A New 4MW LHCD System for EAST

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Abstract. To achieve a steady-state operation of the Experimental Advanced Superconducting Tokamak (EAST) with high parameters and to control its plasma current density profile more actively and effectively, a new 4MW/2.45GHz Lower Hybrid Current Drive (LHCD) system will be upgraded from the present 2MW/2.45GHz system. It is expected to couple more than 3MW lower hybrid power into EAST plasmas and to sustain 0.8MA non-inductive current with a central line averaged electron density at $2\times10^{19}m^{-3}$ and 0.6MA at $4\times10^{19}m^{-3}$. Key technologies developed for new 4MW LHCD system are presented in this paper, which including the power source, multi-junction antenna, high voltage power supplies, different protection and control subsystems. The experimental results with the present 2MW LHCD system are also given briefly in this presentation.

1. Introduction

It is well known that the Lower Hybrid Current Drive (LHCD) is an effective non-inductive approach to modify the plasma current density profile and to improve the plasma confinement in tokamaks [1]. To achieve a steady-state operation of the Experimental Advanced Superconducting Tokamak (EAST) with higher parameters and to control its plasma current density profile more actively and effectively, a 4MW/2.45GHz LHCD system will be upgraded from the present 2MW/2.45GHz system. It is expected to couple more than 3MW lower hybrid power into EAST plasmas and to sustain 0.8MA non-inductive current with a central line averaged electron density at $2\times10^{19}m^{-3}$ and 0.6MA at $4\times10^{19}m^{-3}$.
Key technologies developed for 4MW LHCD system will be presented in this paper, which including the power source, multi-junction antenna, water cooling subsystem, high voltage (HV) power supply, different protection and control subsystems. The experimental results with the present 2MW LHCD system are also given briefly in this article.

2. System Design

The overall structure of the new 4MW LHCD system is same to the present 2MW LHCD system, which is shown in Fig.1. The core of the microwave power source is composed of 20 2.45GHz klystrons and the multi-junction waveguide array is adopted in the design of antenna with the passive sub-waveguides.

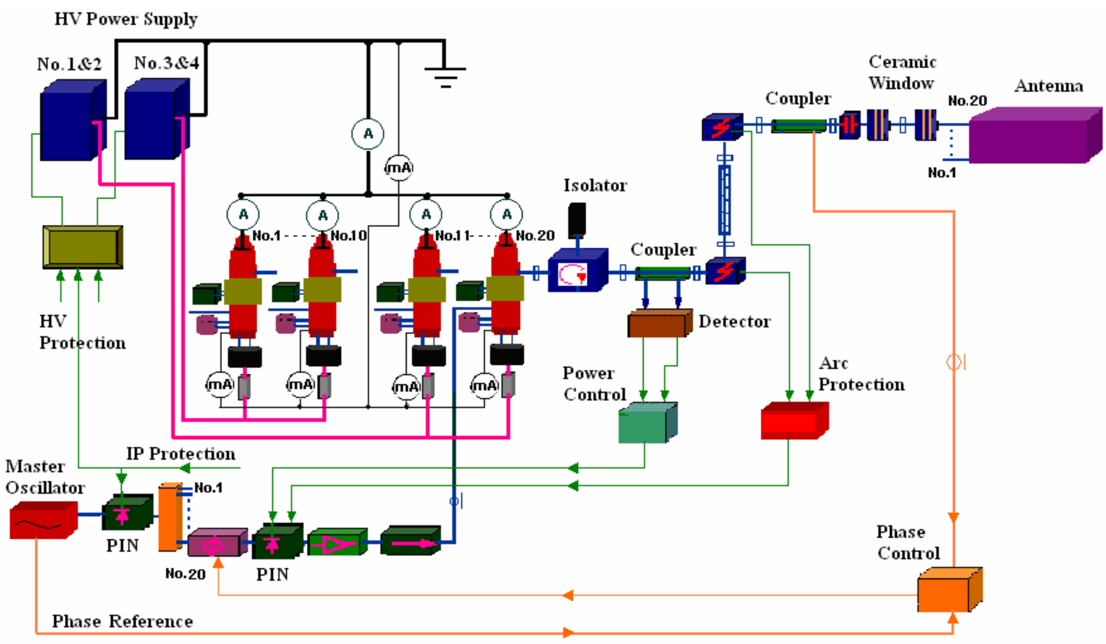


Fig.1. The structure of 4MW LHCD system for EAST

The main technical items of new LHCD system are listed in the following table:

Frequency	2.45GHz
Power	4MW(20×200KW CW)
Pulse width	1000S
Antenna	5×4×8 Multi-junction
$N_{//}$	1.84~2.83
Max. Power Density	30MW/m^2

To meet the need of the new LHCD system, the modification of several subsystems is necessary, which including the klystrons, transmission lines, HV power supplies, water cooling subsystem and overcurrent protection subsystem. The main parts of the new LHCD system will be described as follows.

