

Overview of Keda Torus eXperiment Initial Results

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Abstract. The Keda Torus eXperiment (KTX) is a new reversed field pinch (RFP) device at the University of Science and Technology of China. The construction and assembly of KTX, including the vacuum chamber, conducting shell, magnetic field windings, power supply system, active control coils, vacuum pump and data acquisition system, have been completed in Aug. 1, 2015. Immediately following that, the first plasma was obtained in Aug. 15th, 2015. Intensive conditioning of machine is underway to ramp up plasma current toward full operation. An active feedback mode control system has been built and has been implemented to control the error field around the gaps of the conducting shell. The pulsed power supply systems for poloidal field (PF) and toroidal field (TF), using thyristor and energy storage capacitors, have been tested and commissioned. In the first phase of KTX, the current total storage energy is 1.6 MJ for both PF and TF system. The TF power supply can be operated to realize reversed toroidal field configuration and low q tokamak configuration with flexibility. The fundamental electric-magnetic measurements, 2D double-foil soft x-ray array, multi-channel analysis for x-ray, middle plane H α line, fast reciprocating Langmuir probe and one-chord interferometry are currently used in KTX for commissioning. One chord Thomson scattering system has been design. KTX is being upgraded to the second phase after completion of the first phase. Meanwhile KTX program will address some important RFP physics like the impact of 3D structure on plasma flow, and magnetic turbulence and plasma wall interaction, *etc.*

1. Introduction

Reversed field pinch (RFP) is an important alternation of magnetic confinement fusion (MCF) device configuration. Keda Torus eXperiment (KTX) is a new built medium size RFP device at University of Science and Technology of China (USTC), supported by the Ministry of Science and Technology of China. The mission of KTX is complementary to the existing international RFP facilities. The plasma wall interactions, RFP boundary plasma, transport in different boundary conditions, the single helicity (SH) state and quasi-single helicity (QSH) state are the main physics aspects of KTX.

The KTX project was approved in Oct. 2011 and the physics design and engineering design spent 2 years [1-12]. Finally, the construction was completed in Aug. 1, 2015. Immediately following that, the commissioning began and the first plasma was achieved at Aug. 15, 2015. The preliminary results in the commissioning will be introduced in this paper.

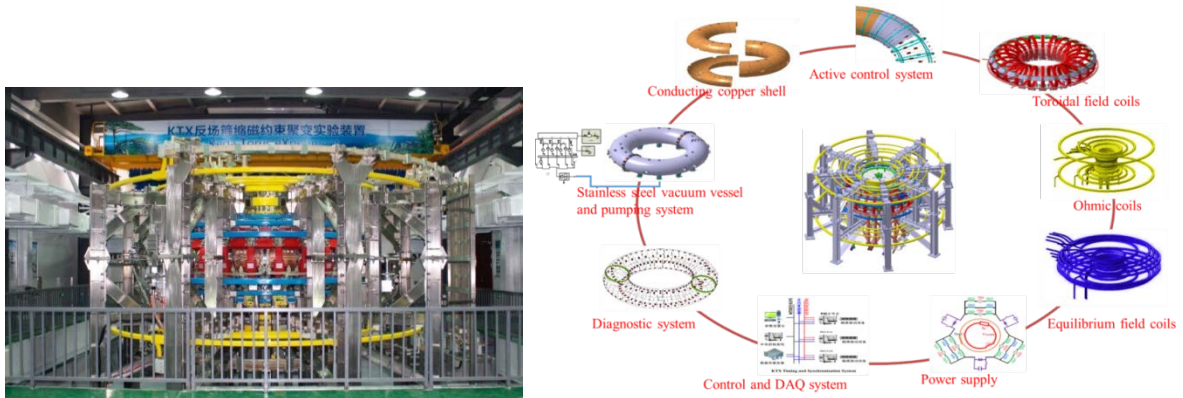


FIG. 1 Picture and Overview of KTX device

2. KTX device composing

2.1.Characteristics of KTX

KTX is a medium size RFP device and the easy operability makes it suitable for the research in the University. The main parameters of KTX are listed in TAB.1

TABLE I: The main parameters of KTX device.

