Physics and Engineering Aspects of the ICRF Heating System on EAST

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Abstract: Radio frequency (RF) power in the ion cyclotron range of frequencies (ICRF) will be one of the primary auxiliary heating techniques for Experimental Advanced Superconducting Tokamak (EAST). The ICRF system provides 6 MW power in primary phase and will be capable of 10MW later. Three 1.5 MW ICRF systems in the range of 25-70 MHz have been put into operation during the EAST 2010 spring campaign. The ICRF launchers are designed to have two current straps and each strap is driven by an independent 1.5MW RF power source. Maximum of the injected RF power reached to1.6MW on the EAST tokamak during 2010 spring campaign. This paper gives brief introduction of the EAST ICRF system capability and especially first primary results on the EAST tokamak during 2010 spring campaign.

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 = 1.75m, a = 0.4m, Bt = 3.5T, pulse length <= 1000 sec) being commissioned at ASIPP. Since the first plasma in 2006, much significant progress has been achieved [1, 2]. Radio frequency (RF) power in the ion cyclotron range of frequencies will be one of the primary auxiliary heating techniques for EAST. The ICRF system will provide more than 6 MW power coupled to the plasma before 2011 campaign and will be capable of 10MW of RF power to the plasma.

ICRF system has been designed to operate in the range of 25-70MHz and operate for long pulse length up to 1000s. The main objectives of EAST ICRF are: 1) to study coupling issue with different plasma edge; 2) to study heating and plasma flow generation with different scenarios; 3) to study profile control by on-axis and off-axis heating schemes for electrons and ions; 4) to study the technology of ICRF hardware and launching systems; 5) to investigate combination of ICRH and LHCD for high performance regime for long pulse plasma discharges. The Heating scenarios for EAST are analyzed by using a parallel version of TORIC, a finite Larmor radius ICRF code [3].

Figure 1 shows the variation of cyclotron resonance frequency of various ion species across the plasma radius. The ICRF heating scenarios for EAST are as follows:

1. H minority heating in D majority plasma. The frequency of 37MHz is good for H minority with 2.5T of the magnetic field.

2. Helium 3 minority heating in D majority plasma. The frequency of 27MHz can be used with 2.5T of the magnetic field.

3. D-Helium 3 mode conversion heating in D majority plasma. The frequency of 26MHz with 3.0T may be possible for the electron heating by using mode conversion.

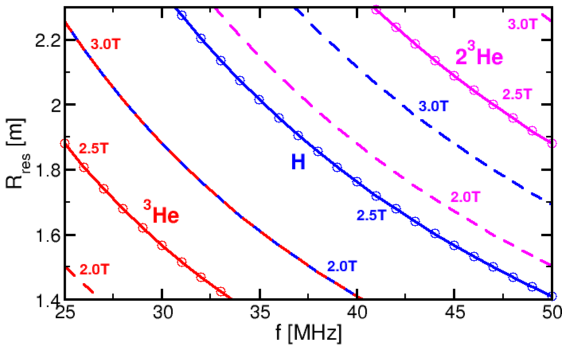


Figure 1 Variation of Cyclotron resonance frequencies of various ion species across the plasma radius

2. The main technical feature of ICRF Systems on EAST

There are four ICRF systems on EAST. Three 1.5MW ICRF systems have put into operation and another 1.5MW ICRF system is under way of construction. ICRF system includes High-power and wide-frequency radio amplifier, the phase shifter system, the matching system and the 2-straps antenna.

The transmission line size is 9 inch. The characteristic impedance is 50 Ω. The dry nitrogen gas is filled at the pressure of 3 atm between inner and outer conductor. In order to satisfy the CW operation the inner and outer conductor can be cooled by the pure water. DC breaker has been used in order to isolate the grounds between RF transmitter and the antenna. The matching system consists of three stub tuner. There are four triple liquid stub tuners for EAST 6.0 MW ICRF heating system. Phase between the straps is controlled in the low power parts of the RF system. The ICH launcher is designed to have two current straps and each strap will be driven by an independent 1.5MW RF power source. Three 1.5 ICRF systems have been employed for RF heating experiment on the EAST during 2010 spring campaign. Maximum of the injected RF power reached to 1.6MW on EAST during 2010 spring campaign.

