# RECENT PROGRESS AND UPGRADE PLAN OF KTX REVERSED FIELD PINCH

Tao Lan[1], Wenzhe Mao[1], Hong Li[1], Jinlin Xie[1], Ahdi Liu[1], Zhengwei Wu[1], Zixi Liu[1], Shude Wan[1], Hai Wang[1], Jian Zheng[1], Peng Yuan[1], Xiaohui Wen[1], Haiyang Zhou[1], Zian Wei[1], Kezhu Song[1], Zichao Li[1], Hangqi Xu[1], Tijian Deng[1], Junfeng Zhu[1], Sen Zhang[1], Yolbarsop Adil[1], Jintong Hu[1], Shoubiao Zhang[2], Peng Fu[2], Lei Yang[2], Yuntao Song[2], Qingxi Yang[2], Jinxing Zheng[2], Qinghua Ren[3], Yingqiao Wang[3],Min Xu[3], Xuru Duan[3], Jinmao Liu[4], Haifeng Liu[4], Yuhong Xu[4], Chijin Xiao[1,5] and Weixing Ding[1], Ge Zhuang[1], Wandong Liu[1]

[1] University of Science and Technology of China, Hefei 230026, China

[2] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China

[3] Southwestern Institute of Physics, P.O. Box 432, Chengdu 610041, China

[4] Institute of Fusion Science, School of Physical Science and Technology, Southwest Jiaotong University, Chengdu 610031, China

[5] Plasma Physics Laboratory, University of Saskatchewan, Saskatoon, Saskatchewan, SK 7N 5E2, Canada

**ABSTRACT**

Recent works on Keda Torus eXperiment (KTX) focused on operation capabilities upgrade. The upgrade design details of the main ohmic power supply, the equilibrium field power supply and the edge active feedback control system have been completed. The electronic system and fast control power supplies of the active feedback control system are under test. The capacitor banks and switching elements of the main power supply for upgrade have been put into production. Advanced diagnostics for 3D physics research, including the terahertz interferometer, double-foil soft x-ray imaging, edge capacitive probe and multi-channel spectrograph system, have been developed for the normal operation and physical analysis at present stage. Based on the present power supply system, the maximum plasma current can reach 300kA and the during time of reversed field pinch state is approaching 3ms. Magnetohydrodynamic (MHD) activities in the ultra-low $q$ configuration are investigated experimentally to explore the plasma self-organization phenomena on KTX device in the current state of operation. The characteristics of various quasi-single helicities (QSHs) in KTX are also investigated in ideal MHD simulations with helical equilibria.

## 1. INTRODUCTION

Keda Torus eXperiment (KTX) is a middle-sized reversed field pinch (RFP) device built at the University of Science and Technology of China in 2015. The mission of KTX is complementary to the existing international Revered Field Pinch (RFP) facilities. The physics aspects of KTX are plasma wall interactions, transport in different boundary conditions, and three-dimensional (3D) effects in reversed field pinch configuration. With the increase of injected heating power and current driving on toroidal magnetic confinement devices, asymmetrical phenomena or 3D effects arise more frequently, which is the nature presentation of plasma self-organization. The main characteristics of RFP are low toroidal field and high β, and the low safety factor (q) profile make MHD activities with multiple different mode numbers easily to be motivated and grow, which exhibit strong self-organization effects. Research results on almost all existing RFP devices have shown that with increased current or ohmic heating power, multiple MHD activities tends to compete with each other and one MHD mode would develop to became the dominant mode. The dominant mode amplitude is so large that the magnetic toplogical structure almost change to a helical structure, and this state in RFP is called quasi-single helical state. Also, tokamak devices, through nominally axisymmetric, display internal plasma symmetry break phenomena with inverse rotational transform q profiles nearly flat or slightly reversed, as reported in the MAST device, TCV, JET and DIII-D. More and more evidences shows that the existence of thoese new 3D equilibrium states with axisymmetric boudary make it essential to study 3D effect and review some issues that hard to be explaned in 2D theoretical framework, so the main research interest and the system upgrade of KTX will be 3D effects in RFP configuration.

