Heating and Confinements by the waves in the Ion Cyclotron Range of Frequencies on EAST

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Abstract:
The paper summarizes the recent experiments performed with Ion Cyclotron Resonance Heating (ICRH) on EAST. Heating and confinement studies using the Hydrogen Minority Heating scheme have been investigated in Ohmic target plasma and in combination with Low Hybrid waves. The experimental results show that local gas injection and reducing the $k_{||}$ improves the coupling efficiency directly. But the ICRF heating efficiency is rather low on EAST. And the Energy Confinements follow Scaling Law. The results show a typical L-mode behavior, i.e. a power dependent confinement degradation. L-mode data agree with ITER98P scaling. Particular efforts have been devoted to investigations of the interaction of ICRF waves with fast ions injected by Neutral beams. Third harmonic ion cyclotron resonance heating of D-beam ions have been achieved for the first time on EAST.

1 Introduction

Experimental Advanced Superconducting Tokamak (EAST) [1-3], a fully superconducting tokamak with divertor configurations, aims to perform long pulse high-performance plasma operation and explore the physics and technology associated with steady-state operation for next-step fusion devices. Since last IAEA FEC, EAST has been upgraded with all ITER-relevant auxiliary heating and current drive systems, enabling the investigation of plasma profile control by coupling/integration of various combinations [4]. RF waves in the Ion Cyclotron Range of Frequency (ICRF) is one of the primary auxiliary heating
techniques on EAST. An overview of the EAST ICRF system is giving in [5]. Lithium wall conditioning was routinely used to reduce both impurity and hydrogen (H) recycling and to improve the ICRF power absorption [6-7]. On EAST, the most commonly used scenario is fundamental heating of a hydrogen minority in a D majority plasma. For this heating regime, ICRH can create high energy H ions, which Coulomb collisionally slow down on electrons, giving rise to strong electron heating. ICRF power of up to 3.3MW has been coupled into plasma[8]. First H-Mode plasmas have been achieved by ICRH alone with this heating regime on EAST[9].

Existing tokamaks such as EAST and future experiments like ITER employ both Neutron Beam Injection (NBI) and ICRF heating for auxiliary heating and current drive. On EAST, NBI and ICRF are usually combined in experiments requiring a large amount of heating power. Earlier experiments with ICRF heating plus NBI heating were performed on PLT [10]. Combined hydrogen NBI heating and second-harmonic ICRF heating was investigated in JFT-2M [11] and in ASDEX [12]. Enhancement of the beam induced high energy tail was not observed in these experiments. Beam acceleration by third harmonic ICRF heating was observed in JET [13]. Here, we report the initial results of the experiments from third harmonic heating of ICRF on EAST.

This paper will present a review of the recent results from ICRF experiments on EAST. After a short review of the EAST ICRF system, we address the coupling, the heating and confinements behavior during the application of ICRH. Further we will report the observation of first experiments of third harmonic heating of ICRF on EAST. Finally, a summary is given.

2 EAST ICRF system for long pulse operation

The EAST ICRF system has been developed to support long-pulse advanced tokamak fusion physics experiments. The source power of the ICRF system is 12.0 MW in total. The range of ICRF frequency is from 25 MHz to 70 MHz. The ICRF system includes RF transmitters, transmission lines, matching systems, feedthroughs, antennas, 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 operation. Each of the 8 ICRF transmitters at 25-70 MHz has been successfully commissioned at full power on water dummy load[5]. 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%.

The ICRF system consists of two antennas, each delivering 6.0 MW of power. One antenna is a two toroidal, two poloidal strap (B-port) antenna and the other is a four strap, folded strap (I-port) antenna. For B-port antenna[5], each strap is powered by one transmitter. Each poloidal pair at one toroidal location are phased at 180 and each toroidal pair is typically operated at [0, π] phasing. For the I-port antenna[5,14], each toroidal strap is powered by a single transmitter and can be phased relative to the other straps. During the 2012 experimental campaign, the ICRF system has been operated at total power up to 800 kW for 30s on long pulse H mode plasma on EAST[15].
3 Study of the ICRF coupling in Ohmic target plasma

One of the importance challenges for EAST ICRH experiments is coupling higher power into the core plasma. The coupling of ICRF waves relies on the tunneling of the fast wave between the antenna structure and the cut-off layer within the plasma. The experimental antenna loading is calculated from the input ICRF power measured by directional couplers and the maximum of the voltage in the transmission line measured by voltage probes. The antenna loading are calculated separately for each strap of each antenna. Here the mutual coupling between the straps are neglecting. Local gas puffing and antenna phasing scanning are been tested to improve ICRF coupling efficiency on EAST. The experimental results show that local gas injection and reducing the $k_{||}$ improves the coupling efficiency directly.

3.1 The ICRF antenna loading

In order to study the ICRF coupling, Some important experiments including changing plasma position and electron density scanning have been performed. We change the gap between the limiter and the plasmas last closed flux surface. The antenna is fixed in dipole phasing. As is shown in Fig. 1, the coupling resistance decreases with the gap. The results show that widening the gap will increase the evanescent layer width and reduce the coupling efficiency. This is also confirmed by the electron density measured by microwave reflectomerty. Fig. 2 shows ICRF antenna loading increase with the line averaged density of the core plasma. This is because Increasing the central electron density is equivalent to pushing the position of the cutoff density to close to the antenna and reducing evanescent layer.

