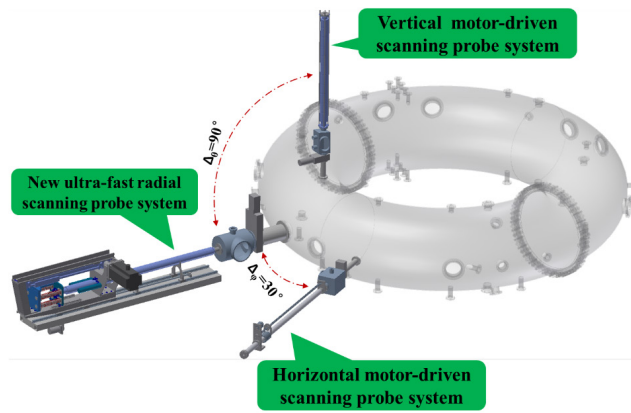


Figure 6. A radial movable probe system for electromagnetic turbulence research.

2.5. New movable Langmuir probe systems

A fast reciprocating probe system and another two slow-moving probe systems based on a step-motor driver are installed on the KTX. The radial coverage range is from the device center to the outside of the vacuum vessel. The aim of the three movable systems is 3D electromagnetic turbulence research in the KTX.

As shown in figure 6, the vertical motor-driven scanning probe system is set 90° away in the poloidal direction from the new ultra-fast radial scanning probe system. The horizontal motor-driven scanning probe system is set 30° away in the toroidal direction from the ultra-fast scanning probe system. This design allows for correlation analysis for magnetohydrodynamic (MHD) modes and turbulence study in the poloidal direction and toroidal direction. The tip of each system could be installed with magnetic probes, Mach probes, Langmuir probes, dual probes, three-point probes or a combination. The ultra-fast scanning probe system can be driven to a maximum speed up to 4 m s^{-1} , which is used for plasma parameter diagnostics at a deeper position, and the other two are mainly used for plasma edge measurements. A four-pin Langmuir probe and a nine-pin Langmuir probe have been used to measure

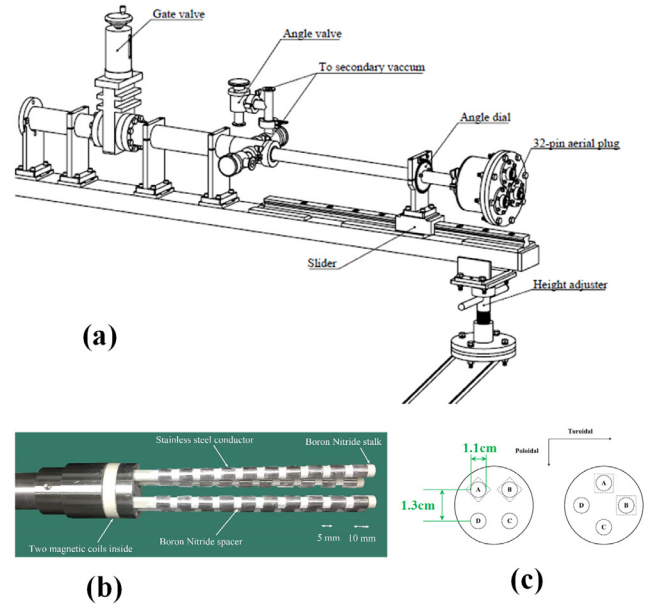


Figure 7. (a) A supporting structure diagram and (b) capacitive probes of the 40 channel plasma potential diagnostic system. (c) A cross sectional view of the capacitive probes.

the edge floating potential and plasma potential based on the probe system for initial turbulence study, which is described in detail in section 3.

2.6. Capacitive probes for electric field measurement

In magnetic confinement configurations, the electric field is a basic and important parameter to study physics related to equilibrium, instabilities and transport for confinement improvement. In RFP, the ‘dynamo’ is the most important mechanism to explain self-organization of RFP configuration [30], which is the result of nonlinear interaction among tearing modes at different resonance surfaces. The ‘Dynamo’ is also relative to magnetic reconnection, abnormal ion heating and magnetic helicity research. It is also reported that the 3D core in a tokamak hybrid operation scenario could also be explained by the ‘dynamo’ effect [31]. Study of the ‘dynamo’ focuses on the electric balance of Ohm’s law within the framework of MHD theory, therefore, electric field diagnostics with high spatial and temporal resolution is very useful to help understand this process.

A 40-channel capacitive probe has been developed to measure the electrostatic parameters, including electric field and plasma potential. Fluctuations and equilibrium components can be analyzed based on this diagnostic. As shown in figure 7(b), the probe consists of four stalks, and each stalk contains ten 1.0cm cylindrical capacitors with 1.5cm axial separation. When inserted into plasma, the probe will measure the ac component of the potential at four locations on a 1.3cm square grid at each of the ten radial locations. By differencing the potential measurement, the probe can measure the electric field along the four sides of the square grid. Each two of the four electric field measurements are of the same field component but are separated by 1.3cm toroidally or poloidally.