After getting the funding from the Ministry of science and technology, the Phase II upgrade of KTX starts and it focuses on the operation capacity promotion to optimize plasma confinement and to improve plasma parameters for quasi single helicity (QSH) state realization. The task is divided into sub objectives during the upgrading: 1) To improve the plasma current up to or even more than 1MA. The capacitor banks of the KTX pulse power supply will be extremely upgraded. 2) To extend the plasma discharge period longer than 100ms. The equilibrium field control system and external 3D active feedback control system, including the saddle coils system covered on the outer surface of the vacuum chamber and the error field correction coils around the poloidal gaps, are well developed. 3) To develop more advanced diagnostic tools to access 3D effect for physical mechanical study. In the last two years, the design of the main power supply, the equilibrium field power supply and the edge magnetic field active feedback control system has been completed. The prototype of the fast control power supply and electric systems developed for the active feedback control system has been produced and is under test, and the MHD control strategy using the active feedback control system has also been programmed. A compact torus injection system (KTX-CTI) has been developed and installed on the middle plane of KTX, using which the magnetic field penetration process of fuelling, external momentum and helicity injection are studied in detail and related with the magnetic reconnection. KTX will become a pre-research platform to test the high-frequency and long-distance CTI, including the performance of the injector machine and its power supply, for application on future fusion devices such as ITER and CFETR. For better density control, a supersonic molecular beam injection (SMBI) system has been designed and installed on KTX. Electron density profile can be provided by the multi-channel interferometer system and the electron temperature distribution can be reconstructed using the SXR emission collected. Error field suppression was realized around the two vertical gaps to extend the plasma discharge duration effectively. Based on the present power supply system, the maximum plasma current can reach 300kA and the during time of reversed field pinch state is approaching 3ms. Magnetohydrodynamic (MHD) activities in the ultra-low safety factor configuration are investigated experimentally to explore the plasma self-organization phenomena on KTX device in the current state of operation. The characteristics of various quasi-single helicities (QSHs) in KTX are also investigated in ideal MHD simulations with helical equilibria.

In this contribution, the progress of hardware development on diagnostics and operation systems will be described. The operation status and recent experiment and simulation results are also involved.

## 2. SYSTEM DEVELOPMENT

A series of facilities have been developed aiming for operation capacity improvement of KTX and 3D physics research, including error field control system at two vertical gaps, additional gas feeding systems, diagnostic tools for 3D phenomena observation and fast control power supply.

