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# OFF-AXIS ECRH EXPERIMENTS ON HL-1M TOKAMAK

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Effective electron cyclotron resonance heating (ECRH) has been demonstrated in many tokamaks [1][2]. Because of the localized absorption of the electron cyclotron wave, it is possible to control the plasma electron temperature profile and plasma current density profile. In this way the negative magnetic shear can be obtained, which may be of benefit to the plasma confinement. Many tokamaks have carried out the experiments, but the results are not in agreement. For example, a steady-state hollow temperature profile or a flat temperature profile has been obtained in the RTP device [3], but in the most of other tokamaks, such as DIII-D, the temperature profile during off-axis ECRH seams to agree with the principle "profile consistency". We are interesting in this problem and investigate the off axis ECRH on HL-1M tokamak. In this paper, the electron temperature profile and some MHD phenomena during off axis ECRH will be described.

ECRH experiments have been carried out on HL-1M tokamak (major radius is 102 cm, minor radius is 26 cm ). A 75 GHz gyrotron was used to provide the total power of 150-350 kW. The pulse duration of the wave is about 30-50 ms. Transmission system consists of oversized wave-guides with diameter 8 cm and some metallic reflectors, as shorn in Fig.1. At the end of wavequide the wave is coupled into the plasma. The efficiency of the transmission line is about 80%. Microwave is launched into plasma perpendicularly to toroidal field at the low field side as an ordinary mode (o-mode).

In HL-1M tokamak, plasma current $I_p$=80-200kA. The electron temperature of the plasma center is about 400-800eV. The mean electron density is in the range of 1.5-3.5 x$10^{13}$cm$^{-3}$. Toroidal magnetic field can be changed from 2.4T to 2.7T. In this magnetic field range, the

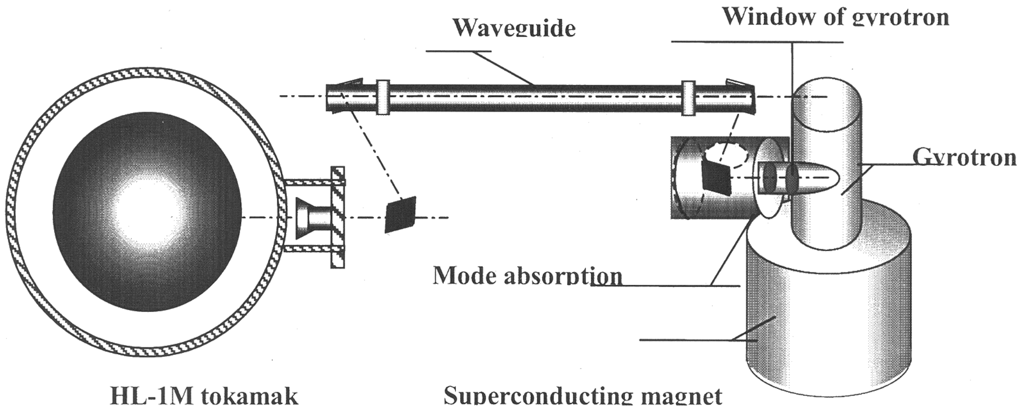


**Fig.1.** ECRH Quasi-Optical Transmission and Antenna System on HL-1M

position of the resonance point of wave with 75GHz can be moved from plasma center to about 10cm at high field side, then off axis ECRH can be studied.

**Plasma heating results:**

During ECRH, electron temperature is measured by electron cyclotron emission (ECE) through a scanning 2mm-microwave receiver and an instrument of soft x-ray energy spectra with three detectors. The electron temperature during ECRH increases more than 50% of that during ohmic heating. Fig.2 (a) shows the electron temperature trace during ECRH, which measured by means of ECE. Fig .2 (b) shows the electron temperature trace measured by soft X-ray energy spectrum. The time resolution of the instrument is about 50 ms. The absolute average electron temperature can be estimated by this measurement, which can be used to calibrate for ECE. According to the temperature profile, measured by ECE diagnosis, the electron temperature of the plasma center during ECRH is increased from 450eV to 750eV.