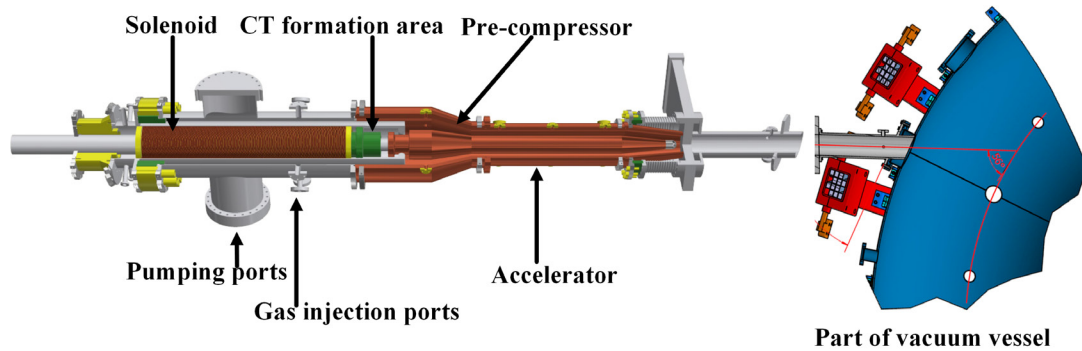


Figure 8. The design of the compact torus and tangential injection window on the KTX vacuum vessel.

Using the two-point technique, the wavenumber spectrum of the measured potential and electric field fluctuations can be calculated. The probe is also instrumented with two magnetic pickup coils that are used for probe alignment. For easy identification, the four stalks are labeled as A, B, C and D. The four stalks are fixed on the tip of the supporting platform, shown in figure 7(a), and are inserted into the midplane window, thus the axes of the stalks are approximately in the radial direction. The supporting and sealing structure allows movement in the radial direction and rotation around the axis of the supporting pole. The probe can be aligned into two configurations, as shown in figure 7(c). If stalk A and stalk B are lined in the toroidal direction, two points measurement of the electric field in the toroidal and poloidal directions enables correlation analysis of the wavenumber spectrum. If stalk A and stalk C are lined in the toroidal or poloidal direction, a single point measurement of the poloidal and toroidal electric field at the center of the diamond can be obtained.

The capacitor formed between the plasma and the electrode of the probe is called a ‘coupling’ capacitor. Usually, plasma potentials are typically hundreds of volts. To measure the high potentials, a capacitive divider circuit is applied. An operational amplifier isolates the probe circuit from the digitizer. This amplifier has a constant unity gain at low frequencies and rolls off at high frequencies with a 3 dB point at 100 kHz. The overall frequency response of the system is $13 \text{ Hz} < f < 100 \text{ kHz}$, and the digitizer is set to 250 kHz for tearing mode fluctuation analysis at present. Figure 7(b) shows the probes without protection. In fact, the tips of the stalks are shielded with boron nitride shells during the experiment. To minimize erosion of the shells and guarantee the accuracy of the capacitance measurement, the plasma temperature is supposed to be less than 200 eV around the probes. In the current discharge state of the KTX, the electron temperature is much less than 200 eV, so the probes can be inserted very deep into the plasma. Spectral analysis and correlation analysis of electric potential from this capacitive probe system on KTX plasma have been made for instability studies, and the results will be described in more detail in other papers.

2.7. Initial data analysis of eddy current probes

Eddy current probes were not applied at first on the KTX, however, full coverage of eddy current probes in the KTX is

unique. The main mission of the eddy current probes is to measure eddy current directly as an input signal for active feedback control of RWM and resistive tearing modes. However, this diagnostic can also be used to measure the vortex electric field induced near the shell with spatial resolution about 0.2 mV m^{-1} . The significance of eddy current probes is that they take into consideration the impact of external current for thin shell machines, because when the plasma discharge duration is much longer than the shell penetration time, a lot of diagnostic and data analysis based on ideal boundary conditions is ineffective. After a full upgrade of the data acquisition channels, the eddy current flow in the whole shell of the KTX can now be measured.

A new method for measurement of plasma displacement using eddy current probes on the KTX has been put forward. The model is based on multipole moment expansion of the poloidal eddy current, which is more accurate than conventional methods based on symmetrical magnetic probes. Through an analytical analysis of many current filaments and numerical simulations of the current through distribution in toroidal coordinates, the scaling relation between the first moment of the eddy current and the center of gravity of the plasma current is obtained. The origin of the multipole moment expansion of the eddy current in the KTX is retrieved simultaneously. Preliminary data on the plasma displacement have been collected using these two methods during short pulse discharges in the KTX device, and the results of the two methods are in reasonable agreement [32].

3. Compact torus injection system

Fuel injection is an important issue for future fusion reactors for density control and rising bootstrap current [33, 34]. The maximum neutral particle injection speed by most existing conventional feed systems, such as pellet injection, ultrasonic molecular beam injection and gas puffing, is only about 2 or 3 km s^{-1} . It is hard to feed fuel in the core area of fusion plasma at this speed, so the development of a fueling system with higher injection speed and higher efficiency is necessary. A Marshall gun [35] can generate gas with speed up to 30 km s^{-1} , and compact torus (CT) plasma [36] can be accelerated up to 2500 km s^{-1} by electromagnetic force.

