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EAST ion cyclotron resonance heating system for long pulse operation

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ABSTRACT

Radio frequency (RF) power in the ion cyclotron range of frequencies (ICRF) is one of the primary auxiliary heating techniques for Experimental Advanced Superconducting Tokamak (EAST). The ICRF system for EAST has been developed to support long-pulse high-β advanced tokamak fusion physics experiments. The ICRF system is capable of delivering 12 MW 1000-s RF power to the plasma through two antennas. The phasing between current straps of the antennas can be adjusted to optimize the RF power spectrum. The main technical features of the ICRF system are described. Each of the 8 ICRF transmitters has been successfully tested to 1.5 MW for a wide range of frequency (25–70 MHz) on a dummy load. Part of the ICRF system was in operation during the EAST 2012 spring experimental campaign and a maximum power of 800 kW (at 27 MHz) lasting for 30 s has been coupled for long pulse H mode operation.

1. Introduction

The research objectives of EAST are to perform advanced tokamak research in high performance regime and to explore methods for achieving a steady-state operation for a tokamak fusion reactor. EAST is a fully superconducting tokamak ($R = 1.75$ m, $a = 0.4$ m, $B_t = 3.5$ T, pulse length ≤ 1000 s) at ASIPP. Since the first plasma in 2006, significant progress has been achieved [1–3]. Radio frequency (RF) power in the ion cyclotron range of frequencies (ICRF) is one of the primary auxiliary heating techniques for EAST. With a frequency range of 25–70 MHz, the ICRF system on EAST provides plasma heating and current drive through various scenarios over a range of magnetic fields.

The main goals of the EAST ICRF program are the following: (1) coupling issue with different plasma edge; (2) heating and plasma flow generation with different scenarios; (3) current profile control by on-axis and off-axis heating schemes for electrons and ions; (4) technology of ICRF hardware and launching systems aiming at long pulse operation; (5) to investigate the combination of ICRH and LHCD for high performance long pulse plasma discharges. To achieve these research goals, a 12 MW long pulse and wide frequency range RF system has been designed and constructed. Fig. 1 shows the variation of ion cyclotron resonance frequency of various ion species across the plasma radius. Some typical ICRF scenarios on EAST are as follows: (1) $f_{RF} = 37$ MHz, $B_{t0} = 2.5$ T: H minority heating in D majority plasma; (2) $f_{RF} = 27$ MHz, $B_{t0} = 2.5$ T, ^{3}He minority heating in D majority plasma; (3) $f_{RF} = 27$ MHz, $B_{t0} = 3.0$ T D-^{3}He mode conversion heating in D majority plasma for electron heating.

The ICRF system is designed to operate at any frequency from 25 to 70 MHz. The phases between the antenna current straps are adjustable. Two antennas based on different designs have been developed and fabricated. The main technical features of this RF system are described in Section 2 and recent activities and summary are reported in Section 3.

2. The main technical features of the ICRF Systems on EAST

In order to satisfy the requirements of heating on EAST, a 12 MW ICRF system with long pulse operation at megawatt levels in a frequency range of 25–70 MHz has been designed as a part of the research and development (R&D) for EAST. Part of the ICRF system (6 MW) has been operating in the 2012 experimental campaign. The other 6 MW system will be available for the 2014 experimental campaign. The RF transmitters of 12.0 MW have tested in a matched

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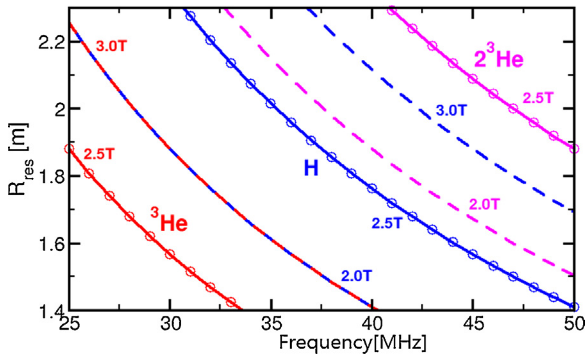

Fig. 1. Cyclotron resonance frequencies of various ion species across the plasma radius vs. magnetic field. All expected scenarios will lie below 50 MHz.

Table 1
The design feature of ICRH system.

