Development and Preliminary Commissioning Results of a Long Pulse 140 GHz ECRH System on EAST Tokamak (Invited)*

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Abstract A long pulse electron cyclotron resonance heating (ECRH) system has been developed to meet the requirements of steady-state operation for the EAST superconducting tokamak, and the first EC wave was successfully injected into plasma during the 2015 spring campaign. The system is mainly composed of four 140 GHz gyrotron systems, 4 ITER-Like transmission lines, 4 independent channel launchers and corresponding power supplies, a water cooling, control & inter-lock system etc. Each gyrotron is expected to deliver a maximum power of 1 MW and be operated at 100-1000 s pulse lengths. The No.1 and No.2 gyrotron systems have been installed. In the initial commissioning, a series of parameters of 1 MW 1 s, 900 kW 10 s, 800 kW 95 s and 650 kW 753 s have been demonstrated successfully on the No.1 gyrotron system based on calorimetric dummy load measurements. Significant plasma heating and MHD instability suppression effects were observed in EAST experiments. In addition, high confinement (H-mode) discharges triggered by ECRH were obtained.

Keywords: gyrotron system, ECRH, millimeter wave, EAST, steady-state operation

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

1 Introduction

The experimental advanced superconducting tokamak (EAST)\(^1\) has been in operation since 2006; the main auxiliary systems, including neutral beam injection (NBI)\(^2\), lower hybrid current drive (LHCD)\(^3\) and ion cyclotron resonance heating (ICRH)\(^4\) have also been installed. Since the ECRH scheme has many advantages in magnetic fusion devices, it was developed and studied in the W7-X\(^5\) and LHD\(^6\) stellarators, as well as most tokamaks such as DIII-D\(^7\), ASDEX\(^8\), HL-2A\(^9\) and KSTAR\(^10\), where it has been applied to plasma startup, plasma heating, current density profile control and stabilization of magneto hydrodynamics (MHD) modes etc. The long pulse ECRH system, which has been designed to meet the requirement of steady-state operation in EAST, has been planned since 2011. The general preliminary design of the system was completed in 2012, and all sub-systems have been under development since 2012. Two gyrotron systems were installed in 2014 and the first EC wave injection has been demonstrated successfully during the EAST 2015 spring campaign. Some representative results have been obtained in the commissioning experiments.

2 Development of the ECRH system on EAST

2.1 General design of system

2.1.1 The choice of gyrotron frequency

Gyrotrons play the key role as high power millimeter wave sources in the development of the ECRH system. The normal operation range of toroidal magnetic fields, when X2 heating mode is employed, is about 2.0-3.0 T
on EAST tokamak, corresponding to an EC wave frequency that would fall into the range of 140-170 GHz. According to the development progress of gyrotrons [11] around the world, two kinds of gyrotron were considered, those being the 170 GHz gyrotron developed for ITER and the 140 GHz gyrotron, which is used widely in ASDEX-U, HL-2A, W7-X etc. In order to fit most experiments of EAST in a wide range of magnetic fields, the 140 GHz gyrotron was adopted finally such that the EC wave would be coupled to plasma as an X2 mode.

2.1.2 Layout design of system

According to the overall arrangement of EAST ports, an equatorial port M was reserved for the ECRH system; correspondingly, the gyrotron system could be located in an adjacent building to the EAST hall. Considering the space limitations of the port M and gyrotron building, 4 sets of gyrotrons were designed. The schematic circuit diagram is shown in Fig. 1. The system is composed of 4 gyrotron systems, 4 waveguide transmission lines consisting of various evacuated corrugated waveguide components, 4 independent channel launchers and corresponding diversified power supplies, water & oil cooling system, control & inter-lock system, auxiliary vacuum system etc. Two cathode power supplies are employed to power the gyrotrons, with each cathode power supply feeding two gyrotrons, and an independent body power supply and dummy water load configured for every gyrotron. Each gyrotron is expected to deliver a maximum power of 1 MW and be operated at 100-1000 s pulse length. A total generated power of 4 MW is a goal of this system.