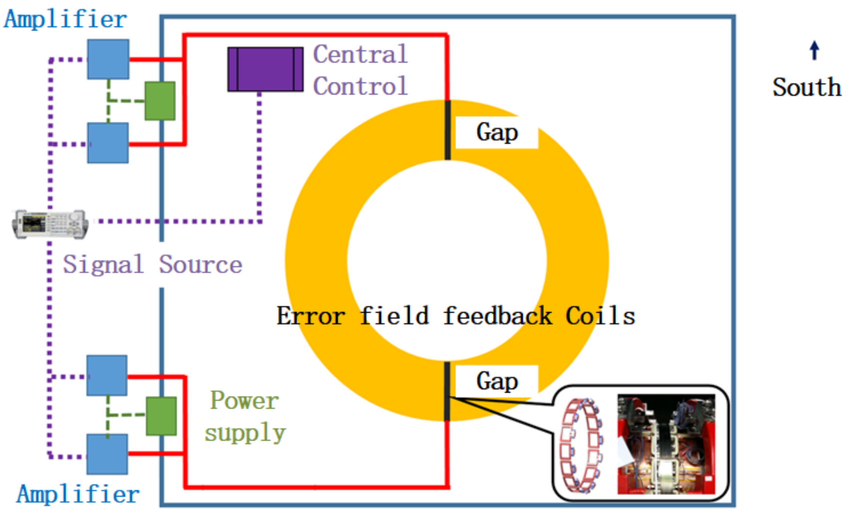


*FIG. 1. Open loop control strategy of error field at two vertical gaps.*

### 2.1. Error field suppression at vertical gaps

Two vertical gaps are distributed at each side of the conducting shell ring on KTX vacuum vessel, which incorporates the unique "double C" design for accessibility to and easy maintain. Eddy currents induced by plasma current and coil current of poloidal magnetic field produce radial magnetic field (error field) at the two insulated vertical gaps, and enhance deteriorate confinement. To suppress error field and improve discharge duration, an open loop control system has been applied at two vertical gaps, and the control strategy is shown in fig 2. The distribution of radial field is measured under various operation conditions without external magnetic field around the gaps. It is found that the main contribution to the error field is the m=1 component, which is mainly generated by the image current of plasma for equilibrium. Preprogram voltage waveforms are amplified and feed to the 16 error field coils distributed poloidally around each gap by 16 independent power amplifiers. The effect of the error field suppression is shown in fig 3, which shown the radial magnetic field distribution in the poloidal direction. The peak error field amplitude decreases from about 100 Gauss to about 10 Gauss, and the discharge time was extended by about 30%.

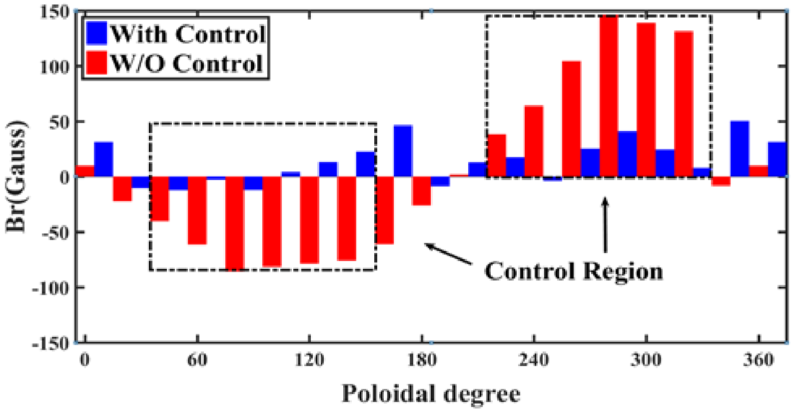


*FIG. 2. Poloidal distribution of radial field at one vertical gap with (red bars) and without (blue bars) error field control.*

### 2.2. Additional fueling system: Compact torus injection (KTX-CTI) and supersonic molecular beam injection (SMBI)

Density limit is a common physics issue on different toroidal magnetic confinement configurations, including tokamaks, stellarators, and reversed field pinch, so high density limit physics is another research limit on KTX. On the other hand, density control is important to improve plasma current and temperature. Gas puffing is generally method for fuelling for most of the devices before gas breakdown phase, however, it is hard to feed fuel deep into the core of plasma with gas puff only. On KTX, KTX-CTI and SMBI have been installed on KTX for fuelling during the discharge as shown in fig 4 and fig 5. The former can not only be used for fuelling, but also can be used to study helicity transport and tangential momentum injections. The SMBI is also a powerful tool to study turbulence induced transport by modifying density profile in the edge.

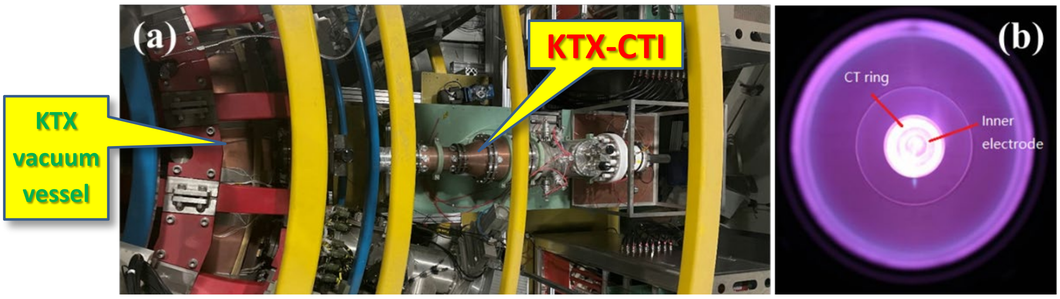


*FIG. 3.(a) KTX-CTI installed on KTX and (b) CT discharge ring photoed by visible light camera*