RF amplifier

Three are four RF transmitters to output RF power up to 6.0MW. Each transmitter can have 1.5MW output, and the range of the RF frequency of three transmitters can be changed from 25 MHz to 70MHz. Another 1.5MW transmitter is from 30MHz to 110MHz. The transmitters have ±2MHz -3db working bandwidth. The diagram of the transmitter is shown in Figure 2. The system includes RF generator, waveform controlling, pre power amplifier, control and protection system, high voltage power supply, and two stages high power amplifiers.

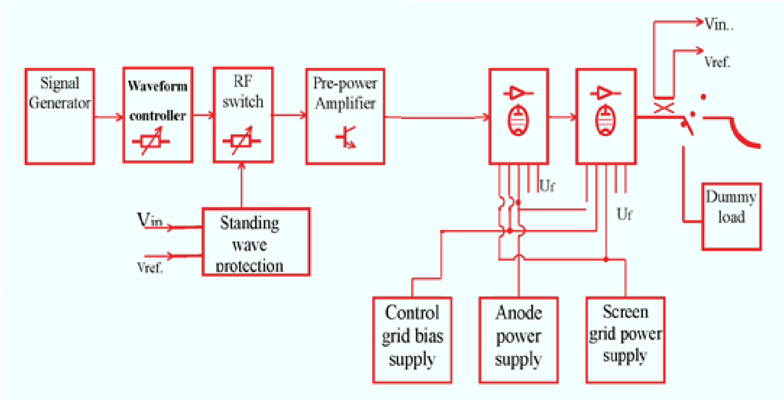
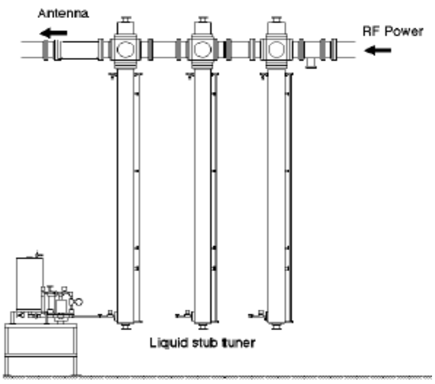


Figure.2 1.5MW RF amplifier

The waveform controlling system based on a computer control has an ability to control RF transmitter to output the arbitrary waveform and to change the RF frequency quickly. The pre power amplifier is a wide-band transistor amplifier. The output RF power is around 5kW.The powerful tetrodes (TH525 and TH535) are used for high power amplifiers. Each amplifier can output 100kW and 1.5MW separately.

The RF matching system

There are four triple liquid stub tuners for EAST 6.0 MW ICRF heating system. A schematic diagram of a liquid stub tuner is shown in Figure 3a.Figure 3b is shown the triple liquid stub tuners of EAST ICRF System. It utilizes the difference of radio frequency wavelengths in gas and in liquid due to the different relative dielectric constants. The liquid (i.e. oil silicon) is filled between inner conductor and outer conductor. By using a pump to control the liquid level, the parameters of this matching system can be changed. Due to the CW operation, the inner and outer conductor of the liquid stub tuner must be cooled by pure water. The maximum length and the diameters of the inner and outer conductor of the liquid phase shifter are 740mm, 100mm and 230mm respectively.



(a)

(b)

Figure.3 liquid phase shifter

ICRF Antenna systems

There are two ports for ICRF in EAST, as shown in figure 4. The phase between the current straps can be change in 0-360. For long pulse operation, the antennas have many cooling channels inside the current strap, cavity wall, the faraday screen and vacuum transmission line. In order to adjust the coupling of the antenna to plasma, the antenna can be moved a little in radial direction. The current straps located 10mm from the back surface of the Faraday screen. The front surface of the faraday screen is located 8mm from the limiter. There are two current straps per antenna arranged in a toroidal array. They are spaced with the gap of 14.2cm. The each current strap is 108mm wide and 10mm thick, and its edge is rounded to reduce the electric field strength around the current straps. The polodially curvature of the current strap is 767mm. The material of the strap is stainless steel 316L. The faraday screen is designed as water cooled and single layered tube. The material of the tube is also stainless steel 316. Each of two screens consist 42 tubes. There are four 8 inch vacuum transmitter lines (VTL), vacuum feedthroughs for I port and two 8 inch for O port. Its characteristic impedance is 50Ω.