The system layout design is optimized due to limited space in EAST and the gyrotron building. The final layout is shown in Fig. 2. The distance between two gyrotrons is about 4.5 m to prevent mutual magnetic disturbance, and the measured stray magnetic field coming from the EAST tokamak and its poloidal coils power supply is lower than 2 Gauss in the horizontal direction and less than 5 Gauss in the vertical direction, which satisfies the requirement of gyrotrons. The length of the transmission line is 30 m approximately.

Fig. 1 The schematic circuit diagram of the ECRH system

Fig. 2 The layout of gyrotron systems and transmission lines of ECRH system on EAST
2.2 Gyrotron system

2.2.1 Gyrotrons

The gyrotrons come from two manufacturers. Two tubes, numbers 1 and 3, are made by Gycom Ltd., Russia, and the other two are provided by CPI, USA. Their main parameters are shown in Table 1. They are all designed to operate at 140 GHz with a power goal of 900 kW-1 MW and pulse length goal of 100-1000 s. Diamond windows and Gaussian output beams are employed in all gyrotrons. The differences between the two kinds of gyrotron focus on the cavity mode, the cathode and filament, cathode voltage, efficiency, ion pump, matching optic unit (MOU) and collector power limit. A two-mirror MOU is used with the Gycom gyrotrons, and a single mirror MOU is adopted for the CPI Gyrotrons. An internal ion pump is used in the Gycom gyrotrons, which can only be started when the main magnet is charged. Two external ion pumps, which can be operated at any time, are designed in the CPI gyrotron, which makes maintaining the gyrotron vacuum easier. An oil cooling system is required to improve the insulation of the electron gun and remove the heat from the filament or ceramic in all gyrotrons.

Table 1. Main parameters of gyrotrons

<table>
<thead>
<tr>
<th></th>
<th>No.1 and No.3</th>
<th>No.2 and No.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Gycom</td>
<td>CPI</td>
</tr>
<tr>
<td>Type</td>
<td>Diode</td>
<td>Diode</td>
</tr>
<tr>
<td>Cavity mode</td>
<td>TE22.8</td>
<td>TE28.7</td>
</tr>
<tr>
<td>Max. output power</td>
<td>1 MW</td>
<td>900 kW</td>
</tr>
<tr>
<td>Pulse length</td>
<td>100-1000 s</td>
<td>100-1000 s</td>
</tr>
<tr>
<td>Output beam</td>
<td>Gaussian beam</td>
<td>Gaussian beam</td>
</tr>
<tr>
<td>Collector type</td>
<td>Depressed</td>
<td>Depressed</td>
</tr>
<tr>
<td>Collector power limit</td>
<td>1.1 MW</td>
<td>1.8 MW</td>
</tr>
<tr>
<td>Cathode voltage</td>
<td>−46 kV</td>
<td>−59 kV</td>
</tr>
<tr>
<td>Beam current</td>
<td>43 A</td>
<td>40 A</td>
</tr>
<tr>
<td>Body voltage</td>
<td>+25 kV</td>
<td>+22 kV</td>
</tr>
<tr>
<td>Filament power</td>
<td>1000-1200 W</td>
<td>200-250 W</td>
</tr>
</tbody>
</table>

The No.1 and No.2 systems have been installed and partially tested; the No.3 and No.4 gyrotrons have been ordered and will be ready to test in 2016. Fig. 3 shows the general view of installed No.1 and No.2 gyrotron systems.

Fig.3 The installed No.1 and No.2 gyrotron systems for EAST

2.2.2 Magnets system

Magnets include a superconducting magnet, collector coil and gun coil. Two different magnet designs are used for the Gycom and CPI gyrotrons respectively; they ensure the performance of the gyrotron especially in the long pulse operation mode.

A traditional liquid helium superconducting magnet is employed in the No.1 gyrotron system. There is only one coil to generate a 6 T magnetic field in the Gycom superconducting magnet. In order to ensure the coaxial alignment of Gyrotron and magnet, two adjustable rings, located at the top and bottom of the magnet respectively, are designed to hold the gyrotron; a magnetic field probe is used to check the field profile, and then a dummy tube is employed to check the electron beam in the collector again before the gyrotron is installed. The Gycom gun coil is a separate coil which is located near the body and is commonly set to zero. A three-phase 200 Hz electromotor-like coil system is adopted as the collector sweep coil for the No.1 Gycom gyrotron, and an additional DC collector coil is used to adjust the vertical central position of the beam.

