Production and electron heating of over-dense plasmas by 2.45 GHz electron Bernstein waves on CHS

R. Ikeda, H. Igami, K. Toi, S. Kubo, M. Takeuchi, C. Suzuki, T. Shoji[a],
T. Shimozuma, Y. Yoshimura, H. Takahashi, T. Mutoh and CHS Experiment Group

National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan
[a] *Department of Energy Engineering and Science, Nagoya University, Furo-cho, Nagoya, Japan*

e-mail : r.ikeda@nifs.ac.jp

Production and heating of over-dense plasmas by 2.45 GHz microwave system under very low field condition was performed and demonstrated on CHS. In this experiment, microwave systems were arranged to aim at taking place mode conversion of launched electron cyclotron wave effectively into electron Bernstein wave (EBW). Power deposition profiles in produced over-dense plasmas were measured directly by using power modulation technique at various magnetic configurations. Power deposition was in over-dense region. To clarify wave trajectories, power absorption mechanism and mode conversion, the numerical analysis by a ray-tracing method was performed. Calculated ray-trajectories achieved near the region where power deposition was experimentally observed.

1. Introduction

Production of low temperature plasmas using 2.45 GHz electron cyclotron wave (ECW) was attempted under very low field conditions (B_t < 0.1 T) on the Compact Helical System (CHS). It is expected that such plasma is effective to study plasma transport and electrostatic fluctuations because their measurements are possible by Langmuir probe [1]. Moreover, over-dense plasmas produced in lower filed condition may contribute to study of MHD physics because it becomes high beta plasma. We aimed at converting ECW into Electron Bernstein wave (EBW) to generate higher-performance plasmas. EBW is expected to electron heating and current drive in over-dense plasmas. EBW has characters that it is electrostatic wave, is strongly absorbed even in low temperature plasmas. EBW cannot transmit in vacuum region and requires mode-conversion processes, so-called X-B mode conversion [2] and O-X-B mode conversion [3]. This study aims at clarifying the mode conversion, propagation and absorption of EBW by detailed measurements of the power deposition profile and numerical analysis by ray-tracing in a low temperature plasma at very low field.

2. Experimental system and diagnostics

CHS is a small low-aspect-ratio heliotron/torsatron device. The major radius is 1.0 m and averaged minor radius is 0.2 m. In order to produce and heat plasma, two 2.45 GHz ECH systems which the maximum output power of each oscillator is 20 kW were installed as shown in Fig. 1. The maximum modulation-frequency of ECH power was up to 10 kHz. Microwave having TE_{10} mode is launched from both oscillators. Finally, the injection mode of ECH#1 is converted to TE_{11} mode which the components of electric filed is perpendicular to todoidal magnetic field by a twist waveguide and a rectangle-circular waveguide. This launching method expects perpendicular injection of X-mode. ECH#2 is converted to TE_{11} mode which electric filed is parallel to todoidal magnetic field by a rectangle-circular waveguide. This launching method expects oblique injection of O-mode. Although it is rough estimation, the angle of main lobe on the mouse of ECH#1 and ECH#2 launchers is about 90 degree and about 55 degree, respectively. Therefore, the directivity of injected waves is not local and these polarizations would become elliptical.

We used mainly a triple Langmuir probe, 2mm microwave interferometer. A triple Langmuir probe measures simultaneously electron density (n_e), electron temperature (T_e) and space potential. This probe is movable in the perpendicular direction from an upper port. The central line averaged electron density is measured by 2 mm microwave interferometer. The local electron density measured by the probe is calibrated by line averaged electron density. The generation of plasmas is performed in hydrogen gas.

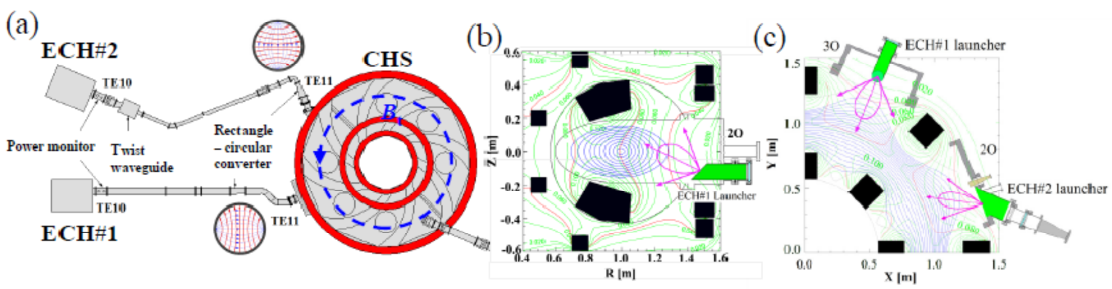

Fig.1 (a) Location of CHS and 2.45 GHz ECH systems. (b) Poloidal cross-section in ECH#1 port. (c) Toroidal cross-section in equatorial plane.