The EAST ICRH systems consist of two port-mounted antennas that have two current straps, each of which at I port is grounded at the center, and have a coaxial feed line connected to each end of the current strap Fig4/5(left). After going through two vacuum feedthroughs, the top and bottom coax feed lines of each current strap are connected to each other in a resonant loop configuration. The length of the current strap that coupled power to plasma is 700mm. The antenna at O port are folded, end grounded with a central current feed, as shown in Fig4/5 (right). The length of the current strap is 750mm. A 1.5MW RF transmitter is attached to the antenna through a matching system. The matching system consists of three stub tuner. Phase between the straps is controlled in the low power parts of the RF system.

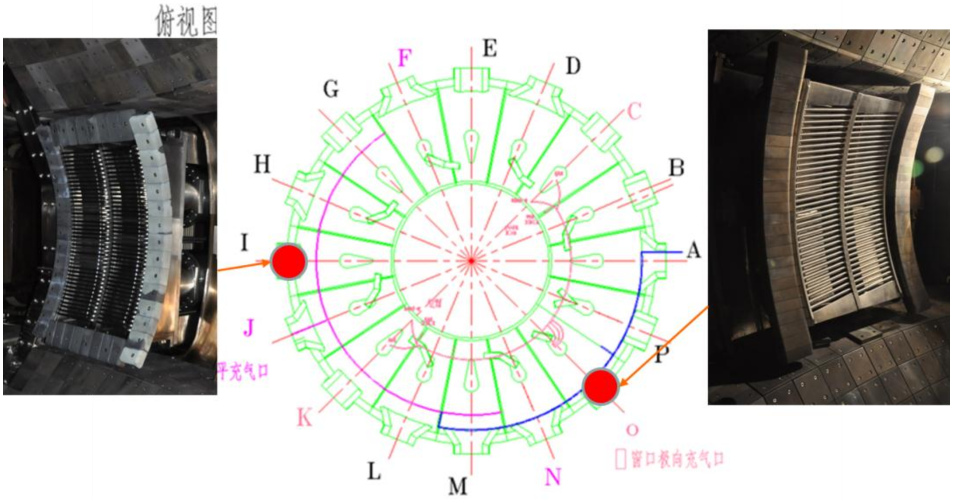


Figure 4 the ICRF Antenna system on EAST

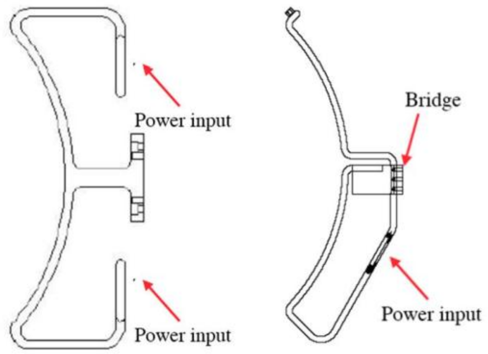


Figure 5 Current strap of I port 2-strap antenna (left) and O port 2-strap antenna (right)

3. Modeling by using The TORIC Code

Numerical calculations of ICRF heating scenarios for H Minority heating with 2.5T and 37MHz and Helium 3 Mode Conversion heating with 3.0T and 26MHz in D plasma have been perform for a single toroidal mode number 23 by using global wave code, TORIC[3]. The main parameters for study are as follows.