One of the motivations for developing a CT system is for feeding in the KTX and RFP-related physics studies, such

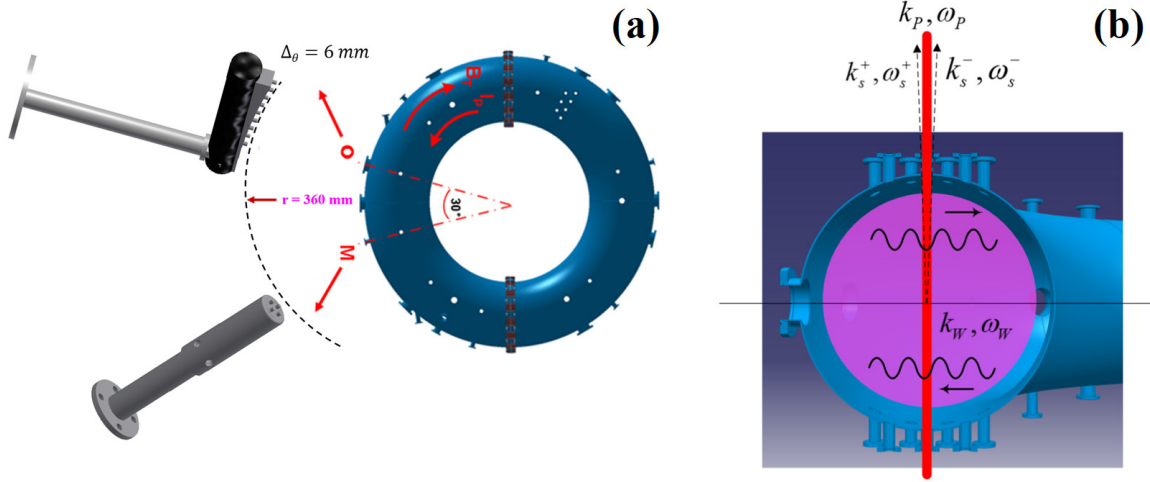


Figure 9. (a) A diagram of edge probe arrangement on the KTX vacuum vessel windows, and (b) a diagram of the forward scattering signal collection on the KTX.

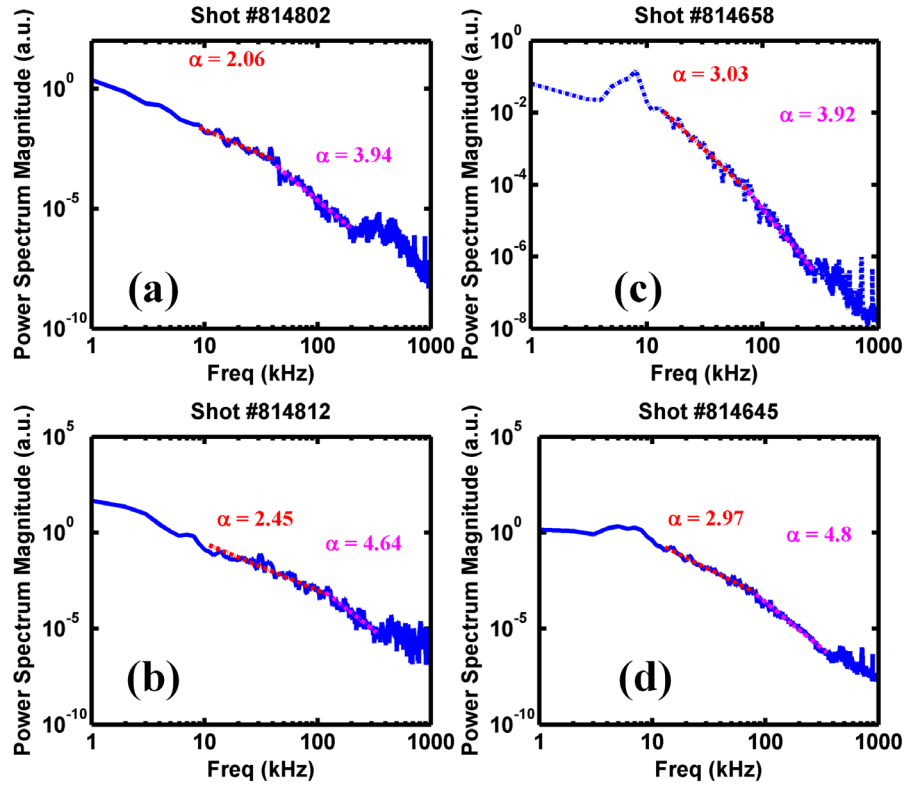


Figure 10. Energy spectra of the floating potential in low- q high-current discharge (a) at radial position $r = 38$ cm, (b) at radial position $r = 33$ cm and in low-current tokamak discharge (c) at radial position $r = 38$ cm, and (d) at radial position $r = 33$ cm.

as density limit, momentum driving and helicity injection. Another motivation is the previous research and testing of the future CT system on the CFETR program in China [37]. The design of a CT injection system has been completed, as shown in figure 8, and the mechanical component processing is underway. The length of the CT gun is about 3 m, and the injection mass for once is from 10 μg to 50 μg . CT plasma will be injected in the tangential direction of the KTX vacuum vessel torus, and the angle is about 56° relative to the axial. The voltage between electrodes is from 10 kV to 40 kV, corresponding to a maximum injection speed up to 200 km s^{-1} . In

the KTX-RFP configuration, high speed is not necessary for injection in the deep core of plasma, because the toroidal field is weak, however, the surplus power could be useful for future reactor feeding scaling research into input power versus injection speed for the system.