Major radius	1.4m
Minor radius	0.4m
Thickness of vacuum vessel (stainless steel)	6mm
Thickness of conducting shell (copper)	1.5mm
Plasma Current	0.5MA (phase 1), 1.0MA (phase 2)
Loop voltage	0~50V
Plasma inductance	2.9uH
Total magnetic flux	3WB (phase 1), 8WB (phase 2)
Electron temperature	300eV (phase 1), 800eV (phase 2)
Plasma density	$\sim 10^{19} \text{ m}^{-3}$
Maximum TF	0.35T (phase 1), 0.7T (phase 2)

The system composing of KTX is shown in FIG. 1.

The composite shell on KTX is a combination of a stainless steel vacuum chamber with a thickness of 6mm and a thin copper shell with a thickness of 1.5mm, providing an opportunity for studying resistive wall mode instability. The copper shell is composed of multilayer over the vertical gaps to minimize the error field generated by the eddy current.

The unique double-C design of KTX vacuum vessel allows easy access to interior of the KTX for first-wall modifications and investigations of power and particle handling, a largely unexplored territory in RFP research leading to demonstration of the fusion potential of the RFP concept.

4x24 saddle coils over the shell surface, 4x48 magnetic probes and 4x24 saddle sensors inside the copper shell are used for active feedback control, shown in FIG. 2. Each saddle coils can be controlled independently. The boundary magnetic field, boundary radial flux and local current can be used as the input parameters for different active feedback control scenarios. The power feedback control strategy is being now tested to suppress error field using the coils around the vertical gaps.

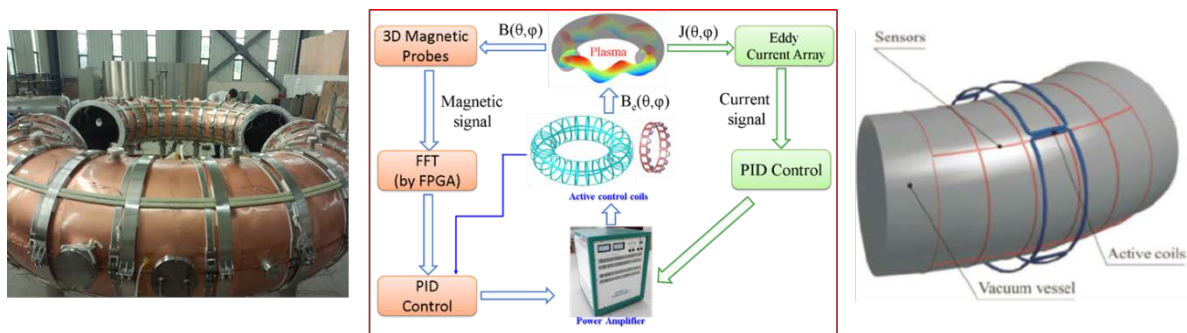


FIG. 2 Active feedback control system

2.2. Baking, Pumping and fuel system

The KTX baking system innovatively achieves the inductive heating of vacuum vessel by eddy current through driving high-frequency current oscillations in toroidal field coils, since the traditional heating belt is not suitable for the composite shell of KTX. Temperature-measuring thermocouples are embedded between vacuum vessel and conducting wall. The designed bakeout temperature is 150°C.

The volume of KTX vacuum chamber is 4.2m³ and the area of inner chamber surface is 22m².

The KTX pumping system includes 4 high-vacuum turbomolecular pumps, 1 fore-vacuum roots pump, 1 dry compressing pump and 1 cryopump. The total pumping speed is 4800l/s for H₂ gas. Six compound gauges with pressure range from 10⁻⁷ Pa to 1atm and 1 fast gauge with 2ms response time are used to measure the pressure values. An in situ residual gas analyzer (RGA) is used to monitor the gas composition. The ultimate vacuum of KTX after the construction reaches 2.0x10⁻⁶Pa. In the commissioning period with H₂ as discharge gas, the vacuum is around 2.0x10⁻⁵Pa.