An integrated superconducting magnet, including two main coils, X-coil and Y-coil for transverse steering and a gun coil, was designed for the CPI gyrotron. In the first installation, the X-coil and Y-coil should be optimized to ensure the alignment of gyrotron and magnet at very low cathode voltage. The CPI gyrotron also uses a room-temperature coil to sweep the electron beam across the collector surface at an AC frequency of 10 Hz, and in addition, a small DC current component is used to move the vertical position of the beam. The temperature profile of the collector will be checked again before the long pulse test, using RTD probes attached to the collector’s outer surface.

2.3 Power supply system

The power supply (PS) system consists of cathode high voltage power supplies (HVPS), body HVPS, and superconducting (SC) magnet, collector coil, ion pump, and filament power supplies.

Four gyrotrons will be fed by two sets of cathode power supplies, with each power supply capable of delivering −60 kV/80 A in continuous wave (CW) mode, and also −70 kV/100 A for 100 s. A pulse step modulator (PSM) type is used in the cathode HVPS. It has a capability of fast modulation up to 1 kHz, which is intended for the potential application of MHD suppression by modulated ECRH. It has a fast response time of less than 10 µs once a fault signal is received, and the maximum energy dissipated in a gyrotron is less than 10 J in an arc event. The first cathode HVPS has been installed and tested as shown in Fig. 4. The second will be completed in the beginning of 2016.

Each gyrotron will use an independent body HVPS, which plays a key role in the collector depression scheme to increase the efficiency of the gyrotron and reduce the heat load on the collector. The body HVPS has an
output capability of +30 kV/100 mA in the CW mode, with the response time less than 5 ms and the dissipated energy is also less than 10 J in an arc event.

Several kinds of lower voltage power supplies are developed for the gyrotron system, and their typical operation parameters are shown in Table 2.

![The installed cathode HVPS for the ECRH system](image1.png)

**Table 2.** Typical operation parameters of power supplies

<table>
<thead>
<tr>
<th>Gyrotron system</th>
<th>No.1</th>
<th>No.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC magnet PS</td>
<td>0-60 A</td>
<td>0-55 A</td>
</tr>
<tr>
<td>Filament PS</td>
<td>AC 39 V/35 A</td>
<td>AC 28 V/7 A</td>
</tr>
<tr>
<td>Ion pump PS</td>
<td>3.5 kV/1 mA</td>
<td>5 kV/1 mA</td>
</tr>
<tr>
<td>Collector coil PS</td>
<td>Three phase AC</td>
<td>AC 8.8 A</td>
</tr>
<tr>
<td></td>
<td>112 V/8.1 A</td>
<td>DC 2.5 A</td>
</tr>
<tr>
<td></td>
<td>DC 3 A</td>
<td></td>
</tr>
</tbody>
</table>

2.4 Transmission line system

After comparing two types of transmission line (TL) system, including the quasi optical TL adopted in W7-X and millimeter microwave waveguide TL used in many tokamaks and the LHD device, an ITER-like TL system using a 63.5 mm diameter evacuated waveguide system was adopted for EAST. Each TL is a chain consisting of corrugated waveguides, a waveguide switch, dummy load, miter bends, polarizers, DC break, bellows, CVD window, and gate valve, which are shown schematically in Fig. 1. The function of each component is similar to the ITER design. The total power loss of each TL is about 10%-15%. When the approximately 10% power dissipated in the MOU and internal loads is taken into account, the remaining 75%-80% fraction of the generated gyrotron power can be injected into EAST. There is a significant difference between the dummy loads for the different gyrotron systems. A large quasi-optical load is used for the Gycom gyrotron system, which has a power capability of 1 MW CW; the load for the CPI gyrotron comprises two sections, where 80% of the power in the HE11 mode could be absorbed by an attenuator type waveguide load first, with the remaining power absorbed by a small terminal quasi-optical load.