2.1 Power Source

The power source of the 4MW LHCD system is composed of the low power microwave drive and 20 high power microwave klystrons. The drive of the klystrons consists of one master oscillator, one PIN modulator, two power dividers and 20 independent microwave chains. The master oscillator has three outputs: two 30dBm outputs are connected to power dividers respectively and one 20dBm output is acted as the phase reference of the phase control subsystem. The power divider has 12 outputs, 10 of which are used and 2 reserved. The maximum output of each microwave chain is 3W, which is made up of one digital phase shifter, one PIN switch, one DC break, one amplifier with the voltage controlled attenuator and one power detector. The output of each drive chain is connected to the microwave input of the corresponding klystron with a coaxial cable.

The technical parameters of 20 high power microwave klystrons are listed in the table 1 and as the core of 4MW LHCD system's power source, the klystrons are installed on a two level platform, which is shown in Fig.2. Transmission lines working in a TE_{10} mode are installed between klystrons and the antenna. Each transmission line consists of a four-port high power ferrite isolator, a standard rectangular waveguide (WR430) with a length of 30m to 40m, a flexible rectangular waveguide of 1m, two 99% Al_2O_3 ceramic windows, two bidirectional couplers and so on [2]. The total loss of each transmission line is about 1.0dB to 1.1dB. The waveguide between two ceramic windows is filled with 1 atmospheric pressure nitrogen to smooth the wave transmission. If the ceramic window closer to the tokamak breaks down, the nitrogen will be pumped out and the vacuum will be maintained by the second ceramic window.

TABLE 1: TECHNICAL PARAMETERS OF THE KLYSTRON.

Operating frequency	2.45GHz
Output power	200KW
Input microwave power	0.3~1.0W
Gain	53dB
Input HV power	Max 420KW
Beam voltage	-40~-46KV
Beam current	10A
Efficiency	⩾50%

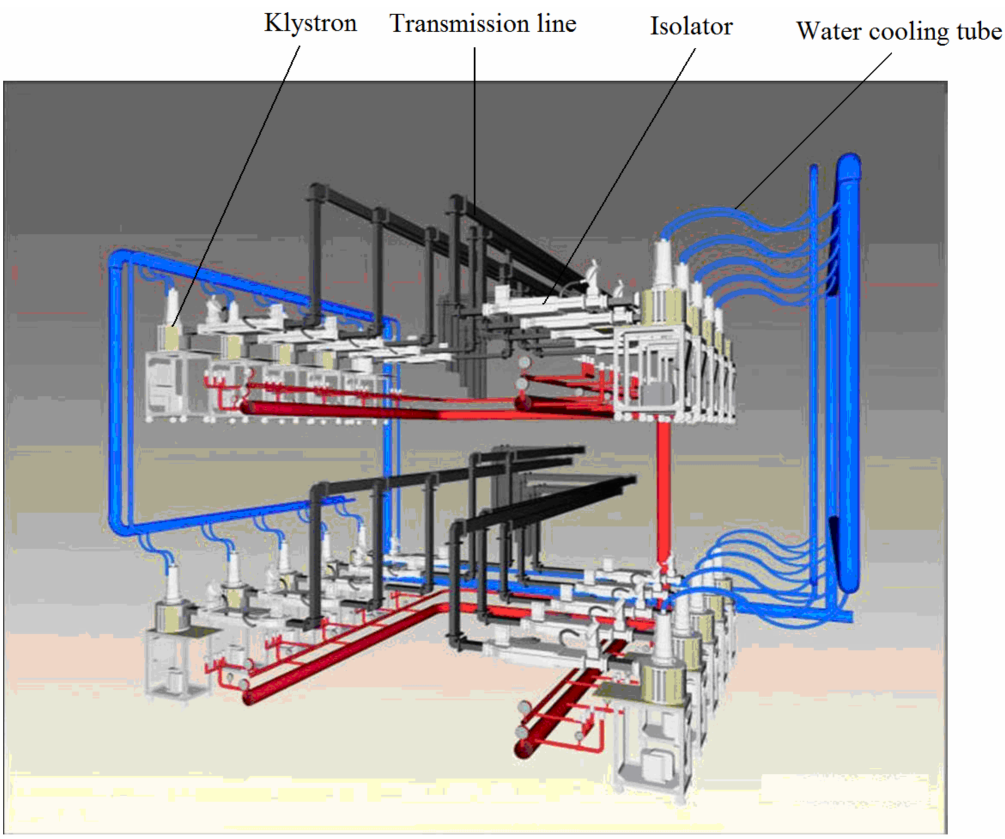
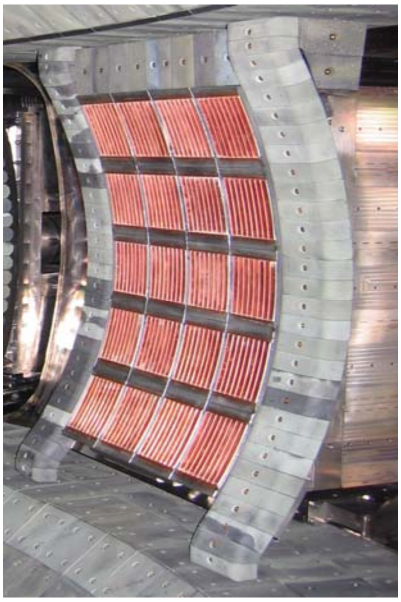