3. Power deposition measurement by power modulation technique

Power deposition profiles in produced over-dense plasmas were measured directly by using power modulation technique at various magnetic configurations [4]. In this experimental campaign of CHS, the modulation frequencies of the ECH#1 and #2 power was adopted to be 7 kHz and 9 kHz from the consideration of global energy confinement time. Figure 2 is radial profiles of electron density, n_e, electron temperature, T_e, the response in electron pressure (= n_eT_e) for modulated ECH powers from ECH#1 and ECH#2 sources, δp_e, and phase lag, Φ_{pe}, difference between δpe and the modulated ECH power at B_{ax}/B_{res} = 100%, 70% and 50 % (B_{res} = 0.0875 T). Maximum electron density exceeds about 3 times O-mode cutoff density (n_{co} ~ 7.5x10^{16}m^{-3}). Power deposition profile corresponds to δp_e-profile and the peak position is in over-dense region. The bottom of phase lag coincides with the peak position. These results suggested that injected powers as mode-converted EBW were transmitted to over-dense region.

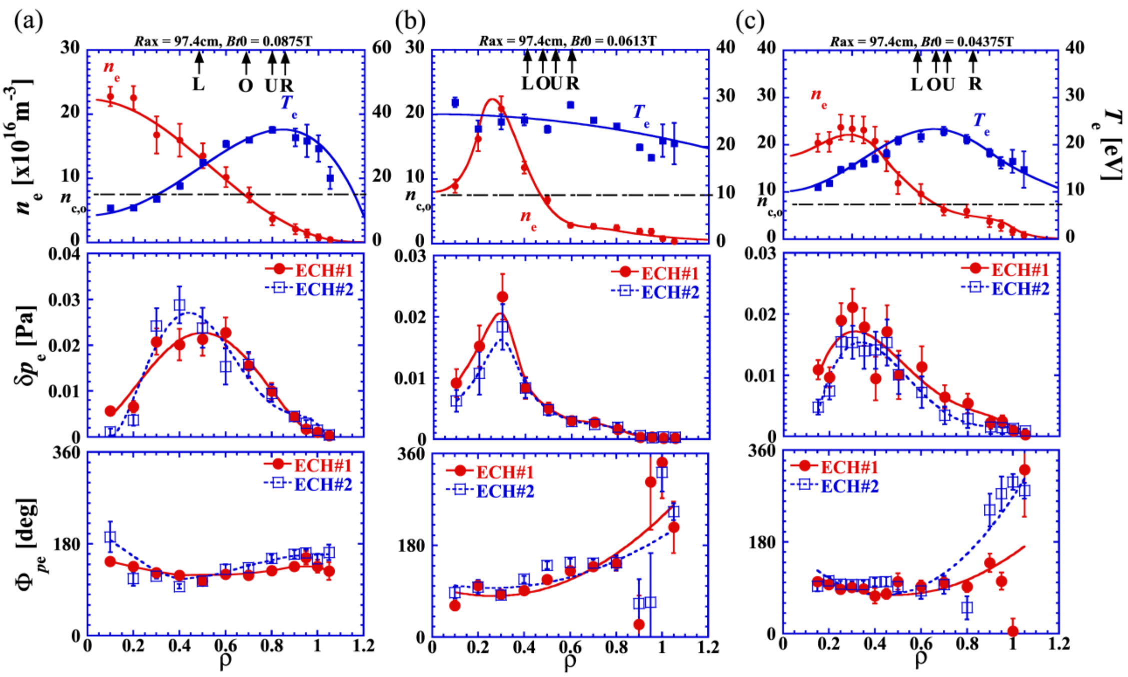

Fig.2 Radial profiles of electron density, n_e, electron temperature, T_e, the response in electron pressure (= n_eT_e) for modulated ECH powers from ECH#1 and ECH#2 sources, δp_e, and phase lag, Φ_{pe}, difference between δpe and the modulated ECH power in B_{t0}/B_{res} = 100% (a), 70% (b) and 50% (c). Data for ECH#1 and ECH#2 are shown with circles and squares, respectively. The positions of R, L, O and U indicate the right hand, left hand and O-mode cutoff layers, and upper hybrid resonance layer, respectively.

