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EAST ion cyclotron resonance heating system for long pulse operation

Y.P. Zhao [a], X.J. Zhang [a,*], Y.Z. Mao [a], S. Yuan [a], D.Y. Xue [a], X. Deng [a], L. Wang [a], S.Q. Ju [a], Y. Cheng [a], C.M. Qin [a], G. Chen [a], Y. Lin [b], J.G. Li [a], B.N. Wan [a], Y.T. Song [a], F. Braun [c], R. Kumazawa [d], S. Wukitch [b]

[a] *Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China*
[b] *MIT Plasma Science and Fusion Center, Cambridge, MA 02139, USA*
[c] *Max-Planck Institute for Plasma Physics, D-85748 Garching, Germany*
[d] *National Institute for Fusion Science, Toki 509-5292, Japan*

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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 $\leq$ 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

* Corresponding author. Tel.: +86 55165592846.
E-mail address: xjzhang@ipp.ac.cn (X.J. Zhang).

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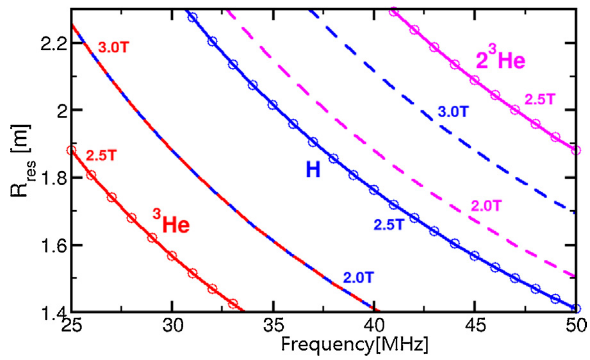

Fig. 1. Cyclotron resonance frequencies of various ion species across the plasma radius vs. magnetic field. All expected scenarios will lie below 50 MHz.

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

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.

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

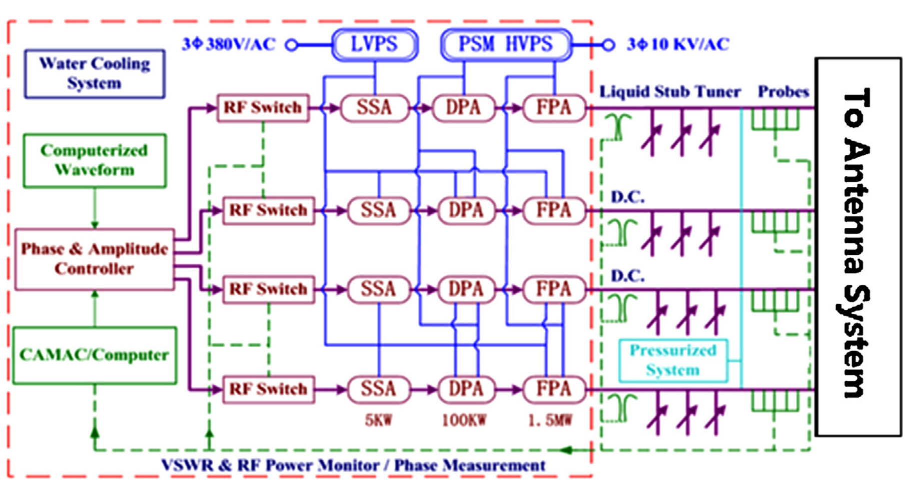

Fig. 3. Block diagram of the ICRF system on EAST.