Fig.2. The structure of the klystron and waveguide assembly

2.2 Multi-junction Antenna

To meet the need of plasma physics, the multi-junction waveguide array (5 rows×4 columns) shown in Fig.3 is adopted in the design of antenna. Each main waveguide, whose width is expanded from 54.6mm to 101mm by the H-plane transformer, is divided into 8 active sub-waveguides with a fixed adjacent phase difference of 90^{o} and the passive sub-waveguides are inserted between waveguides and both sides. Thus the whole launcher is composed of 185 sub-waveguides, 160 active sub-waveguides and 25 passive sub-waveguides, and the size of each sub-waveguide is 109.2mm×10mm with a thickness of 2mm.The water cooling tubes put between two waveguide rows and the graphite guard limiters are designed to protect the antenna from overheating [2].
The parallel refractive index $N_{//}$ of the antenna can be adjusted from 1.84 to 2.83 by changing the phase difference between the adjacent main waveguides and its power density spectrum is demonstrated in Fig.3. For a better coupling, the antenna can be moved horizontally up to 300mm by a hydraulic position controller.



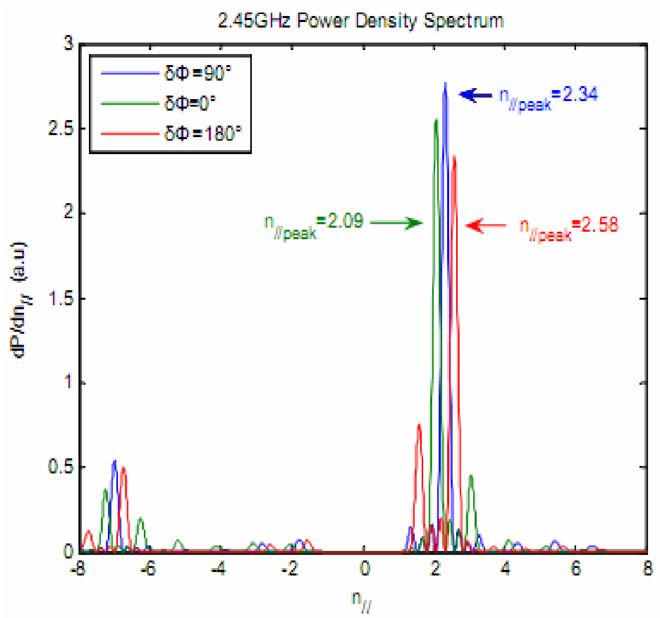


Fig.3. The installed LHCD antenna and its power spectrum

2.3 HV Power Supplies

Four sets of high voltage power supplies, each feeds five klystrons, are employed in the new 4MW LHCD system. The rated voltage and current of each new 200KW klystron's high voltage input are -42KV and 9A. Thus, it is necessary to upgrade the present phase controlled HV power supplies from -33KV/40A to -46KV/50A. For making the best use of the present HV power supplies, four sets of -20KV/50A power supplies based on the Pulse Step Modulator (PSM) technology are used in the design of new HV power supplies. A PSM power supply and a present HV power supply are connected in series to form a needed -46KV/50A power supply.

Because of the limitation of the phase controlled HV power supplies, the rise time of new HV power supplies is about 50ms. For a faster rising, the phase controlled HV power supplies should be replaced with the PSM HV power supplies in the future.

2.4 Water Cooling Subsystem

The high power devices in the LHCD system, such as klystrons, transmission lines, multi-junction antenna and so on, are in need of water cooling. Each new 200KW klystron needs a water flow of 20T/h instead of the former 100KW klystron's 10T/h. According to the demands of different devices, two water pumping stations with different output pressures are designed in the water cooling subsystem. The water pressure of one station is 8 atm for the cooling of klystrons, solenoids, high power ferrite isolators and antenna. The other is 4 atm for the cooling of transmission lines and ceramic windows.