Two sets of hot tungsten wires inside the vacuum vessel are mounted in two toroidally symmetrical ports for pre-ionization.

Two piezoelectric crystal gas valves are installed at top ports as present fuel system. The gas flow range is 0~500sccm. And the response time is 2ms. Pellet injection and compact torus injection are considered as the alternatives.

2.3.Power supply systems

Currently, the KTX power supply system contains ohmic heating power supply (OHPS) and toroidal field power supply (TFPS). The equilibrium field power supply has been designed and will be upgraded in the next phase. Both OHPS and TFPS are based on the thyristor and energy storage capacitors. The present total storage energy is 1.6MJ, which the OHPS and TFPS contain 1.0MJ and 0.6MJ, respectively. More energy storage capacitors will be added to achieve 1MA plasma object. The flexibility for TF power supply provides reversed toroidal field and stable toroidal field operations. The stable toroidal field operation corresponds to the low-q tokamak discharge in this magnetic configuration.

2.4.Central control and Data acquisition system

The central control system coordinates all the subsystem features including discharge configuration, gas puffing, timing system, signal test setting and safety & interlock. It's developed by EAST colleges as well as takes account the characteristics of KTX device [8, 9].

The Data acquisition system can deal with different diagnostic signals and provides convenient HDF5 & MDSplus data storage and access. More data interface will be added.

The plasma control system has been designed on EPICS, which provides kinds of control algorithms for the active control system.

2.5.Diagnostic system

The fundamental electromagnetic and spectrum diagnostics are equipped during the commissioning [4]. The present diagnostics are as follow,

- 1). Total 1464 channels electromagnetic probes have been installed on the machine, including flux coils, Rogowski coils, Mirnov coils and saddle sensors.
- 2). Fast reciprocating probe for radial profile measurement, covering half the vacuum vessel.
- 3). 2D Double-foil soft X-ray diagnostic system for temperature measurement based on photodiode detector. The time resolution is 4us for fast MHD physics research.
- 4). Eddy current probes array is mounted to study the plasma instabilities such as resistive wall mode and tearing modes.
- 5). Spectrum diagnostics including $H\alpha$ measurement and bolometer.
- 6). Fast CCD camera with 500frame/sec.
- 7). 1channel 650G solid source interferometer system is installed.
- 8). A Thomson scattering system is designed and will be installed in the next year.

More advanced diagnostics will be developed in the next phase.

3. The preliminary results of commissioning

The commissioning began at Aug. 1, 2015 followed by completion of the construction and is still in ongoing. The commissioning focuses on the wall conditioning, testing of KTX

machine and its sub-systems, exploring the operation parameters, and debugging the fundamental diagnostics.

3.1. Wall conditioning

The inductive baking is successfully tested in the commissioning period. The steady temperature reaches 100°C in 20 minutes and maintains at this value throughout the baking. The RGA provides an intuitive picture for inductive baking shown in FIG. 3. The results indicates that the gas absorbed on the wall is significantly released in the baking process.