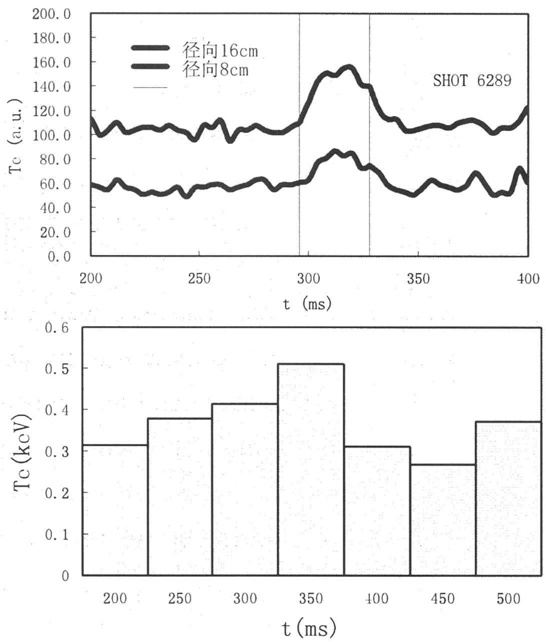


**Fig.2** (a) the electron temperature trace during ECRH, which measured by means of ECE. (b) the electron temperature trace measured by soft X-ray energy spectrum.

The heating efficiency depends on plasma electron density obviousely. In general, the heating efficiency is higher in 1.5-3x$10^{13}$cm$^{-3}$ density range. At the lower density ( < 1.5x$10^{13}$cm$^{-3}$ ) the absorption of the wave is weaker, because the plasma optical depth is thinner. On the other hand, at the higher density (>3x$10^{13}$cm$^{-3}$) the refraction of the wave can not be negligible, (the density is higher than 5.6x$10^{13}$cm$^{-3}$, the microwave will be reflected from cut off layer). To increase the absorption efficiency of wave it is necessary to move the resonance point near to plasma axis. So the absorption is sensitive to the toroidal magnetic field. When the magnetic field is more than 2.6T, the plasma absorption becomes stronger.

The temperature profile during off-axis ECRH has been modified slightly comparing with that during Ohmic stage. Fig .3 shows the electron temperature profiles in shot 6261. In this shot, the toroidal magnetic field is about 2.5T, the resonance point of the wave is about 8cm from the plasma center. The temperature profile inside the deposition radius becomes flat slightly. When the resonance point is near the plasma center, the temperature profile can not be obtained completely, because the spectrum can not cover all the ECE frequency range. But we can confirm that the plasma current profile has been changed in this situation by soft X- ray diagnosis.

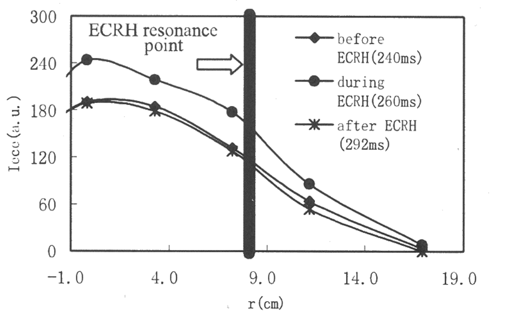


**Fig.3** Electron temperature profile during off axis ECRH (ECW is injected after 250ms) Bt=2.5T, Ip=150kA, ne=$1.5x10^{13}cm^{-3}$

## Sawtooth oscillation of soft x ray during ECRH

Sawtooth oscillations are observed by the arrays of soft X- ray diodes on the HL-1M tokamak. During ECRH both the period and amplitude of the sawtooth of soft X- ray are varied, and some double sawteeth appear during ECRH. The complete double sawtooth cycle in the plasma center has four phases: a rise, a disruption with smaller relative amplitude, another rise and another disruption with greater relative amplitude. For chords far away from the plasma center, the sense of the sawtooth is reversed. The formation of the double sawtooth can be explained as the following physical picture: The current density profile or q – profile has been changed due to the off axis ECRH. If there are two q=1 surfaces, the m=1/n=1 magnetic islands will develop in the two q=1 surfaces. When the reconnection and mixing of the magnetic island encompass the magnetic axis completely, the double sawteeth in the plasma center and the reversed double sawteeth outside of the q = 1 surface can be observed[4]. The typical double sawtooth during ECRH in shot 6313 are shown in Fig.4. In this shot $B_t$=2.6, $n_e$=$1.5x10^{13}cm^{-3}$, $I_p$=150kA, $P_{ECW}$=300kW. Because the toroidal magnetic field is higher, so the resonance point is near to the magnetic axis and the complete reconnection occur in both q=1 surfaces. In some situations, the complete reconnection may not occur in both q=1 surfaces. only partial reconnection can occur and the sawteeth in the center plasma may not be in