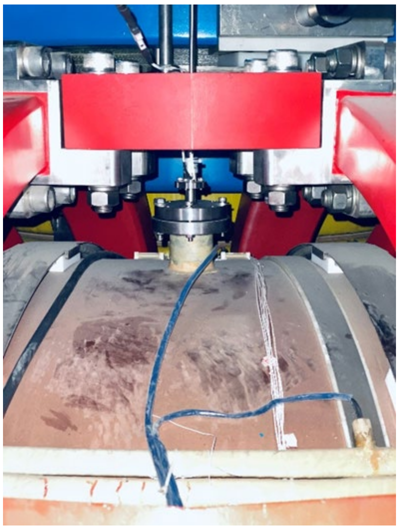

*FIG. 5. Accelerator jet of SMBI installed on KTX*

### 2.3. Diagnostic development and initial results

1) Double-foil soft X-ray imaging diagnostic system

A 320-channel double-foil soft X-ray diagnostic system has been designed and developed on KTX for cross section imaging of electron temperature. The 320 light-of-sight paths are collected by 16 photodiode arrays (AXUV-20ELG from Opto Diode Corporation), which are set at 8 different windows. The windows are distributed at two different toroidal positions. The emission collection angles and positions are designed using Bayesian experimental method (BED) aiming for bean like hot core in QSH operation state of KTX as shown in fig 6. Once QSH state is realized on KTX, the asymmetry imaging can be captured from the reconstructed 3D electron temperature distribution at two different toroidal viewpoints.

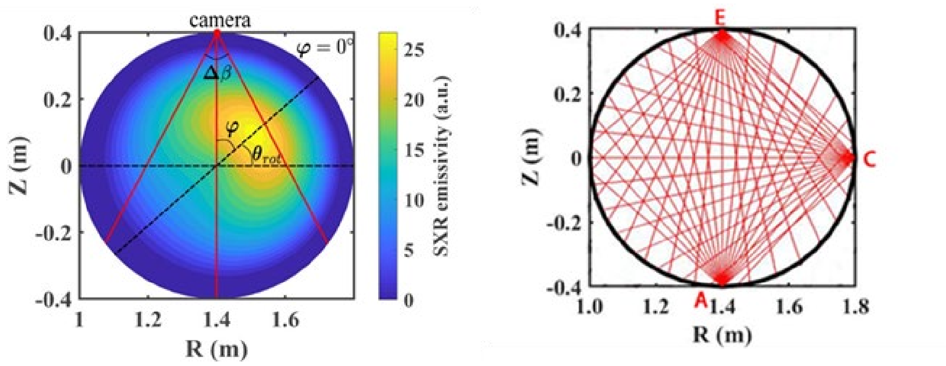


*FIG. 6. (a) Simulated SXR emissivity in QSH state and the definition of design parameters using BED, and (b) the optimized experimental design of emission beams for SXR tomography cameras*

2) Multi-channel interferometer using terahertz solid-sources

Terahertz (0.65 Thz) solid state sources based interferometer with time response up to (0.1 microsecond) has been successfully installed on KTX. The single chord interferometer system has been upgraded to a 5 chord system. The optical design and elements have been optimized to fully use limited power source (~2 mW), so that Thz radiation is detectable by fundamental mixers. The beam waist is improved below 21 mm to minimize transmission loss and improve spatial resolution. The electron density profile on KTX with circular cross section can be reconstructed by an asymmetric Abel inversion as shown in fig 7. The fast time response enables density high frequency fluctuations measurement with bandwidth up to 1 MHz.