$\mathrm{ne}(0) = 4.0\mathrm{e}+13cm^{-3}$,$\mathrm{T}_i(0) = \mathrm{T}_e(0) = 1.2\mathrm{keV}$,$\mathrm{T}_i(\mathrm{sep}) = \mathrm{T}_e(sep) = 0.2\mathrm{keV}$

H Minority Heating in D plasma: $\mathrm{f}_{rf} = 37\mathrm{MHz}$ and $\mathrm{B}_0 = 2.5T$,

D − 3HeMode Conversion Heating: $\mathrm{f}_{rf} = 26\mathrm{MHz}$ and $\mathrm{B}_0 = 3.0T$

The density and temperature are assumed to have parabolic profiles inside the separatrix:

$$n_e(\rho) = \left(n_0 - n_{sep}\right)(1-\rho^2)^{0.5} + n_{sep}\ \ ,\mathrm{T}_e(\rho) = T_e(0)(1-\rho^2)^1$$

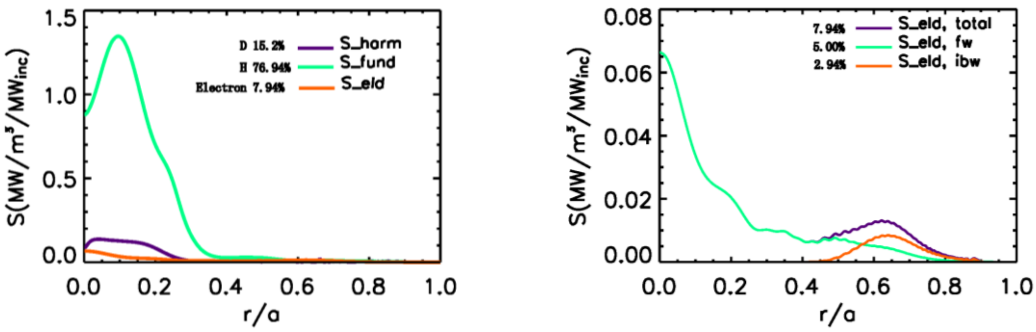


Figure 6 the radial power deposition profiles for 3% H minority heating in D plasma

Fig6 displays the power deposition profiles of the plasma species for 3% H in 97% D plasma. Over 92.1% of total absorbed power is going to plasma ions through the fundamental cyclotron resonance of H and the second harmonic resonance of D with P_H=76.9% and P_D= 15.2%. The rest is absorbed by electrons through ELD and TTMP or by mode-converted IBW with P_e =7.9% and P_{IBW}=2.9%. This is clearly seen in Figure 6 as the on-axis heating profile of H ion.

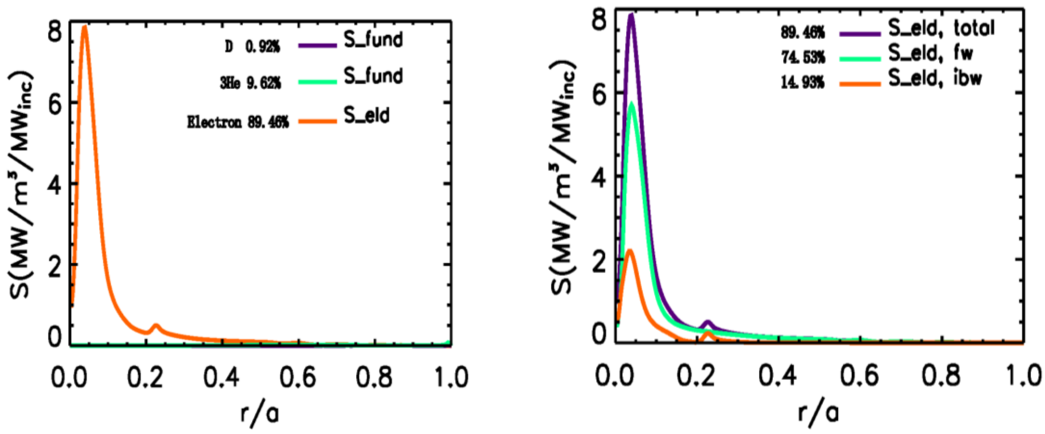


Figure 7 Radial power deposition profiles for 20%Helium3 Mode Conversion Heating in D plasma

In mode conversion heating scenarios in D majority plasma with Helium 3 minority, fast wave are mode converted to short wavelength waves. The Ion-ion hybrid resonance layer is between Helium 3 and D ions and located at the plasma center with Helium 3 concentration of ~20%. These waves damp strongly on electrons, giving rise to electron heating on the shorter time scale of electron-electron collisions, as is shown in figure7. The power partition among the absorbing species was as follows: the absorbed RF power due to fast wave and mode conversion electron heating in figure7 is 89.46%.The fast wave power is absorbed via fundamental ^{3}He cyclotron damping is 9.62%. The remaining 0.92% of the power is absorbed via fundamental Deuterium cyclotron damping on the tokamak high field side.