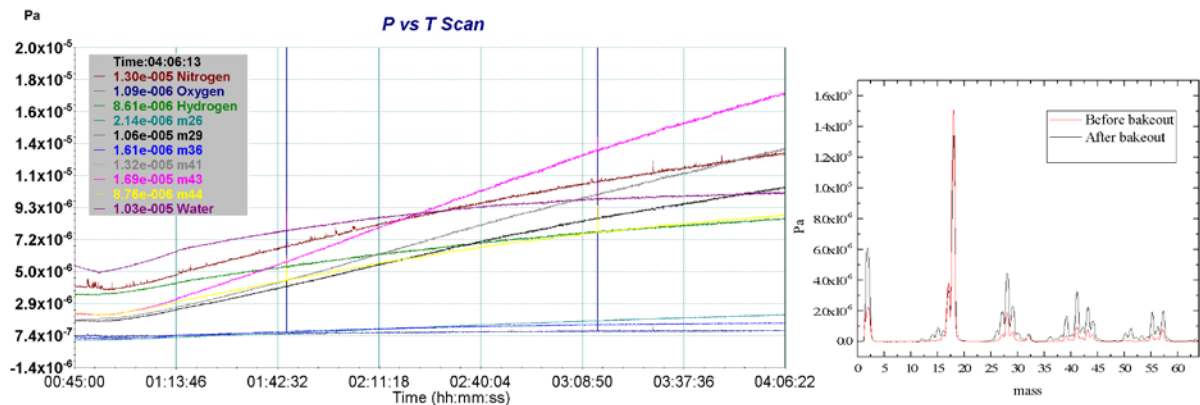


FIG. 3 The mass pressure vs time scan for 4 hours from RGA.

DC glow discharge clean (GDC) is implemented on KTX as a regular wall conditioning routine. The GDC working gas could be Ar, He and H₂ with pressure range of 10~100Pa. The typical GDC image is shown in FIG. 4. From the mass spectrometry, GDC has slight effect on decreasing high molecular weight gas.

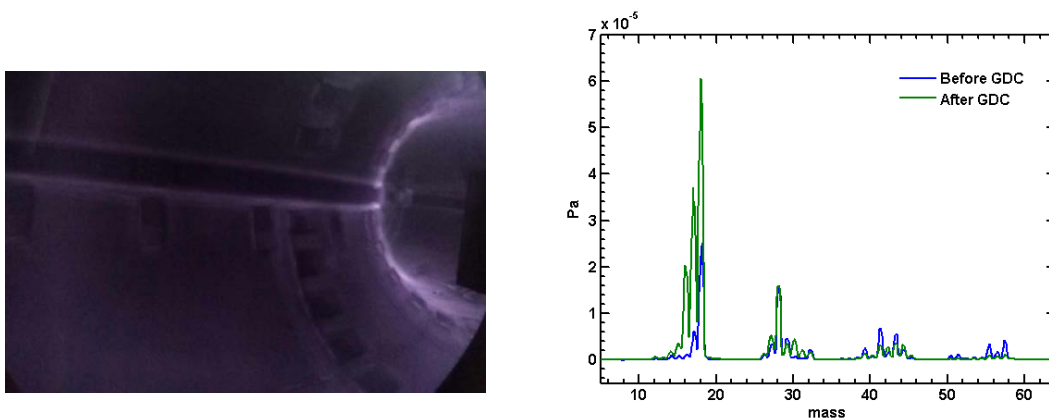


FIG. 4 DC GDC image and mass spectrometry comparison on before and after GDC.

3.2. TF and OH power supply systems

The 4 sets of capacitor charger have been successfully tested. The maximum charger power reaches 260kW, which guarantees the charging time can be less than one minutes for current capacitor banks.

The installation and debugging of OH and TF power supply was completed before the construction of KTX. The current in the OH coils driven by OHPS is shown in FIG. 5 (a), and the inductive toroidal single loop voltage, as FIG. 5 (b), is also presented.

The two operations of TF power supply, i.e. stable TF and reversed TF, are successfully made and shown in FIG. 5 (c), which provides feasibilities for different discharge schemes. The maximum toroidal magnetic field reaches 0.17T in present commissioning.