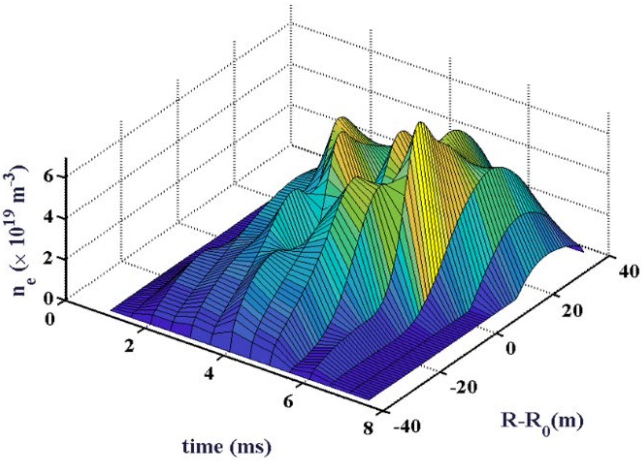


*FIG. 7. Reconstructed electron density profile from the 5-chord interferometer diagnostic system on KTX*

3) Eddy current probe array on KTX

The fully covered eddy current probe array is a unique diagnostic tool on KTX. Each pair of eddy current probe is composed by two magnetic probes installed on two sides of the composite shell. The eddy current in the shell can be derived by the magnetic probes from the difference between the inner and outer magnetic fields. 320 two-dimension magnetic probes (for measuring the toroidal and poloidal magnetic fields) are located unevenly along the toroidal direction, and along the poloidal direction. The time evolution of the two dimensional local eddy currents in the shell along the toroidal and poloidal directions is given experimentally with eddy current probe arrays as shown in fig 8.

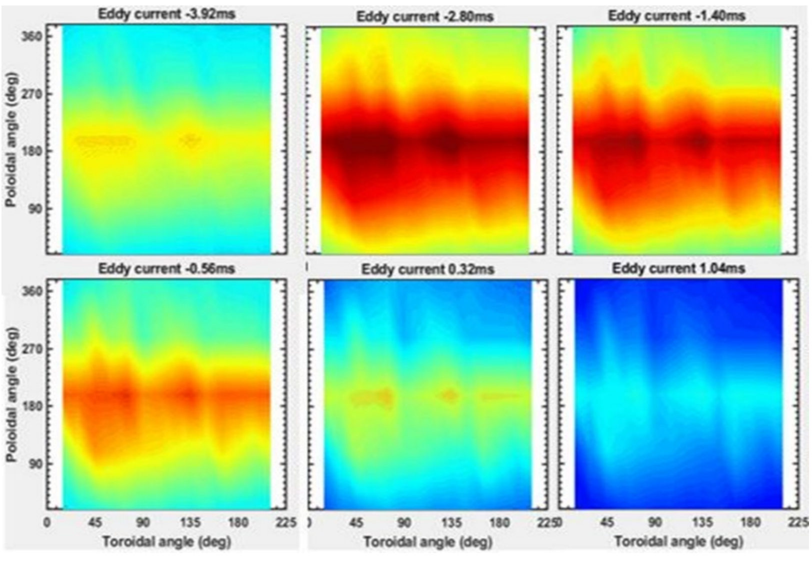


*FIG. 8. Time history of eddy current amplitude from eddy current probe arrays on KTX*

### 2.4. Fast control power supply

The IGBT switch is used to develop fast control power supply for the active feedback control system. The inverse module of IGBT is shown in fig 9, and a prototype of the active feedback control power supply has been tested as shown in fig 10. In the given current flat top section of 100A DC, the output current is 99.25-100.85A, and the corresponding current accuracy is 0.85A, which meets the requirement of current accuracy 1A. At a given DC of 100A, the signal is a voltage signal directly measured by the differential probe, and the output voltage is a square wave pulse signal with an amplitude of 200V and a frequency of 1/25μs=40kHz, which satisfies the requirements of output voltage of 200V and output frequency of 0.1-1kHz.