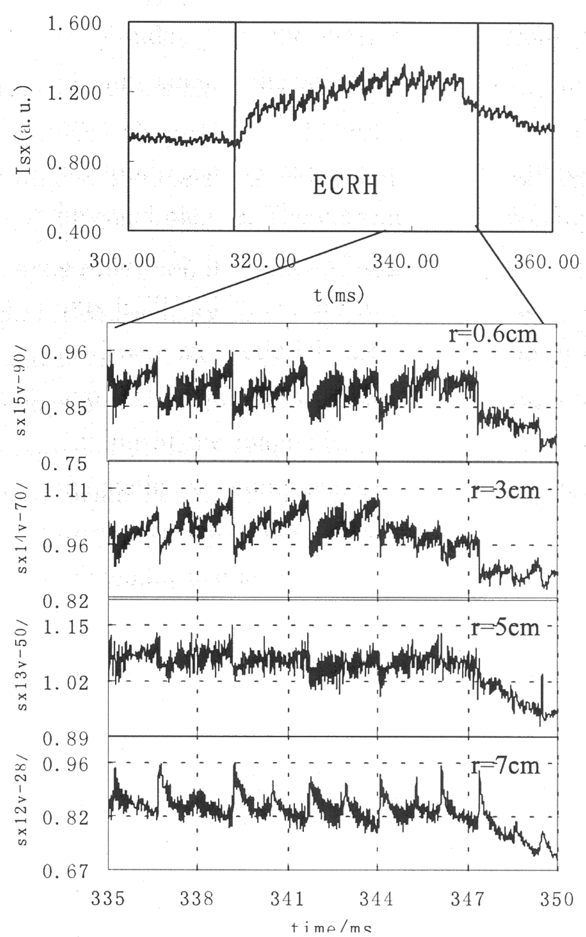


**Fig.4** The typical double sawtooth during ECRH in shot 6313 $B_t$=2.6, $n_e$=$1.5x10^{13}cm^{-3}$, $I_p$=150kA, $P_{ECW}$=300kW.

double. Fig.5 expresses In this case the center sawteeth are single and the outside sawteeth are double . It means that the reconnection of the islands inside q=1 surface encompass the center of plasma and the reconnection of the islands outside q=1 surface do not occur at the center of plasma. To compare with the soft x ray during off-axis ECRH, the sawteeth during on-axis heating are observed. When the toroidal magnetic field Bt is 2.69T, the resonance point move to plasma center. In this situation, the sawtooth before ECRH and during ECRH have not changed as shown in Fig.6.

In conclusion, electron heating by ECRH has been performed in HL-1M tokamak. It has been confirmed that the off-axis ECRH can effect the plasma current density profile through analysis of the soft x-ray measurements, when the absorption of the wave is stronger. In this situation, the negative magnetic shear occurs. When the resonance point is far away form the plasma center, the electron temperature profiles have been modified slightly, because of the weaker absorption at the edge of plasma. The deposited power and plasma density are most important factors for controlling the plasma profiles by ECRH.

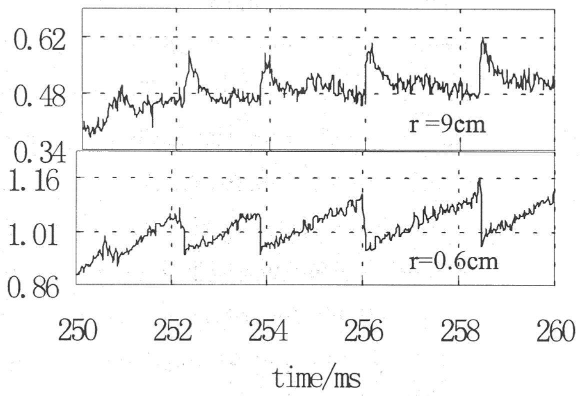


**Fig.5** The soft x ray trace during ECRH with the toroidal magnetic field Bt=2.58T.

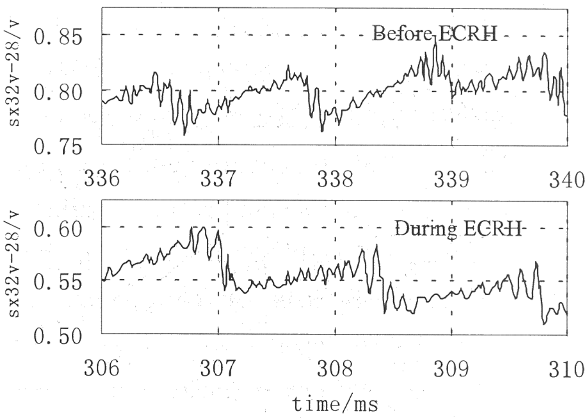


**Fig.6** The sawtooth evolution during on-axis ECRH in shot 6307 Bt=2.69T,ne=1.6x1013cm3,Ip=150kA, Pecrh=300kW

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