4. Experimental progress on electromagnetic turbulence

The relationship between the magnetic and electrostatic fluctuations can be important to help understand the mechanism

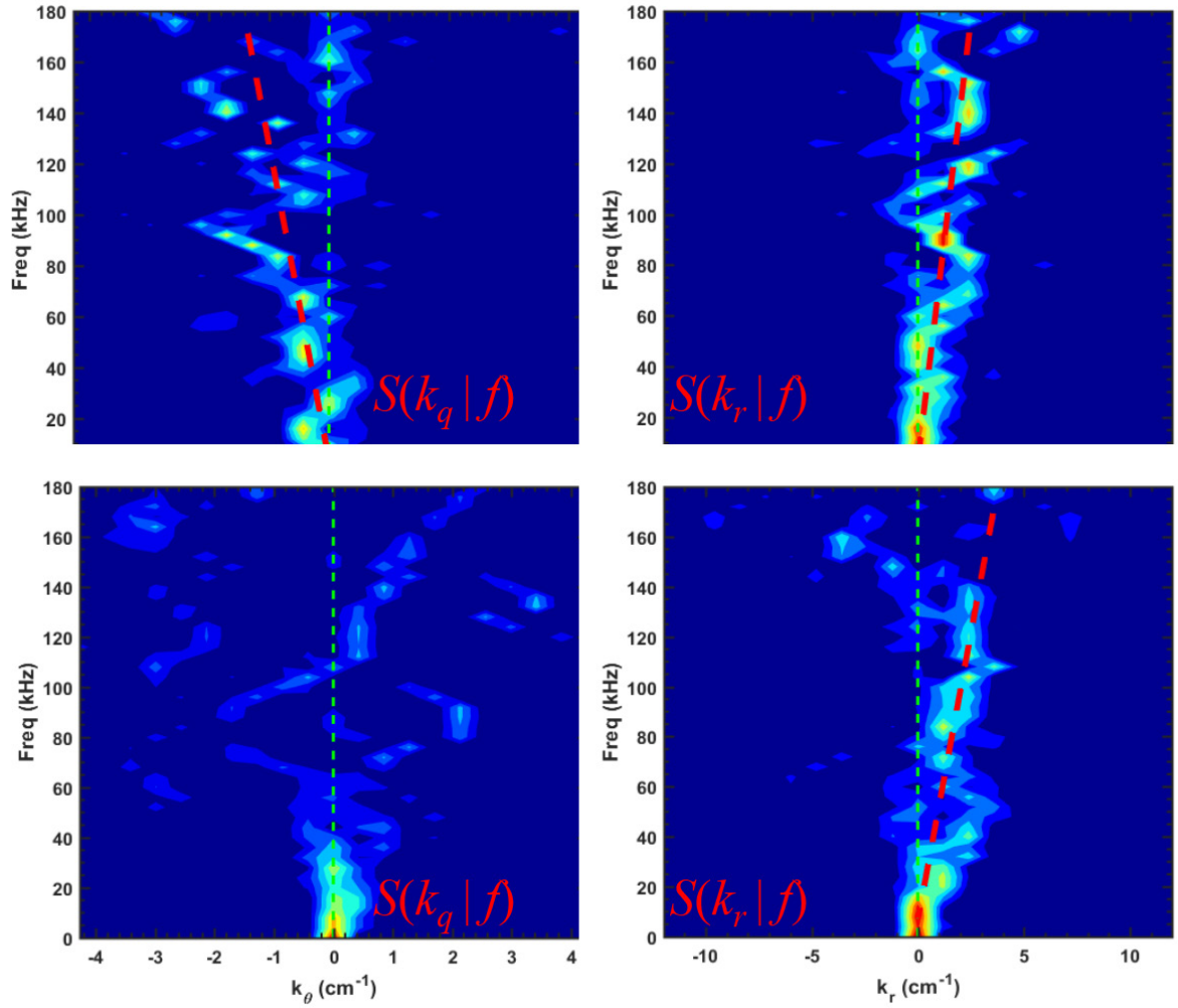


Figure 11. Conditional wavenumber–frequency spectra for low- q large-current discharge (a) $S(k_\theta|f)$, (b) $S(k_r|f)$ and for low-current tokamak discharges (c) $S(k_\theta|f)$, (d) $S(k_r|f)$. In the poloidal wavenumber–frequency spectra, the positive sign means the ion diamagnetic direction. In the radial wavenumber–frequency spectra, the positive sign means the outward direction.

behind abnormal transport, which cannot be explained by a single type of fluctuation. It is reported that high-frequency electrostatic fluctuation mainly causes the particle loss in the edge of the RFP plasma, and gives only less than a 15% contribution of energy loss [38].

In the experiment, a four-pin Langmuir probe and a nine-pin Langmuir probe at different toroidal positions are used to measure the edge floating potential and plasma potential. As shown in figure 9(a), the nine-pin rake-like probe is inserted from the ‘O’ horizontal window, and the tips of the probe array are arranged at the same radial position in the poloidal direction of the cross section of the vacuum vessel. The distance in the poloidal direction Δ_θ is 6 mm. The four-pin Langmuir probe is set 30° away in the toroidal direction at the ‘M’ horizontal window, as shown in figure 1. Both probes can be set at the same radial position of $r = 36$ cm from the center axis of the inside vacuum vessel. The middle two tips at the ‘M’ window are at the same poloidal position with the bottom tip of the rake-like probe at the ‘O’ window. This

arrangement allows the application of correlation analysis of electrostatic fluctuations in the poloidal direction and in the toroidal direction.

