Recent progress of the development of a long pulse 140GHz ECRH system on EAST

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Abstract. A long pulse ECRH system with a goal of 140GHz 4MW 100~1000s has been developed to meet the requirement of steady-state operation on EAST. Gycom gyrotrons are employed in the No.1 and No.3 systems, CPI gyrotrons are used in the No.2 and No.4 systems. The development of the two Gycom gyrotron systems has been finished. The first short pulse EC wave injection has been demonstrated successfully during the EAST 2015 Spring campaign. In the commissioning and operation towards steady-state operation, 0.4MW 100s has been injected to plasma successfully by using the No.1 system, 4.7keV 102s L-mode and 102s H-mode plasma have been achieved on EAST with the help of ECRH. Recently, a longest pulse of 0.55MW 1000s has been obtained based on calorimetric dummy load measurements on the No.3 gyrotron. The No.2 gyrotron also has been installed and partially tested, 500kW 80s has been demonstrated in the dummy load. The remaining No.4 gyrotron will be ready to test in 2018 or 2019. The whole 4MW system will be completed within two years. The 400s fully non-inductive H-mode operation would be expected in the next four years in the condition of fully tungsten diverter on EAST.

1 . Introduction

The 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] also have been installed. A 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. The system is mainly composed of four 140GHz gyrotron systems, 4 ITER-like transmission lines, 4 independent channel launchers and corresponding power supplies, water cooling, control & interlock system etc. Each gyrotron is expected to deliver a maximum power of 1MW and be operated at 100s~1000s pulse lengths. Gycom gyrotrons are employed in the No.1 and No.3 systems, CPI gyrotrons are used in the No.2 and No.4 systems. Two gyrotron systems were installed in 2014 and the first short pulse EC wave injection has been demonstrated successfully during the EAST 2015 Spring campaign [5]. Significant plasma heating and MHD instability suppression effects were observed. In addition, high confinement (H-mode) discharges triggered by ECRH were obtained.

2 . A long pulse ECRH system on EAST

2.1 Overview of the system

Considering the development progress of gyrotrons[6] around the world, two kinds of gyrotron were considered, those being the 170GHz gyrotron developed for ITER and the 140GHz gyrotron, which is used widely in ASDEX-U, HL-2A, W7-X, etc. The normal operation range of toroidal magnetic fields is about 2.0T~3.0T on EAST tokamak. In order to fit most experiments of EAST in a wide range of magnetic fields, the 140GHz gyrotron was adopted finally such that the EC wave would be coupled to plasma as an X2 mode.

According to the overall arrangement of EAST ports, an equatorial M port 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 M port and gyrotron building, 4 sets of gyrotrons were designed. The system layout design is optimized due to limited space in EAST and the gyrotron building. The final layout is shown in Fig.1. 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

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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. The system is composed of 4gyrotron 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.[7]. 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.

Fig. 1.The layout of gyrotron systems and transmission lines.

2.2 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 140GHz with a power goal of 900kW~1MW and pulse length goal of 100s~1000s. 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 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. A series of parameters of 1MW 1s, 900kW 10s, 800kW 95s and 650kW 753s have been demonstrated successfully on the No.1 gyrotron system. Recently, a longest pulse of 0.55MW 1000s has been obtained based on calorimetric dummy load measurements [8] on the No.3 gyrotron. The No.2 gyrotron also has been installed and partially tested, 500kW 80s has been demonstrated in the dummy load. The remaining No.4 gyrotron will be ready to test in 2018 or 2019.

Table 1. Main parameters of gyrotrons.