2.5 Protection and Control Subsystems

The protection and control subsystems are designed to meet the demand of the physical experiments on EAST and the security of LHCD system. The demand of EAST experiments mainly includes: the radiated microwave power and the phase difference between the adjacent main waveguides of the antenna can be adjustable; the parameters can be set remotely by EAST central control system and the experimental data of LHCD system can be accessed remotely. The demand of system security mainly includes: the protection of arc and high reflected microwave power; the overcurrent protection of the klystrons' electron collector and body; the measurement and monitoring of the devices' state and physical parameters.

The LHCD protection and control subsystems consist of the LHCD central control console, the arc and high reflection protection subsystem, the power/phase control subsystem and the data acquisition and processing subsystem. Due to the advantage of high realtime performance and reliability for mission-critical applications, QNX realtime operation system (RTOS) is adopted for guaranteeing the successful operation of LHCD system in the physical experiments [3]. As the most widely used tool for the storage and management of the complex scientific data in the magnetic fusion energy program, MDSplus is also employed in the EAST LHCD system and a researcher with permissions can access data stored in this database anywhere on the internet [4].

3. Experimental Results

The plasma shape and position could be optimized to maximize the wave coupling into the plasma with newly developed plasma control algorithm. Maximum 1.2MW power of LHW at a fixed parallel refractive index $N_{||peak} = 2.3$ has been successfully delivered, with 80% power being coupled into the plasma. With the assistance of LHCD system, the low loop voltage plasma startup has been studied for reducing the current ramping rate in the PF coils and increasing the safety of machine operation.

The fully non-inductive plasma discharge with double null configuration has been sustained over 60s when about 600KW LHW power applied, which is shown in the Fig.4. The longer plasma discharge will be obtained if the performance of heat load on the plasma facing components (PFCs) is improved [5].

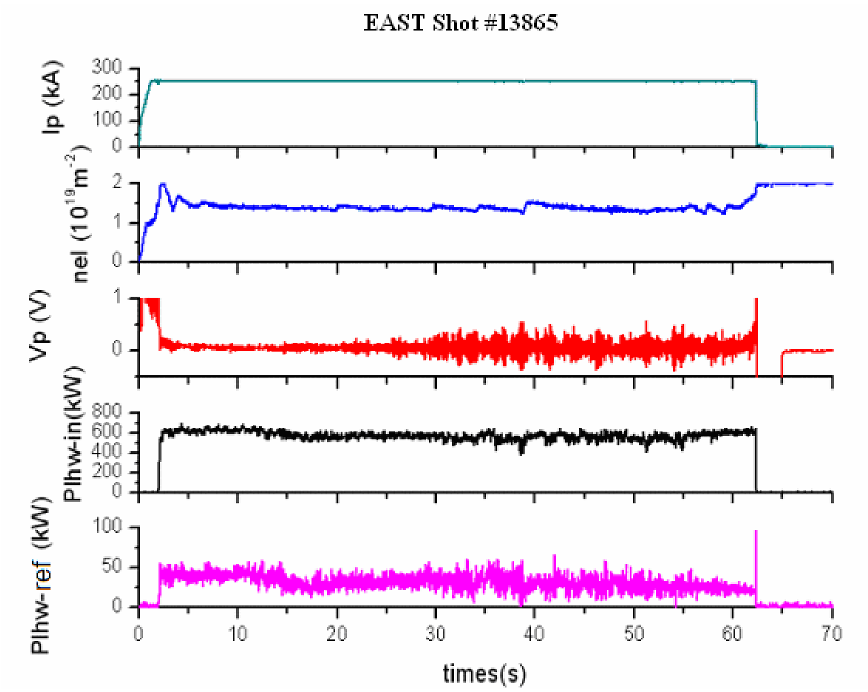


Fig.4. Plasma discharge over 60s with 2MW LHCD system on EAST.
The curves from top to bottom: plasma current, central line averaged density, loop voltage, LHW forward power, LHW reflected power.

4. Summary

The 4MW/2.45GHz LHCD system for EAST will be built up based on the present 2MW/2.45GHz system and the modification of several subsystems is now in progress. With new 4MW LHCD system, it is expected to couple more than 3MW lower hybrid power into EAST plasmas and to sustain longer non-inductive current with high plasma parameters for operating tokamak in a steady state and studying advanced plasma physics. Meanwhile, there is still some space for the improvement of the whole system.

Acknowledgements

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