4. Experiments setup

The first ICRF experiments have been carried out by using the Helium 3 minority heating scenarios with Helium 3 gas puff at 2.0s, RF turn on at 2.5s and RF turn off at 3.1s. The frequency is 26 MHz at 2.6T and the antennas of O port are used. RF power up to 1.6MW is delivered to the LHW heated plasma, however no changes in T_e are observed with RF injection during those shots, as can be found in figure8 before and during the phase of ICRH. From figure 9, which shows the time evolution of the Kα intensities of all the medium-Z elements, one can see when the ICRF was switched on the line emissions of the metallic impurities immediately increased. After the ICRF was switched off, these metal line emissions rapidly decreased to a much lower level till the end of the discharge. One possible reason is that there are fewer metallic impurities in the LHW heated plasmas than in the ICRF–LHW plasmas.

There is too much Hydrogen in the plasma during this campaign. H-^{3}He hybrid layer, which located in the plasma edge or at low field side, originates from the hydrogen layer due to the high H concentrations. In order to increase the ICRF coupling, we intentionally tried gas puffing with different time scales; however, the heating effect was not clear. The front antenna surface is a D-shape and the plasma is also a D shape, however, the distance between the current strap and the last closed flux surface is too much longer (9 cm) so that the RF coupling is very low. Another reason is that the single pass absorption is very much lower during this campaign. So we see no response in plasma and small increase in impurities. We expect the heating effect to be clear for the autumn campaign by upgrade the following things such as reducing H concentrations, shortening the distance between the antenna and the last close flux surface and starting with higher plasma parameters and good confinement.

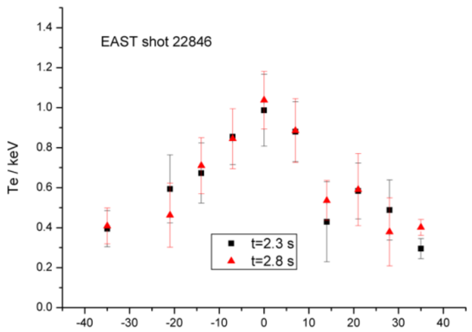


Figure 8 the radial profile of the electron temperature

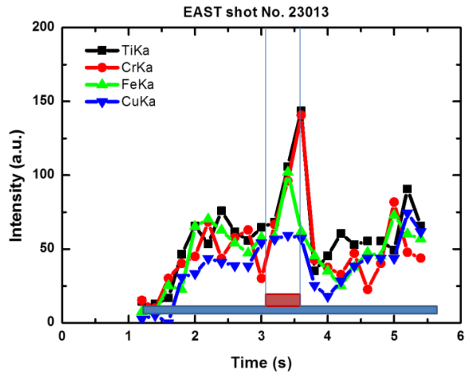


Figure 9 Time traces of Kα intensities emitted from Ti, Fe, Cu and Cr.

5. Conclusions

We presented the brief introduction of the EAST ICRF system capability. Since 2006, the EAST ICRF system has been designed and fabricated. Three 1.5MW ICRF systems have put into operation in 2010 spring campaign. Up to a 1.6MW RF power was coupled to the D shape plasma with O port antenna. Based on the first experimental campaign, we expect the ICRF experiments to be better for the 2010 autumn campaign by shortening the antenna plasma distance and reducing Hydrogen concentrations on the shaped plasmas starting with higher plasma parameters and good confinement.

Acknowledgments

We are grateful to the EAST operation and diagnostics group. This work was supported by the ITER Relevant Foundation in China (Grant No 2010GB110000). This work is supported partly by the National Natural Science Foundation of China under Grant No. 10928509 and by the Knowledge Innovation Program of the Chinese Academy of Sciences No. Y05FCQ0126.

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