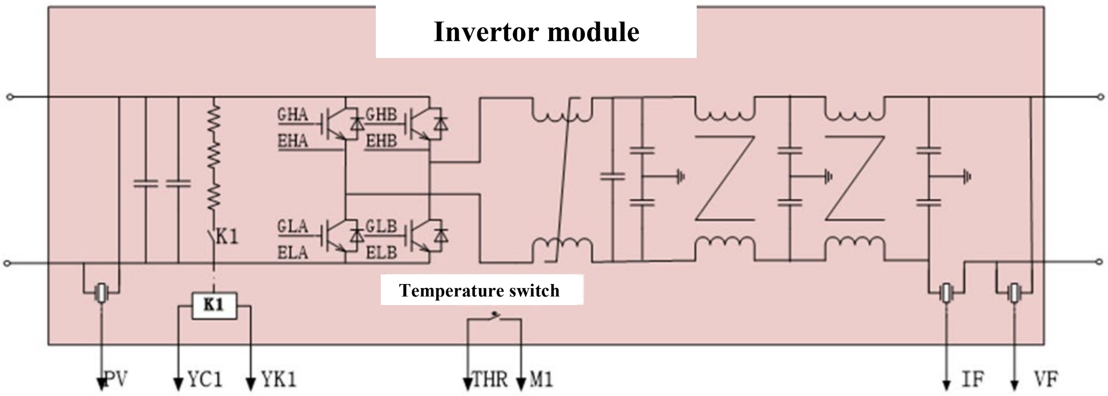


*FIG. 9. Invertor module of IGBT switch.*

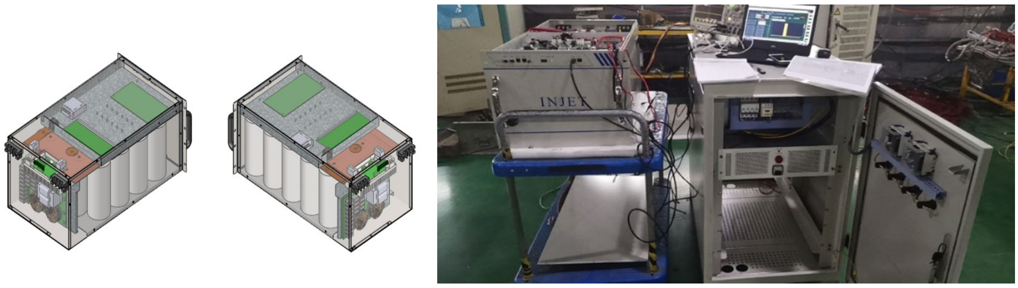

*FIG. 10. Prototype of the active feedback control power supply*

## 3. INITIAL RESEARCH ON THREE-DIMENSIONAL EFFECT

### 3.5. Recent operation status of KTX

The power supply of KTX has not been upgraded and replaced yet, so the maximum plasma current and RFP duration time are improved a little mainly relying on wall conditioning and density control. The maximum plasma is about 300 kA, and was reached in ultra-low q discharges as shown in fig 11. The field reverse time in

RFP discharge can reach about 3 ms as shown in fig 12.