4. Estimation of mode conversion and power deposition by ray-tracing

It was investigated from results of modulation experiments that injected waves were clearly absorbed in over-dense region. However, it is unclear how the incident waves are transmitted and absorbed there. Moreover, it is not clarified yet whether or not the abovementioned mode conversion scenario occurs effectively due to long wavelength and low directivity. Therefore, we have investigated wave trajectories, power deposition mechanism and mode conversion by using a ray-tracing method developed for LHD plasmas [5]. In this paper, we researched transmission and power deposition by O-X-B mode conversion scenario.

O-X-B mode conversion is the following scenario. When electron density exceeds O-mode cutoff density, obliquely injected O-mode converts slow X-mode mode conversion point where the O-mode cutoff coincide the left-hand cutoff of X-mode. O-X mode conversion ratio [3] is

$$C_{\mathrm{OX}} = \exp\left[-\pi k_0 L_{\mathrm{n}} \sqrt{\frac{\beta}{2}} \left\{ 2(1+\beta)\left(N_{//,\mathrm{opt}} - N_{//}\right)^2 + N_w^2 \right\} \right].$$

$$N_{//,\mathrm{opt}} = \sqrt{\beta(1+\beta)}$$

Here, k_0 is wave number in vacuum region, L_{n} is scale length of density gradient, β is Ω_{ce}/ω, $N_{\|}$ is parallel component of refractive index, N_{w} is the refractive index which is perpendicular to the direction of magnetic file and the direction of density gradient. If $N_{\|,\mathrm{opt}} = N_{\|}$ and $N_{\mathrm{w}} = 0$, O-mode converts perfectly to slow X-mode. If this condition is not satisfied, an evanescent region occurs between the O-mode cutoff and the left-hand cutoff. Slow X-mode converts to EBW at upper hybrid resonance (UHR) layer.

To survey the realization of O-X-B scenario, C_{ox} is estimated. Profiles of electron density and electron temperature are profiles of solid line in Fig. 2. Figure 3 shows contour plots of C_{ox} which are calculated from ECH#1 and ECH#2 port as function of injection angle to toroidal direction, ξ, and poloidal direction, ζ, in the case of $B_{\mathrm{t0}}/B_{\mathrm{res}}$ = 100 %, 70 % and 50 %. The range of the transverse of these plots indicates area which corresponds to angle of radiation pattern of microwave. The angle of radiation pattern above -3dB is about 90 deg on mouse of ECH#1 launcher and about 55 deg on mouse of ECH#2 as shown in Fig 1 (b) and (c). These plots show that mode conversion points spreads relatively over wide range. These results indicate that O-X-B scenario is also realized from both ECH launchers. To research ray trajectories and power deposition, we select some target positions where C_{ox} was relatively high ($C_{\mathrm{ox}} > 0.5$). In the case of $B_{\mathrm{t0}}/B_{\mathrm{res}}$ = 100%, target positions and mode-conversion ratios (ξ, ζ, C_{ox}) are (-40, -10, 0.71), (28, 0, 0.78) and (-8, -6, 0.98) on ECH#1, and (26, -7, 0.96) and (32, -2, 0.76) on ECH#2. In the case of 70%, (ξ, ζ, C_{ox}) are (-15, -5, 0.99), (-25, 0, 0.58) and (30, 6, 0.89) on ECH#1, and (22, -6, 0.78), (26, -2, 0.98) and (31, 0, 0.77) on ECH#2. In the case of 50% (ξ, ζ, C_{ox}) are (-6, -13, 0.53), (-5, -10, 0.83) and (1, -5, 0.53) on ECH#1, and (32, -4, 0.55), (-3, -12, 0.97) and (0, -10, 0.92) on ECH#2.