RF output power	12.0 MW
Frequency range	25–70 MHz
Operation mode	Continuous wave (CW)
Transmission line	9 in. coaxial transmission line, water cooled
Matching system	Triple liquid stub tuners, water cooled
Antenna	A two-strap antenna and a four-strap antenna, water cooled

dummy load where an RF output power of 1.5 MW was achieved in the designed frequency range.

The design features for EAST ICRF heating system is shown in Table 1.

The ICRF system includes RF transmitters [4–6], transmission lines, matching systems [7], feedthroughs [8], antennas [9–11], and antenna loading measurement units, and data acquisition units, high voltage power supplies, phase shifters, and DC breakers. Each of these units is designed for continuous wave (CW) operation. Fig. 2 shows the view of the 12 MW ICRF transmitter system.

2.1. RF power amplifiers

There are eight RF transmitters in the ICRF system. A block diagram of ICRF system with four RF transmitters is shown in Fig. 3. The RF transmitter units are shown in the section enclosed by the red dashed line. Each transmitter system includes an amplitude and frequency control and monitor unit, an RF power amplifier chain, a direct current (DC) high voltage power supply (HVPS) [12,13] and a cooling system. Each stage of the ICRF system has built-in sufficient water cooling and can be run in the continuous wave (CW) mode.

Fig. 2. View of 12.0 ICRH system In EAST ICRF hall.

Each RF power amplifier chain consists of a low power part and a high power part. The low power part is composed of a phase and amplitude controller (PAC), a computerized waveform generator, and an RF switch. The PAC has four RF output ports each designed to produce a 20-mW (13 dBm) RF signal with an adjustable phase shift from 0° to 360°. The waveform generator produces a desired reference pulse waveform. The RF switch in the amplifier chain to cut off RF power immediately as soon as the fraction of the reflected power has been detected to exceed a specified value. The high power part includes a three-stage RF power amplifier chain (Fig. 4), i.e. a 5 kW-stage broadband solid state amplifier (SSA), a 100 kW-stage tetrode (Thales TH535) driver power amplifier (DPA) and a 1.5 MW-stage tetrode (Thales TH525) final power amplifier (FPA), which is tunable from 25 MHz to 70 MHz. The gains of the SSA, DPA and FPA are approximately 46 dB, 14 dB and 13 dB, respectively. In order to protect the components of the amplifier and to achieve a stable operation of the transmitter, the DC HVPS for tetrodes are based on pulse step modulation (PSM) technology because of its great advantages, such as fast response, low short-circuited energy, and flexibility.

RF transmitter tests were conducted with a matched dummy load over a frequency range from 24 MHz to 70 MHz in the step of 1 MHz. Fig. 5 shows the test results of three transmitters. The maximum RF output power of ∼1.5 MW has been achieved from 25 MHz to 65 MHz with efficiency varying from 60% to 70%. The gains of about 14 dB and 13 dB were obtained for the DPA and the FPA, respectively. At $f_{RF} > 65$ MHz, both RF output power and

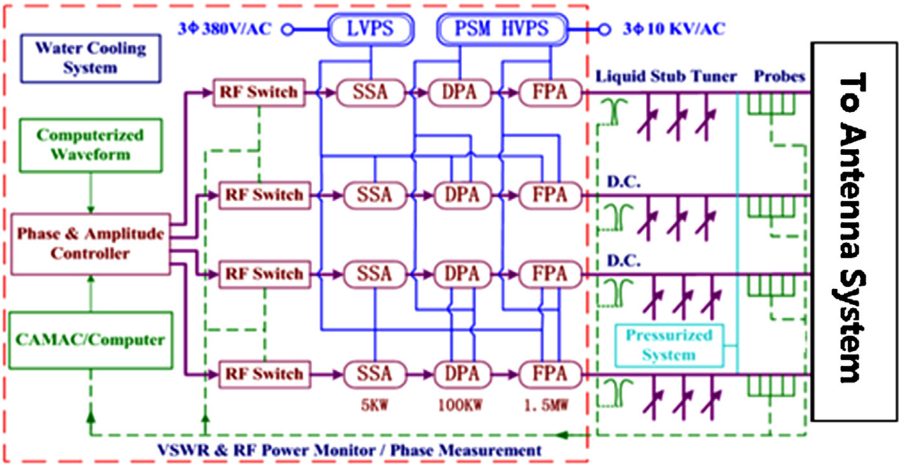

Fig. 3. Block diagram of the ICRF system on EAST.

