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Electron Bernstein wave heating via OXB mode conversion process in LHD
LHDにおけるOXBモード変換過程を介した電子バーンシュタイン波加熱実験

Hiroe Igami[1)], Shin Kubo[1,3)], Takashi Shimozuma[1)], Yasuo Yoshimura[1)], Hiromi Takahashi[1)], Hiroshi Idei[2)], Masaki Nishiura[1)], Shinya Ogasawara[3)], Ryohei Makino[3,)] Ryuhei Kumazawa[1)] and Takashi Muto[1)]

伊神弘恵, , 久保伸, 下妻隆, 吉村泰夫, 高橋裕己, 出射浩, 西浦正樹, 小笠原慎哉, 牧野良平, 熊沢隆平, 武藤 敬

1)National Institute for Fusion Research Institute, 322-6, Oroshi-cho, Toki, Gifu, 509-5292, Japan
2)Research Institute for Applied Mechanics, 6-1 Kasuga-koen, Kasuga, Fukuoka, 816-8580, Japan
3)Department of Energy and Technology, Nagoya University, Nagoya 464-8463, Japan
1)核融合科学研究所 〒509-5292 岐阜県土岐市下石町322-6
2)九州大学応用力学研究所 〒509-5292 福岡県春日市春日公園6-1
3)名古屋大学大学院工学研究科エネルギー理工学専攻 〒464-8463

The gradient changes of the stored energy and the ECE signals were observed with turning on/off of the ~1MW, 77GHz, millimeter wave launching from the lower field side in the high dense plasma in the Large Helical Device (LHD). The line -averaged electron density was more than the cutoff density of the 77GHz electromagnetic wave. Electron cyclotron heating by the electron Bernstein wave via the Ordinary –eXtraordinary –EBW (O-X-B) mode conversion process was performed.

1. Introduction

Electron cyclotron heating (ECH) with the electron Bernstein wave (EBW) has been regarded as a possible way to heat the high dense plasma where the electron density is more than the cutoff density of the electron cyclotron (EC) wave since the EBW has no density limit in propagation. Normal electromagnetic (EM) propagation modes, they are, the ordinary (O-) mode and the extraordinary (X-) mode cannot propagate the region beyond the cutoff of each mode. Since the EBW is the electrostatic wave that propagates in the hot magnetized plasma, the EBW is required to be excited via the mode conversion process from the slow X-mode at the upper hybrid resonance (UHR) layer where the slow X-mode shows a characteristic of the electrostatic wave. The EM wave should be launched from the outside of the plasma so that it connects with the slow X-mode propagating toward the UHR layer. In the Large helical Device (LHD), launching the slow X-mode from the high field side [1,2] and launching the O-mode obliquely to the external magnetic field from the low field side are applicable [3,4] to excite the EBW. Here we report the experimental result of the EBW heating with the latter method with launching high power (~1MW) 77GHz millimeter wave.

When the O-mode is launched from the low field side, the launched O-mode connects to the slow X-mode with the ratio given by an analytical form as follows with variables near the cutoff [5].

$$T = exp\{-k_0 \pi L_n(\beta/2)^{1/2}[2(1+\beta)(N_{//}-N_{//opt})^2+N_v^2]\} \quad (1)$$

Where, k_0 is the wave number in the vacuum, L_n is the scale length of the density gradient, $N_{//opt}=\{\beta/(1+\beta)\}^{1/2}$ ($\beta=\Omega_{ce}/\omega$), $N_{//}$ is the parallel component of the refractive index, N_v is the component of the refractive index that is perpendicular to the external magnetic field and the direction of the density gradient. If $N_{//} = N_{//opt}$ and N_v =0, the launched power is fully mode converted to the EBW. As $N_{//}$ deviates from $N_{//opt}$ and/or $|N_v|$ is not zero, the evanescent region for the O-mode appears between the plasma cutoff and the light-handed cutoff and reflection occurs to some extent. In the parameter range of the LHD, T in eq. (1) indicates this Ordinary(O)-extraordinary(X)–EBW(B) mode conversion rate T_{OXB} since the width of the evanescent region of the X-mode between the UHR layer and the right-handed cutoff is thick enough so that the slow X-mode cannot pass through the evanescent layer toward the low field side and fully mode converted to the EBW.