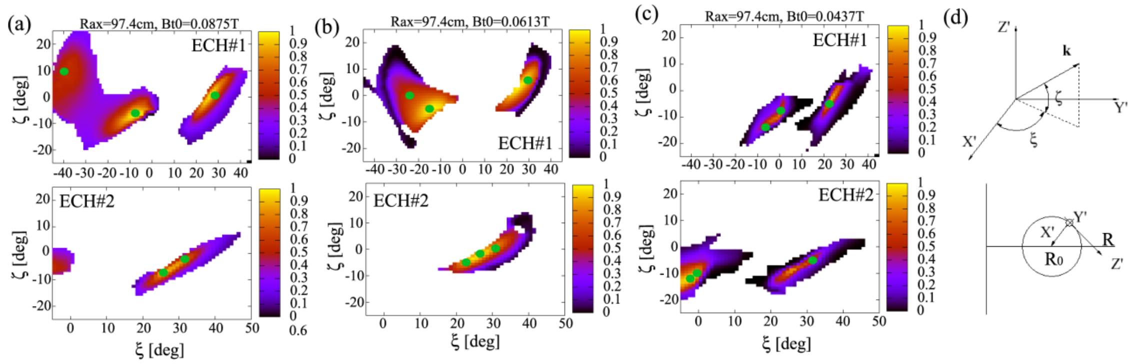

Fig.3 Contour plots of O-X mode conversion ratio, Cox, as function of injection angles of toroidal direction, ξ, and poloidal direction, ζ, in B_{t0}/B_{res} = 100% (a), 70% (b) and 50% (c). (d) Coordinates of launching angles ξ and ζ. Circle points are injection target on O-X mode conversion plane in (a), (b) and (c).

The rays propagate towards these points and restart at the point beyond the evanescent region. When rays reach cutoff layer of low field side, the component of the refractive index that is parallel to electron density gradient direction, N_v, reaches zero. So, $N_\perp$ reaches N_w. It is assumed that refractive index vector, $\boldsymbol{N}_s$, consisted of N_w and $N_\parallel$ just before evanescent region is conserved in evanescent region. These ray-trajectories are shown in Fig. 4. These rays were absorbed as EBW in over-dense region. Figure 5 shows radial profiles of Ω_{ce}/ω, $N_\parallel$, $N_\perp$, and power absorption in B_{t0}/B_{res} = 100 %, 70 % and 50 %. There are almost no differences in power deposition region of wave injected from ECH#1 and ECH#2. The value of $|N_\parallel|$ increased rapidly as soon as slow X-mode converts to EBW. The value achieved about 5 - 30. This large shift of $|N_\parallel|$ causes strong Doppler-shifted fundamental or harmonic electron cyclotron resonance damping. In the case of 100 %, fundamental electron resonance layer received Doppler-shift. In the case of 50 %, Doppler-shifted 2nd harmonic and 3rd harmonic resonance damping occurred. Although the deposition regions are similar in these on-axis conditions, $N_\parallel$ in 50% require lager value compare with one in 100%.   In the case of 70%, fundamental and 2nd harmonic resonance layers locate in edge region (ρ > 0.7). The injected power was absorbed near plasma center by Doppler-shifted fundamental and 2nd harmonic resonance layers. These power deposition regions are relatively similar to experimental result shown in Fig 2. There are high possibilities that incident waves transmitted there.

It's necessary to bring in calculation of multi-ray and power distribution of radiation pattern of microwaves to estimate power deposition profile more in detail.

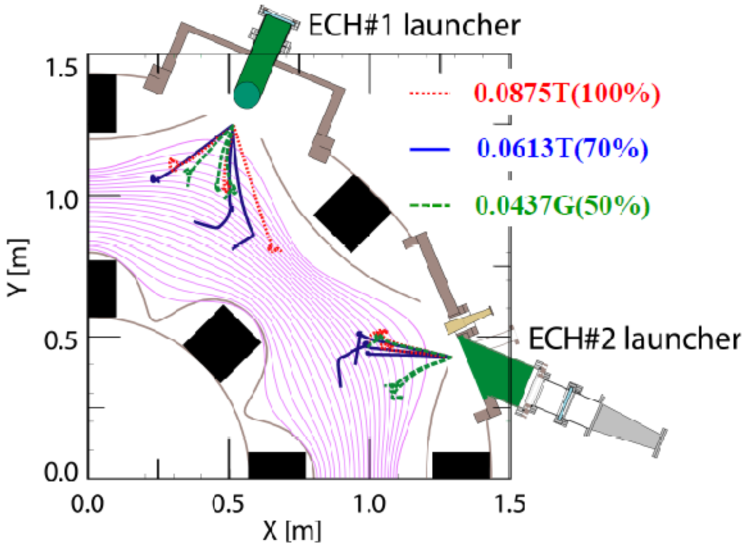

Fig.4 Trajectories of rays launched from ECH#1 and ECH#2 port in B_{t0}/B_{res} = 100 %, 70 % and 50 %.