The electron density fluctuation is measured from the collection of forward scattering signals [39] of the center chord interferometer system. The chord-averaged electron density waveform can be achieved simultaneously. As shown in figure 9(b), a 650 GHz probing beam goes vertically through the center chord of the vacuum vessel with the incident wave vector k_p and frequency ω_p . The electron coherent structures with wave vector k_w and frequency ω_w , rotating along the poloidal direction in the small cross section of the KTX, will encounter the probing beam twice, which will generate two forward scattering beams almost symmetrically distributed around the injection beam. The transmission aperture of the vacuum ports is 35 mm. Given the geometry limitation of the device and optical arrangement, the forwarding scattering signal with an angle less than 2° can be collected by the plasma mixer. The characteristic length of scattering is

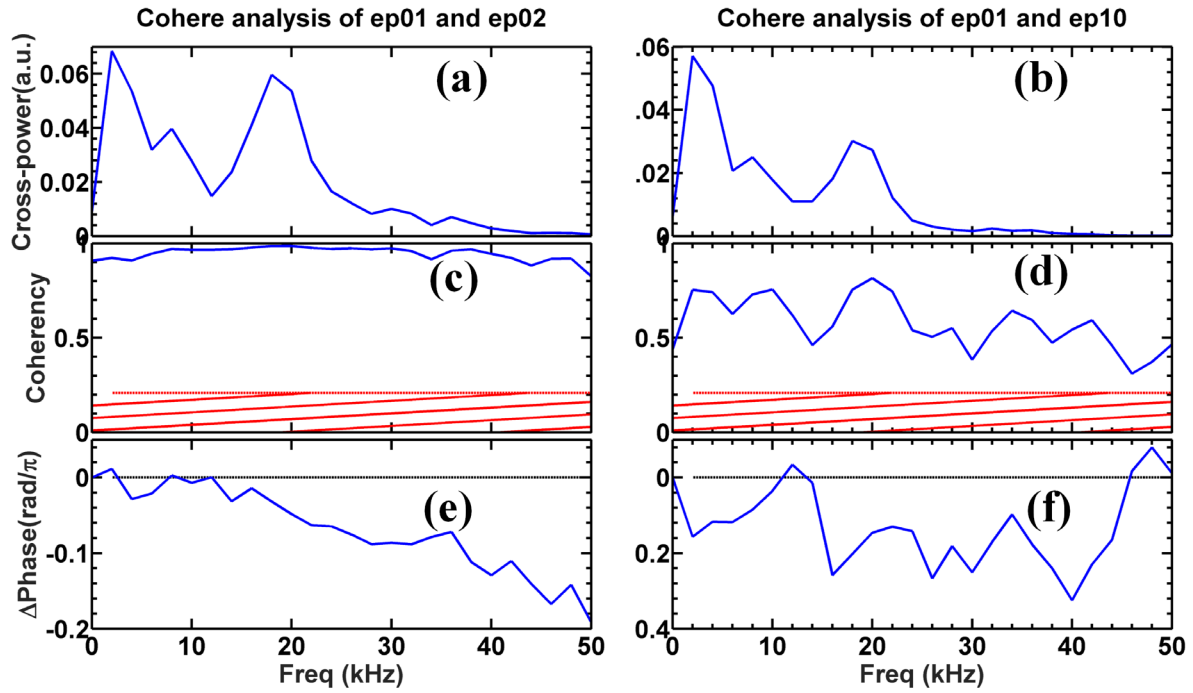


Figure 12. Low-current tokamak discharges showing: the cross power of floating potential fluctuation (a) between tip ep01 and tip ep02 of the ‘O’ window probe in the poloidal direction, and (b) between tip ep01 of the ‘O’ window probe and tip ep02 of the ‘M’ window probe in the toroidal direction; coherency of floating potential fluctuation (c) between tip ep01 and tip ep02 of the ‘O’ window probe in the poloidal direction, and (d) between tip ep01 of the ‘O’ window probe and tip ep02 of the ‘M’ window probe in the toroidal direction; and phase difference (e) between tip ep01 and tip ep02 of the ‘O’ window probe in the poloidal direction, and (f) between tip ep01 of the ‘O’ window probe and tip ep02 of the ‘M’ window probe in the toroidal direction.

about 0.2 cm, the maximum value of the measured k_W is about 5 cm^{-1} and the resolution of the density fluctuation wave vector is $\sim 2 \text{ cm}^{-1}$.

4.1. Edge floating potential fluctuations

The energy spectrum of edge floating potential fluctuations at different radial positions for high-current low- q discharge and low-current tokamak discharge is shown in figure 10. The exponentials in scaling-law at different radial positions indicate different turbulence development states. We can see that fluctuation up to 200 kHz exists in both discharges, and for low-current tokamak discharge, there is an obvious peak around 10 kHz. At a deeper radial position, the low-frequency peak tends to broaden, which is internal tearing mode-like fluctuations.