![Graph](image-url)  
**FIG. 1:** ICRF antenna loading versus gap between the limiter and the plasmas last closed flux surface.
3.2 Improving the ICRF coupling with low $k_{||}$ operation and gas puff

Experiments aiming at improving the coupling of the ICRF antenna have been carried out in EAST. The results from EAST show altering the antenna phasing from \((0, \pi, 0, \pi)\) to \((0,\pi,\pi,0)\) have a good effect on the coupling. This highlights that reducing the $k_{||}$ can improve the coupling efficiency directly. But ICRF heating efficiency also reduce with lower $k_{||}$. The good heating can be achieved in combined use of B-port ICRF antenna.

Local gas injection has recently been tested as a tool to improve coupling of ICRF waves on EAST. The influence of the gas injection in front of the antenna on the coupling resistance has been observed. The coupling resistance during gas injection experiment is higher than the coupling resistance without gas injection. The reason for this is because the density in the plasma edge is more higher with gas injection.

4 Hydrogen Minority Heating in Deuterium plasma

On EAST, lithium wall conditioning was routinely used to reduce both impurity and hydrogen recycling and to improve the ICRF power absorption. Thus, heating and confinement studies using the Hydrogen Minority Heating scheme can be investigated in the purely ICRF heated plasma.

4.1 Heating efficiency

The effective power absorbed by the plasma is determined with the procedure as shown in [16]. Fig. 3 is a summary plot of the absorption coefficients. Fig. 3 shows the dependence of ICRF heating efficiency versus the plasma density. But the ICRF heating efficiency is averaged 35%, rather low on EAST. One reason for this is because that the coupling of ICRF is not good for EAST target plasma. And thus the direct ICRF power loss in the
SOL can consume a significant fraction of the coupled power, leading to greatly reduce the core ICRF heating efficiency. We can see that the ICRF heating efficiency increase with the density. The preheating of LHW can also improve ICRF heating efficiency.

**FIG. 3: ICRF absorption efficiency**

### 4.2 Confinements of ICRH in L mode plasma

The confinement of purely ICRF heated plasmas has be studied on EAST. Fig. 4 summarizes the energy confinement times versus the ITER89-P empirical energy confinement time scaling[17]. The result of calculation shows that there is a good agreement with the result of the ITER89-P empirical scaling. Beside, the confinement times are normalized to those during the Ohmic phases in order to eliminate isotope effects. And we found that the energy confinement of ICRH essentially follow an L-mode scaling.

**FIG. 4: the energy confinement of ICRH in L mode plasma**
5 Beam acceleration by 3rd Harmonic ICRF Heating

Experiments on third harmonic deuterium damping of ICRF waves were carried out in deuterium plasmas, with a plasma current of 0.45MA and a toroidal field of 1.70 T. Up to 2.0MW of ICRF power were applied at a frequency of 35 MHz. In this configuration, the third cyclotron harmonic deuterium resonance layer of the majority ions is located at near the centre of the plasma. The first and second harmonic layers of hydrogen are marginally present in the scrape-off layer. On EAST, NBI and ICRF are usually combined in the experiments requiring a large amount of heating power. However, the RF power absorbed by the beam ions (deuterons) was small and no synergetic effect was observed because the minority heating regime was employed.

In the last campaign, particular efforts have been devoted to investigations of the interaction of ICRF waves with fast ions injected by Neutral beams. The experiment with combined deuterium NBI heating and deuterium third harmonic ICRF heating was performed. These experiments were carried out to study the relative importance of the various absorption mechanisms in deuterium plasmas with ICRF third harmonic heating in the plasma centre. In particular, the experiments were also aimed at assessing the strength of direct electron damping in EAST target plasma. Third harmonic ion cyclotron resonance heating of D-beam ions have been achieved for the first time on EAST. Significant beam acceleration was observed. The reason for this is because that ICRF wave can interact with the energetic beam ions. The presence of fast ions injected by NBI can result in absorption of ICRF power, as shown in Fig. 5.

![FIG. 5: Experimental Observations on beam acceleration with combined NBI heating and ICRF third harmonic heating on EAST.](image)

6 Conclusion and Summary

In summary, it has been shown that, on EAST, ICRH has proven to be a useful tool for heating. Experiments aiming at improving the coupling of the ICRF antenna have been carried out on EAST. Either reducing the gap or increasing the density can increase the
antenna loading. Local gas injection and reducing the $k_{||}$ can also improve the coupling efficiency directly. But reducing the $k_{||}$ have to sacrifice some heating efficiency of the ICRF. Heating and confinement studies using H minority heating regime show a typical L-mode behavior. The ICRF heating efficiency is averaged $35\%$, rather low on EAST. The heating efficiency can be improved when combined with the lower hybrid wave.

The initial experiments involving the interaction of ICRF waves with fast ions injected by Neutral beams are performed on EAST. Third harmonic ion cyclotron resonance heating of D-beam ions have been achieved for the first time on EAST. Acceleration of D ions is also confirmed by neutron yield. This improvement of the neutron yield during combined NBI and ICRF heating can be explained by a build-up of the NBI Injected fast ions accelerated by the ICRF wave.

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