	No.1	No.3	No.2 and No.4
Manufacturer	Gycom		CPI
Type	Diode		Diode
Cavity mode	TE22,8		TE28,7
Max. output power	1MW		900kW
Pulse Length	100~1000s		100~1000s
Output beam	Gaussian beam		Gaussian beam
Collector type	Depressed		Depressed
Collector power limit	1.0 MW	1.3MW	1.8MW
Cathode voltage	-46kV		-59kV
Beam current	42		40
Body voltage	+25kV		+22kV
Filament power	1000~1200W		200~250W
MOU	Two mirrors		Single mirror
SC magnet	Liquid helium	Helium free	Helium free

2.3 Transmission lines and launcher

An ITER-Like TL system using a 63.5mm diameter evacuated waveguide system was adopted for EAST. As shown in Fig. 2, each TL is a chain consisting of corrugated waveguides, waveguide switch, dummy load, miter bends, polarizers, DC break, bellows, CVD window, and gate valve. The function of each component is similar to the ITER design [9]. 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.

A launcher with four independent channels was developed for EAST, with the four channels designed in a symmetrical arrangement relative to equatorial plane as well as the M port of EAST tokamak. Each channel uses a fixed focus mirror and a 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 [10], the launcher parameters were decided as follows: the poloidal sweep range is 65° ~ 95°, the toroidal range is 165° ~ 205°, and the definition of these angles is consistent with the GA-TORAY code [11]. The lower two channels of launcher have been installed in EAST prior to the 2015 Spring campaign.

Fig. 2. The layout of transmission lines.

2.4 High voltage power supplies

The four gyrotrons will be fed by two sets of cathode power supplies, with each power supply capable of delivering -60kV/80A in continuous wave (CW) mode, and also -70kV/100A for 100s. The architecture of the cathode high voltage power supply is shown in Fig. 3. 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 microseconds once a fault signal is received, and the maximum energy dissipated in a gyrotron is less than 10J in an arc event. The body HVPS has an output capability of +30kV/100mA in CW mode, with the response time less than 5 microseconds and the dissipated energy is also less than 10J in an arc event.

Fig. 3. The architecture of the cathode high voltage power supply.

2.5 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. The architecture of the control & interlock system is shown in Fig. 4. A central control unit is mainly applied to control 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 gyrotron or waveguide as well as other over-current faults[12], and send a fault signal to switch off cathode and body HVPS within one microsecond. A RF protection sub-system is developed to monitor the forward and the backward RF power [13]. 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 launcher, waveguide switches, and gate valves. A few PXI computer systems are developed for data acquisition [7], polarizer control [14] as well as setting parameters of all power supplies.

Fig. 4. The architecture of the control & interlock system.

2.6 Auxiliary system

A vacuum pumping system is designed to produce the required vacuum of transmission lines, which should be better than 1×10^{-3} 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. In order to handle the heat load in the long pulse operation of 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 8MW 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.

3 . Commissioning results on dummy load

3.1 Alignment commissioning of gyrotron

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. In the initial installation of No.2 gyrotron system, a large vertical tilt and offset resulted in a lower fraction of HE₁₁ content, which was measured by infrared camera and calculated based on phase retrieval analysis [15]. A very careful adjustment by shimming gyrotron structure has been carried out to improve the alignment. Finally the tilt was reduced from 0.39 deg to 0.2deg, and the offset was reduced by about 3 mm shown in Fig. 5. Fig. 6 shows the phase front of the back-propagated beam at the waveguide mouth is seen to be extremely flat after adjustment, the signature of a high quality Gaussian beam. Analysis shows the HE₁₁ purity was increased from 67.5% to 89.5%, which is similar to results of the DIII-D ECRH system [16].

• Adjustments decreased beam tilt by 1/3
↑ Also some improvement in beam center

Fig. 5. The tilt and the offset of the transmission line before adjustment and after adjustment.

Fig. 6. The mode content and the phase front of the back-propagated beam at the waveguide mouth before adjustment and after adjustment.

3.2 Long pulse commissioning on dummy load

Long pulse tests into a dummy load have been carried out for No.1, No.2, and No. 3 gyrotron systems in 2015~2018.