Fig. 4. View of DPA and FPA of 1.5 MW.

efficiency of the transmitters decrease rapidly because of the limitation of operational bandwidth of tetrode tubes.

2.2. The transmission line and RF matching system

The transmission line size is 9 in. to satisfy high power transfer from the transmitter to the antenna, as shown in Fig. 6. The outer conductor diameter is 230 mm, and the inner conductor diameter is 100 mm. The characteristic impedance of the line is 50 Ω. Both the inner and outer conductor can be cooled by the pure water to achieve CW operation. DC breakers [14] are used to isolate the grounds between RF transmitters and antennas. The VSWR monitoring system was used to protect ICRF system. A pressurization system is employed for our transmission line. Dry nitrogen gas is filled between inner and outer conductor. In our case, gas pressure is 3 atm as usual and the voltage standoff is about 40 kV.

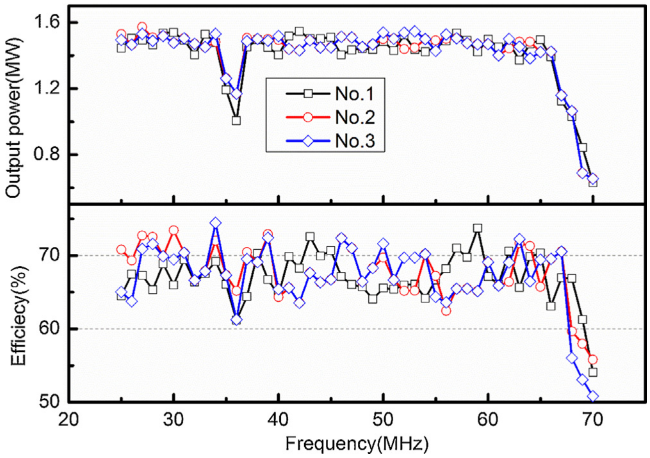

Fig. 5. High power tests of the RF transmitters from 24 MHz to 70 MHz. The frequencies in rf power drop are at 35 MHz and 36 MHz. This power drop was caused by the output circuit of rf final power amplifier. The stated efficiency is HV-RF.

There are eight sets of triple liquid stub tuners for the EAST 12 MW ICRF system. A schematic diagram of a liquid stub tuner is shown in Fig. 7(a) and a picture of three such pairs is shown in Fig. 7(b). The liquid stub tuner is a short-circuited coaxial transmission line with variable length. A liquid stub tuner can avoid the damage associated with the metal contact fingers of a conventional stub tuner [7]. It utilizes the differences of the radio frequency wavelength in gas and in liquid due to the different relative dielectric constants. The liquid (silicone oil) is filled between the inner conductor and the outer conductor. The parameters of this matching system can be varied by controlling the liquid level using a pump. The liquid stub tuner works more reliably than a conventional system because there is no mechanically moving part. The inner and outer conductor of the liquid stub tuner can be cooled by pure water for CW operation.

2.3. ICRF antenna systems

As can be seen in Fig. 5 of Ref. [15], two antennas based on different designs have been developed and fabricated in EAST. In order to