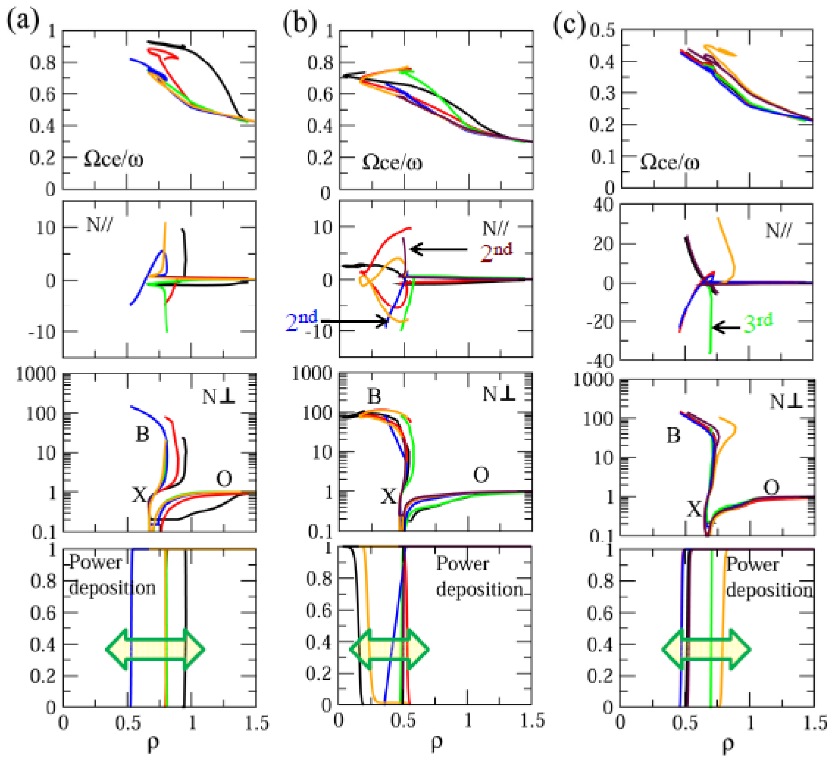

Fig.5 Radial profiles of Ω_{ce}/ω, $N_{\parallel}$, $N_{\perp}$ and power deposition in the case of B_{t0}/B_{res} = 100 % (a), 70 % (b) and 50 % (c).

5. Summary

In CHS, over-dense plasmas beyond 3 times of O-mode cutoff density were successfully produced with 2.45 GHz microwaves at very low toroidal field conditions. Power deposition profiles were measured by the power modulation method, and were concentrated in the over-dense region. Realization of O-X-B mode conversion scenario was estimated by ray tracing. O-X mode conversion region spread widely and the scenario can be expected from both ECH launchers. Calculation results showed that mode-converted EBW was absorbed by Doppler-shifted fundamental or harmonic electron cyclotron resonance because of large shift of $N_{\parallel}$. The power deposition region was similar to the regions where power deposition profiles were measured by modulation method. As an important future work, detailed estimation of power deposition profiles by bringing in multi-ray analysis and power distribution of radiation pattern of microwave. Moreover, the X-B mode conversion scenario is also considered.

[1] K. Toi *et al.*, P J. Plasma Fusion Res. SERIES **6**, 516 (2004).

[2] A. K. Ram *et al.*, Phys. Plasmas **7**, 4084 (2000).

[3] E. MJØLHUS, J. Plasma Physics31, 7 (1984).

[4] R. Ikeda *et al.*, Physics of Plasmas, Vol. 15, pp.072505-1~13, (2008).

[5] H. Igami *et al.*, submitted to Plasma Science and Technology (2009).