The wavenumber–frequency structures for low- q large-current discharges and low-current tokamak discharges are measured as shown in figure 11. Here, the classical two-point technique [40] is used to estimate the wavenumber–frequency spectra, such as $S(k_\theta, f)$ and $S(k_r, f)$. The conditional wavenumber–frequency spectra are calculated as $S(k_\theta|f) = S(k_\theta, f) / \int S(k_\theta, f) dk_\theta$ and $S(k_r|f) = S(k_r, f) / \int S(k_r, f) dk_r$.

Similar to the energy spectrum, fluctuations with a frequency up to 200 kHz, and spatial spectrum up to 5 cm^{-1} can be recognized. In both discharges, the fluctuation spreads in the outward radial direction. The turbulence spectra in low- q discharges are wider than those in the low-current tokamak discharge. And the center concentration at the poloidal

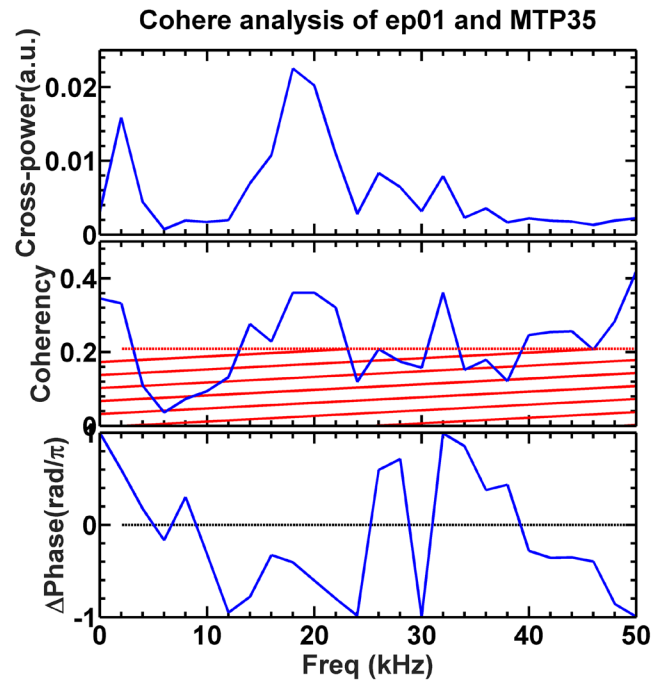


Figure 13. (a) Cross power, (b) coherency and (c) phase difference between floating potential fluctuations and edge Bp fluctuations in low-current tokamak discharge.

wavenumber spectrum for low-current tokamak discharge indicates a larger poloidal spatial structure.

The experiment arrangement is shown in figure 9, as described in section 2. The nine-pin rake-like Langmuir probe

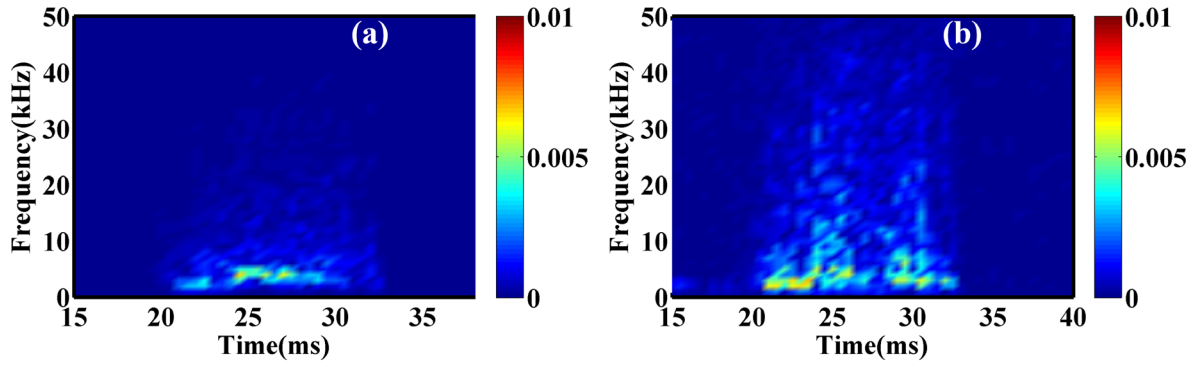


Figure 14. Time–frequency spectra of (a) center chord-averaged electron density and (b) electron density fluctuations by forward scattering in a low-current tokamak discharge.

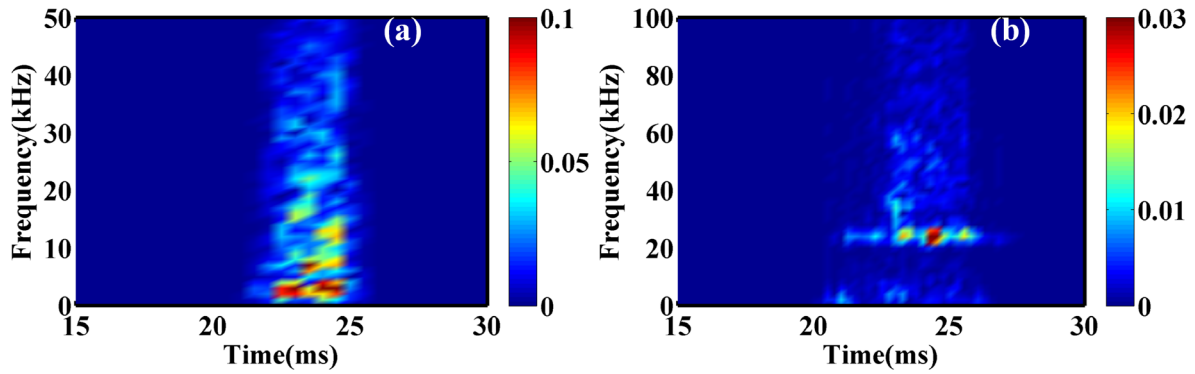


Figure 15. Time–frequency spectra of (a) electron density fluctuation by forward scattering and (b) a Bp edge Mirnov probe in RFP discharge.