2. Experimental set up and results

For ECH by EBW via the O-X-B mode conversion process 1.06MW, 77GHz, millimeter wave was launched from the launcher placed in the

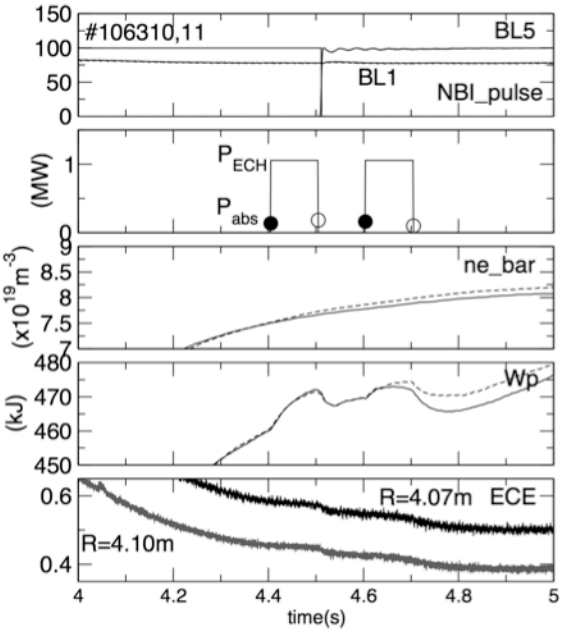

Figure 1: NBI waveforms, ECH pulses, line-averaged electron density, stored energy(Wp), 2nd harmonic ECE signals (not caribrated). (R_{ax}, B_t) = (3.75m, 2.4T). Solid line:LC wave, Dotted line:RC wave launching

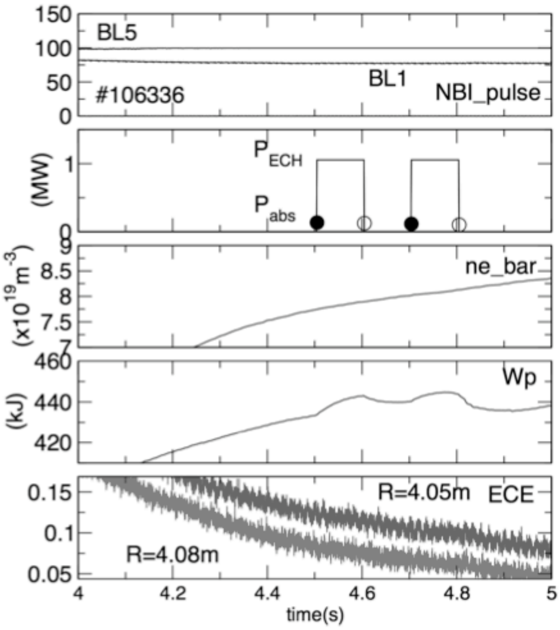

Figure 2: Similar plots to Figure 1. (R_{ax}, B_t) = (3.75m, 2.2T)

horizontal port of the LHD. Figure 1 shows the discharge waveforms in the experiment when (R_{ax}, B_t) = (3.75m, 2.4T) was selected, where R_{ax} is the major radius and B_t is the round averaged magnetic field strength at the magnetic axis. The plasma was sustained by tangential and vertical neutral beam (NB) injections. The line averaged electron density was more than the cutoff density of 77GHz, 7.35×10^{19} m^{-3}. The gradient of the stored energy and the second harmonic ECE signals changed before turning-on and turning-off of the ECH power. The heating efficiency estimated from the change of the temporal differentiation of the stored energy is about 15%. ECH inside the last closed flux surface was performed. Only the O-mode launching can excite the EBW in this experimental configuration, however both cases of the left handed circularly polarized (LC) wave (nearly the O-mode, solid line in Figure 1) and right handed circularly polarize (RC) wave (nearly the X-mode, dotted line in Figure 1) launching, the stored energy changes.

Figure 2 shows the similar waveforms when (R_{ax}, B_t) = (3.75m, 2.2T) was selected. ECH inside the last closed flux surface was also performed. The estimated heating efficiency was also about 15%.

3. Discussion and conclusion

In the previous numerical examination with ray-tracing and eq. (1), the calculated T_{OXB} is more than 90% and the power absorption region is near the last closed flux surface in (R_{ax}, B_t)= = (3.75m, 2.4T). On the other hand, in (R_{ax}, B_t) = (3.75m, 2.2T) aiming for getting high T_{OXB} is prohibited by port wall and possible T_{OXB} is less than 50%, however the power absorption region shifts toward the plasma central region [4]. The launching direction was changed shot by shot to looking for the optimum one, however the estimated heating efficiencies were similar when the gradient of the stored energy changed.

To improve the accuracy of the numerical examination, the following tasks should be performed.

- Considering the width of the launched beam and its intensity.
- Adopting the density and temperature profiles which agree with the profiles in the experiment well including the region outside the last closed flux surface.
- Improvement of the accuracy of the ray tracing near the cutoff.

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