A series of parameters of 1MW 1s, 800kW 95s and 650kW 753s have been demonstrated successfully on the No.1 gyrotron system. These results were obtained on corresponding shots without filament compensation. Fig. 7 shows waveforms of the 650W 753s pulse, the pulse was stopped by an over-current fault.

The best results of 500kW 80s, 800kW 300ms have been achieved successfully on No.2 gyrotron system in

ASIPP, and 460kW 1000s has been obtained in CPI factory testing. Fig.8 shows waveforms of the 500kW 80s pulse with filament compensation.

A series of parameters of 780kW 20s, 630kW 100s and 550kW 1000s have been demonstrated successfully on the No.3 gyrotron system. Fig. 9 shows waveforms of the 550kW 1000s pulse with filament compensation.

Fig. 7. The waveforms of the 650W 753s pulse of the #1 gyrotron.

Fig. 8. The waveforms of the 500W 80s pulse of the #2 gyrotron.

Fig. 9. The waveforms of the 550W 1000s pulse of the #3 gyrotron.

4. Experimental results on EAST

4.1 Verification of polarizer control

The EC waves can propagate in the plasma in the ordinary (O) and extraordinary (X) modes. The toroidal field on EAST is normally in the range of 2.0~2.6T. For 140GHz waves, the interactions happen at the second harmonic electron cyclotron resonance in plasma. Because the ordinary mode is not well absorbed at higher harmonic resonances, we choose the second harmonic extraordinary(X2) as the operating mode. The wave coupling in plasma is determined by the polarization of injected EC wave.

The plasma absorption efficiency is affected by different polarizations. Fig. 10 shows this effect. When the polarization is not right, the EC waves can not be well absorbed by the plasma. The EC waves directly hit the first wall of tokamak. The obvious bright spots can be seen through an infrared camera.

Fig. 10. Influence of different polarization on plasma absorption efficiency.

4.2 First short pulse EC wave injection

The No.1 system was applied in EAST experiments from 2015. The first short pulse EC wave injection has been demonstrated successfully during the EAST 2015 Spring campaign. Significant plasma heating and MHD instability suppression effects were observed. Fig. 11 and Fig. 12 show a typical waveform of ECRH power injected into Ohmic target plasma (plasma current $I_p = 400$ kA, line-averaged density $n_{e,av} = 2.2 \times 10^{19} / m^3$). In can be seen that, when the EC wave with $P_{EC} = 400$ kW turned on, the plasma stored energy (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 good plasma heating effect was obtained by the EC wave.

Fig. 11. Time evolution of I_p , $n_{e,av}$, V_{loop} , ECRH power, T_{e0} , and W_{MHD} with ECRH.

Fig. 12. Effect of ECRH on the electron temperature (T_e).

4.3 Application in 100 s high T_e operation

The long pulse operation also has been attempted to be applied during the EAST 2016 Spring campaign. A fully non-inductive 102s plasma discharge has been sustained successfully by the synergy of LHCD and ECRH[17]. Fig. 13 shows the typical waveforms of ECRH power injected into LHCD target plasma (plasma current $I_p = 400$ kA, line-averaged density $n_{e,av} = 1.5 \times 10^{19} / m^3$), the loop voltage is maintained at zero. 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 75° respectively. The magnetic field on the axis was about 2.5 T, corresponding to the value for the cold 2nd harmonic resonance. Fig. 14 shows the central electron temperature is close to 5keV, which is measured by Thomson scattering diagnostics.

Fig. 13. Time evolution of the I_p , n_e , V_{loop} , ECRH power, LHCD (4.6 GHz) power, and LHCD (2.45 GHz) power for the 102s high T_e operation of EAST.

Fig. 14. The radial distribution of electron temperature for the 102s high T_e operation on EAST.

4.4 Application in H-mode experiments

The long pulse H-mode operation has been attempted to be applied during the EAST 2016~2017 campaign. The minute-long steady-state H-mode discharges on EAST have been realized in the EAST 2016 Autumn campaign [18]. A steady-state H-mode 101s plasma discharge has been sustained successfully by the synergy of LHCD, ICRF, and ECRH in the EAST 2017 Summer campaign.