2.5 Launcher

A launcher with four independent channels was developed for EAST, with the four channels designed in a symmetrical arrangement relative to the equatorial plane as well as the port M of EAST tokamak. Each channel uses a fixed focus mirror and a planar steering mirror, and a section of stainless steel waveguide is adopted to transmit millimeter waves to the focus mirror in the vacuum of EAST. The launcher has a main feature of active cooling in all mirrors which will ensure the availability of CW operation. Through the optimization study of the launcher design, the launcher parameters were decided as follows: the poloidal sweep range is ±5°-±25°, the toroidal range is 165°-205°, and the definition of these angles is consistent with the TORAY code. The lower two channels of the launcher have been installed in EAST prior to the 2015 spring campaign as shown in Fig. 5.

![The installed lower two channels of the launcher in the port M of EAST](image2.png)

2.6 Control & interlock system

A control & interlock system has been developed to ensure the safe operation of the whole system, which consists of several sub-systems, each sub-system having specific functions. A central control unit is mainly applied to control the cathode and body HVPS according to the turn-on and turn-off sequence of a gyrotron, and also to identify the gyrotron silence fault. The control unit is designed using flexible FPGA technology. A fast response interlock sub-system is developed to detect arc events inside the gyrotron or waveguide as well as other over-current faults, and send a fault signal to switch off the cathode and body HVPS within one microsecond. A PLC sub-system is employed to monitor the general status of the whole system including all electric signals, water and oil cooling parameters and vacuum status etc. It is also used to control mechanical movements of the launcher, waveguide switches, and gate valves. A few PXI computer systems are developed for data acquisition, and polarizer control as well as setting parameters of all power supplies. The control and interlock system can be operated remotely from a control room. The first control and interlock system shown in Fig. 6 has been installed and tested successfully.
2.7 Auxiliary system

In order to handle the heat load in the long pulse operation of the system, a large water cooling system was specially built for the ECRH system; all components of the system should be cooled by water. The water cooling system has a maximum heat exchange capability of 8 MW in the CW mode when the environmental wet bulb temperature is less than 28°C and a required water temperature of less than 35°C. Three branches of cooling water could be provided. The first is a special branch which can deliver high pressure (close to 11.5 kg/cm²) for the No.2 & No.4 gyrotron collectors, the second is a high resistance branch feeding all channels in contact with high voltage parts, which should maintain the resistivity better than 10 MΩ·cm, and the third is a normal branch supplying other parts of the whole system.

A vacuum pumping system is designed to produce the required vacuum of transmission lines, which should be better than $1 \times 10^{-2}$ Pa in the long pulse operation. Three pumping ports, which are shown in Fig. 2, are reserved in each TL channel. They are located at MOU, water load and a port close to the CVD window on the launcher side.

3 Preliminary commissioning results

3.1 Alignment of the system

The expected low loss mode of the transmission line is the HE₁₁ mode, and the purity of the mode is very important for the EC wave. Since the tilt of the wave beam plays a more important role for the mode purity of the system than offset, a very careful alignment optimization has been carried out in the initial stage of system installation, and a maximum tilt less than 0.32 degrees was obtained. The typical power profile of the No.2 system is shown in Fig. 7 which is measured at the output of the MOU by an infrared camera. The HE₁₁ purity of 89.5% has been confirmed by phase retrieval analysis \cite{17}, which is similar to results of the DIII-D ECRH system \cite{18}.

3.2 Commissioning results on dummy load

Long pulse tests into a dummy load have been carried out for No.1 and No.2 gyrotron systems. The best results of 500 kW 100 s, and 800 kW 300 ms have been achieved successfully on the No.2 gyrotron system in ASIPP, and 460 kW 1000 s has been obtained in CPI factory testing. However, the CPI gyrotron test was paused in ASIPP because of water leak problems. The system test will resume after the repair process is complete.

A series of parameters of 1 MW 1 s, 900 kW 10 s, 800 kW 95 s and 650 kW 753 s have been demonstrated successfully on the No.1 gyrotron system. These results were obtained on corresponding shots without filament compensation. Fig. 8 shows waveforms of the longest 650 kW 753 s pulse, the pulse was stopped by an arc event inside the gyrotron when the ion pump current increased gradually.