is inserted from the ‘O’ horizontal window, and the tips of nine pins are arranged in a row with the same minor radius. A four-pin Langmuir probe is inserted from another horizontal window ‘M’, which is 30° away from window ‘O’. Signals from two adjacent tips (labeled as ep 01 and ep 02) of the rake-like Langmuir probe are applied to perform coherence analysis in the poloidal direction based on the two-point technique [40]. Signals from one tip of the four-pin Langmuir probe are chosen to perform correlation analysis in the toroidal direction with the signal from one tip of the rake-like Langmuir probe. The left row, in figures 12(a), (c) and (e), shows the poloidal correlation between two floating potential signals, and the right row, in figures 12(b), (d) and (f), shows the toroidal correlation between two floating potential signals. Figures 12(a) and (b) show the cross power between two signals. Figures 12(c) and (d) show the coherency between two signals, and the red shadow shows the background noise level. Figures 12(e) and (f) show the phase difference between two signals for different frequency components. One can see that the highest coherence power density is of low frequency around 2 kHz and around 20 kHz, which shows in the toroidal long-range correlation and in the poloidal short-range correlation. The same modes are also found by analyzing the edge Mirnov arrays, which indicate these are a type of MHD mode. The mode number with 2 kHz frequency is $m = 2$, $n = 1$, and the mode number with 20 kHz frequency is $m = 6$, $n = 1$. For the low-current tokamak discharge, the safety factor

q is provided by a deeply inserted magnetic probe, and the q profile is scanned shot by shot. The results show that the minimum q in the core area is over 2, while the maximum q at the edge is over 6. Since there is no resonance surface for the 2 kHz mode, it may be a kink mode. On the other hand, the 20 kHz mode may be a tearing mode.

Figure 13 shows the correlation analysis between the floating potential of one tip from the ‘O’ window probe and one Bp Mirnov probe at the edge of plasma in a low-current tokamak discharge. It can be seen that there are strong correlations at frequencies around 20 kHz and around 2 kHz, which are similar to the phenomenon in figure 12(b).

4.2. Density fluctuations

As shown in figure 14, the density fluctuation frequency spectrum from the forward scattering signal is compared with the chord-averaged electron density frequency spectrum. A low-frequency MHD mode from around 2 kHz to 4 kHz is shown from both results, however, the forward scattering signal shows more detail in the high-frequency range above 10 kHz for its higher spatial resolution.

The spectra of poloidal magnetic field fluctuations are compared with electron density fluctuation by forward scattering, as shown in figure 15. There is clearly a mode with frequency around 20 kHz in the Bp fluctuations spectrum, while the density fluctuation shows a wider frequency range up to around

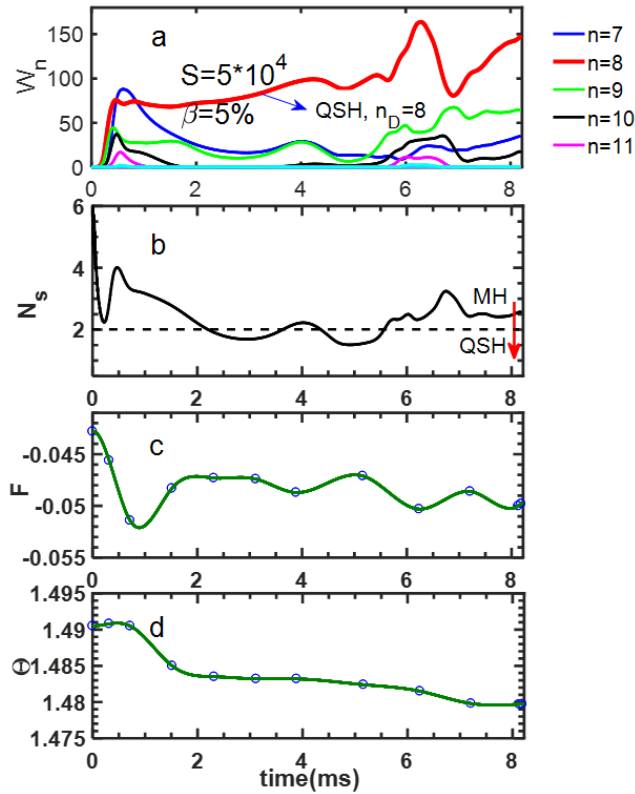


Figure 16. Simulation results from NIMROD in the typical resistive regimes of the KTX: (a) the magnetic energies of different toroidal mode components, (b) the spectral spread N_s , (c) the RFP reversal parameter F and (d) the pinch parameter Θ for $S = 5.0 \times 10^4$ and $\beta = 0.05$.