Fig. 15 shows the typical waveforms with ECRH power injected into target plasma (Shot #73999, $I_p=0.4\text{MA}$, $B_t=2.5\text{T}$, $\text{PRF}=3.0\text{MW}$, $n_e=3.0\times 10^{19}/\text{m}^3$, $T_e=4.0\text{KeV}$, $H_{98y2}=1.1$, USN).

EAST successfully implements the H-mode with small disturbance amplitude edge local mode (ELMs) under conditions of low momentum injection of pure RF heating, tungsten diverters. A fully non-inductive steady-state high-performance plasma with a constrained improvement factor of H_{98y2} greater than 1.1 was obtained, and a soft landing of the plasma operation was achieved through precise control of the advanced magnetic configuration.

Fig. 15. Time evolution of key signals for the 101s H-mode operation of EAST.

The performance degradation in an electron heating dominant H-mode plasma after ECRH termination in EAST was found [19].

As shown in Fig. 16, the stored energy (W_{MHD}) drops after ECRH termination. The reason for the energy confinement degradation may be the shift of LHW power deposition from a central region with lower

diffusivity to a peripheral region with larger diffusivity after ECRH termination[19]. The feedback mechanisms are shown in Fig. 17.

Fig. 16. Time evolution of key signals of the shot # 67256.

Fig. 17. Feedback mechanisms based on parametric dependences of LHW deposition.

4.5 Low loop voltage start-up experiments

We have tried to do the low loop voltage start-up experiments. A experiment results are shown in Fig. 18, With the pre-ionization by ECR and LHW, the minimum central toroidal electric field can be reduced to $\sim 0.16\text{V/m}$.

Fig. 18. Time evolution of key signals for low loop voltage start-up experiments.

4.6 Operation reliability of No.1 system

The gyrotron reliability is an important issue for long pulse plasma operation. The first short pulse EC wave injection using No. 1 gyrotron has been demonstrated successfully during the EAST 2015 Spring campaign. The discharge success rate of this gyrotron is good in the 2015 experiments and in the beginning of the 2016 experiments. Then, the reliability decreased in the first half of 2016 experiments which is shown in Fig.19. There may be some damage inside the gyrotron. In order to solve this problem, we tried to make low-power, improve conditioning and optimize the operation region. Now, the reliability of No. 1 gyrotron is good for 300 kW~500 kW output power.

Fig. 19. The #1 gyrotron reliability when it is following EAST experiment.

5. Future plan

In order to explore high $\beta_N(>2)$ H-mode operation shown in Fig.20 on EAST, #1 system will be upgraded to dual frequency (140/105GHz) mode to fit low B_T (2.5T→1.9T) operation.

For the purpose of upgrading the No.1 gyrotron to dual frequency operation, the collector, mirrors system and electron gun of #1 gyrotron will be upgraded, slight modification of transmission line is required. The parts that need to be upgraded are marked in red fonts in Fig.

21. It is expected to deliver a power of 0.6MW/100s~1000s at 140GHz & 105GHz.

Fig. 20. The β_N in the relationship with internal inductance.

Fig. 21. The composition of the gyrotron, where the parts marked in red fonts are parts that need to be upgraded.

6. Conclusions

A long pulse ECRH system with a goal of 4MW 100~1000s has been developed for EAST, which comprises four 140GHz gyrotron systems. The 3MW system has been installed and partially tested, and long pulse operation of the system has been demonstrated successfully during the EAST 2016~2017 campaign. The remaining No. 4 CPI gyrotron will be ready to start testing in 2018 or 2019, and the whole system will be completed within two years. The 400s fully non-inductive H-mode operation would be expected in the next four years in the condition of fully tungsten divertor on EAST.

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