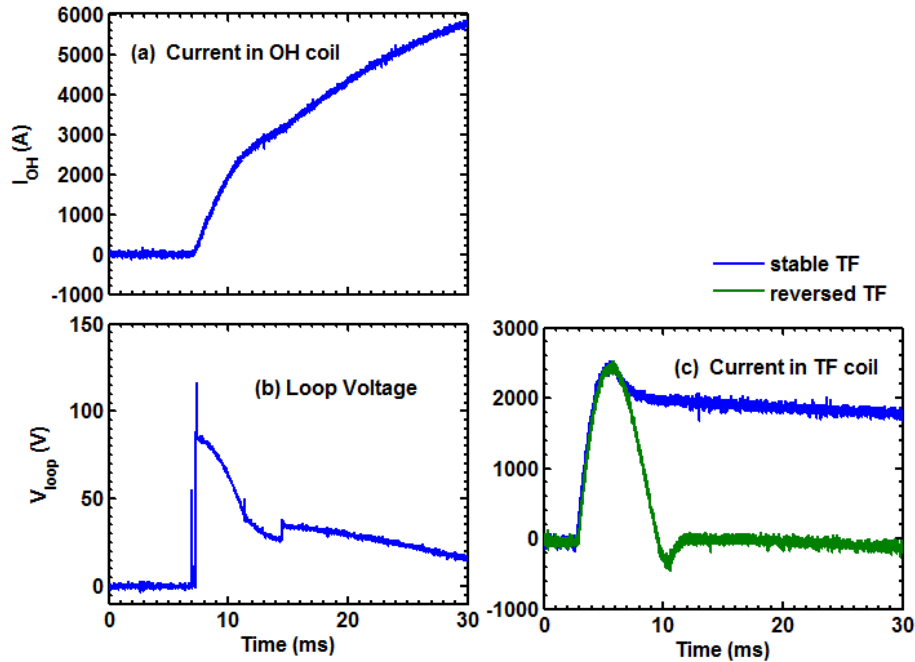


FIG. 5 The current in OH and TF coils by OH and TF power supplies without plasma.

3.3.Operation performance

The first plasma with plasma current up to 108kA has been successfully achieved in Aug. 15, 2015, shown in FIG. 6.

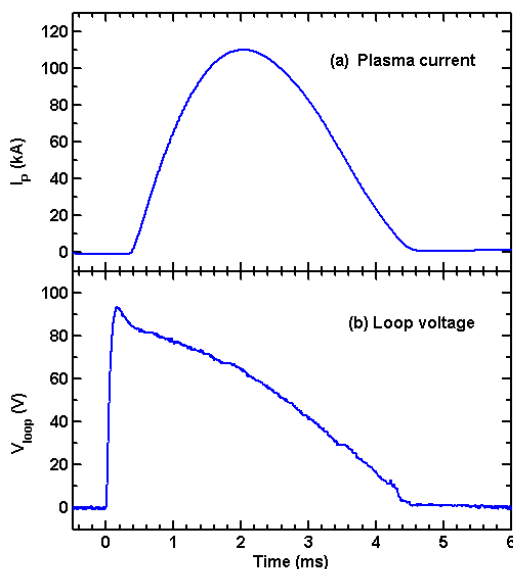


FIG. 6 The toroidal single loop voltage and plasma current for the first plasma discharge.

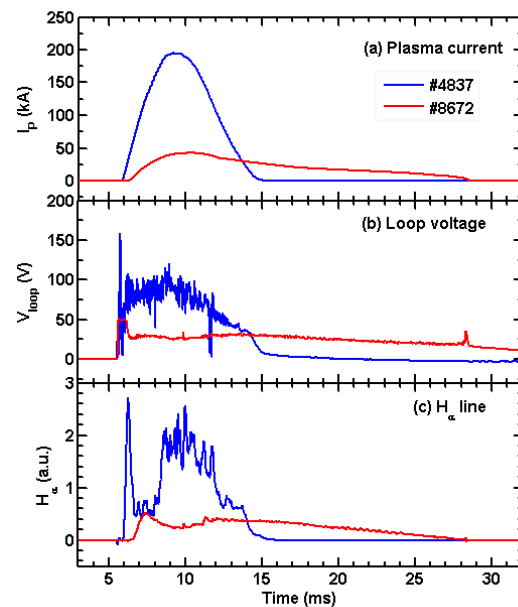


FIG. 7 KTX plasma discharge waveforms.

The maximum plasma current reaches 205kA (blue line and shot 4835 in FIG. 7). And the maximum pulse length is 21ms (red line and shot 8672 in FIG. 7), which is closed to the copper conducting shell penetration time limitation (20ms).