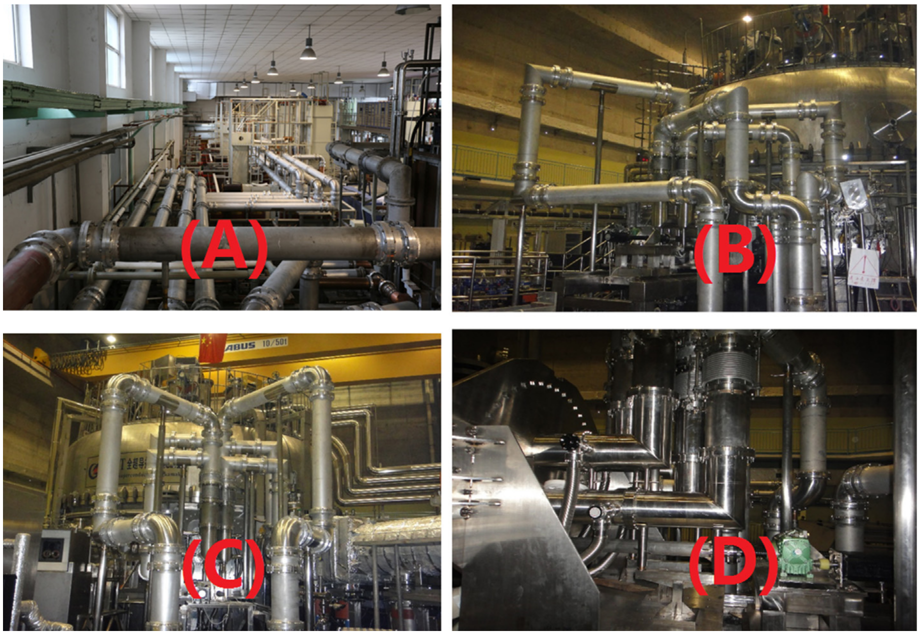

Fig. 6. View of the transmission lines: (A) in the ICRH hall; (B–D) in the EAST hall.

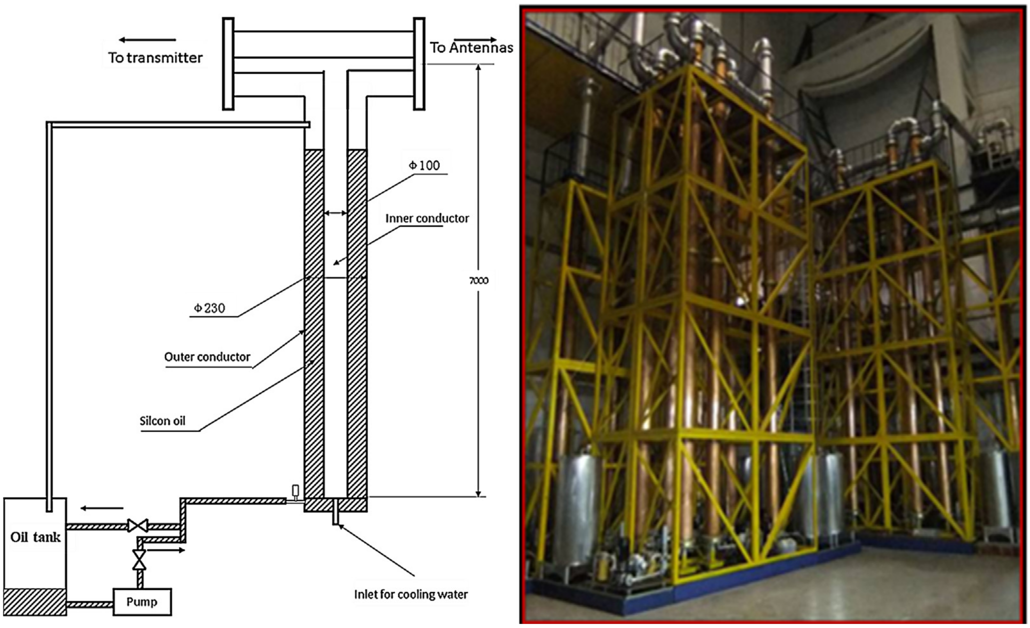

Fig. 7. The triple liquid stub tuners: (a) the diagram of liquid stud tuner; (b) the view of the matching system.

reduce the effect of RF sheath on LH coupling [16], the ICRF antenna at I port has been coated with B4C and installed at B port. A 4-Strap antenna instead of O port antenna has been installed at I ports. Phases between the straps are controlled 0–360° in the low power parts of the RF system. A vacuum feedthrough is chosen to separate the vacuum. Independent water channels are installed to cool the inner conductor of the feedthrough. The vacuum transmission lines (VTL) consist of eight coaxial lines whose diameter is 8-in. Its characteristic impedance is 50 Ω. VTL has a water cooling channel inside the central conductor.

For long pulse operation, the antennas have many cooling channels inside the current straps, cavity wall, Faraday screens and vacuum transmission lines. The cavity wall provides the cooling water path to the Faraday shield tube. The strap has cooling channels along both edges. The current straps are located 10 mm from the back surface of the Faraday screen. The front surface of the Faraday screen is located 5 mm from the limiter. The material of the strap is stainless steel 316L, with the edge of the strap rounded to reduce the electric field strength. The Faraday screen is designed as water cooled and single layered tube. The material of the tube is also stainless steel 316. The Faraday screen of the B-port antenna consists of 42 tubes. Each of the two sections is cooled in series. The faraday screens are coated by B_4C to reduce the impurity radiation during the high power ICRF heating. In order to adjust the coupling of the antennas to plasma, the antennas can be moved slightly in radial direction.