3.3 First injection results on EAST

During the first ECRH experiments, 600 kW EC power has been coupled to Ohmic, NBI and LHCD plasmas in continuous or modulated pulses of durations up to 2 s. It is well known that the resonance condition for the $l$th harmonic can be expressed as

$$\omega_0 - k_\parallel v_\parallel = l\omega_{ce}/\gamma, \quad (1)$$

where $\omega_{ce} = Bq_e/m_e$ is the electron cyclotron frequency, $k_\parallel$ the parallel wave number, $v_\parallel$ the parallel velocity.
and \( \gamma \) the relativistic mass factor. For these experiments with the magnetic field at the plasma center \( B_0 = 2.3-2.5 \) T, the second harmonic X-mode has been used.

Fig. 9(a) shows a typical waveform of ECRH power injected into the Ohmic target plasma (plasma current \( I_p = 400 \) kA, line-averaged density \( n_{e,av} = 2.2 \times 10^{19} / \text{m}^3 \)). In order to guarantee the EC power absorbed in the central region, the toroidal injection angle and poloidal angle were set to be 180° and 15° respectively. The magnetic field on the axis was about 2.5 T, corresponding to the value for the cold 2nd harmonic resonance. It can be seen that, when the EC wave with \( P_{EC} = 400 \) kW is turned on, the plasma stored energy (\( \Delta W_{MHD} \)) and the central electron temperature (\( T_{e0} \)) were increased by 26 kJ and 1 keV respectively, compared with the Ohmic heating phase, which suggests a good plasma heating effect was obtained by the EC wave. As shown in Fig. 9(b), the electron temperature measured by an electron-cyclotron emission (ECE) radiometer increases globally during the ECRH phase. It should be noted here that an apparent decrease in loop voltage (\( \Delta V_{loop} \sim 0.4 \) V) did not result from the current driven by the EC wave, since the EC beam was launched perpendicular to the toroidal field. This change in loop voltage should be attributed to the increase in the Spitzer conductivity.

Fig. 10 illustrates an H-mode discharge with L-H transition triggered by ECRH injection. The L-H transition was triggered at \( t = 3.6 \) s, when ECRH with \( P_{EC} = 400 \) kW was injected. The transition was characterized by a sharp drop in \( D_\alpha \) emission, an increase in line-averaged density (\( n_{e,av} \)) and plasma stored energy (\( \Delta W_{MHD} \sim 78 \) kJ). It is worth mentioning that the significant increment of plasma stored energy should be ascribed both to the increase in total heating power and the improvement of confinement. When EC power was turned off at \( t = 5.5 \) s, the H-mode phase was still sustained by LHCD alone. However, the plasma stored energy was decreased from 181 kJ to 161 kJ with density constant, which indicated that a good plasma heating effect during H-mode was achieved by EC waves.

In addition to effective plasma heating, ECRH or electron cyclotron current drive (ECCD) are also useful for stabilizing various magnetohydrodynamic (MHD) instabilities, particularly the neoclassical tearing modes (NTMs), which limit the achievable plasma performance. It was found in the experiments that the sawteeth period can be shortened during ECRH heating inside \( q = 1 \), and can be lengthened during heating outside \( q = 1 \) (shown in Fig. 11). Preliminary analysis shows no influence of ECRH on the sawtooth period when power is deposited at the edge region (\( \rho > 0.5 \)). In addition, the ECRH effect on tearing mode stabilization was also demonstrated.

Regarding the character of ECCD efficiency, it is very difficult to measure the current drive by the EC wave since its value is quite low. According to the ECCD calculations by means of the TORAY-GA ray-tracing code, the predicted EC current is in the range of \( \sim 14 \) kA with parameters as \( P_{EC} \sim 0.5 \) MW, \( n_{e,av} = 2.0 \times 10^{19} / \text{m}^3 \) and \( T_{e0} = 3 \) keV, which is much lower than the plasma current (typically \( \sim 400-500 \) kA). As a result, the difference in loop voltage between EC injected positively and negatively is very small.

### 4 Conclusions

A long pulse ECRH system with a goal of 4 MW 100-1000 s has been developed for EAST, which comprises
An example of a sawteeth period modified by ECRH/ECCD

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