50 kHz. Compared with electron density fluctuation in a low-current tokamak discharge, there seems to be more internal tearing modes with a wider fluctuation frequency range.

5. Simulation of QSH in the KTX regime

RFP configuration is sustained by the ‘dynamo’, which could be driven by nonlinear coupling among saturated resistive kink modes. However, in simulations, a bifurcation from the standard multi-mode (multiple helicity (MH)) to the single helical mode (SH) regime has been proved. Although pure SH states have not been realized in existing RFP machines, QSH states have been reported in several machines since 1994. In the QSH regime, one $m = 1$ mode dominates, and the amplitude of the other modes is small compared with the dominant mode. A stationary coherent helical structure in the plasma core with closed magnetic flux surfaces has been detected in RFX, and the confinement is greatly improved. The potential formation of a QSH state [12] in the KTX is investigated in resistive MHD simulations using the NIMROD code [41]. The effects of finite resistivity on the mode structure and characteristics of the dominant linear and nonlinear resistive tearing mode in a finite β , cylindrical configuration of an RFP model is investigated.

In the typical resistive regimes of the KTX, where the Lundquist number $S = 5 \times 10^4$, the simulation starts

from an MH state, which transitions to a QSH state when the secondary modes decrease in amplitude, as shown in figure 16(a). Figures 16(b)–(d) show the corresponding evolution of the spectral spread N_s , reversal parameter F and pinch parameter Θ . N_s is used to describe the width of the toroidal spectrum of the $m = 1$ mode, and is defined as $N_s = [(\sum_{n=1} W_{1,n} / \sum_{n'=1} W_{1,n'})^2]^{-1}$. A pure single helicity spectrum means $N_s = 1$, and it is shown in figure 16(b), that when N_s is less than 2, the energy of the $n = 8$ mode dominates, indicating the periods of QSH. F is the reversal parameter, and is defined as the ratio of the edge toroidal magnetic field to the averaged toroidal magnetic field. Here, Θ is the pinch parameter, and is defined as the ratio of the edge poloidal magnetic field over averaged toroidal magnetic field. These two parameters are used to describe the edge reversal status of RFP, and we can see that the QSH status prefers a shallow reversal RFP environment [12]. The simulation indicates that the dominant mode of the QSH state may develop from the linear mode that has the maximum growth rate. The QSH state persists for a longer time compared with that in plasma in the lower β regime, which is intermittent and short in duration. The plasma β appears to be the key parameter to enter the QSH state. It may be possible to obtain the QSH state through auxiliary heating, even at low plasma current to raise the electron temperature, however, in the transition from the MH phase to the QSH phase, the mechanism suppressing the magnetic fluctuations of the secondary modes is not quite clear, and two-fluid effects and anomalous viscosity in higher plasma current regimes may be taken into consideration in the simulation model for future work.

6. Future plan and summary

The upgrade of the KTX machine on the capacity of the plasma current and discharge time has been planned. To raise the plasma over 500 kA, an ohmic power supply with higher voltage and larger capacitance will be added. To prolong the discharge time, an independent equilibrium field power supply will be designed and employed [1], and an edge active feedback control system for the error field and MHD active feedback control will be applied. One direction of physical research in the KTX will focus on the phenomenon and mechanism of the 3D effect of RFP configuration. The other direction of physical research in the KTX will be the exploration of common physical issues among tokamak, stellarator and RFP, such as disruption, density limit and electromagnetic turbulence. For these studies, more new diagnostic systems will be developed, for example, multi-channel polarization interferometers, 3D double-foil SXR diagnostic systems and gas puffing imaging.

Before the upgrade of the KTX machine, some diagnostics have been added, and advanced research in the current state of discharge has started. The complementary diagnostics over the last two years include a multi-channel interferometer system, TS system, SXR fluorescence system, impurity and IDS, new movable Langmuir probe systems for 3D electromagnetic turbulence research and capacitive probes. The data acquisition

system for edge magnetic probes has been upgraded to its full capacity. Data from eddy currents has been first applied for plasma displacement analysis, and the graphic of eddy current flow in the whole shell of the KTX can now be drawn. A new CT system is in progress for feeding and density limit study.

For the initial study of turbulence in the current state of discharge, the possible correlation between the edge electrostatic fluctuation and the MHD mode is shown from the experimental results on the KTX in both low-current tokamak discharge and RFP discharge. The low-frequency electrostatic modes, up to 20 kHz, showing the same frequency and similar mode spectra as those of MHD modes, which may be global kink or tearing modes, were detected on the edge electrostatic potential fluctuations and the center chord electron density fluctuations. Compared with low-current tokamak discharges, the fluctuations tend to show a wider spectrum in RFP discharges.

Acknowledgments

The authors wish to thank Jay K. Anderson, Brett Chapman, James Drake, Dominique Franck Escande, Sadao Masamune, Piero Martin, Maria Ester Puiatti, John S. Sarff and the whole international RFP community for their strong and continued support. This work was supported by the Ministry of Science and Technology of People's Republic of China under contract No. 2017YFE0301700 and the National Natural Science Foundation of China under Grant Nos. 11635008, 11605199, 11775220 and 11375188. This research was also supported by the National Key Scientific and Research Equipment Development Project of China under Grant No. ZDYZ2013-2.

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