Reversed field configuration discharge with maximum 1.5ms period of reversed toroidal magnetic field at wall is successfully obtained, shown in FIG. 8. The minimum reversal parameter F reach -0.4 and the maximum pinch parameter Θ is about 2.0.

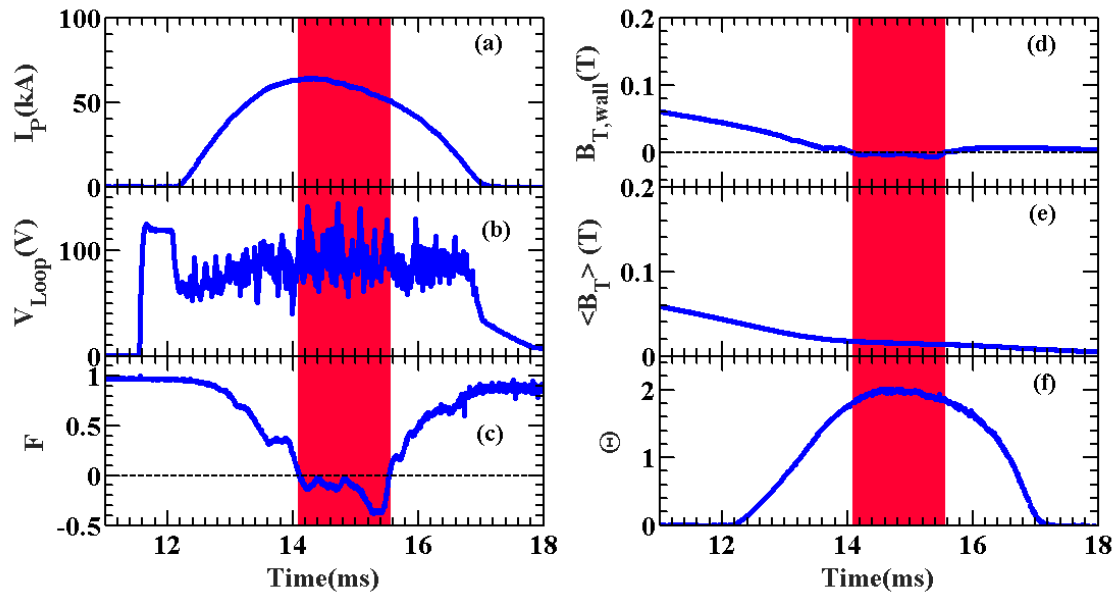


FIG. 8 The discharge evolution in RFP configuration. The plasma is in the RFP state ($F < 0$), marked as the red shadow region. (a) plasma current; (b) toroidal loop voltage; (c) reversal parameter F ; (d) the toroidal magnetic field at wall; (e) averaged toroidal magnetic field; (f) pinch parameter Θ .

4. Future plan

The experimental and upgrade plan for future is as follow,

- 1). To achieve 300kA/20ms (5-10ms RFP configuration) high temperature plasmas.
- 2). Upgrade of power supply
 - a). OH heating power supply (12MJ) for 1MA plasma (Phase 2).
 - b). TF power supply for 0.7T toroidal field (Phase 2).
 - c). Equilibrium field power supply for plasma position control.
 - d). Active feedback power supply.
- 3). Full diagnostics sets come along with upgrade of power supply
 - a). Terahertz Interferometer and polarimetry (current profile).
 - b). Thomson Scattering system (pressure profile).
 - c). Spectroscopy measurements for impurities.

5. Summary

The new RFP device KTX has been successfully built within 4 years. With the completion of construction, the engineering commissioning starts. Inductive baking and GDC are implemented for wall conditioning. The power supply system, data acquisition system and diagnostics are successfully tested. The first plasma, reversed field configuration, 200kA plasma and 20ms pulse have been achieved in the commissioning period, but there is still much space for improvement. In the next phase, the capability of power supply and advanced diagnostics will be upgraded for in-deep physics research.

KTX could be an advanced RFP facility for MCF research and a great platform for education. Future research will focus on resistive wall mode control, 3D physics, boundary condition, QSH control and inductive current drive method optimization.

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