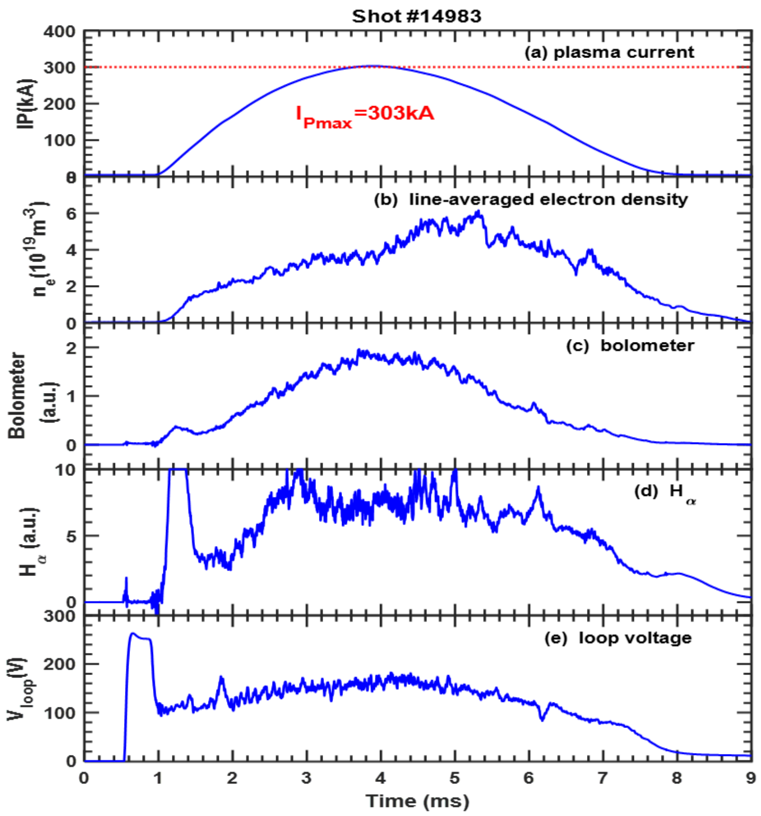


*FIG. 11. Discharge waveforms with maximum plasma current above 300kA in ultra-low q plasma on KTX*

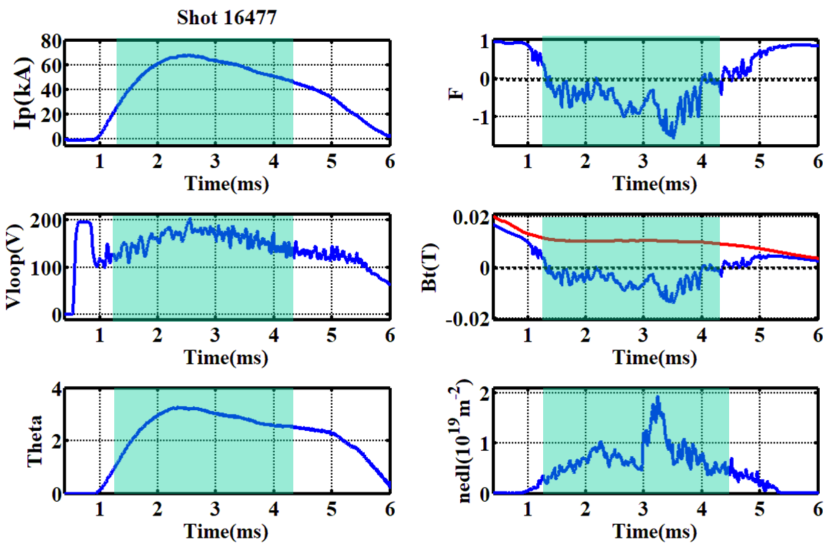


*FIG. 12. Waveforms of plasma parameters in RFP discharge on KTX*

### 3.6. Ultra-low q plasmas on KTX

Discharge waveforms of ultra-low q plasma are shown in fig 13, using equilibrium reconstruction code. The external toroidal field is almost constant, and edge safety factor decreases with the increasing of plasma current. The gradient of safety factor in the core area becomes negative, corresponding to hollow parallel current density structure.