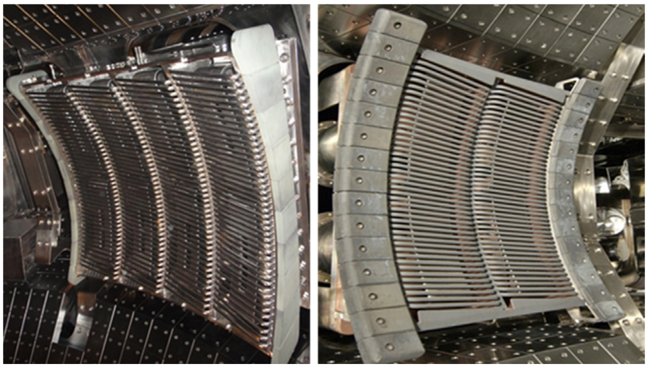

Fig. 8. The ICRF antenna systems: four-strap antenna at I-port (left) and two-strap antenna at B-port (right).

The ICRF antenna at B port (Fig. 8 (right)) is grounded at the center and has a coaxial feed line connected to each end of the current strap. The length of the current straps that couple power to plasma is 700 mm. The ICRF antenna at I-port has four current straps. The antenna straps are end-grounded center-fed folded design as shown in Fig. 8 (left). The length of the current straps is 750 mm. Four 1.5 MW RF transmitter are connected to each antenna. Phases between the straps are controlled in the low power parts of the RF system.

3. The ICRF heating experiments in EAST

The performance of ICRF heating has progressed steadily in the EAST [17]. Initial ICRF experiments started in 2010 [18,19]. A

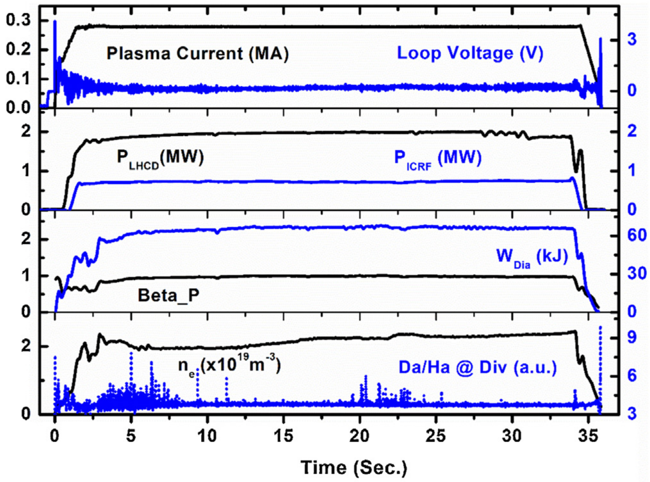

Fig. 9. Long-pulse H-mode over 32 s achieved in EAST 2012 campaign with combined LHCD and ICRH.

6.0 MW ICRF system has been operating since the 2012 experimental campaign. During the last two experimental campaigns, ICRF experiments were carried out at the fixed frequency of 27 MHz, achieving effective ions and electrons heating with the H minority heating (H-MH) mode. The H-MH heating method has had the best plasma performance, and has helped achieve H-mode by ICRF alone in 2012 [20]. The first successful application of the ICRF heating in the D (He3) plasma was also achieved in this campaign [17].

4. Summary

Great efforts have been made to develop the key technologies for long pulse high power operation of the ICRF system on EAST. The antennas and transmitters for long pulse and high power operation have been developed. Vacuum feedthroughs, transmission lines and matching components for long pulse high power operation are under construction and they will be available in 2014.

In conclusion, a 12.0 MW ICRF system at 25–70 MHz has been successfully commissioned at full power on water dummy load. An averaged maximum RF output power of 1.5 MW for each transmitter has been achieved in a frequency range of 25–65 MHz with an efficiency varying from 60% to 70%. During the 2012 experimental campaign, the ICRF system has been operated at total power up to 800 kW for 30 s on long pulse H mode plasma in EAST [21,22] (Fig. 9). Another 6 MW ICRF system is available for next campaign. As a result, the ICRF system will have a capability of delivering more than 10 MW of RF power to the plasma for long pulse length up to 1000 s.

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