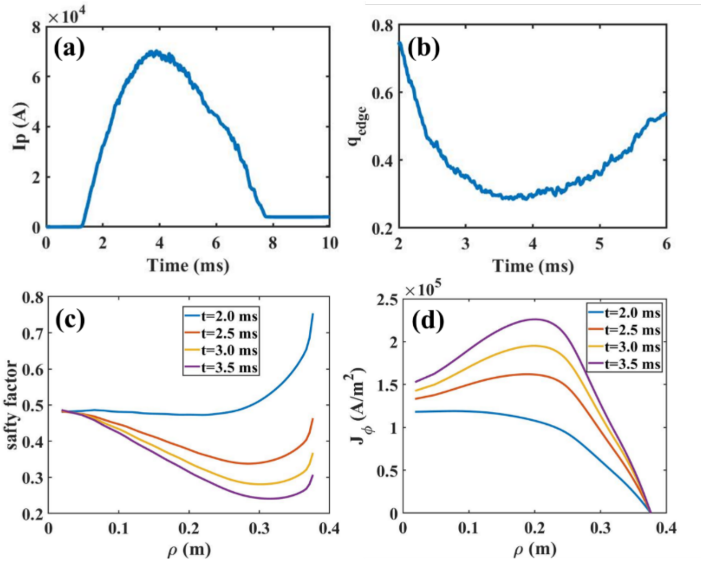


*FIG. 13. Waveforms of (a) plasma current, (b) edge safety factor and profiles of (c) safety facor, (d) current density at 2.0ms, 2.5ms, 3.0ms and 3.5ms*

### 3.7. Simulations of 3D equilibrium reconstruction on KTX

3D helical model of QSH equilibria was investigated under toroidal modenumber $N_{fp}$=6, 7 and 8 with KTX geometric parameters. The Mercier criteria is utilized to study interchange mode stabilities from the perspective of the magnetic shear, which indicates that interchange modes get more stable with the negative magnetic shear at the core plasma region. Meanwhile, the negative magnetic shear could dramatically enhance the amplitude of the dominant mode in the QSH state with $N_{fp}$ = 6. The transition from Multi-helicity (MH) state to QSH is also simulated by adjusting magnetic shear in the core area as shown in fig 14.

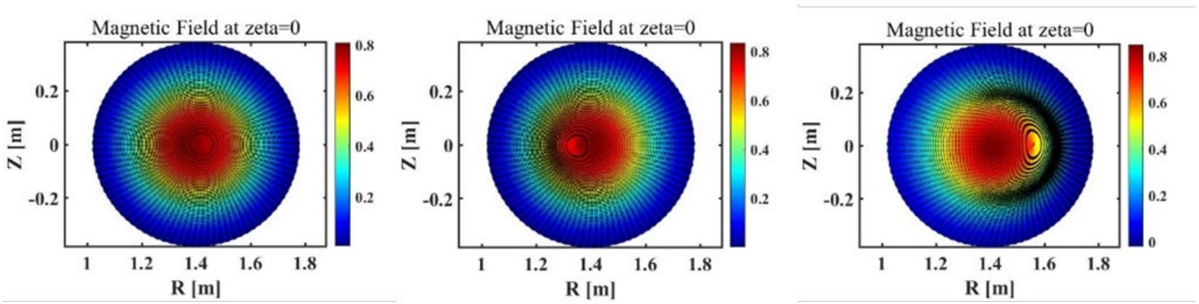


*FIG. 14. Simulation of MH equilibria transition to QSH equilibria by decreasing central q value and magnetic shear in the core area*

## 4. SUMMARY

The upgrading of KTX operation capacity is in progress. The design of the power supply for ohmic field and equilibrium magnetic field coils have been completed, the capacitor banks and switching elements of which have been put into production. The electronic system and fast control power supplies of the active feedback control system are under testing. Diagnostic system, aiming for 3D physics study, such as multi-channel SXR imaging, multi-channel interferometer, eddy current probe arrays, have been developed and applied on KTX. Recent experimental research focus on operation scheme optimization and ultra-low $q$ study before new power supply assembled, and 3D helical model of QSH equilibria was also simulated and investigated.


## ACKNOWLEDGEMENTS

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